FlexTOE: Flexible TCP Offload with Fine-Grained Parallelism

Rajath Shashidhara [1], Tim Stamler [2], Antoine Kaufmann [3], Simon Peter [1]

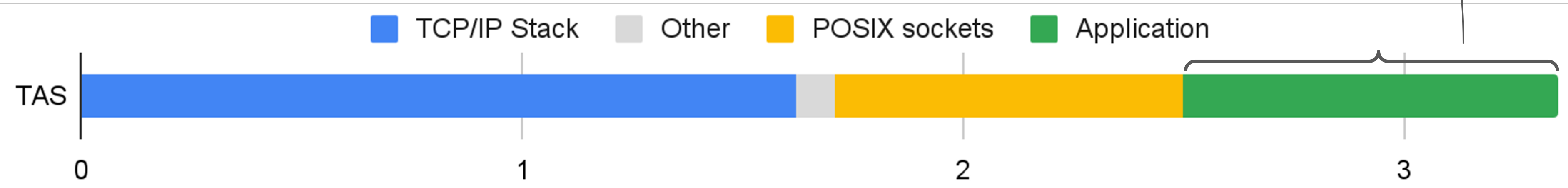
[1] University of Washington, [2] MPI-SWS, [3] The University of Texas at Austin

High CPU Overhead of TCP

- TCP remains the default protocol in the datacenter
- But TCP stacks have high CPU overhead
    - Even with modern optimized stacks (TAS, Snap, ...)

only 26%

CPU profile of Memcached with 32B requests/responses



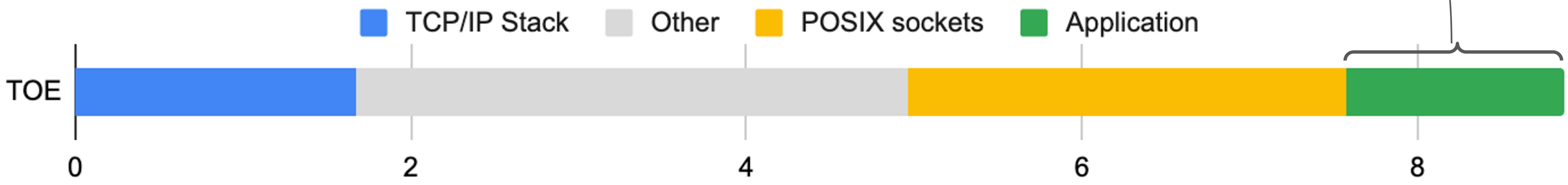
To go further, we need to offload...

Need for ***Flexible*** TCP Offload

- **Flexibility**: Datacenter networks evolve rapidly
  - Operators need flexibility for **agile development**
- **Existing TOEs are hardwired**: slow upgrade cycles

only 16%

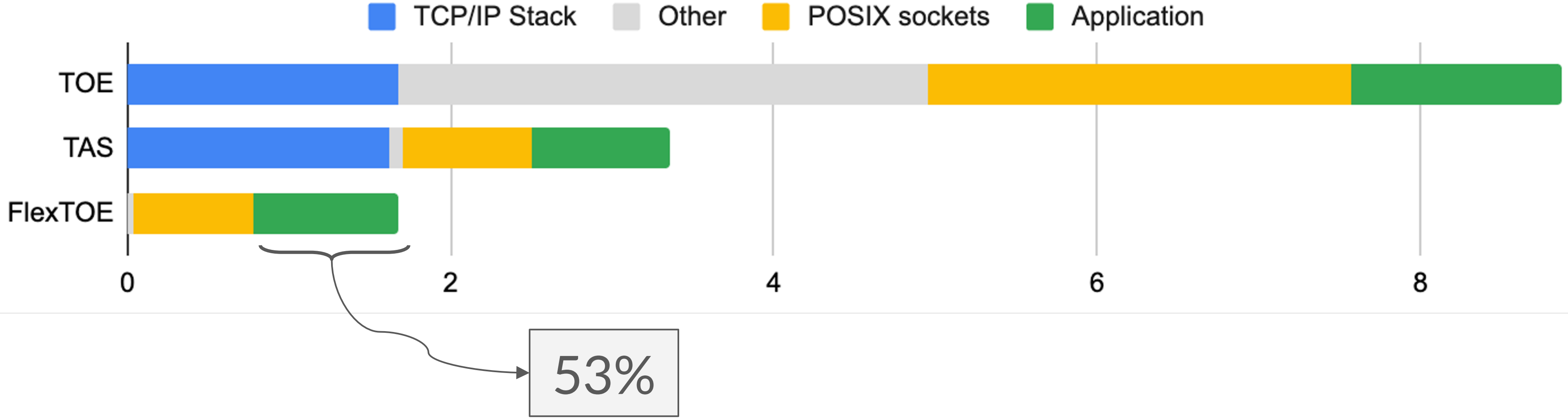
CPU profile of Memcached with Chelsio Terminator TOE



TCP Offload:
Can we get *flexibility* and *performance*?

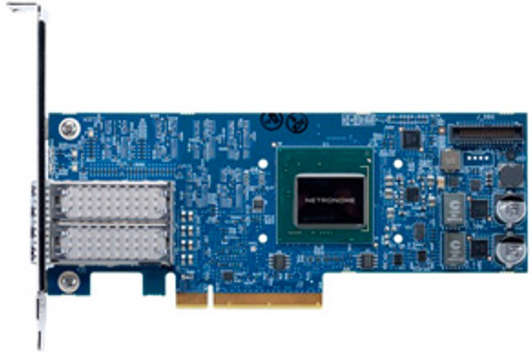
FlexTOE: Flexible, High Performance TCP Offload

- Eliminates all host TCP stack overheads
- Supports POSIX-sockets, DCTCP/Timely congestion control
- Fully extensible (software development velocity), with eBPF support



53%

TCP Offload to SmartNICs - Challenges



SmartNICs are flexible but **restrictive**:

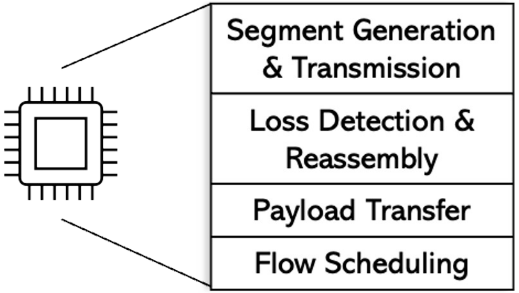
- Eg: Netronome Agilio, Mellanox BlueField, Pensando DSC, Fungible DPU, ...
- **Parallel** architectures geared towards **stateless** offloads
- **Many wimpy cores** with **limited memories**

TCP connections are processed **sequentially**:

- **Stateful** code paths track in-flight segments
- Stringent **per-packet time budgets**
- **Sensitive to reordering**

Traditional TCP stacks perform poorly on SmartNICs

Traditional stacks:
Sequential, Monolithic



Segment Generation & Transmission

Loss Detection & Reassembly

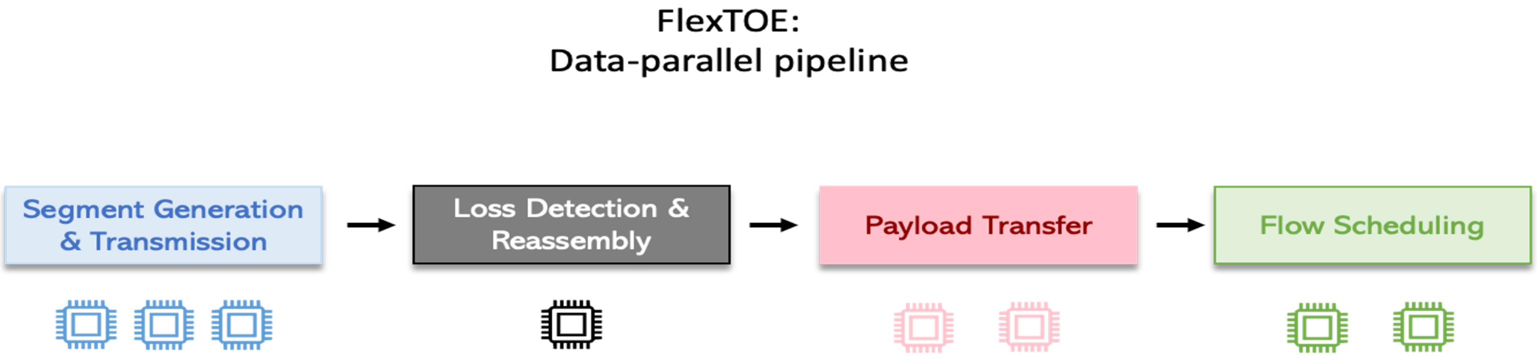
Payload Transfer

Flow Scheduling

FlexTOE: Flexible, High-Performance TCP Offload with Fine-grained Parallelism

To provide **high performance** and **flexibility**, FlexTOE leverages:

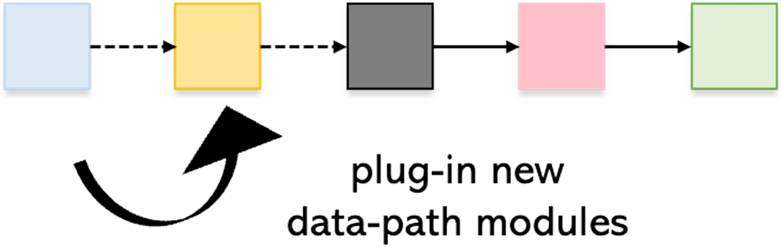
- **Modularity**: fine-grained modules keep private state and communicate explicitly
- **Fine-grained parallelism**: Modules may be replicated, sharded, execute out-of-order
- **One-shot data-path offload**: Payload is never buffered on the NIC



FlexTOE Flexibility: XDP

Supports eXpress Data Path (XDP) modules implemented in eBPF

- Operate on raw packets
- Shared state via BPF maps

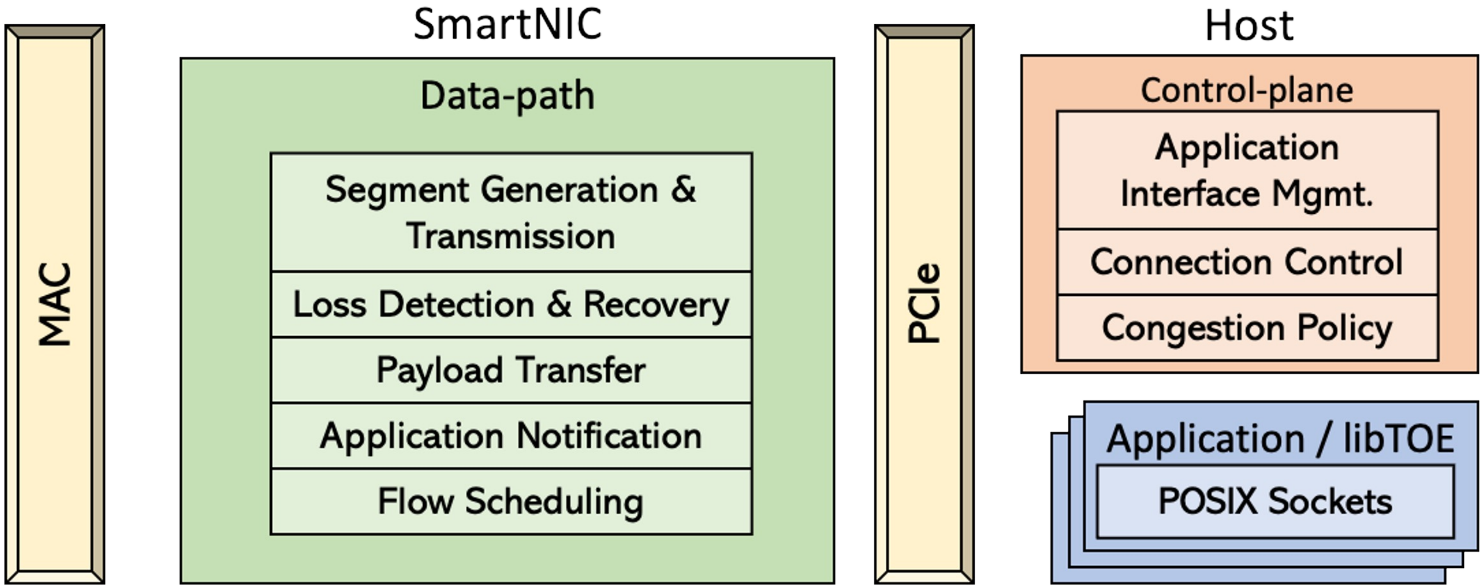


Implemented common datacenter features

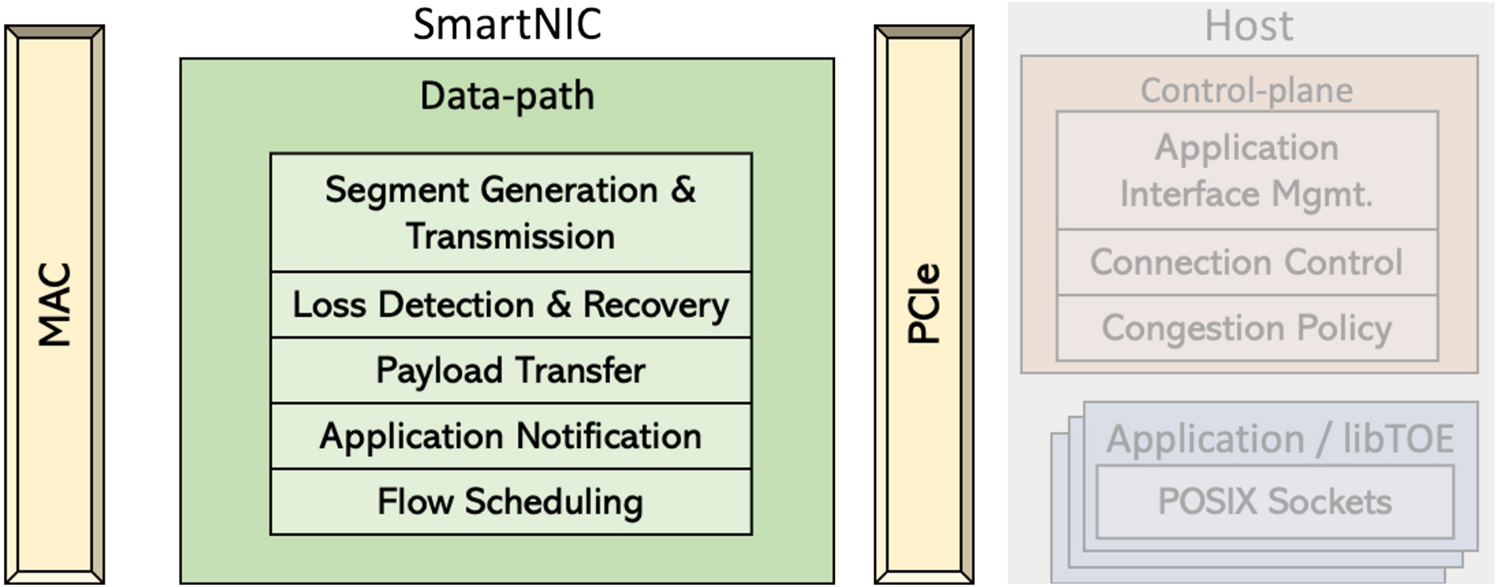
- Tracing, Statistics & Profiling
- Connection Firewalling
- VLAN encapsulation/decapsulation
- tcpdump

AccelTCP's [NSDI20] connection splicing in 24 lines of eBPF at NIC line rate!

FlexTOE Offload Architecture

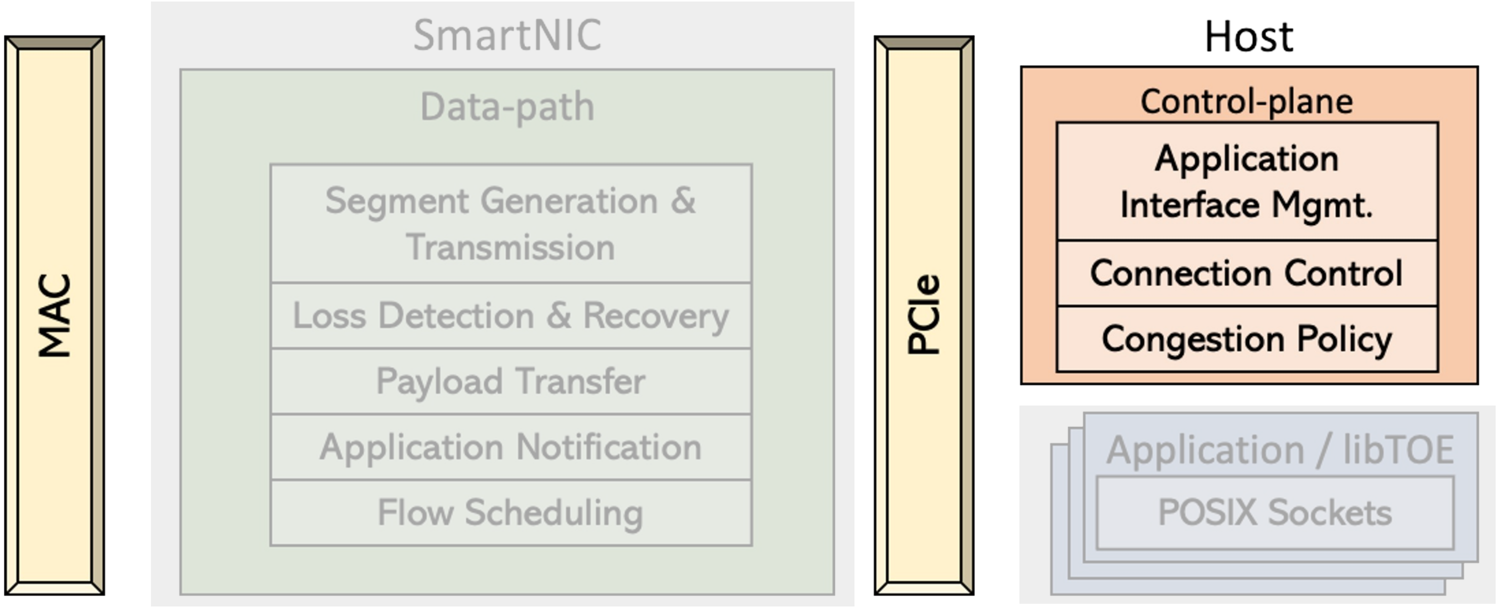


FlexTOE Offload Architecture



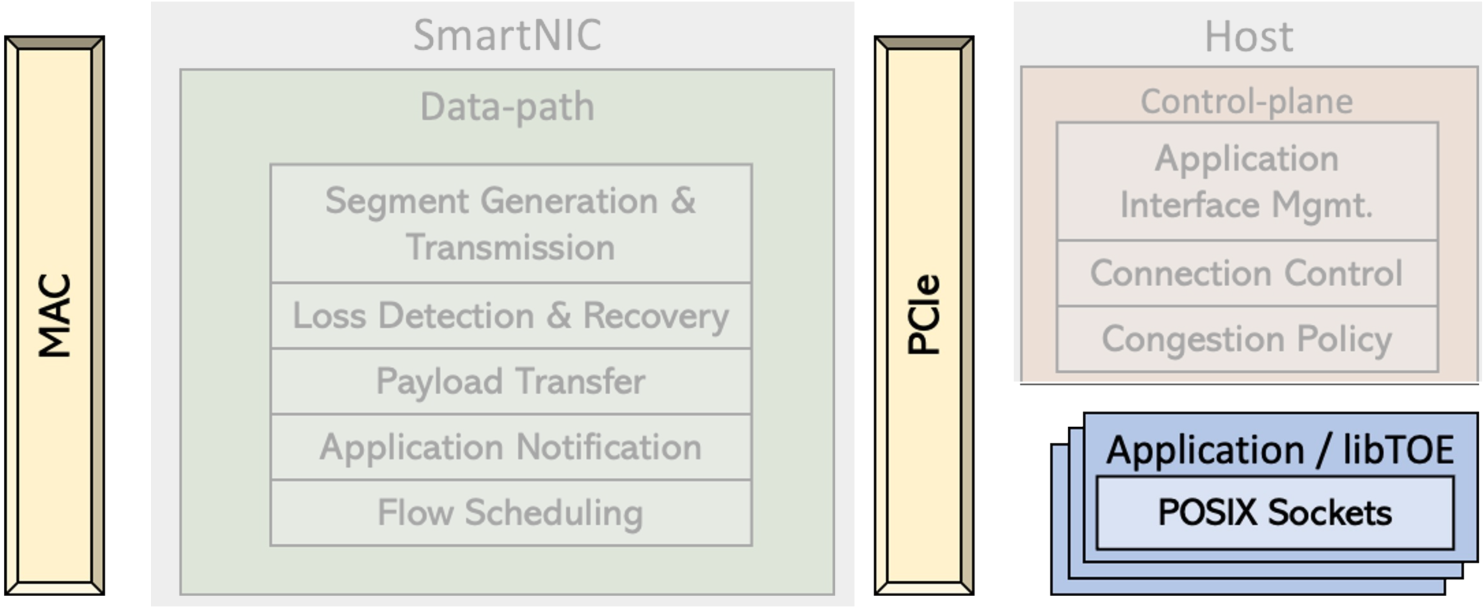
- **Data-path**: per-packet transport logic for established connections

FlexTOE Offload Architecture



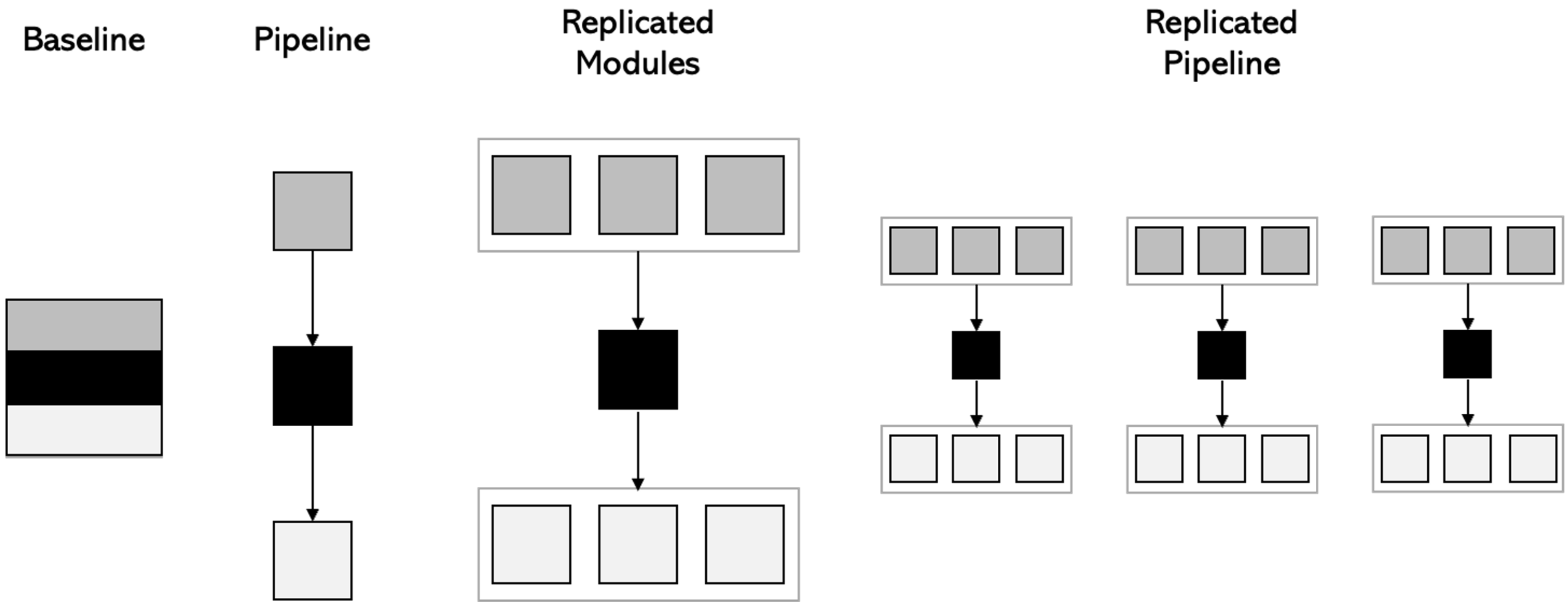
- **Control-plane**: policy, management and infrequent recovery code-paths

FlexTOE Offload Architecture

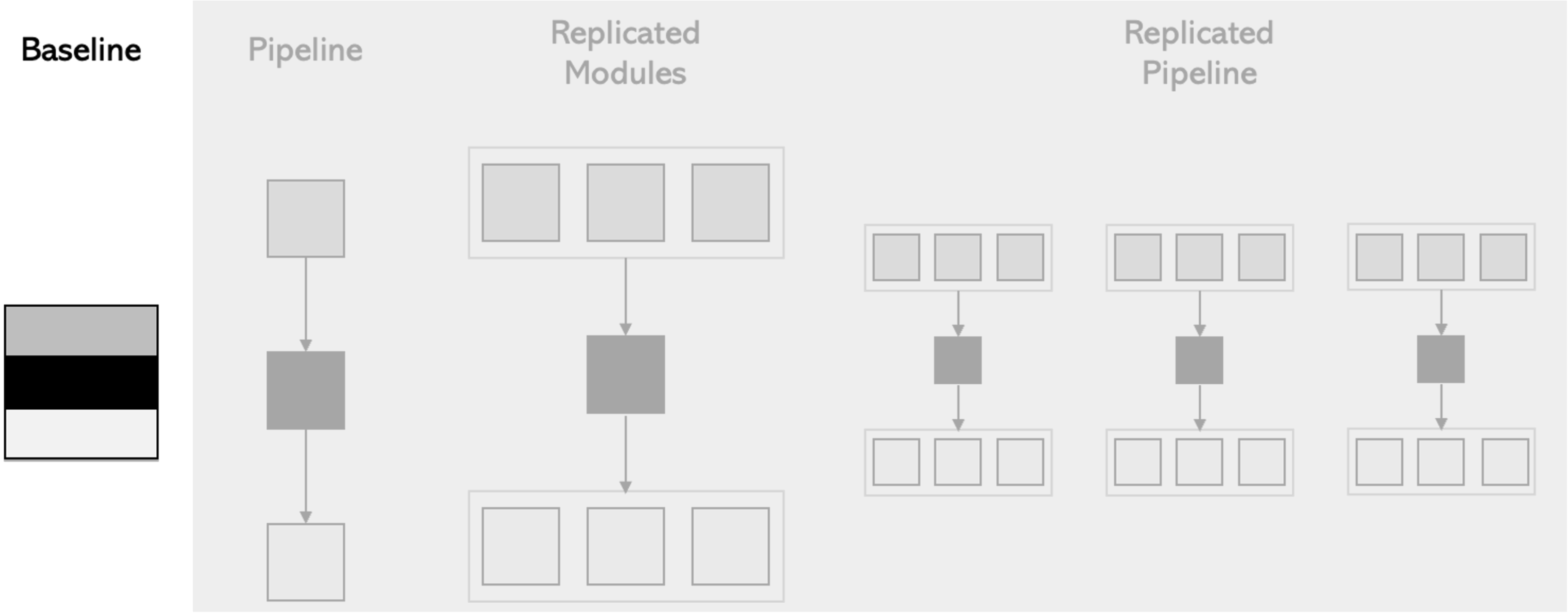


- **libTOE library:** provides POSIX sockets to the application with kernel-bypass

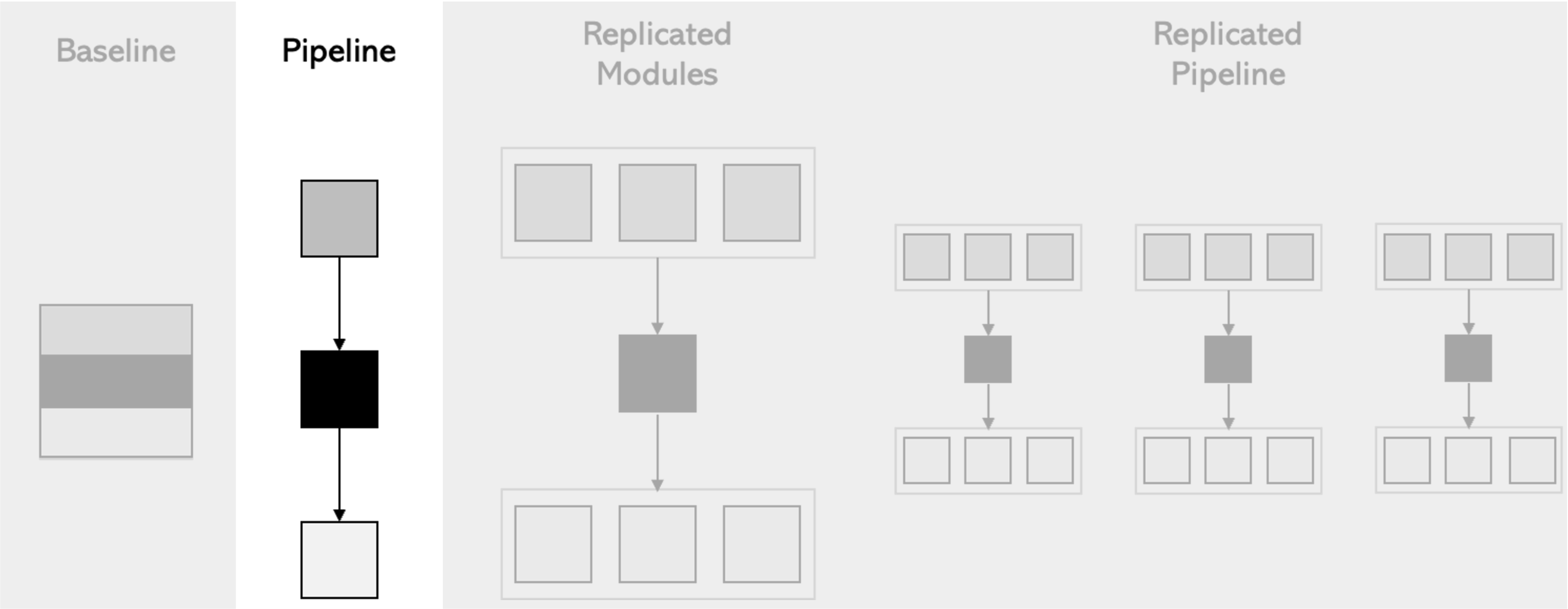
Parallelizing the TCP Data-path for Offload



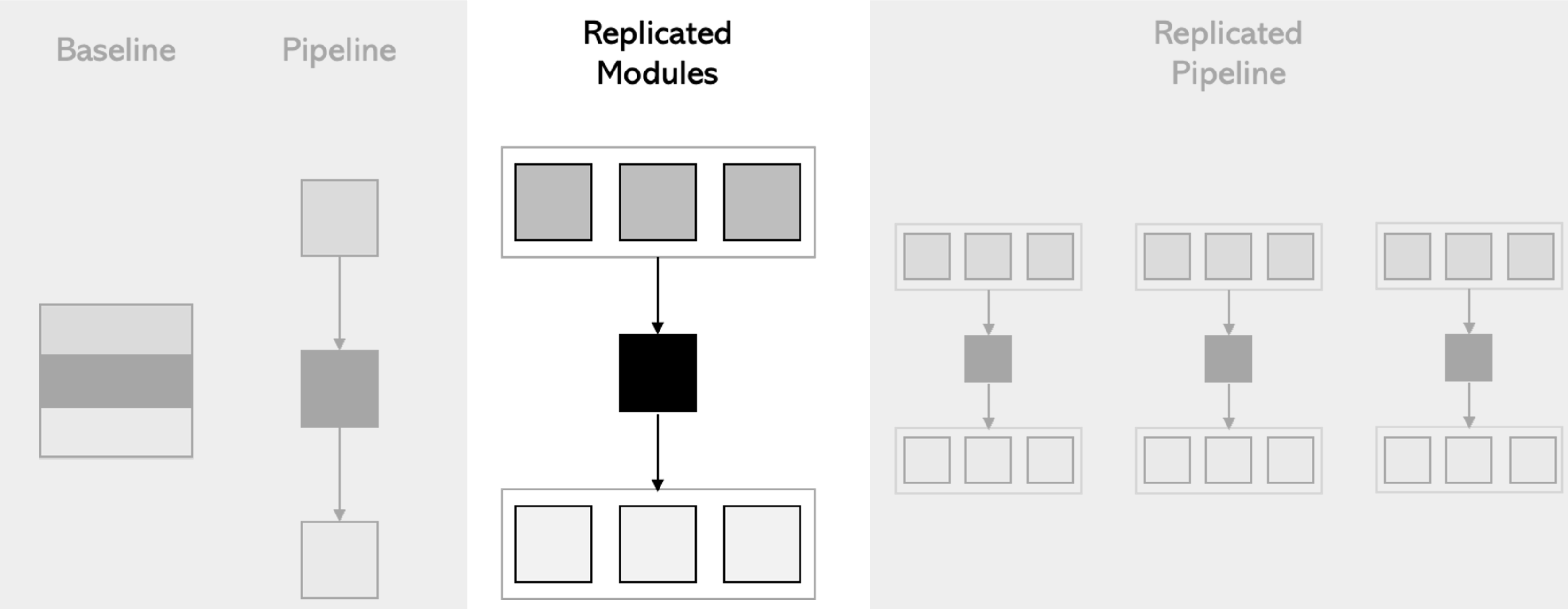
Parallelizing the TCP Data-path for Offload



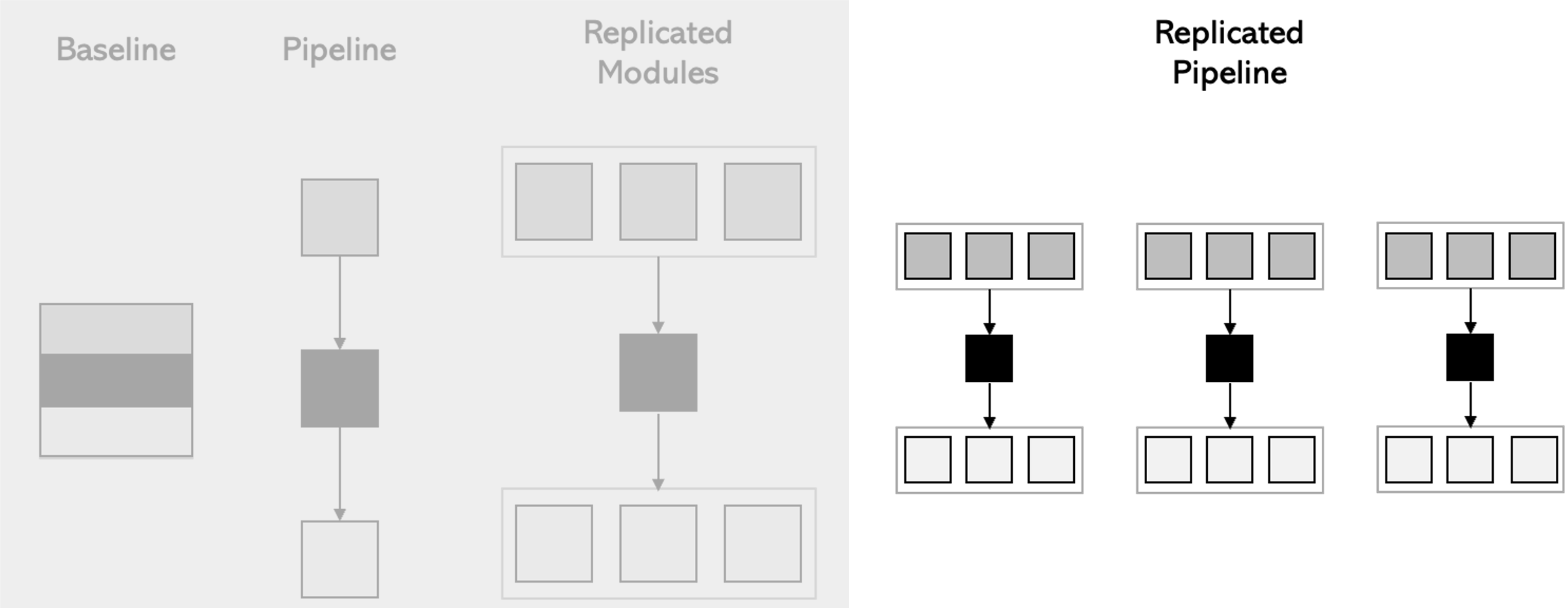
Parallelizing the TCP Data-path for Offload



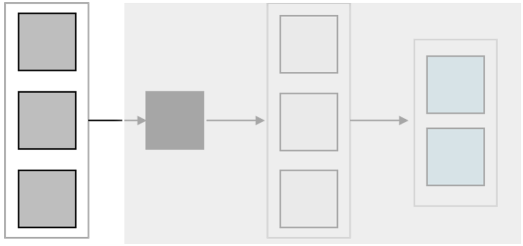
Parallelizing the TCP Data-path for Offload

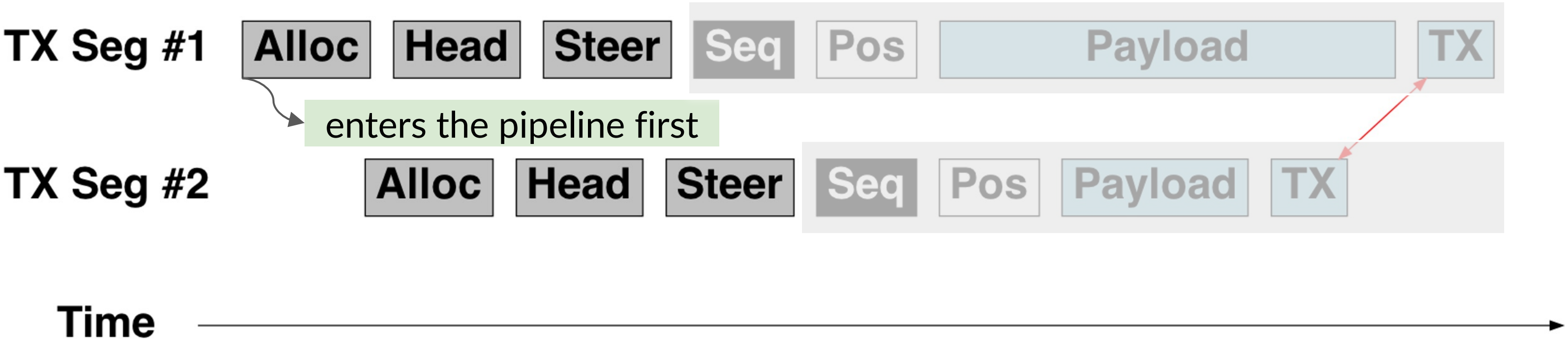


Parallelizing the TCP Data-path for Offload



Parallel TCP Processing Example: Transmit (TX)



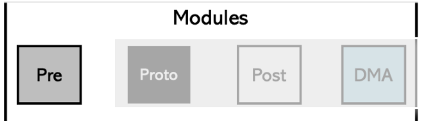


TX Seg #1 Alloc Head Steer Seq Pos Payload TX

enters the pipeline first

TX Seg #2 Alloc Head Steer Seq Pos Payload TX

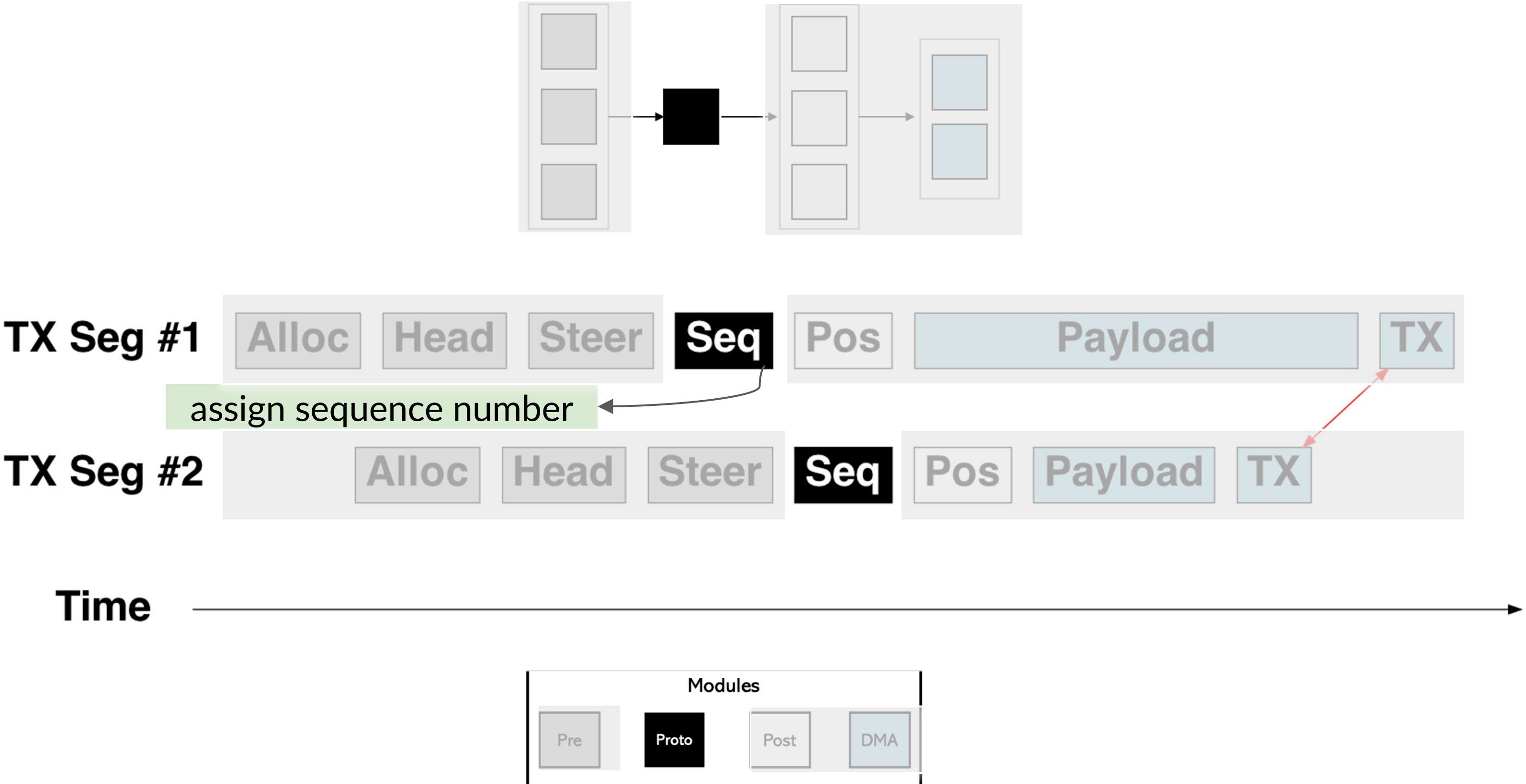
Time



Modules

Pre Proto Post DMA

Parallel TCP Processing Example: Transmit (TX)



TX Seg #1 Alloc Head Steer Seq Pos Payload TX

assign sequence number

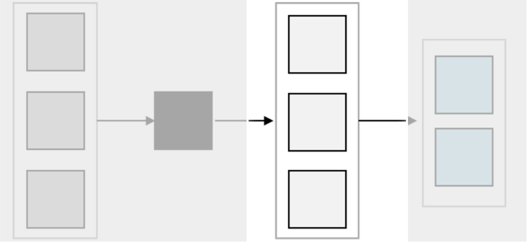
TX Seg #2 Alloc Head Steer Seq Pos Payload TX

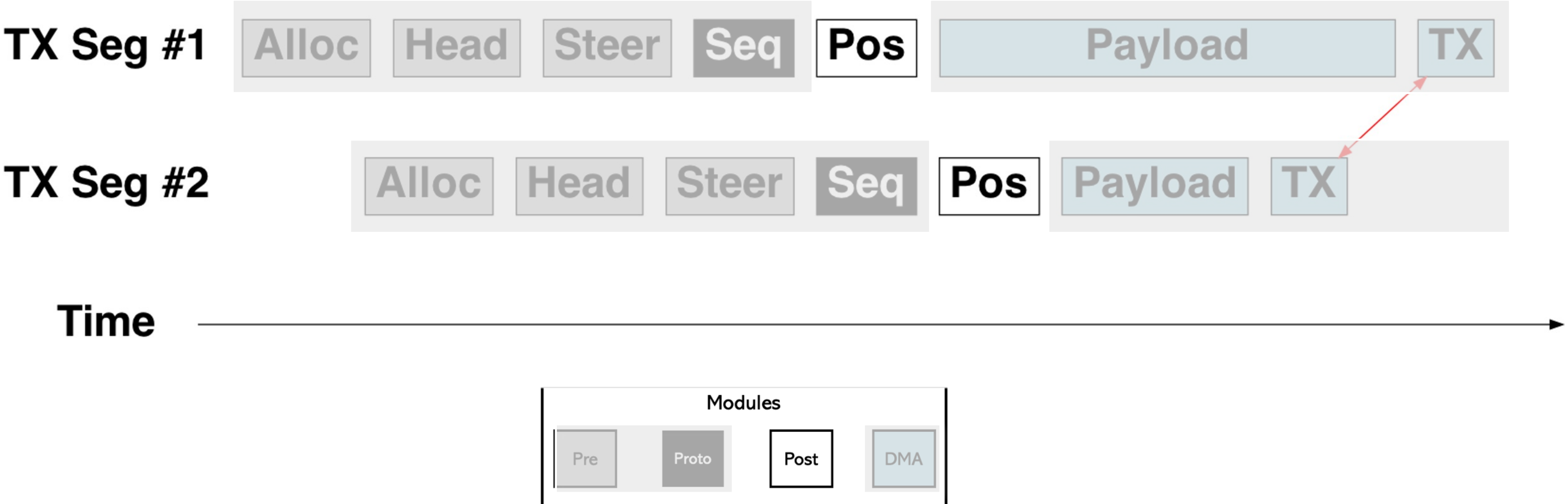
Time

Modules

Pre Proto Post DMA

Parallel TCP Processing Example: Transmit (TX)





TX Seg #1

Alloc

Head

Steer

Seq

Pos

Payload

TX

TX Seg #2

Alloc

Head

Steer

Seq

Pos

Payload

TX

Time

Modules

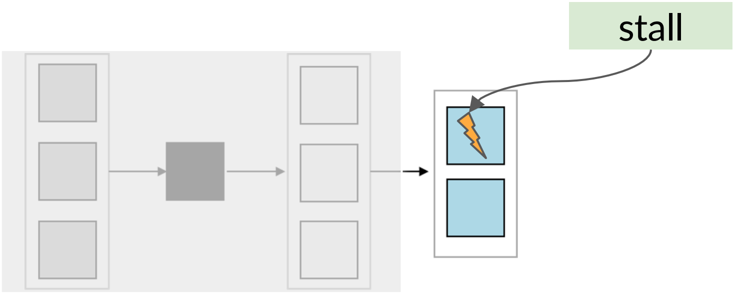
Pre

Proto

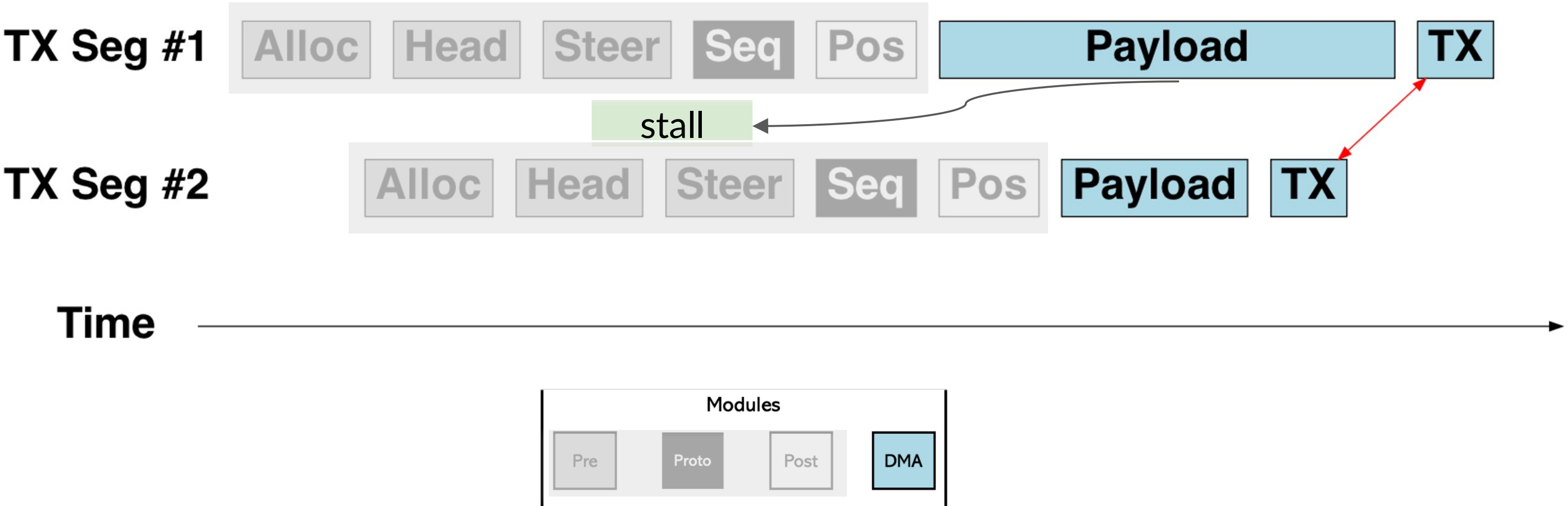
Post

DMA

Parallel TCP Processing Example: Transmit (TX)



stall



TX Seg #1

Alloc Head Steer Seq Pos Payload TX

stall

TX Seg #2

Alloc Head Steer Seq Pos Payload TX

Time

Modules

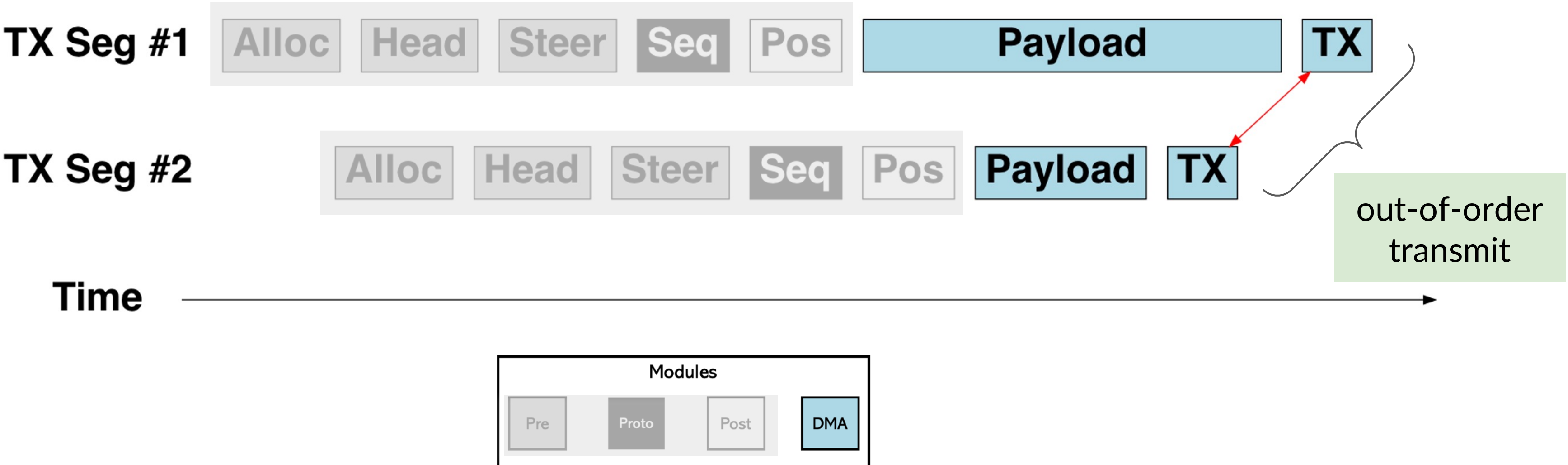
Pre Proto Post DMA

Parallel TCP Processing Example: Transmit (TX)

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

but …

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

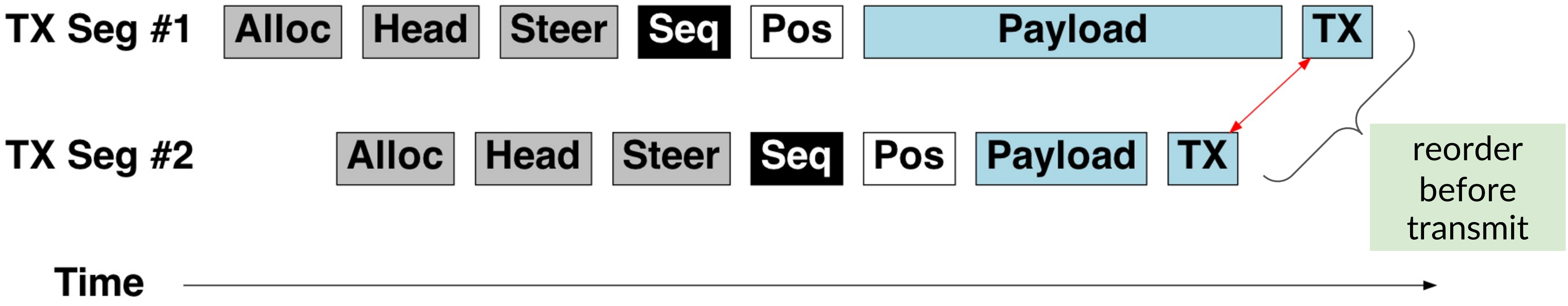


out-of-order transmit

Parallel TCP Processing Example: Transmit (TX)

FlexTOE:

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

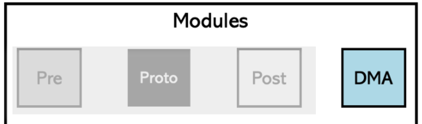


TX Seg #1 Alloc Head Steer Seq Pos Payload TX

TX Seg #2 Alloc Head Steer Seq Pos Payload TX

Time

reorder before transmit



Modules

Pre Proto Post DMA

Evaluation

Evaluation Setup

Intel Xeon Gold 6138 CPU, 20 cores @ 2 GHz with 40GB RAM

Compare:

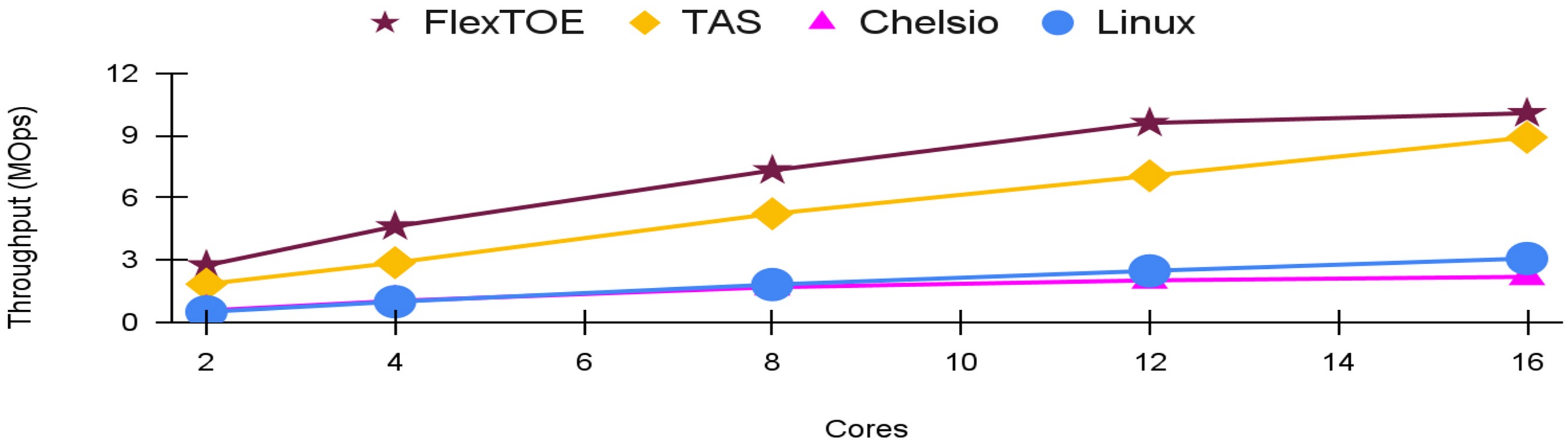
- FlexTOE (flexible offload) on Netronome Agilio CX40 SmartNIC @ 40 Gbps
- Linux (in-kernel stack): Intel XL710 @ 40 Gbps
- TAS (kernel-bypass): Intel XL710 @ 40 Gbps
- Chelsio TOE (inflexible offload): Terminator 6 @ 100 Gbps

Identical application binaries across all baselines.

Benefits of Offload: Throughput Scalability

Memcached throughput, varying number of server cores

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

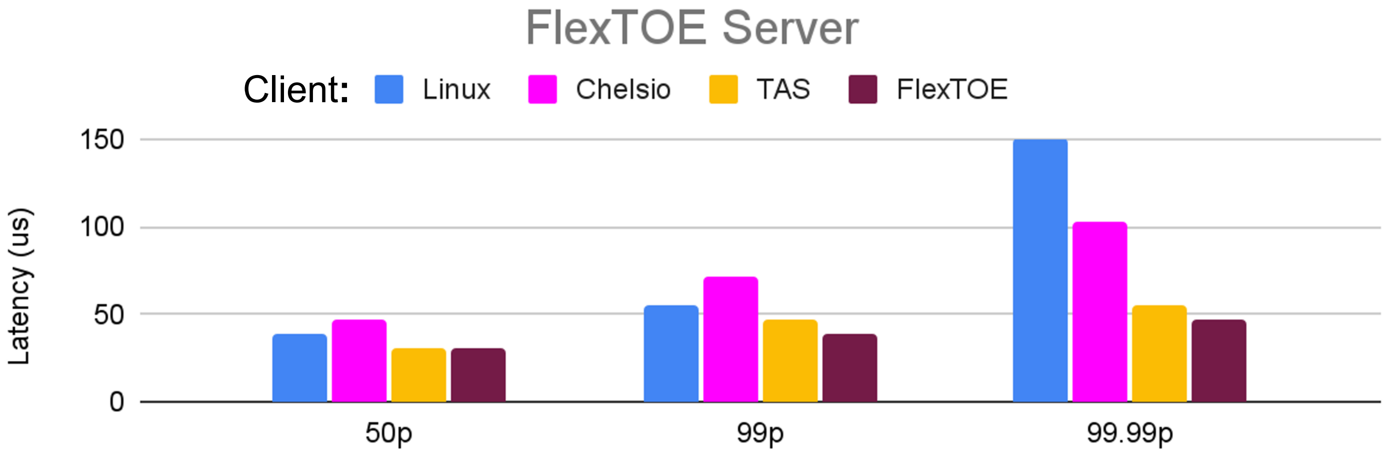


Offloaded CPU cycles may be used for application work

Benefits of Offload: Low Tail-Latency

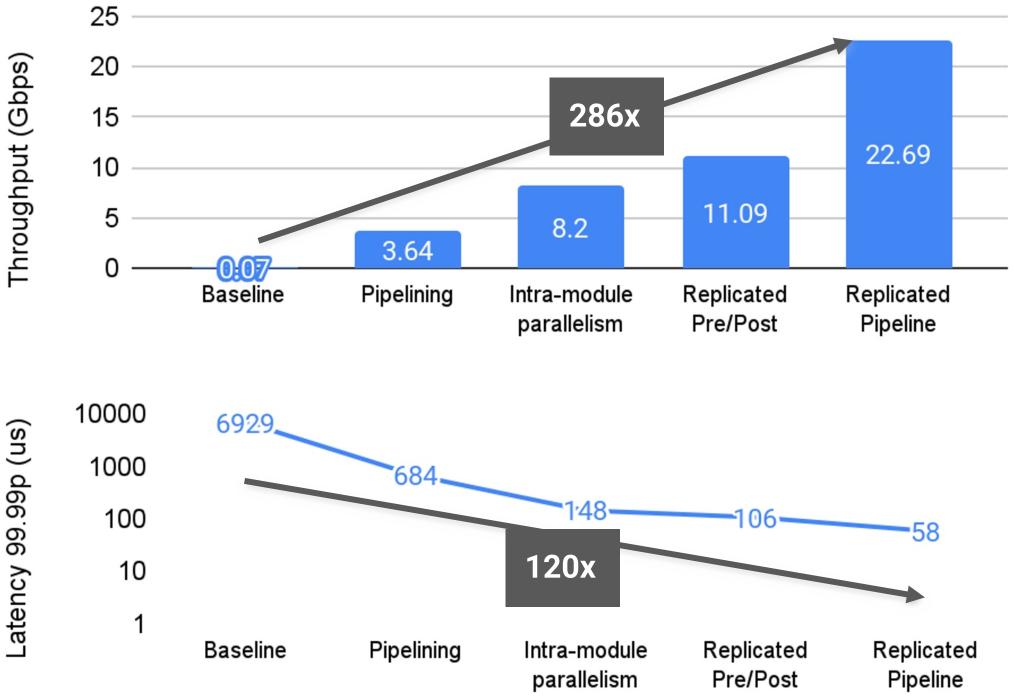
Memcached latency distribution across different stack combinations

FlexTOE achieves the lowest median and tail latencies



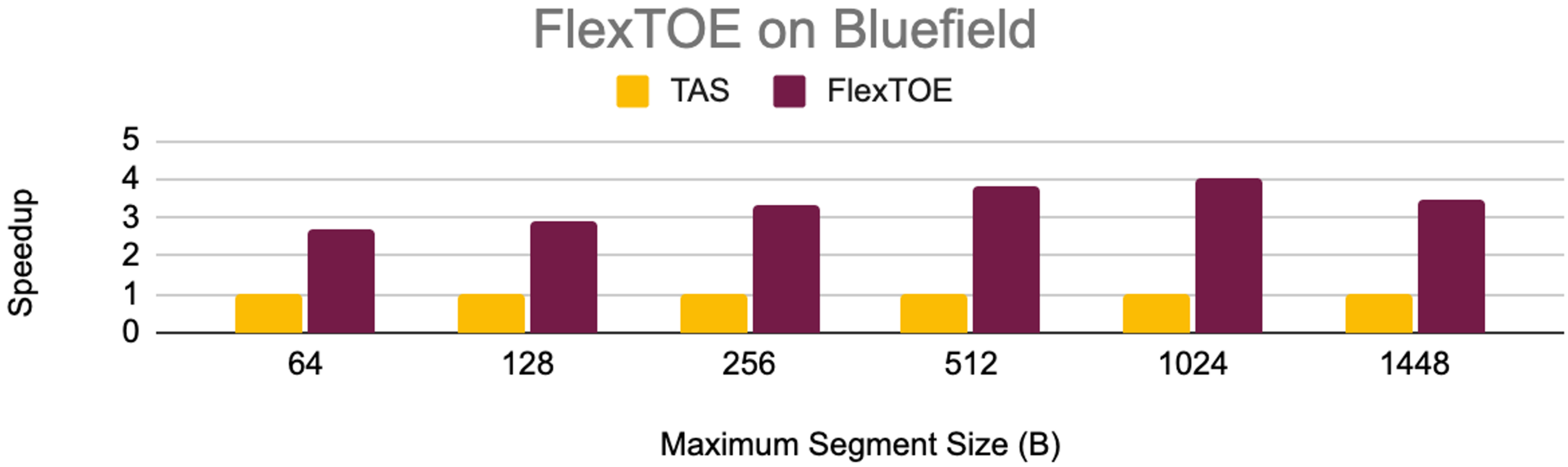
Offload provides excellent performance isolation

Is Fine-grained Parallelism Necessary?



Exploiting both intra- and inter-connection parallelism is necessary

Data-path Parallelism: Does it Generalize across Platforms?



Single connection speedup by 4x on Bluefield (and 2.4x on x86)

FlexTOE: High-performance **and** Flexible TCP Offload

- Eliminates all host TCP stack overheads to save CPU cycles for the application
- Data-path parallelism via fine-grained modules with out-of-order processing
- Easily extensible with full user-space programmability
  - `tcpdump` with packet filtering
  - VLAN encap/decap
  - Firewall
  - Connection splicing

FlexTOE is open-source: https://github.com/tcp-acceleration-service/FlexTOE