Designing Transport-Level Encryption for Datacenter Networks

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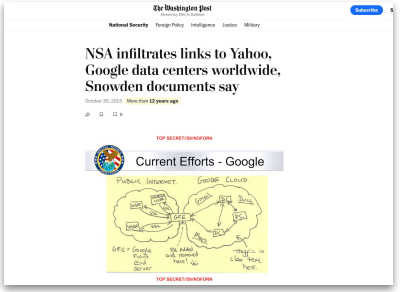
informatics

Encryption in the Internet

- -2010
  - Encryption was exceptional [Bittau et al., USENIX Sec'10]
- 2010-
  - Google rolled out default SSL encryption
- 2015-
  - More encryption: QUIC, ECH, DoH, ML-KEM etc.

Encryption in datacenters

- 2013
  - Plaintext data breach
- Today
  - TLS is ubiquitous
  - Bad actors exist
    - Malicious insiders [Mogul and Wilkes, HotNets'23]
    - Compromised tenants [Arzani et al., NSDI'20]



The Washington Post, 2013

Engineering at Meta, 2019

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- High-throughput, low-latency RPCs
  - Software overhead and head-of-line blocking matter

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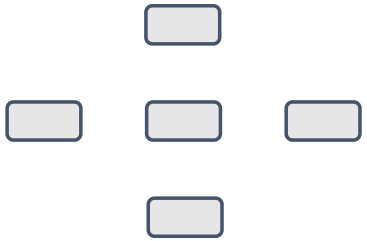

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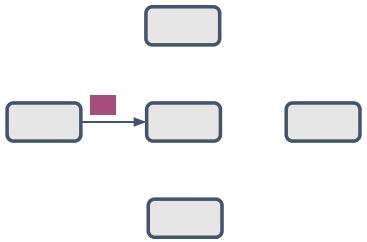

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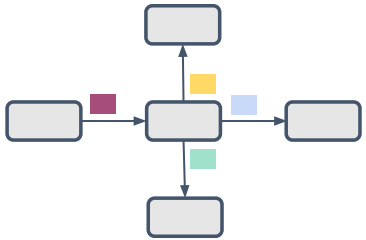

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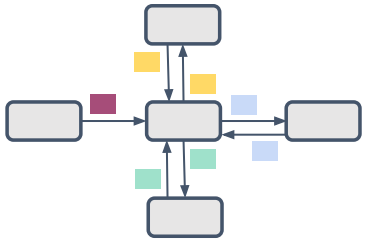

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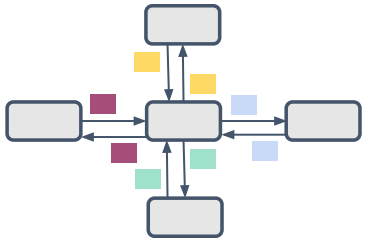

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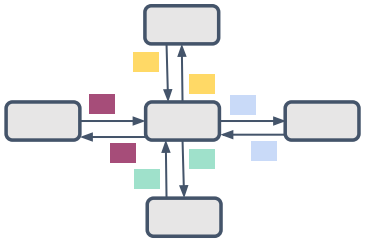
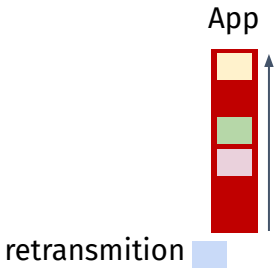


Intra-connection HoLB

on packet loss



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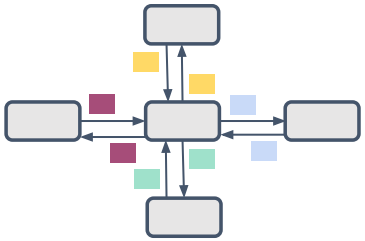

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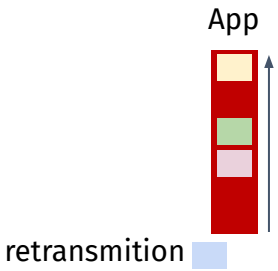

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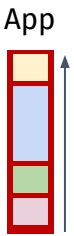

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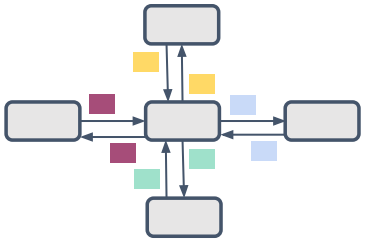

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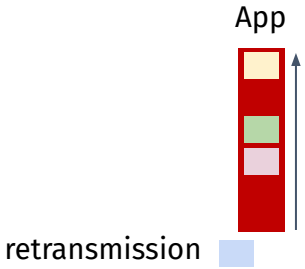

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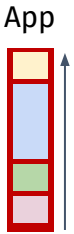
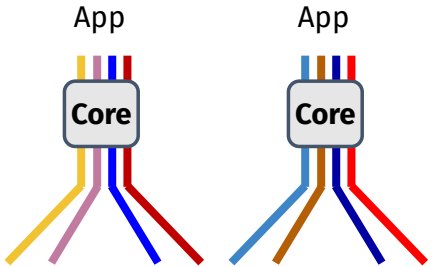
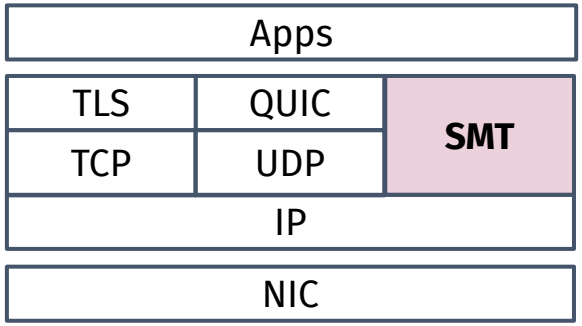


Inter-connection HoLB on CPU cores



SMT design goals



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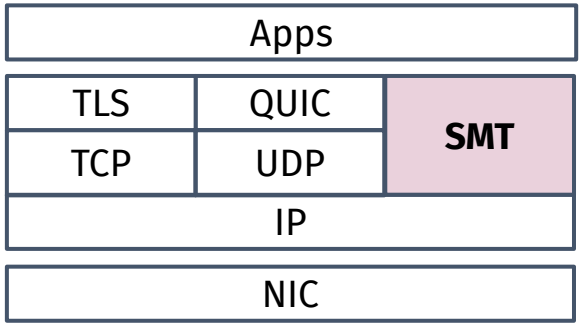

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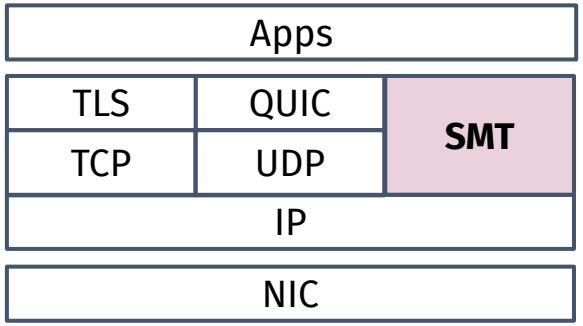

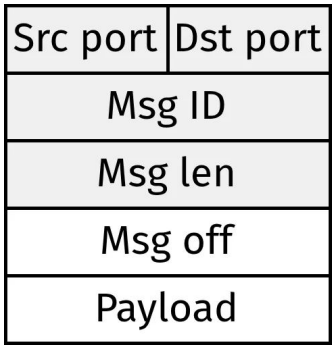

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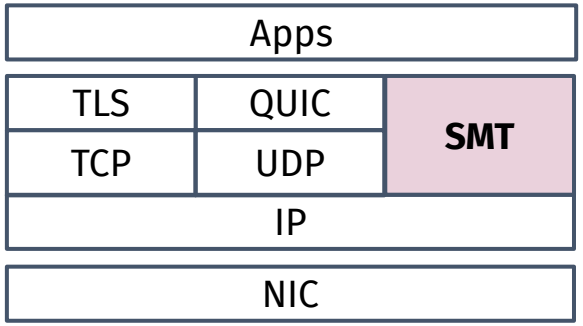

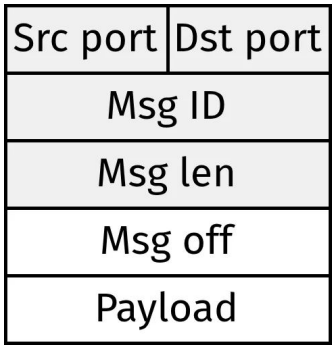

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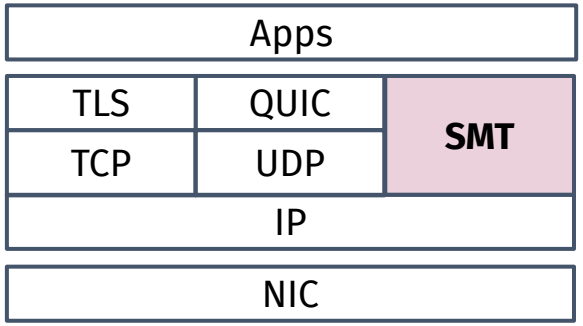

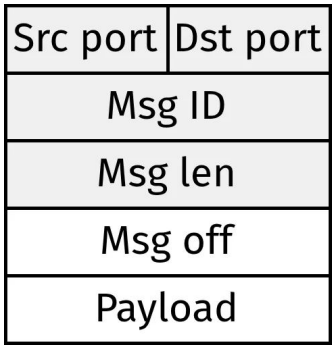

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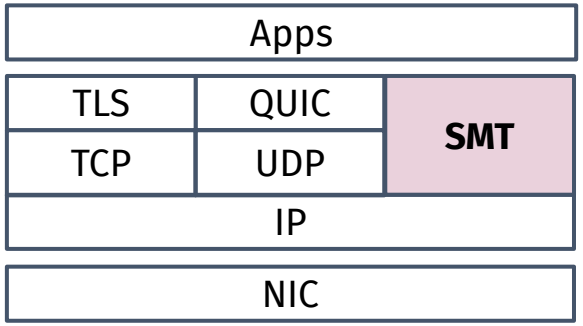
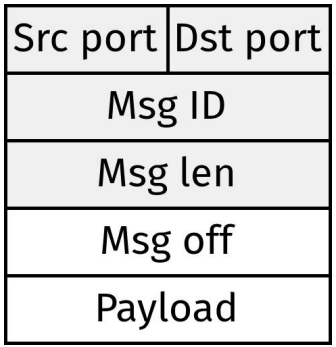
- Native transport
  - No UDP encapsulation





Why not QUIC?

QUIC's design point

SMT's design point

	Internet	**Datacenter**
Latency	1–100 ms	**1–100 µs**
HoLB	Path	**Path & CPU cores**
Middlebox Interference	High	**Low**
HW Offload	Optional	**Must**

Other options?

- Encrypted transports
  - TcpCrypt [USENIX Sec'10], TCPLS [CoNEXT'21]
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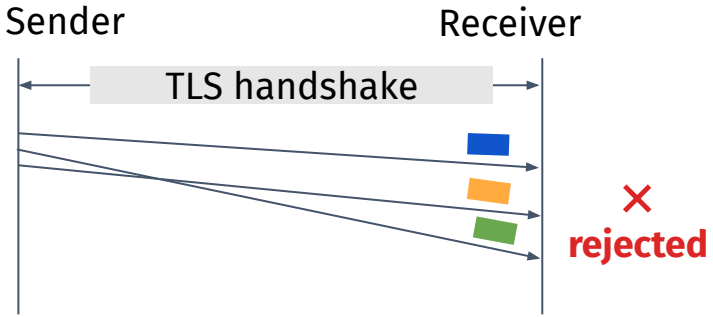
No existing approach combines TLS encryption + message abstraction, but Homa could be a middleground

Why not TLS *over* a message-based transport?

- TLS assumes in-order bytestream
  - Record rejection for out-of-order messages
  - Per-message handshake is too slow



SMT architecture

- Handshake in the app
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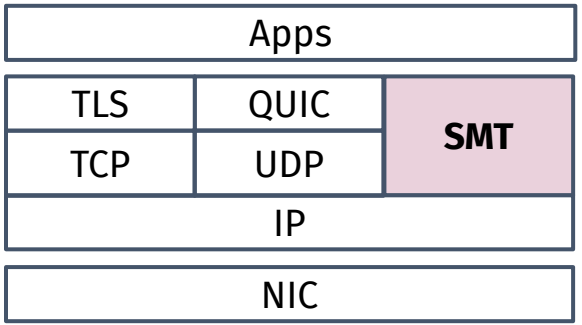

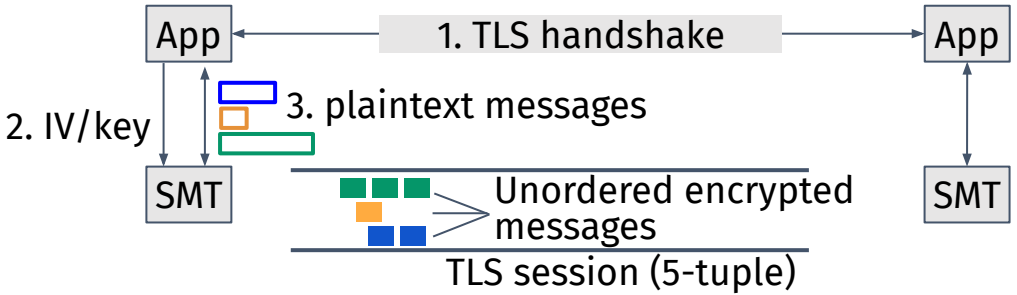

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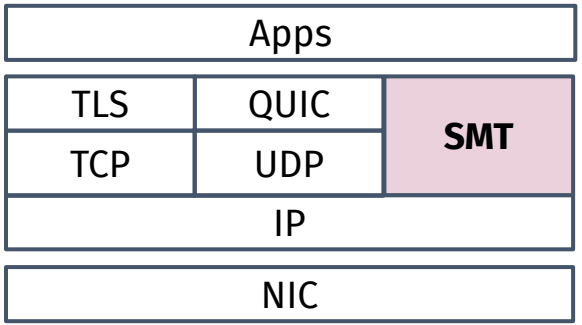

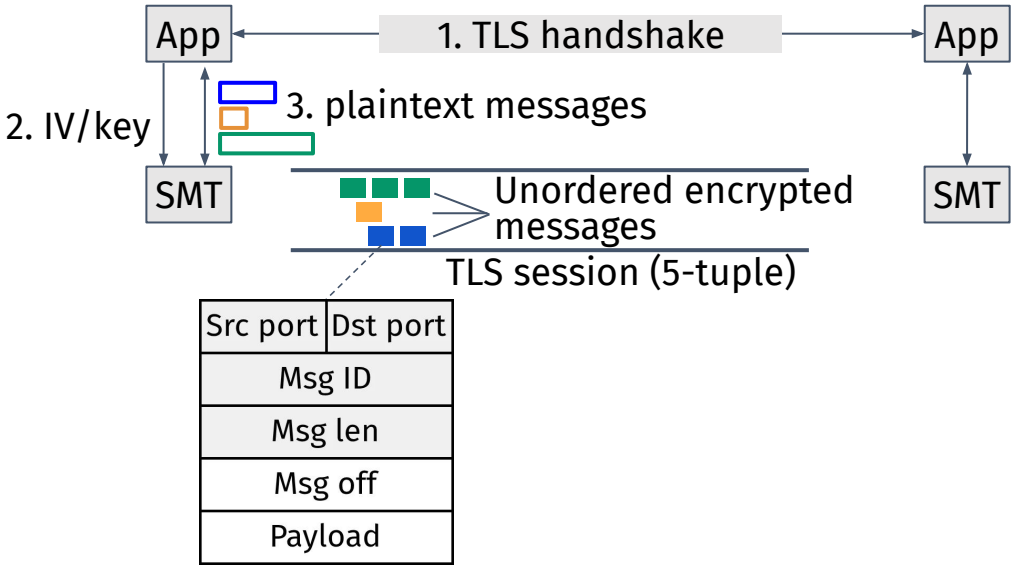

SMT key design components

- Message format based on the TLS record protocol
  - TLS offload with TSO
- Per-message record sequence number space
  - Transport integration enables replay protection

SMT message and packet format

- **Goal: TSO/GSO with TLS offload**

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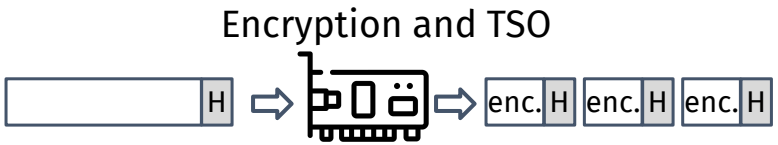

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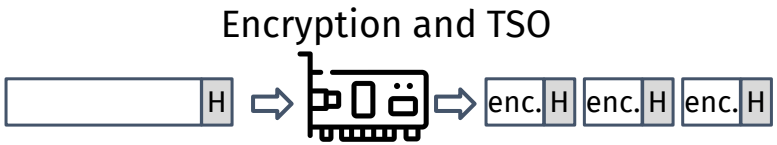

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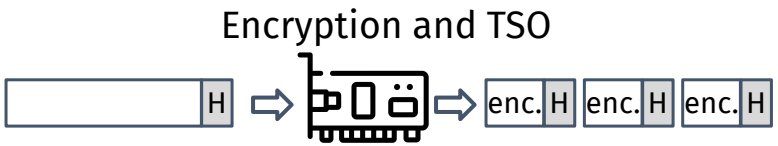

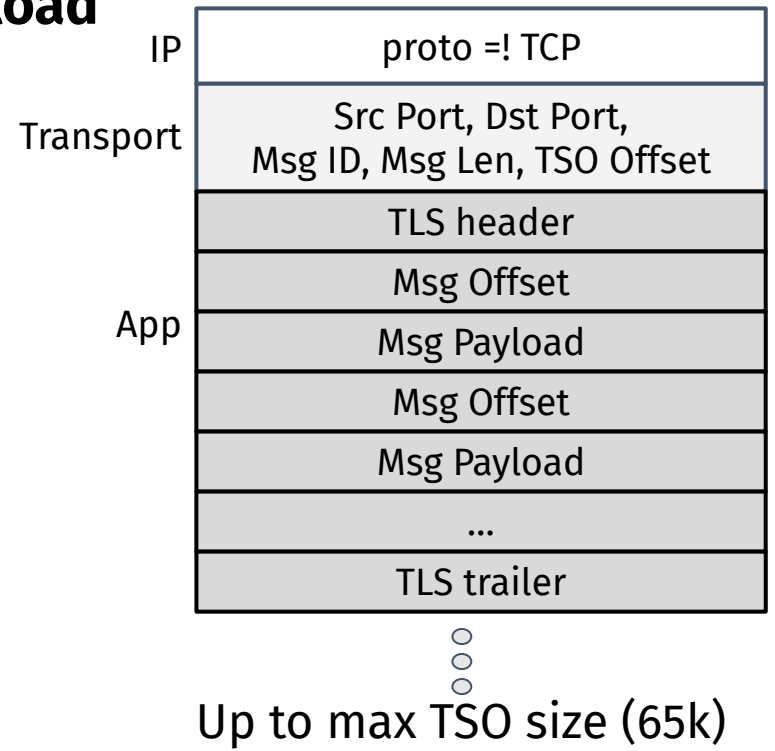

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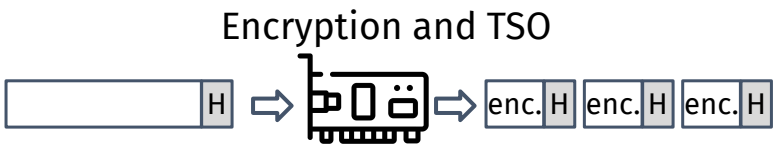

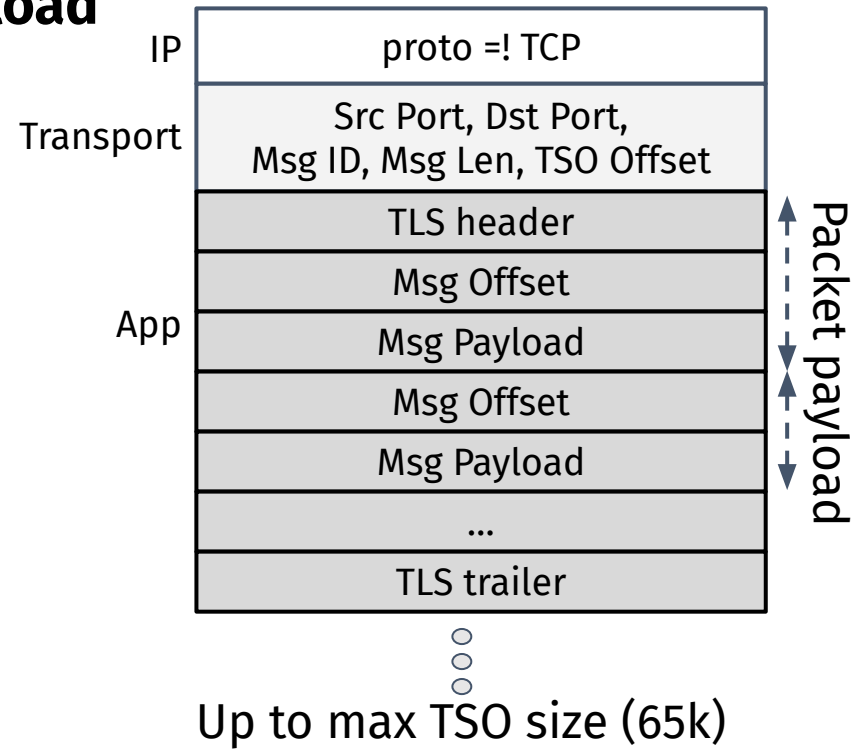

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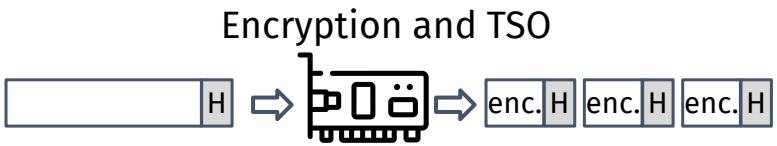

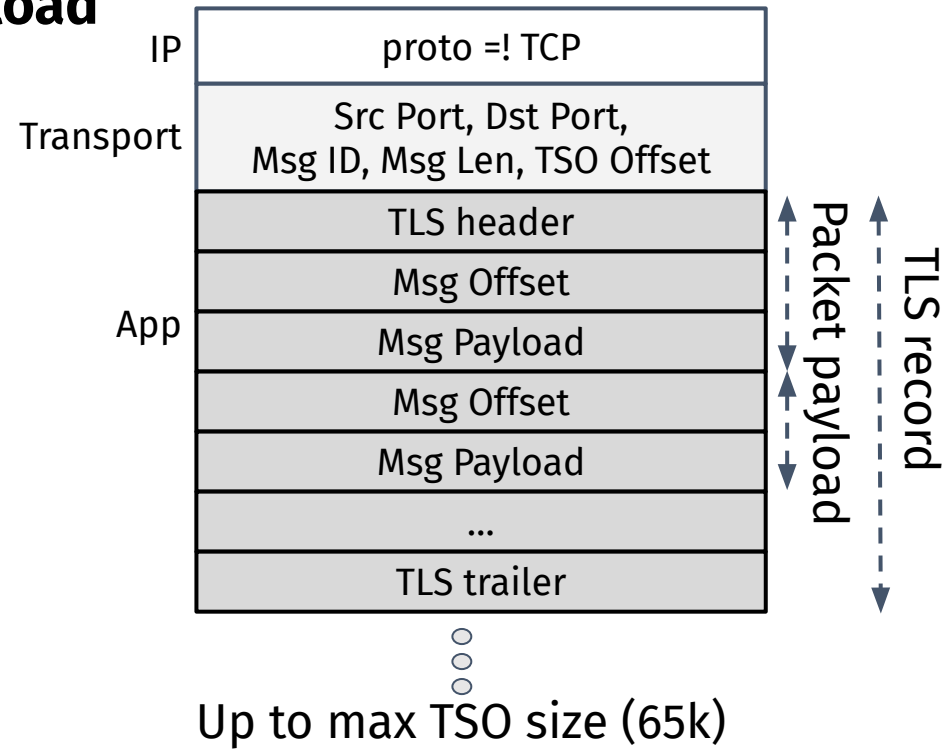

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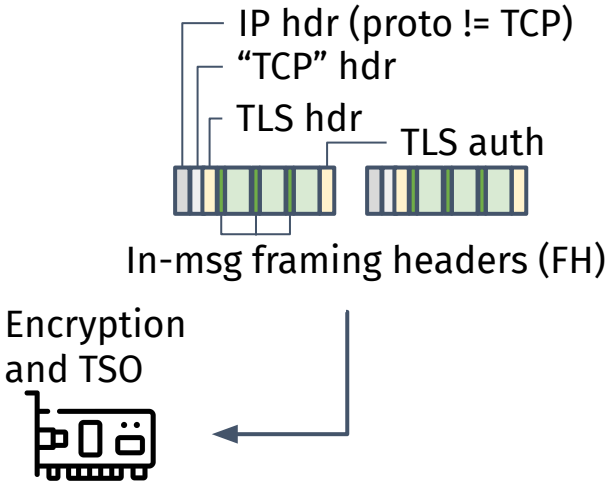

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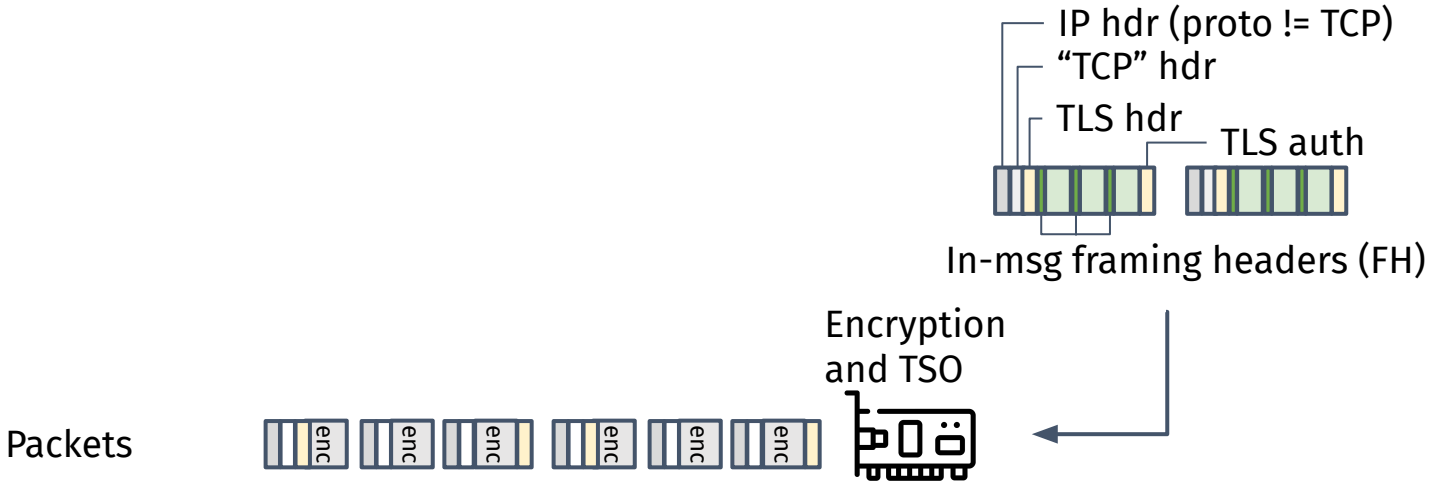

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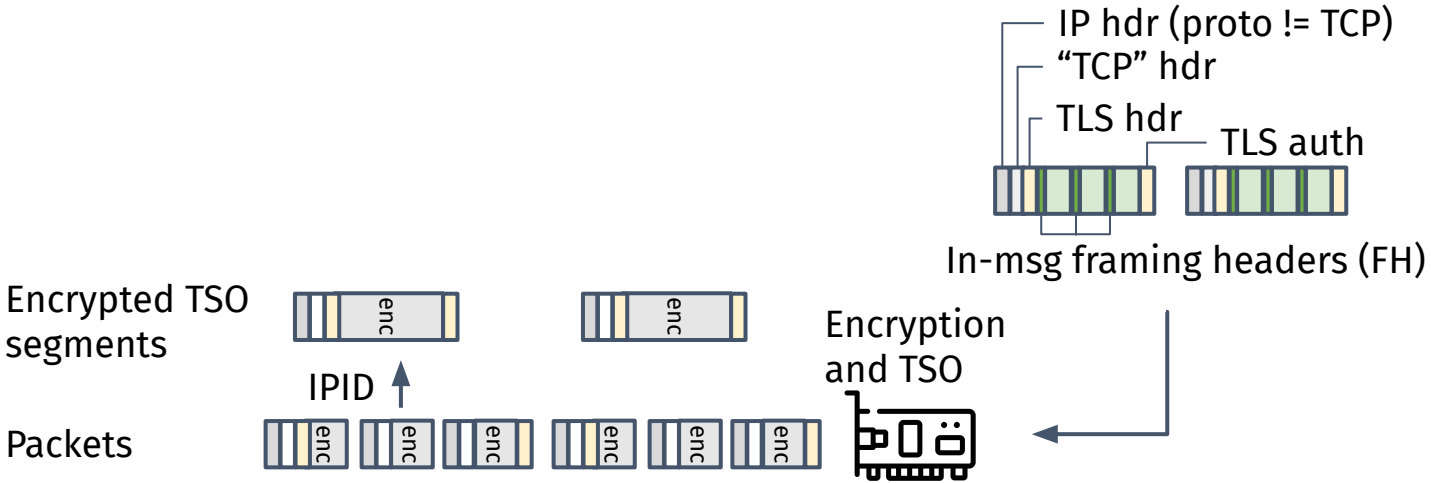

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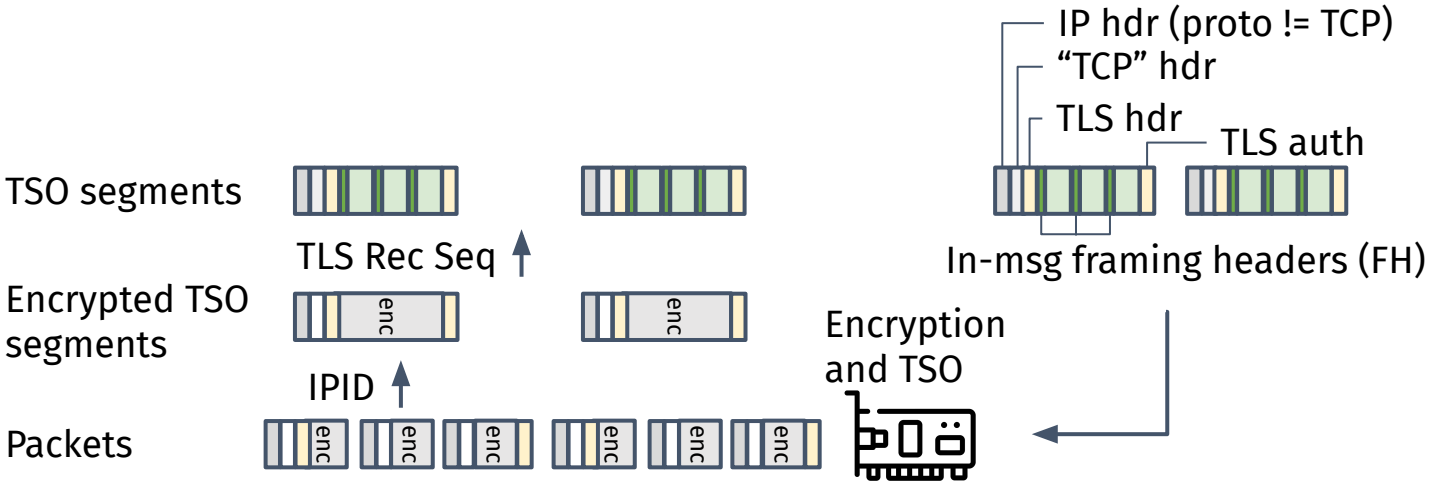

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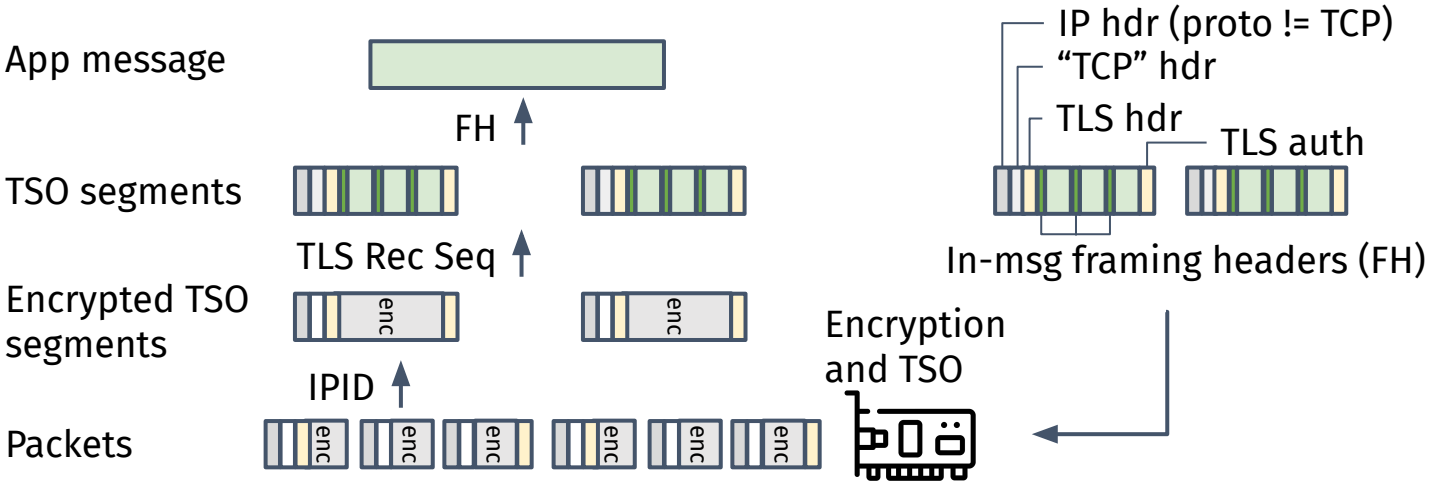

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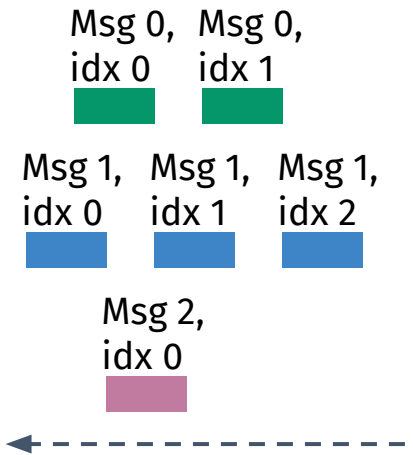

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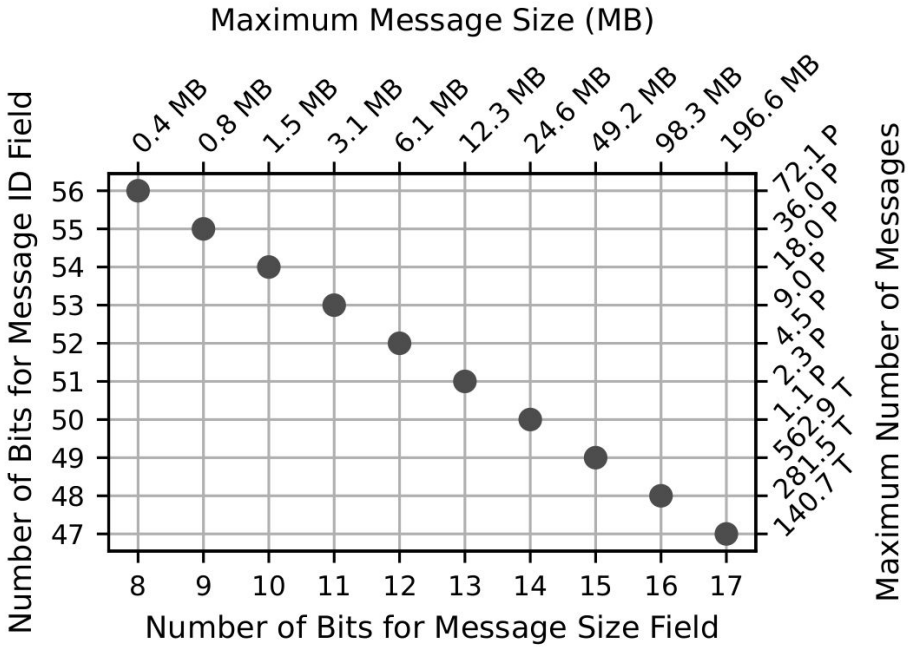

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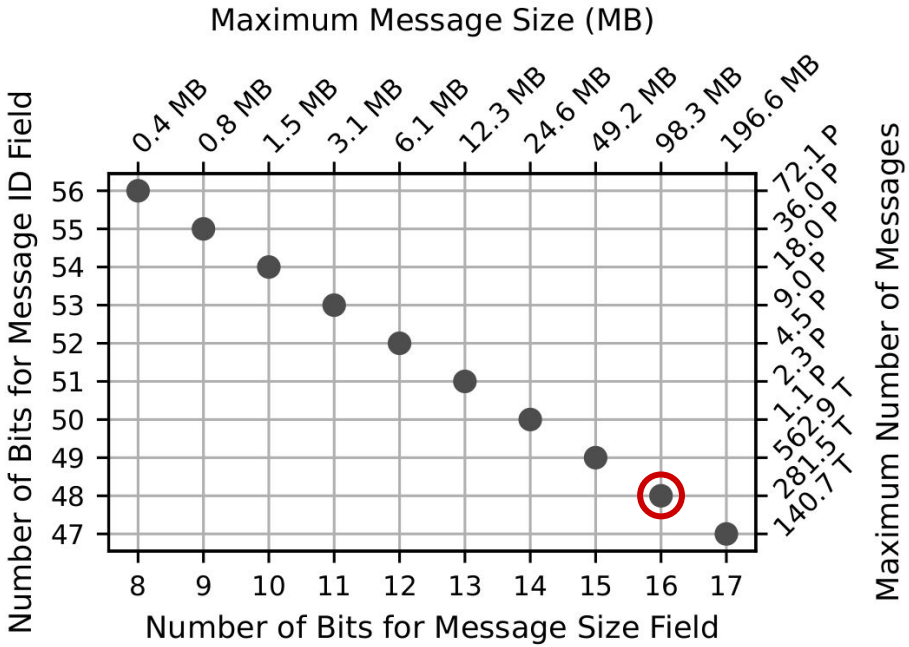

SMT and TLS 1.3 security guarantees

Authentication	TLS 1.3 handshake	**Same as TLS/TCP**
Confidentiality & Integrity	AEAD (AES-GCM); SMT also provides message integrity (unlike Homa)	**Same as TLS/TCP**
Order protection	Per-message via per-message record seqno; monotonic within message	**Per-message**
Non-replayability	Composite 48-bit msg ID + 16-bit record index ensures session uniqueness	**Guaranteed**
Length concealment	Compatible with TLS padding; msg length field can include padding	**Supported**

Out-of-order TLS offload

- Per-message record seqno is essential for TLS offload
  - NIC expects in-order record arrival
    - We can update NIC's expectation,
      but not atomically
  - Message-based transports send messages
    in any order

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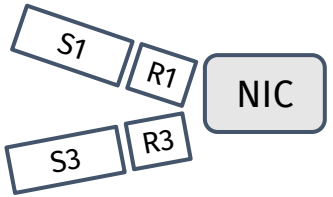

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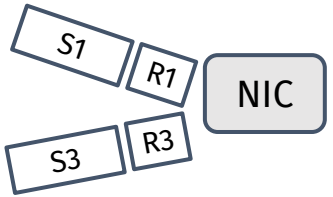
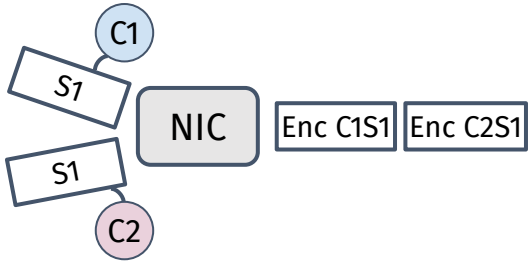
  - NIC expects in-order record arrival
    - We can update NIC's expectation, but not atomically
  - Message-based transports send messages in any order
    - Per-message record seqnos allow the sender to use separate *flow contexts*



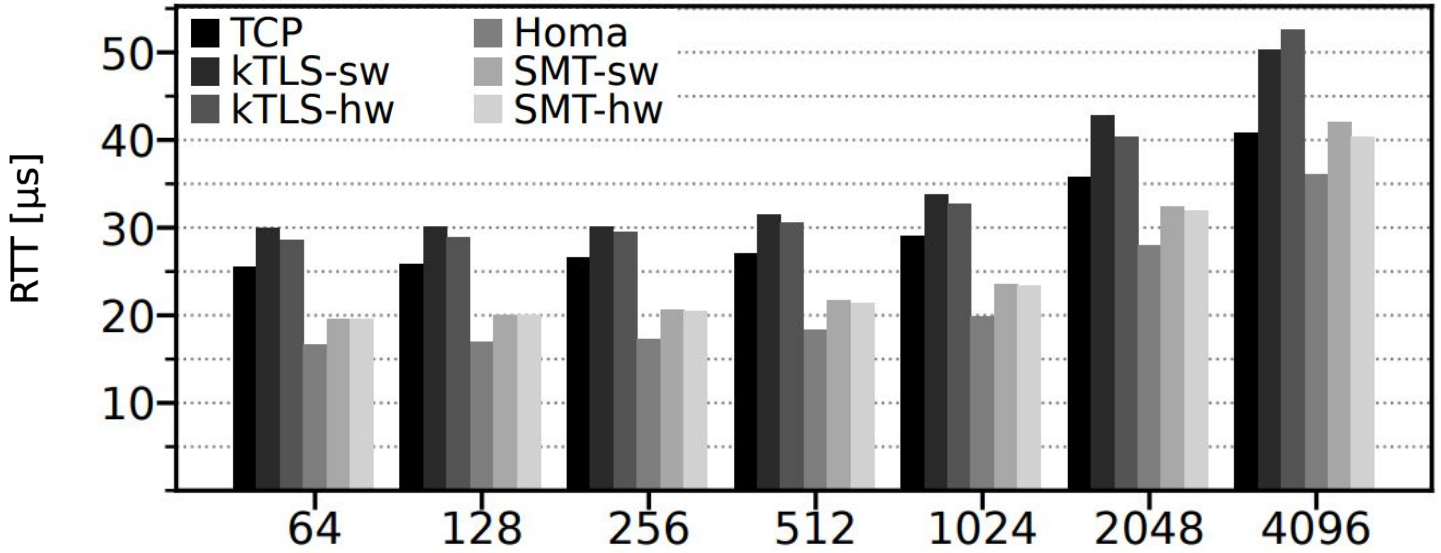


Implementation

- 2800 LoC patch on Homa/Linux kernel module
- 300 LoC patch on NVIDIA mlx5 driver
  - Driver change: adjust encryption offset + generalize flow context
- Open source: github.com/uoenoplab/smt
  - New version coming soon

Unloaded latency

- SMT outperforms kTLS by 21–32% with hw offload and 16–35% without it

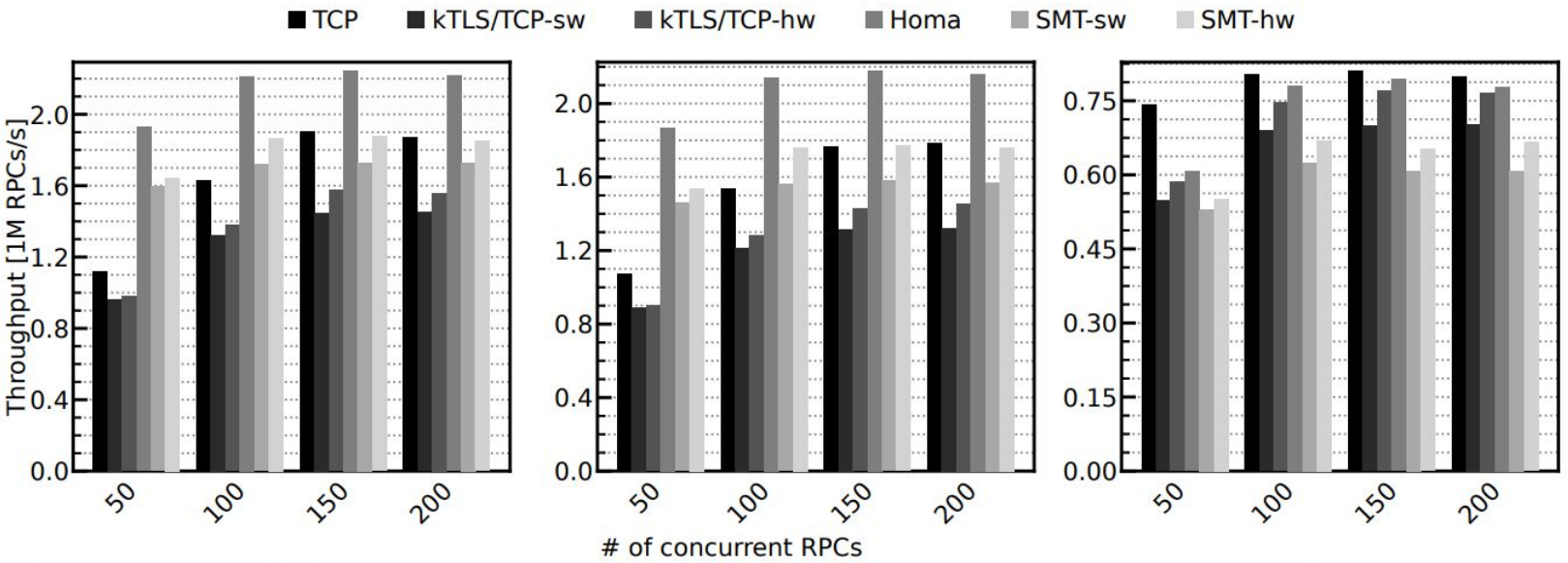


Loaded throughput

16-40% improvements

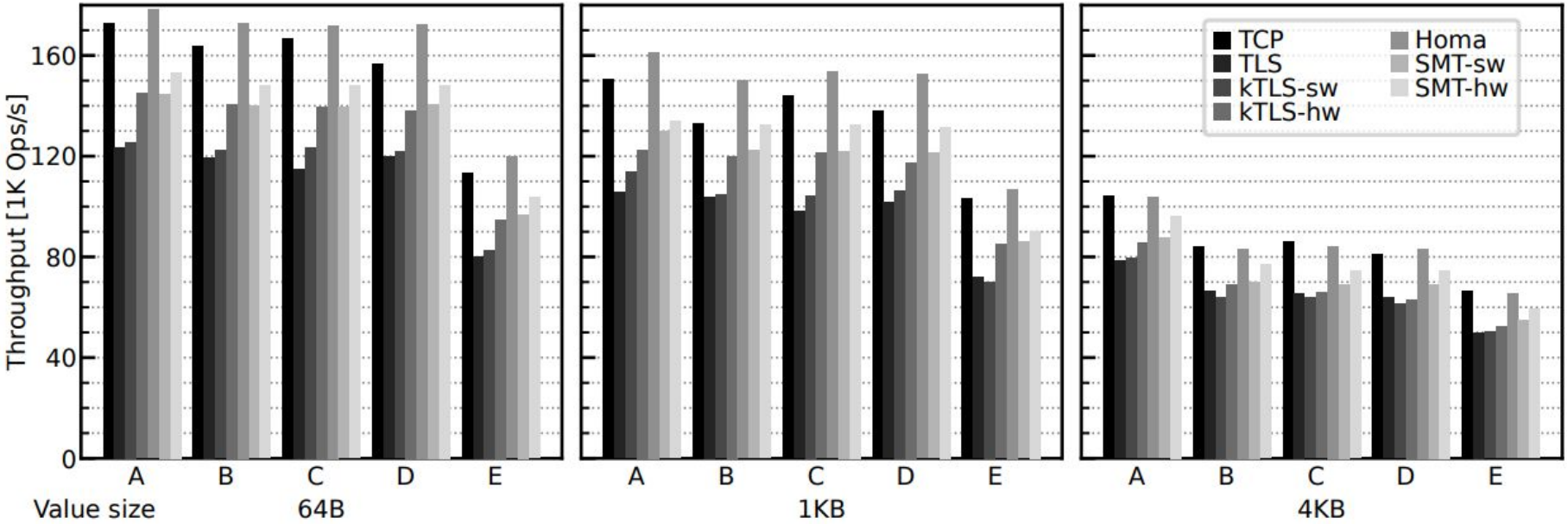
16-41% improvements

Homa is unoptimized large message throughput yet



Redis throughput

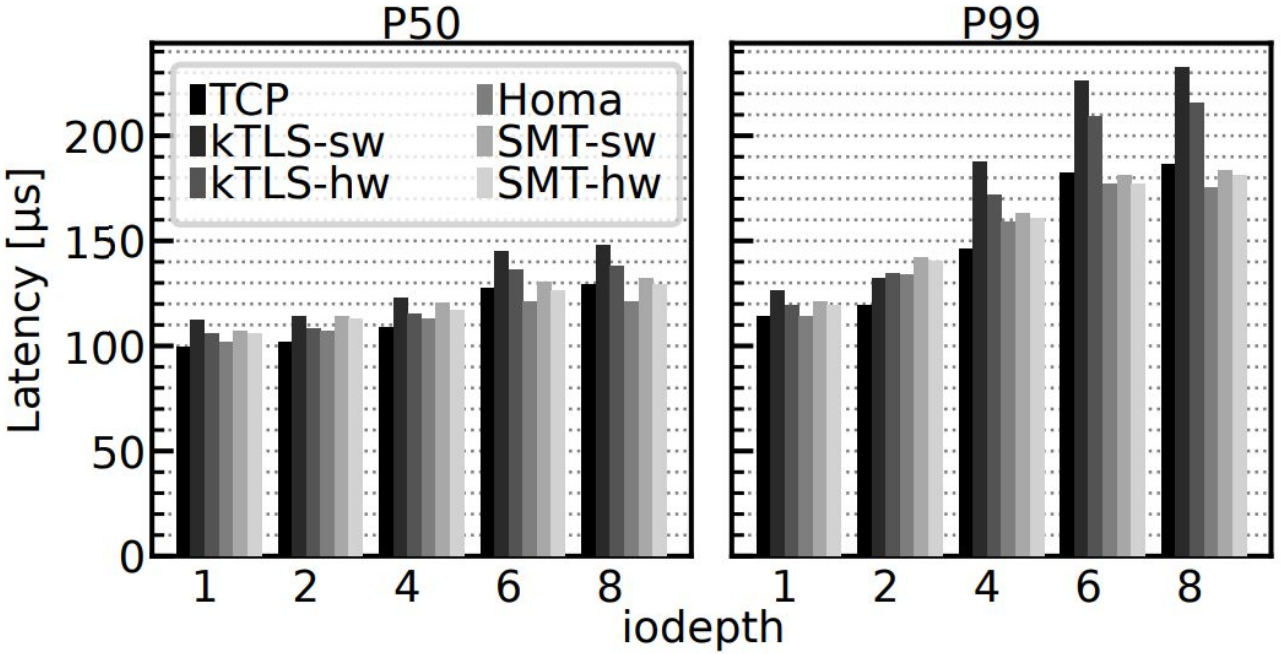
- SMT outperforms kTLS by 5–13 % with TLS offload and 8–17 % without it



Workload A: Update heavy; Workload C: Read only

NVMe-oF (In-kernel application) throughput

- P50 - up to 7 % (with TLS offload) or 15 % (without it) improvement
- P99 - up to 16 % (with TLS offload) or 21 % (without it) improvement



Discussion & future directions

Message integrity	Integrity via AEAD — Homa lacks checksum offload
IPv6 / Segmentation	No IPID in IPv6 — use TSO for up to 2 segments; hopefully NIC vendors embed “TCP” seqno to non-TCP packets
Receive-side offload	NIC doesn't route non-TCP packets to crypto engine; need more flexible/programmable parser
PSP support	Could support PSP in addition to TLS; challenges remain without NIC support
In-network compute	Compatible with MTP [NSDI’25] — plaintext msg ID/length enables boundary detection
Post-quantum	Inherits TLS 1.3 PQ resistance; NIC supports 256-bit keys; larger HW benefit

Conclusion

- SMT: Message-based, encrypted transport for datacenters
  - Linux kernel implementation as Homa/Linux extension
- Ongoing work
  - Improving implementation and performance
  - Detailed specification
    - targeting I-D submission for IETF 126

See more details in our IEEE S&P paper