Autonomous NIC Offloads

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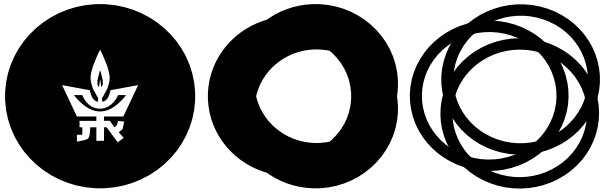
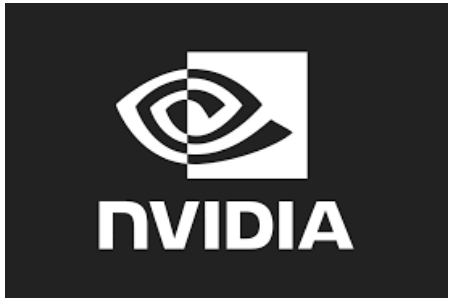




How to accelerate application layer (L5) computations transparently to software TCP/IP?

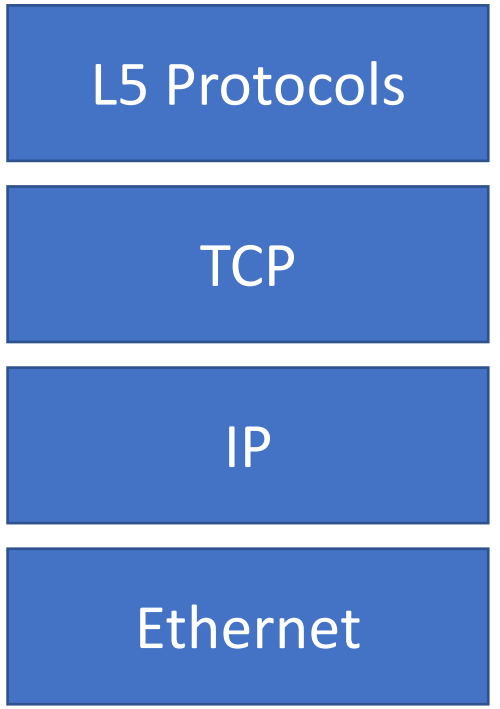
Offloading data-intensive layer-5 protocols

L5P examples

- tls
- nvme-tcp
- http
- grpc
- thrift
- iscsi
- nbd

Computation examples

- encryption
- decryption
- digest
- copy
- pattern matching
- (de)serialization
- (de)compression



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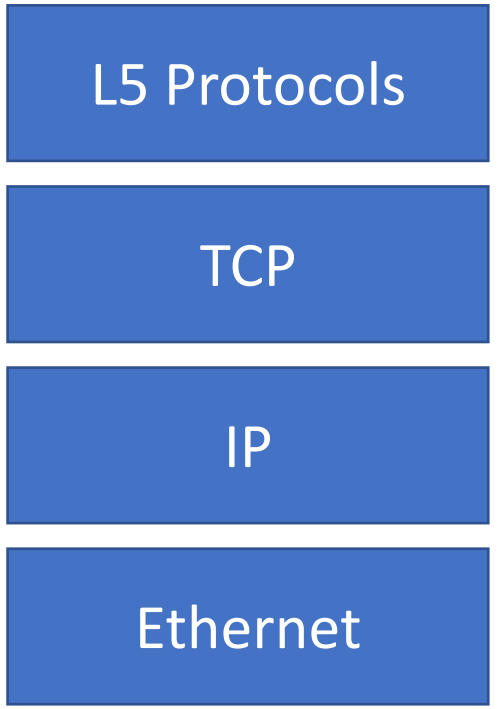

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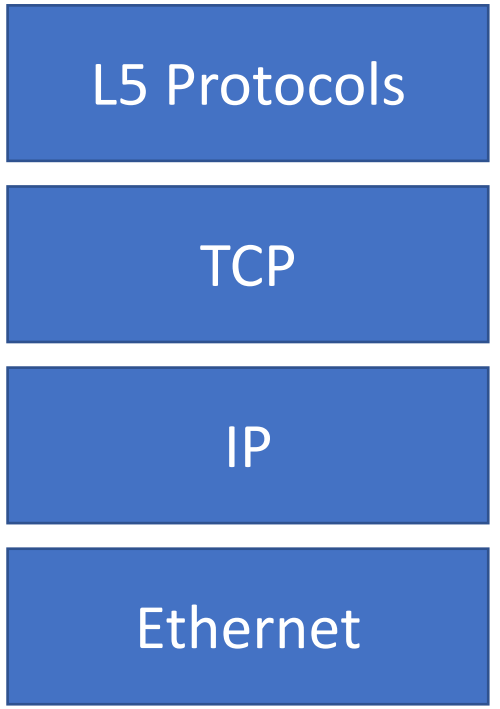
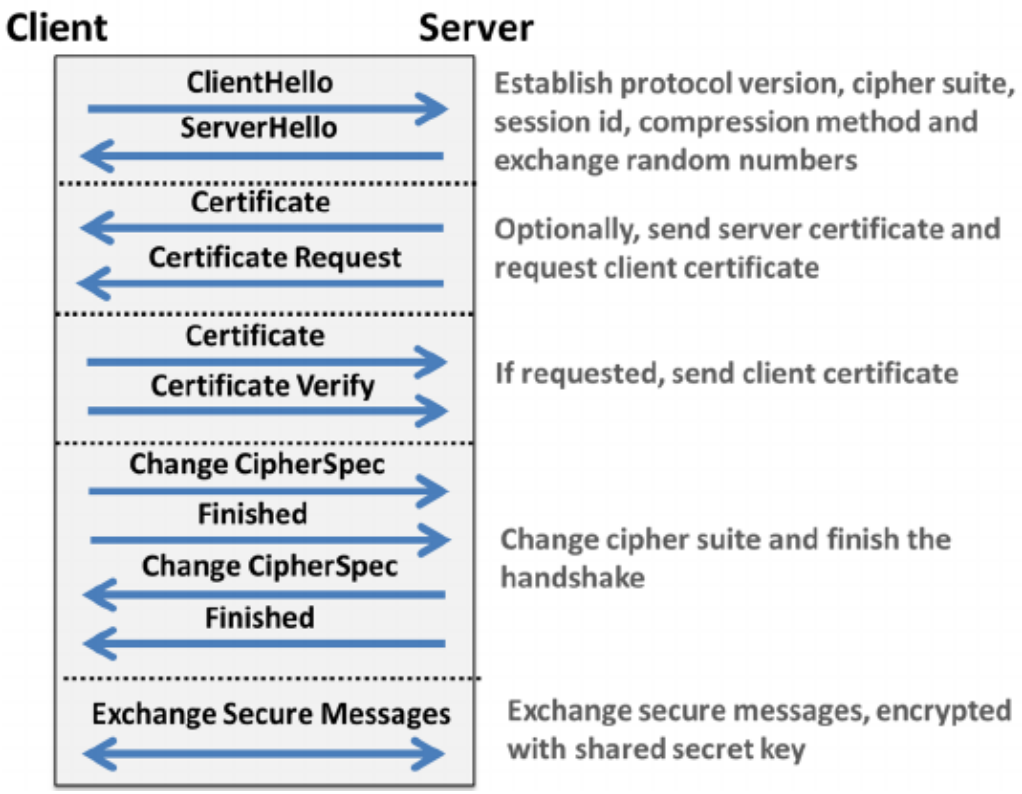


What is TLS?

- Most popular way to encrypt TCP traffic
- 2 stages
  - Handshake
  - Data transfer



What is TLS?

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- 2 stages
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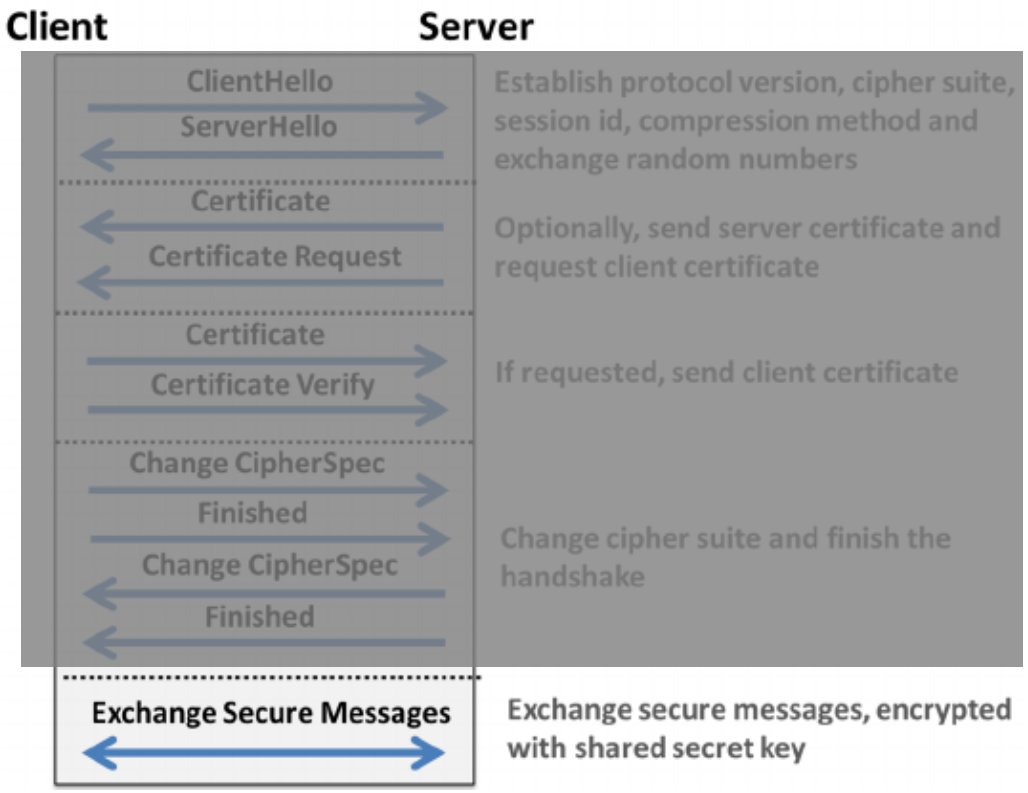
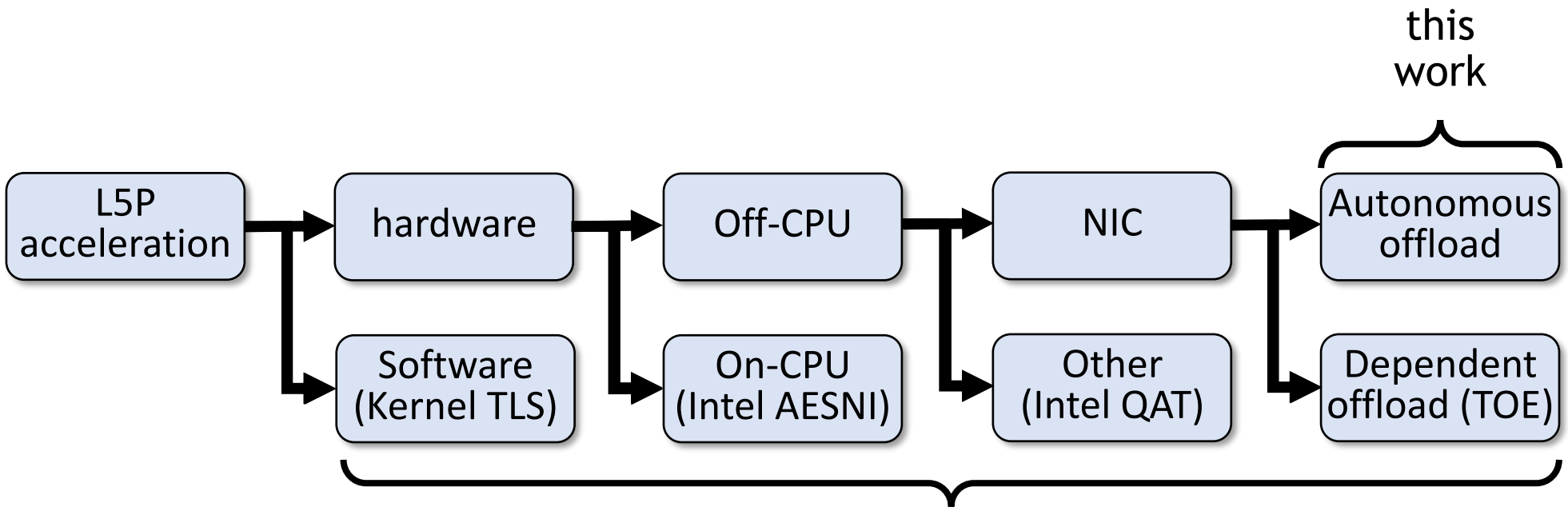
  - Data transfer
- We focus on data transfer

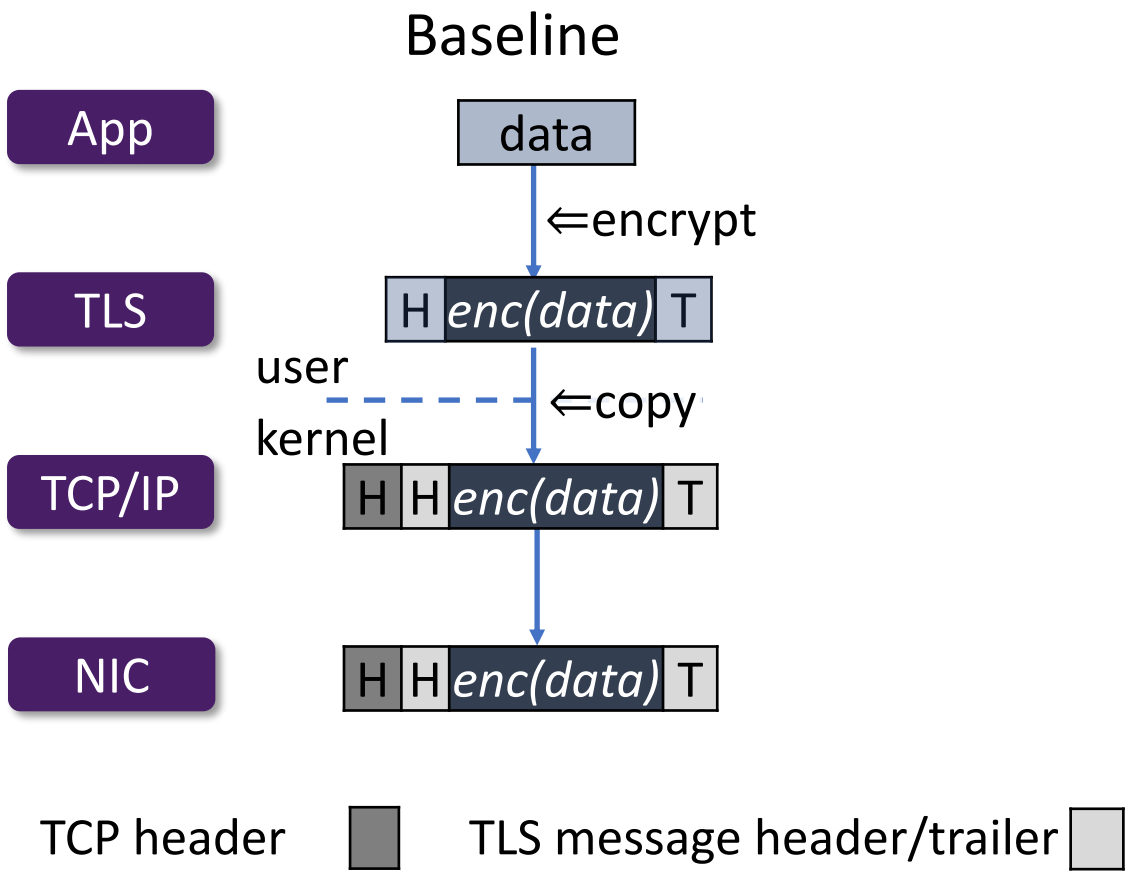


Design Space

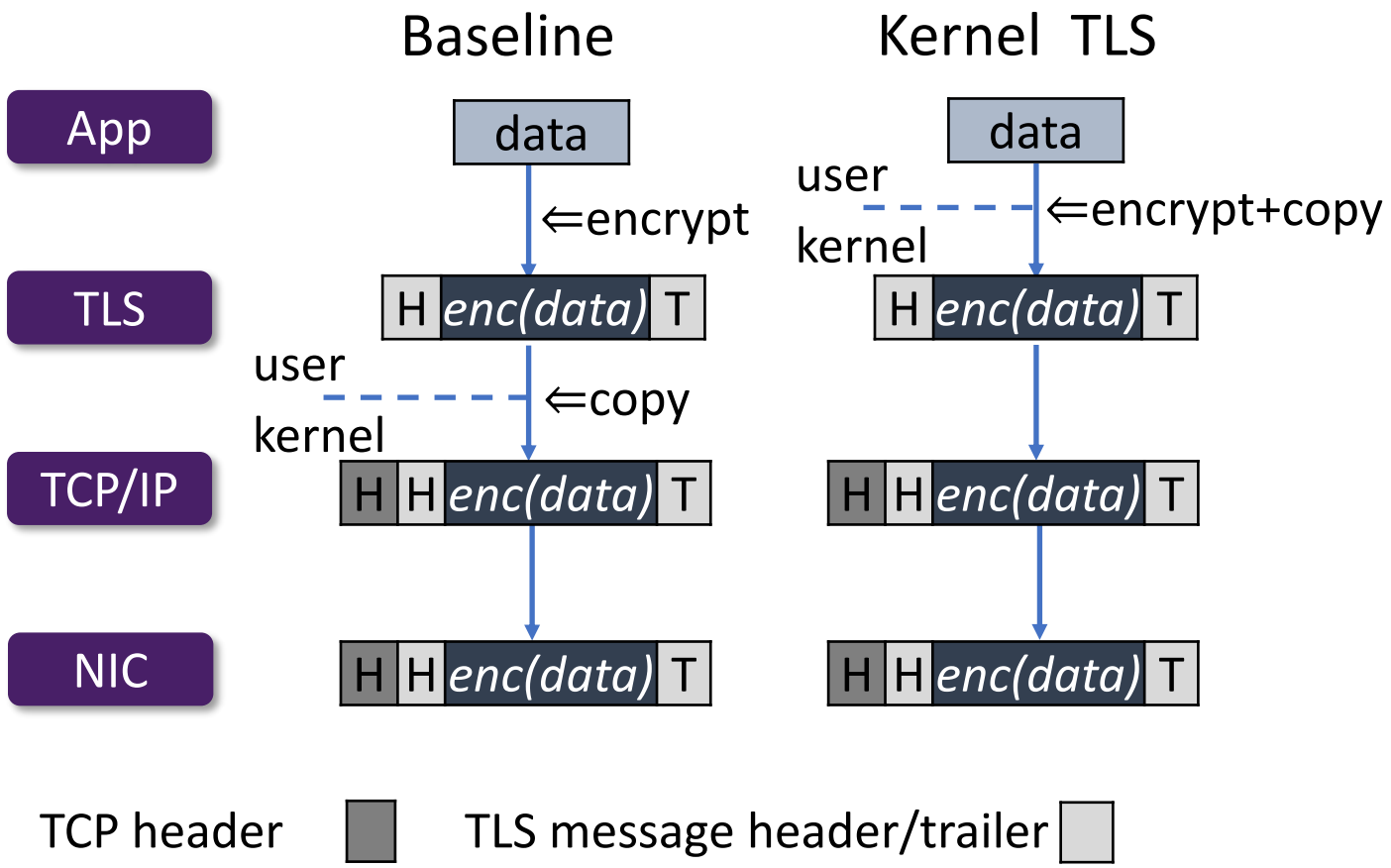


Pros	Cons
Eliminates CPU overhead	Overhead on recovery from reordering/loss
Works with software TCP, IP, routing, QoS, firewall, etc.	

Software specialization



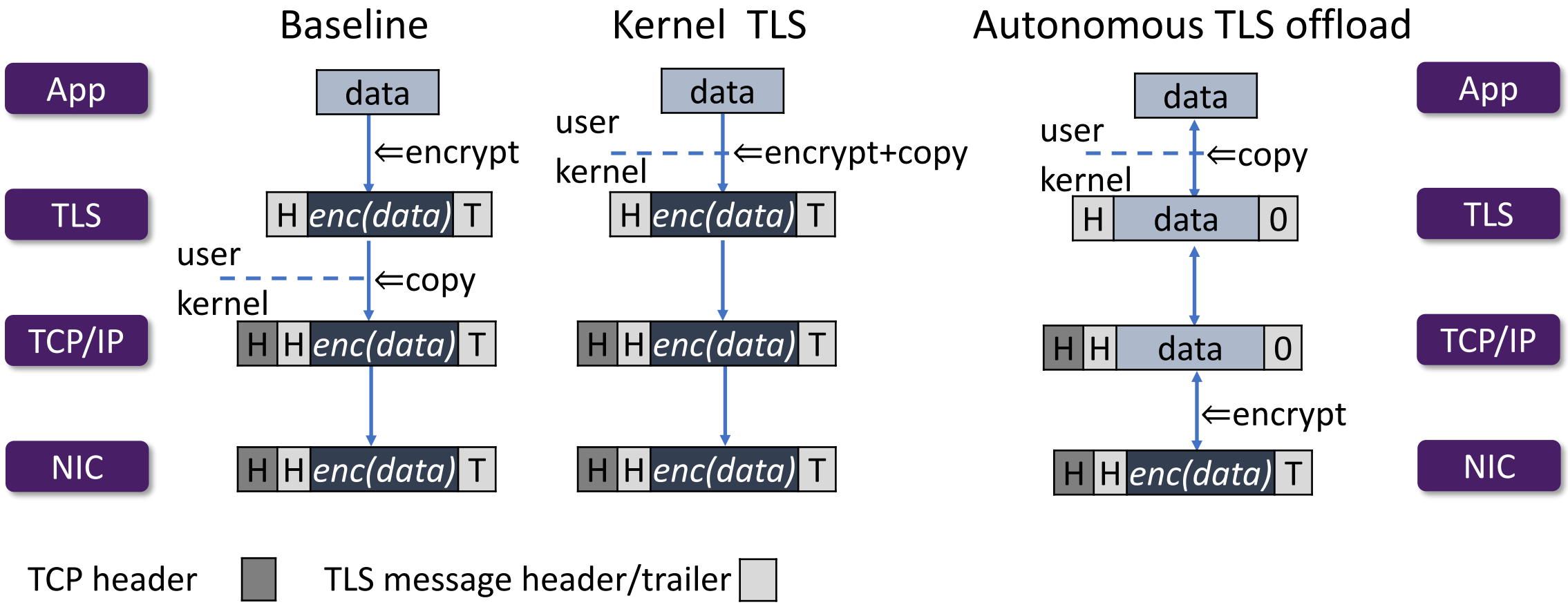
Software specialization



Kernel TLS enables

- Cross layer optimization
- Direct communication between NIC and TLS layers

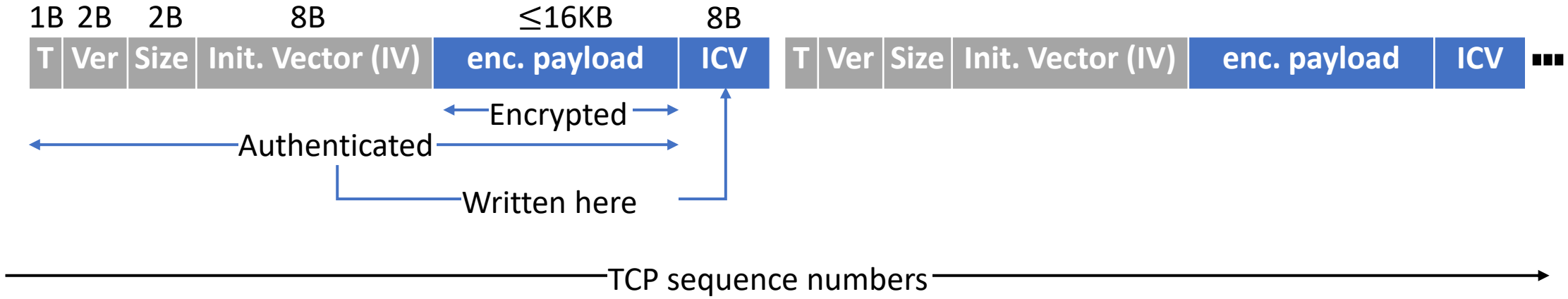
Autonomous NIC offload: TLS



TLS protocol background

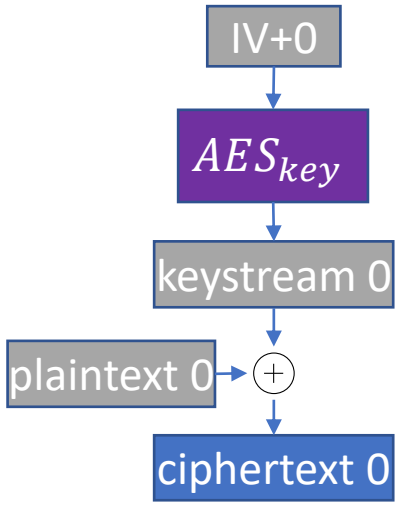
TLS records

TLS is a stream of 16KB records over TCP



TLS record crypto

- TLS AES-GCM enc/dec algorithm
  - Uses (i) per-stream key & (ii) the per-record IV



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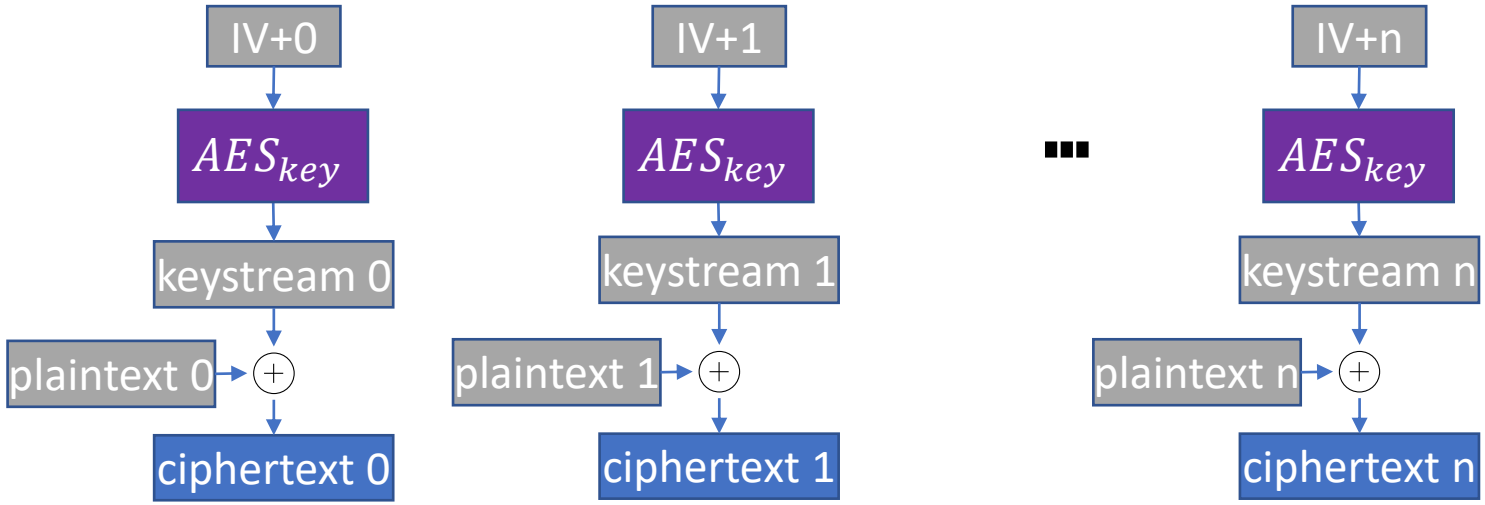

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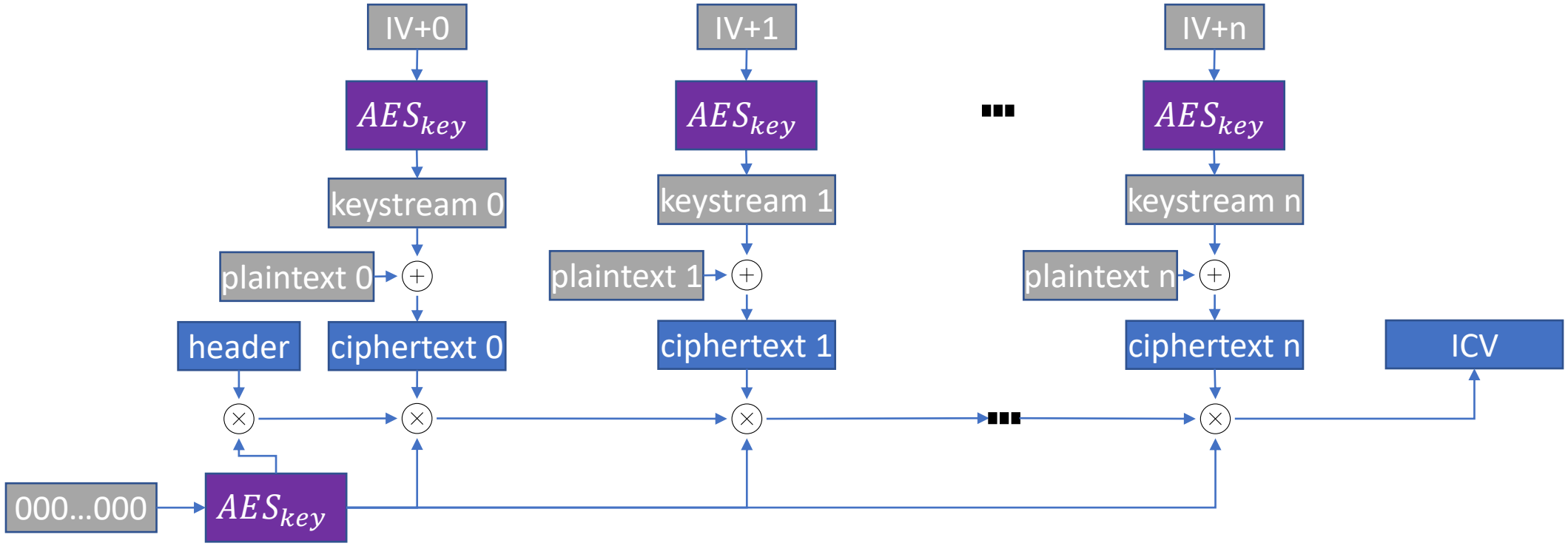
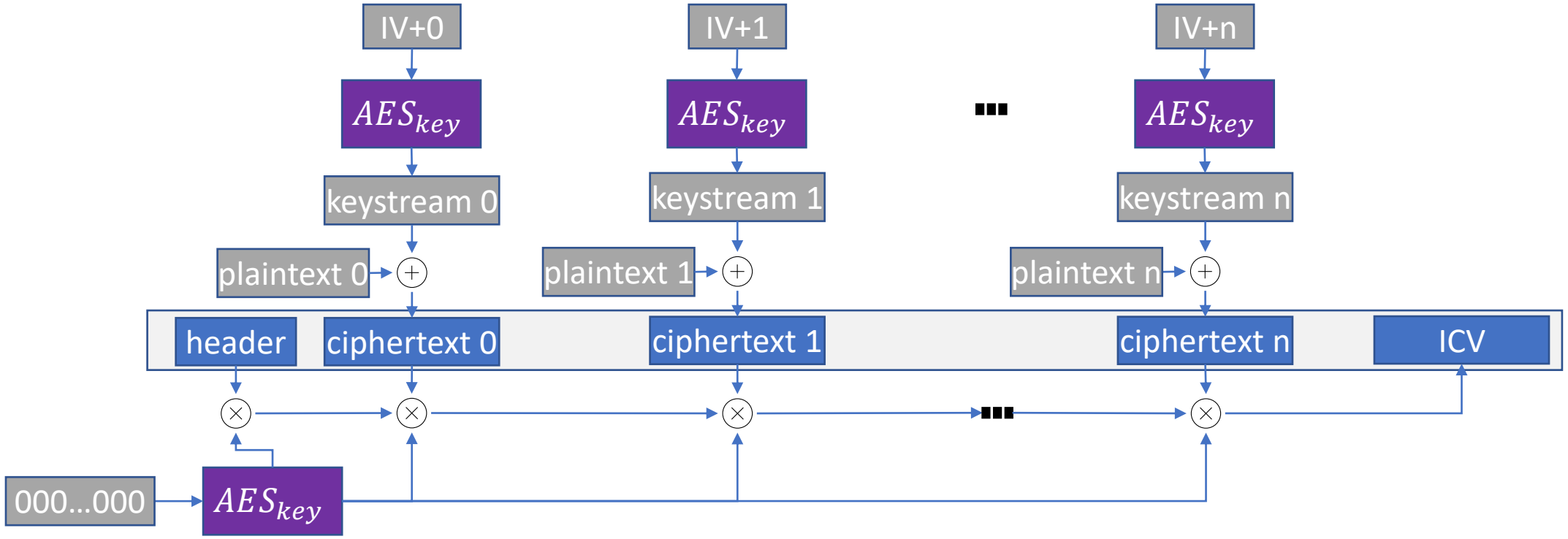


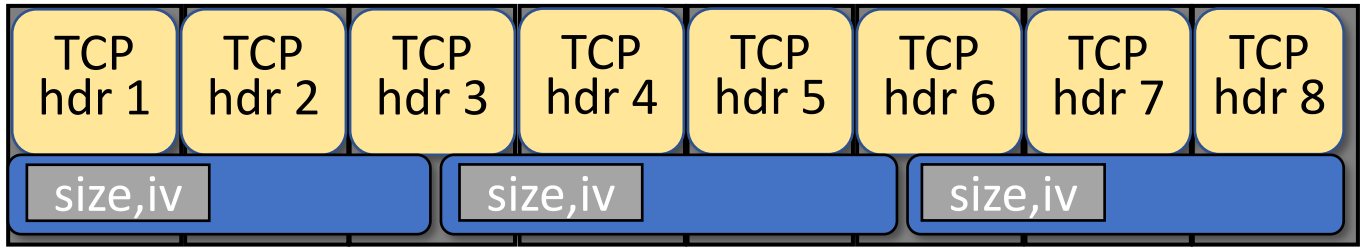
TLS record crypto properties

- Can be computed incrementally
- Byte-granular input
- Size preserving output
- Message independent state



Transmit offload in-sequence

- NIC offload Implementation is simple
  - Incrementally offload using NIC contexts



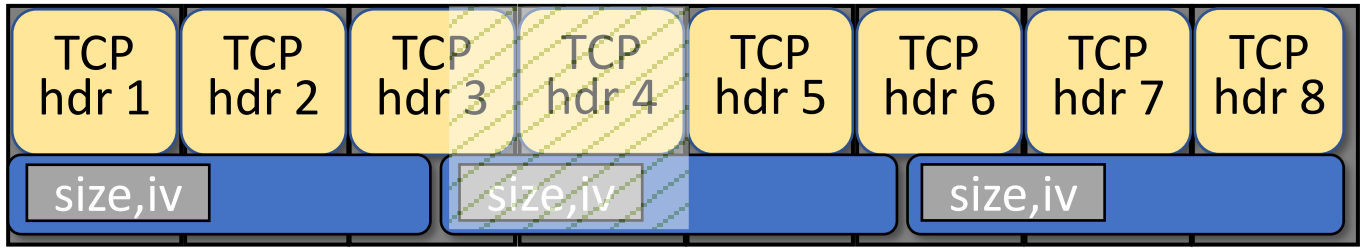
NIC contexts

Static state
- crypto keys

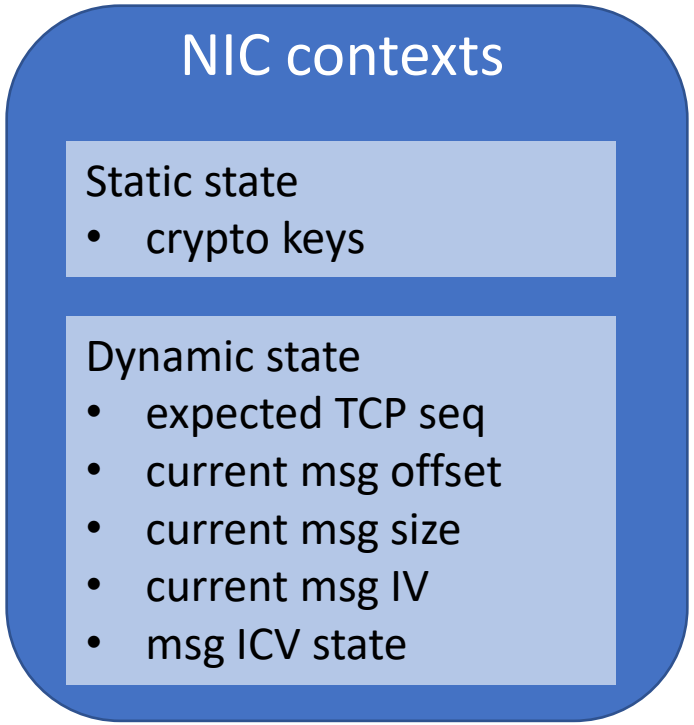
Dynamic state
- expected TCP seq
- current msg offset
- current msg size
- current msg IV
- msg ICV state

Transmit offload out-of-sequence

- Wrong dynamic NIC context state
- Context recovery needs only the message prefix
  - Driver can get the prefix from software TLS

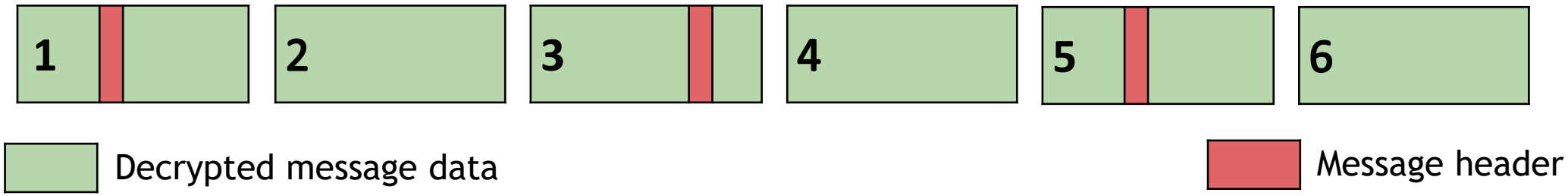


- Reuse TCP transmit buffer for storing data
  - TCP ACKs release data in TLS record granularity



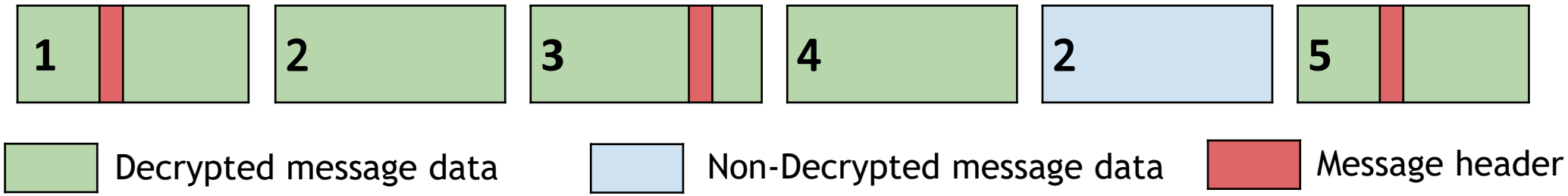
Receive offload in-sequence

- NIC offload Implementation is simple
  - Incrementally offload using NIC contexts
- Hardware reports one bit per packet
  - is packet decrypted and authenticated?



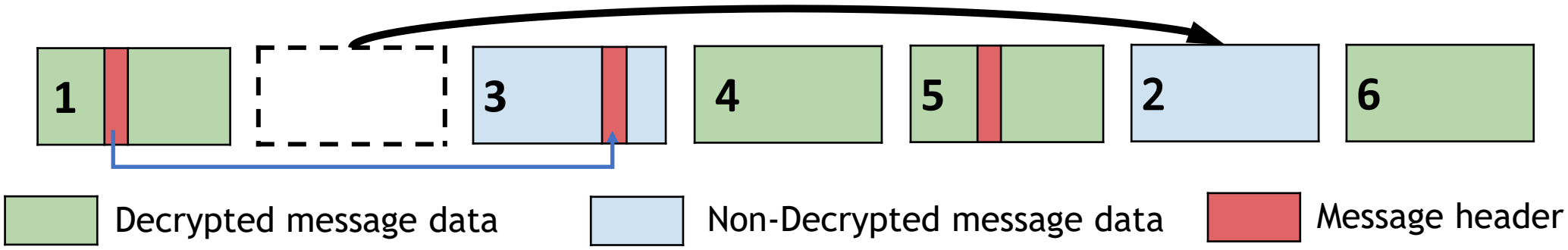
Receive offload retransmission

- Retransmissions bypass offload
  - Software fallback



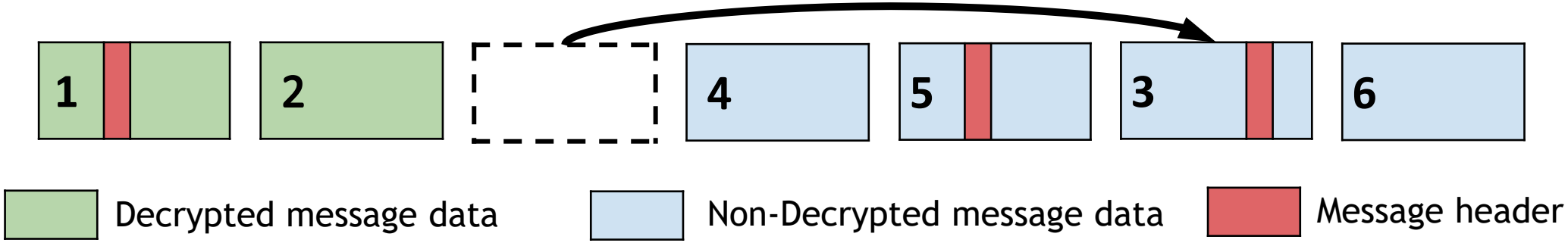
Receive offload data reordering

- Record data reordering
  - Skip hardware to skip to the next record
  - Continue offloading



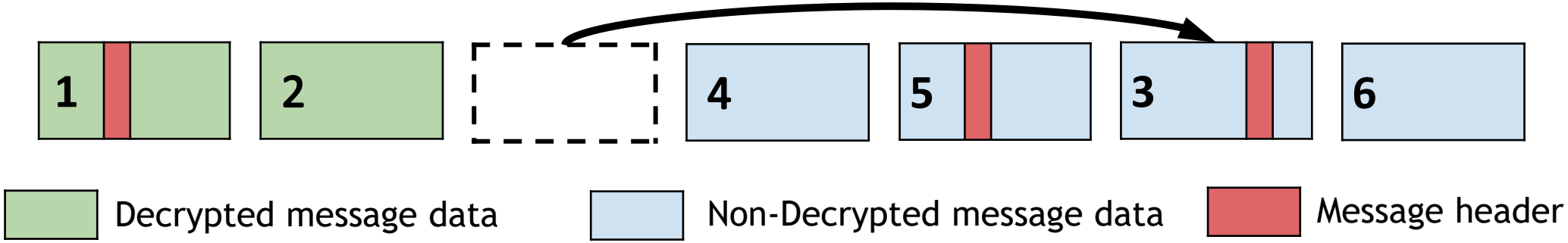
Receive offload header reordering

- Record header reordering
  - Stops hardware NIC offloading
  - Software must recover NIC context to continue



Receive offload recovery problem

- NIC context recovery on receive is non-trivial:
  - Stopping packets to recover NIC context is impossible
    - Packets keep coming
  - Software alone cannot recover during traffic
    - Need to combine software and hardware

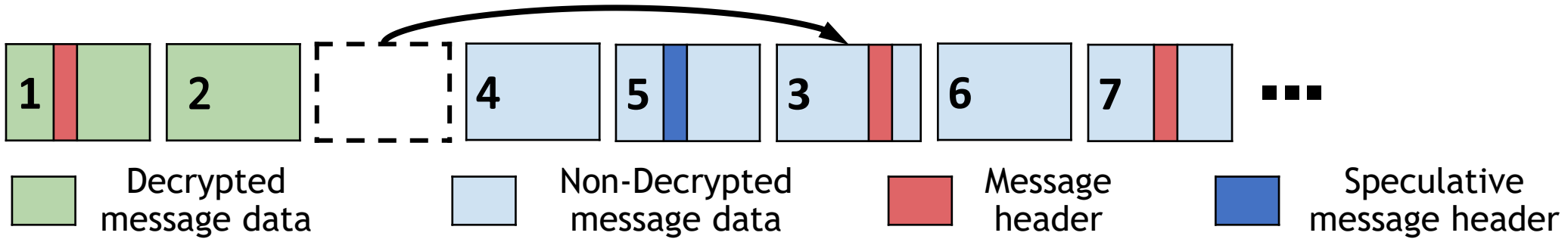


Receive offload recovery solution

NIC context recovery relies on:

(1) Speculatively finding TLS message header magic pattern

- TLS message type and version (0x170303)



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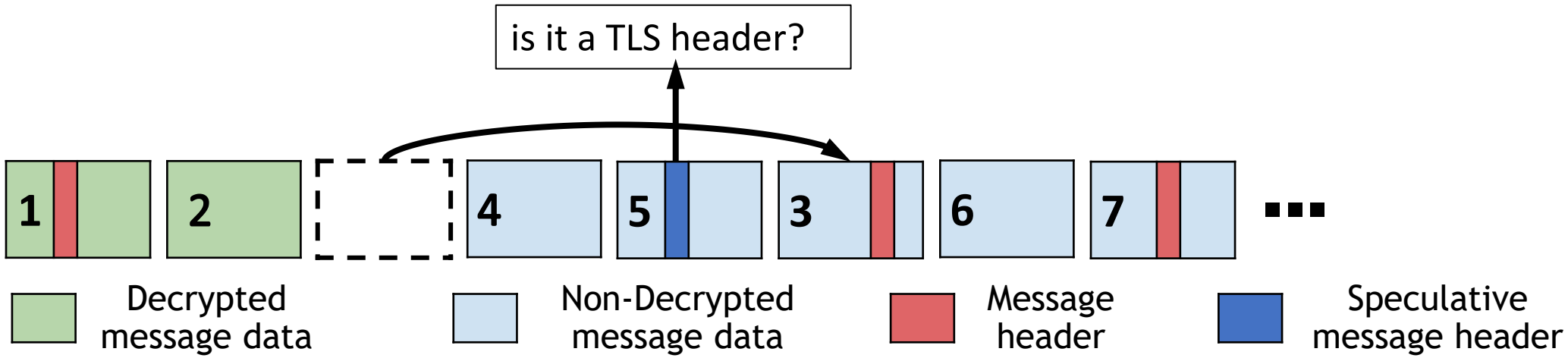
(2) Requesting software to confirm that this is indeed a TLS header, while



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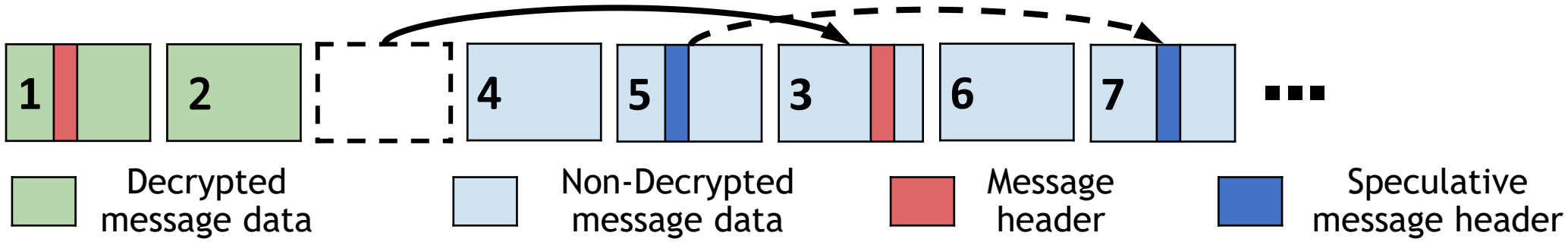

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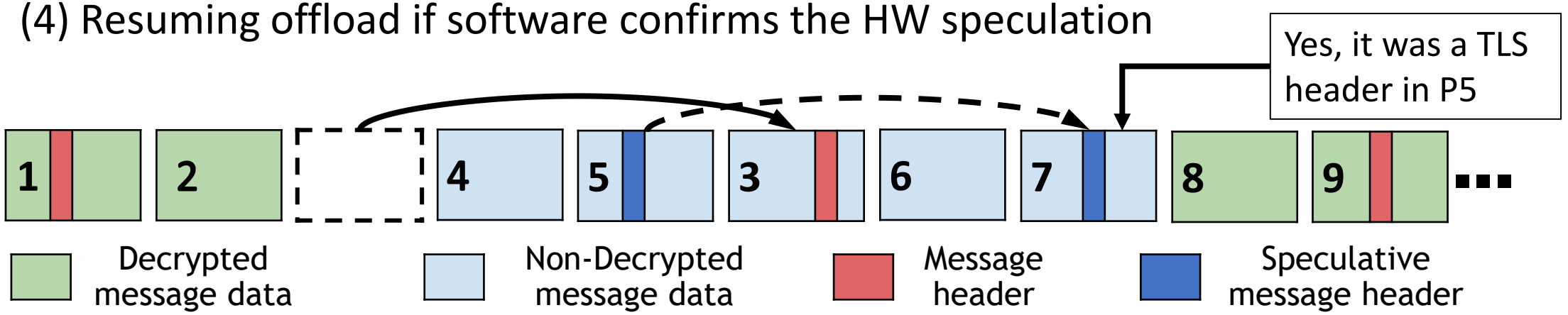
(4) Resuming offload if software confirms the HW speculation



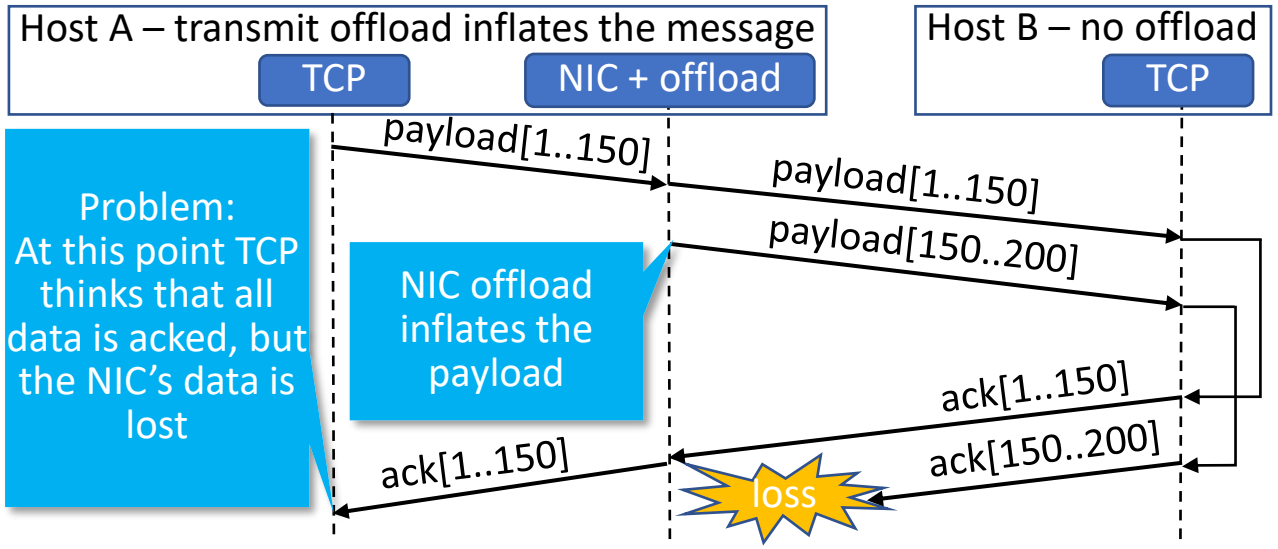
Autonomous offload properties

- What computations are autonomously offloadable?
  - Most computations, but not all

- What L5Ps are autonomously offloadable?
  - Many L5Ps, but not all

When computation is autonomously offloadable?

- On transmit, it must be size-preserving
  - This precludes transmit compression offloads



When computation is autonomously offloadable?

- On transmit, it must be size-preserving
- It is computable on TCP packets of any size
  - This precludes some block ciphers (AES-CBC) which operate on 16B blocks

When computation is autonomously offloadable?

- On transmit, it must be size-preserving
- It is computable on TCP packets of any size
- It uses constant-size message-independent state
  - It cannot depend on all stream payload
  - It can depend on message metadata (message sequence)

When computation is autonomously offloadable?

- On transmit, it must be size-preserving
- It is computable on TCP packets of any size
- It uses constant-size message-independent state

- Many computations fit this requirement
  - encryption
  - decryption
  - digest
  - copy
  - pattern matching

When L5Ps are autonomously offloadable?

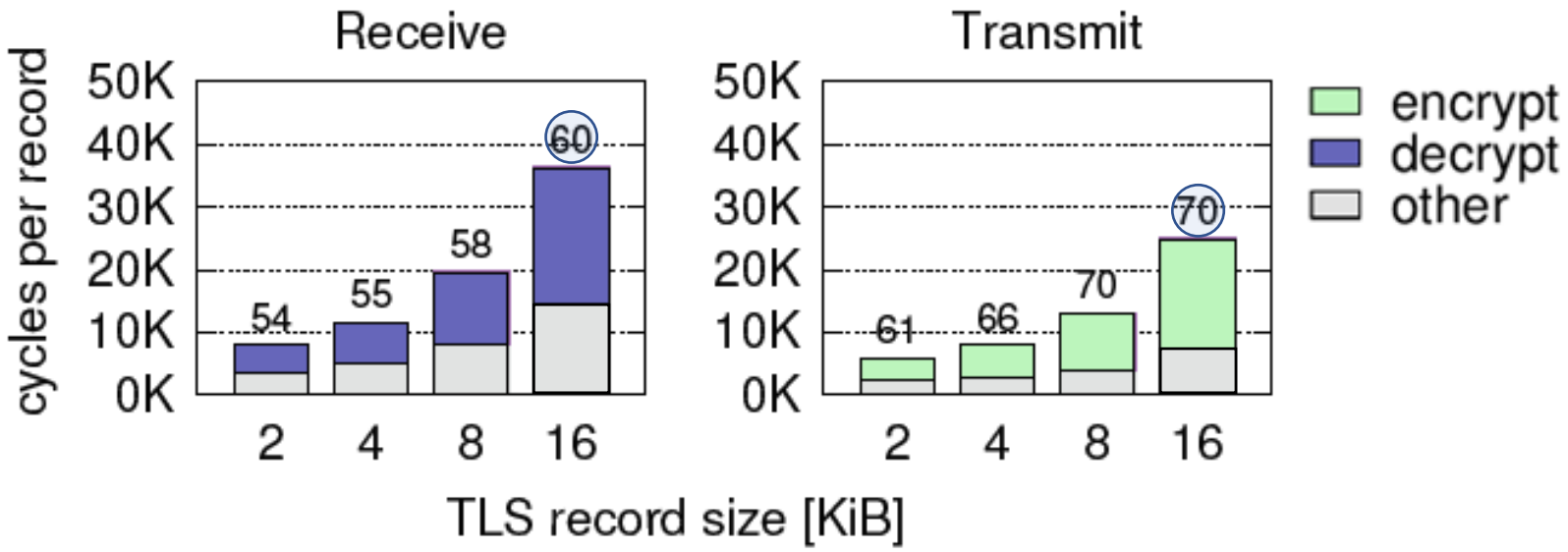
- The protocol message header must contain:
  1. Message length field
  2. Plaintext magic pattern (version/opcode)
- Together these enable hardware-driven NIC context reconstruction

- Many protocols fit this requirement
  - http/2
  - memcached
  - iscsi
  - smb
  - thrift
  - grpc
  - nbd

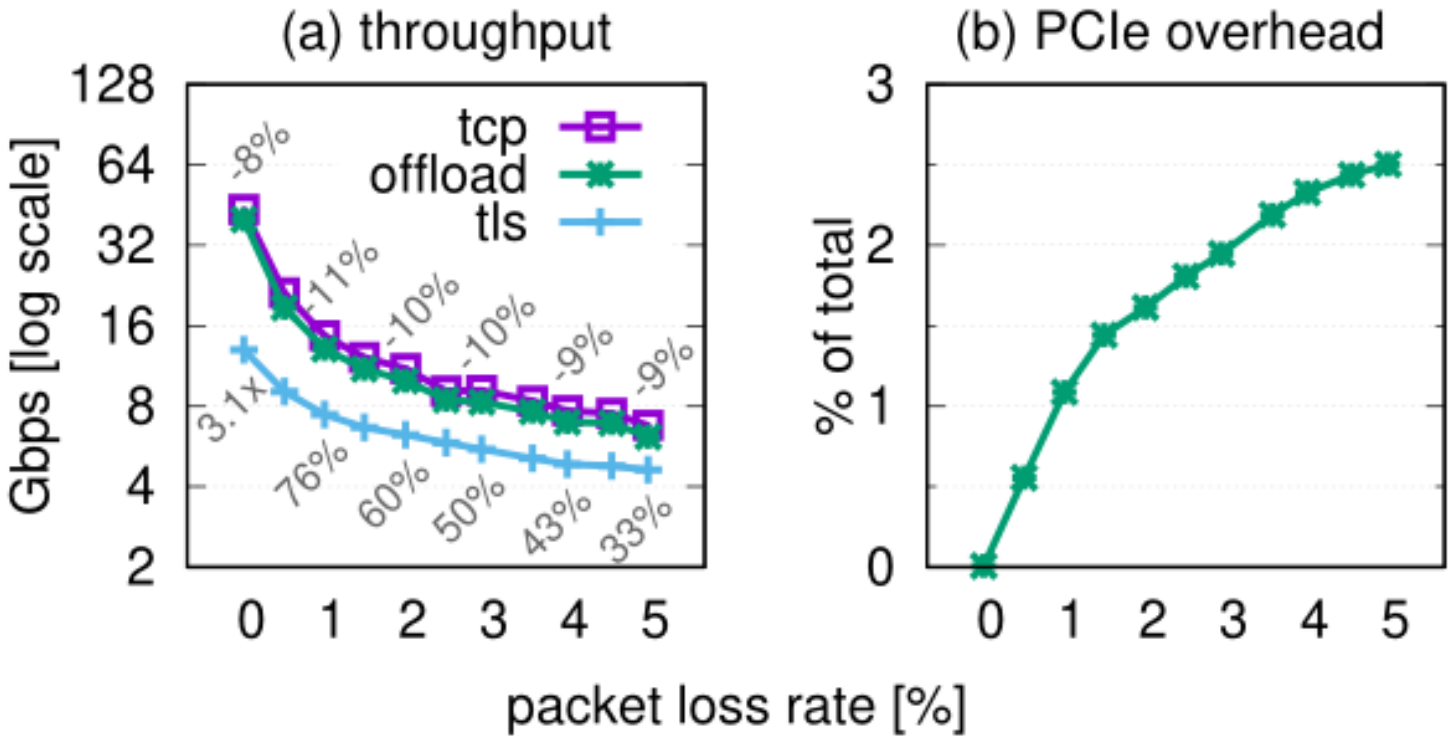
Implementation

- TLS crypto offload is available in Mellanox ConnectX6-Dx NICs:
  - OpenSSL: 1381 LoC (available upstream)
  - Linux kernel: 2223 LoC (available upstream)
  - Mellanox NIC driver: 2095 LoC (available upstream)

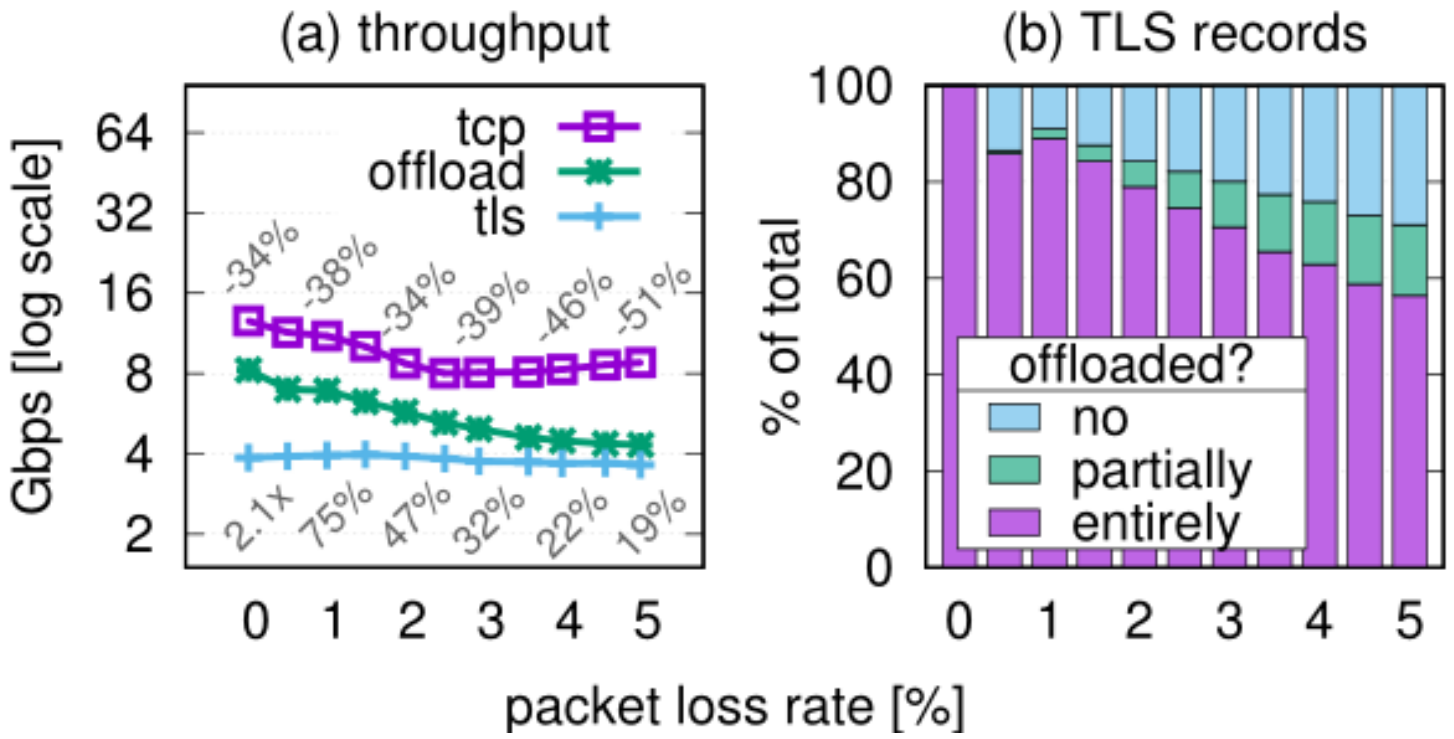
TLS cycle breakdown



Packet loss on transmit



Packet loss on receive



Conclusion

- Designed a new framework, called **autonomous NIC offloads** for accelerating L5P computations efficiently while cooperating with software TCP/IP

- Implemented support for **TLS crypto offload** and **NVMe-TCP copy and digest** offloads in Mellanox ConnectX NICs

- Evaluation shows our approach improves throughput by up to 3.3x, and reduce CPU utilization by up to 60% and latency by up to 30%