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Serving Netflix Video at 400Gb/s on FreeBSD

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EuroBSDCon 2021

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Outline:

- Motivation
- Description of production platform
- Description of workload
- To NUMA or not to NUMA?
- Inline Hardware (NIC) kTLS
- Alternate platforms

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Motivation:

- Since 2020, Netflix has been able to serve 200Gb/s of TLS encrypted video traffic from a single server.
- How can we serve ~400Gb/s of video from the same servers?

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Netflix Video Serving Workload

- FreeBSD-current
- NGINX web server
- Video served via sendfile(2) and encrypted using software kTLS

Netflix Video Serving Hardware

- AMD EPYC 7502P (“Rome”)
    - 32 cores @ 2.5GHz
    - 256GB DDR4-3200
        - 8 channels
        - ~150GB/s mem bw
            - Or ~1.2Tb/s in networking units
    - 128 lanes PCIe Gen4
        - ~250GB/s of IO bandwidth
            - Or ~2Tb/s in networking units

Netflix Video Serving Hardware

- 2x Mellanox ConnectX-6 Dx
  - Gen4 x16, 2 full speed 100GbE ports per NIC
    - 4 x 100GbE in total
  - Support for NIC kTLS offload
- 18x WD SN720 NVME
  - 2TB
  - PCIe Gen3 x4

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Performance Results:

- 240Gb/s
- Limited by memory BW
  - Determined empirically by using AMDuProfPCM

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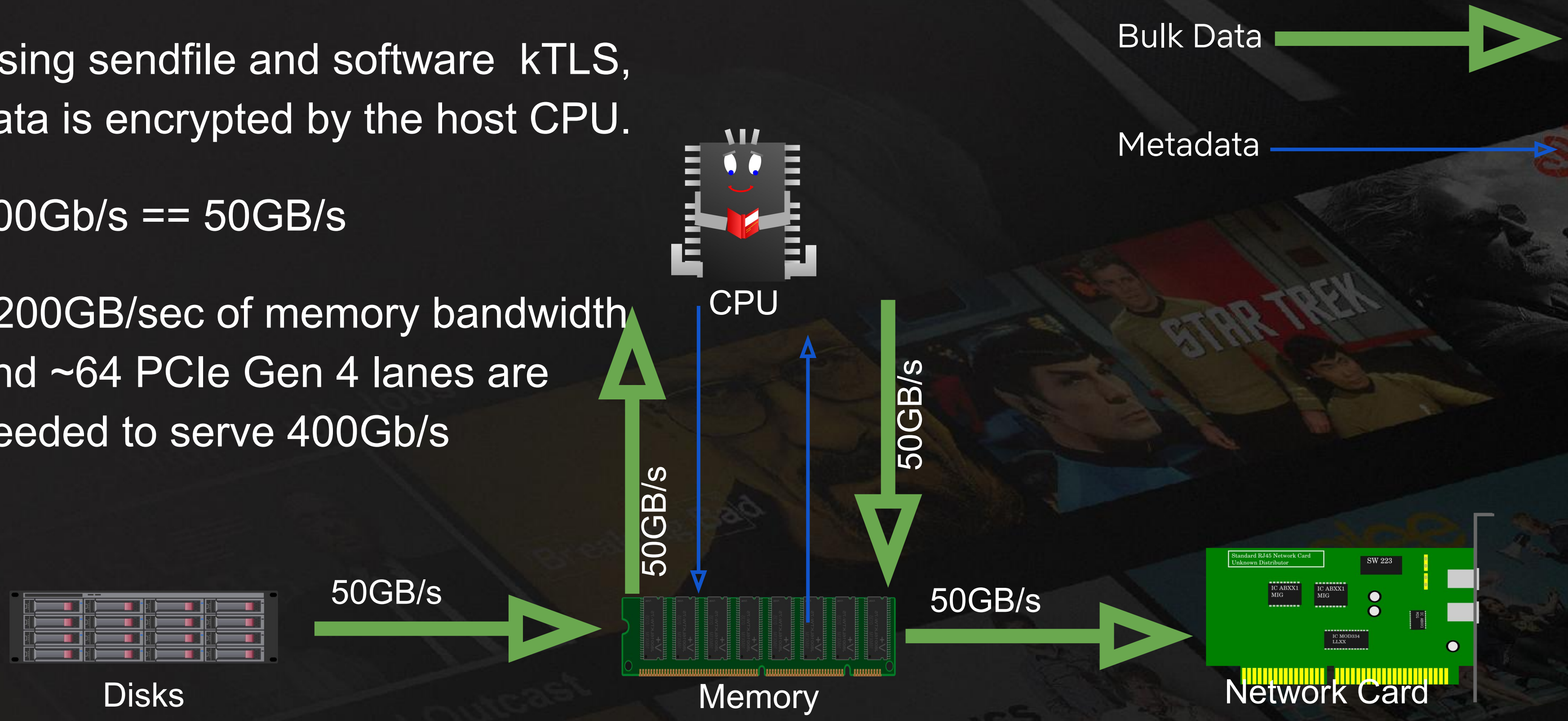
Netflix 400Gb/s Video Serving Data Flow

Using sendfile and software kTLS, data is encrypted by the host CPU.

400Gb/s == 50GB/s

~200GB/sec of memory bandwidth and ~64 PCIe Gen 4 lanes are needed to serve 400Gb/s



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Can NUMA get us to 400Gb/s

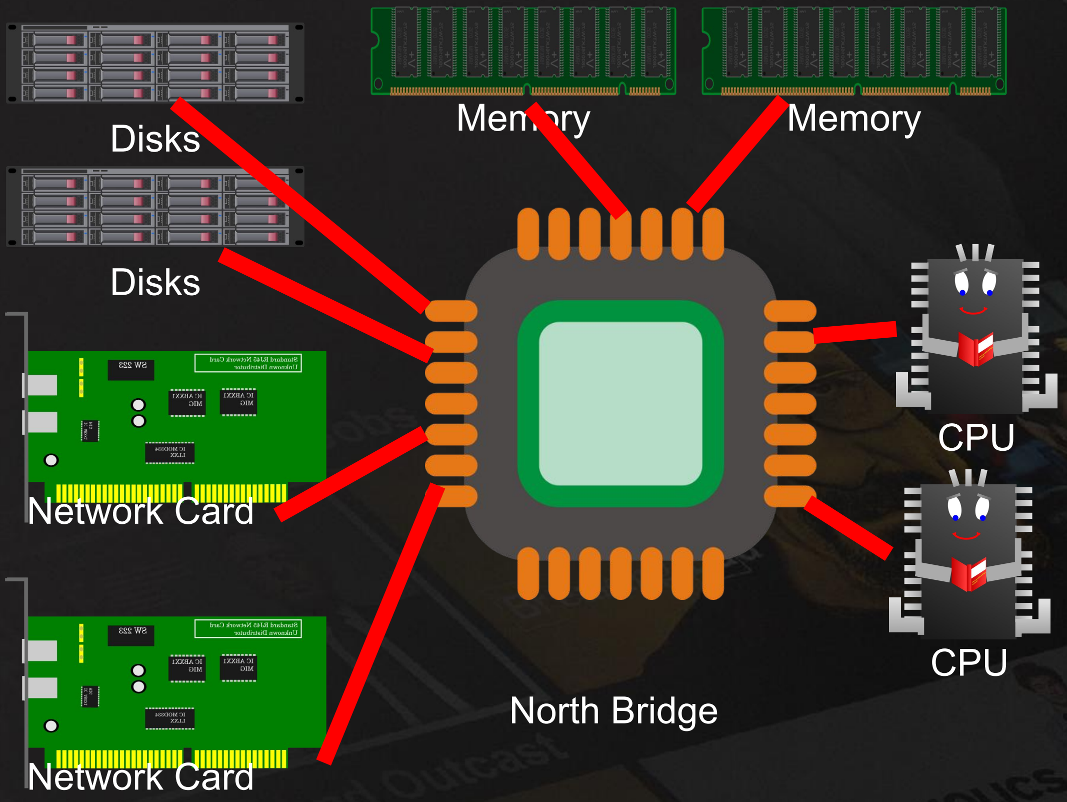
- Use STREAM benchmark bandwidth as a proxy
    - Single Node: 150GB/s
    - Four Nodes: 175GB/s

What is NUMA?

Non ***U***niform ***M***emory ***A***rchitecture

That means memory and/or devices can be “closer” to some CPU cores

Multi CPU Before NUMA



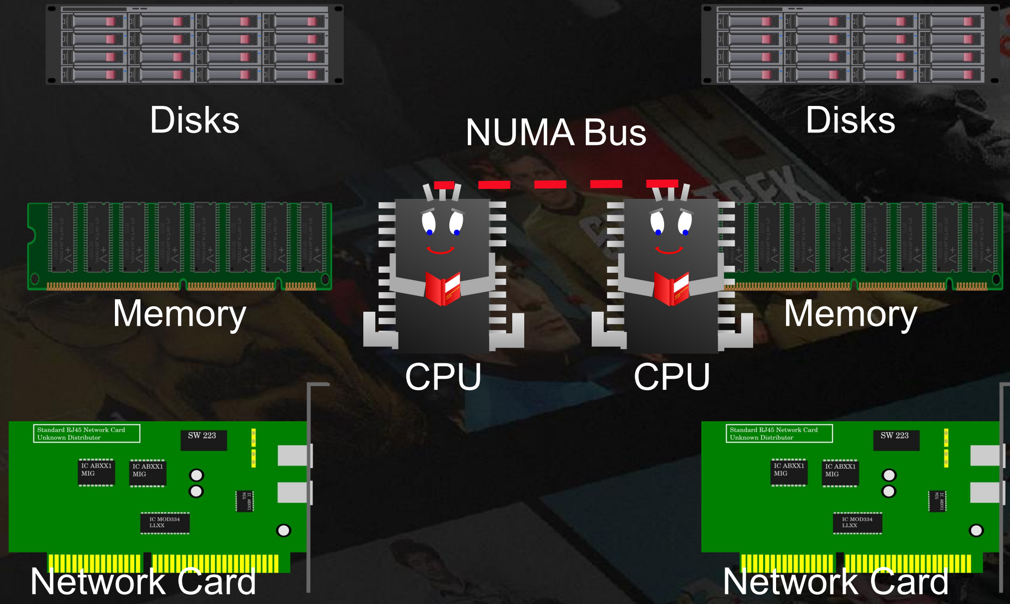
Memory access was *UNIFORM:*

Each core had equal and direct access to all memory and IO devices.

Multi Socket system with NUMA:

Memory access can be ***NON-UNIFORM***

- Each core has unequal access to memory
- Each core has unequal access to I/O devices



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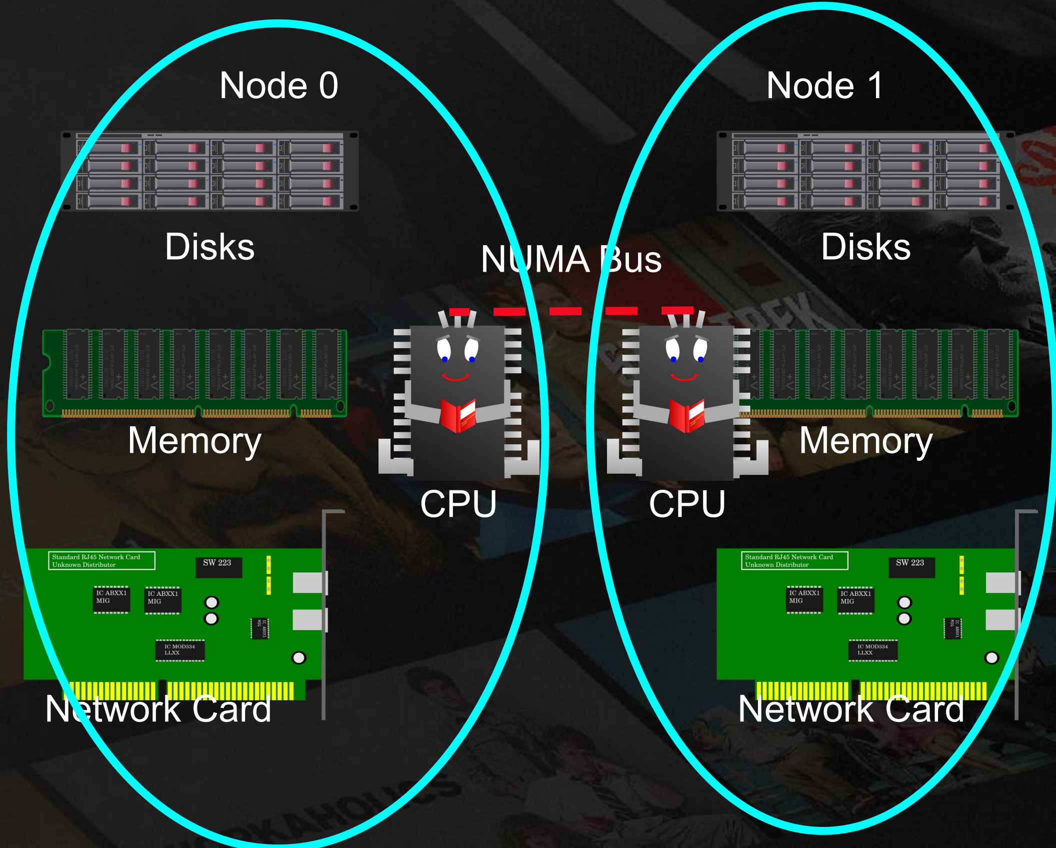
Present day NUMA:

Each locality zone called a “NUMA Domain” or “NUMA Node”



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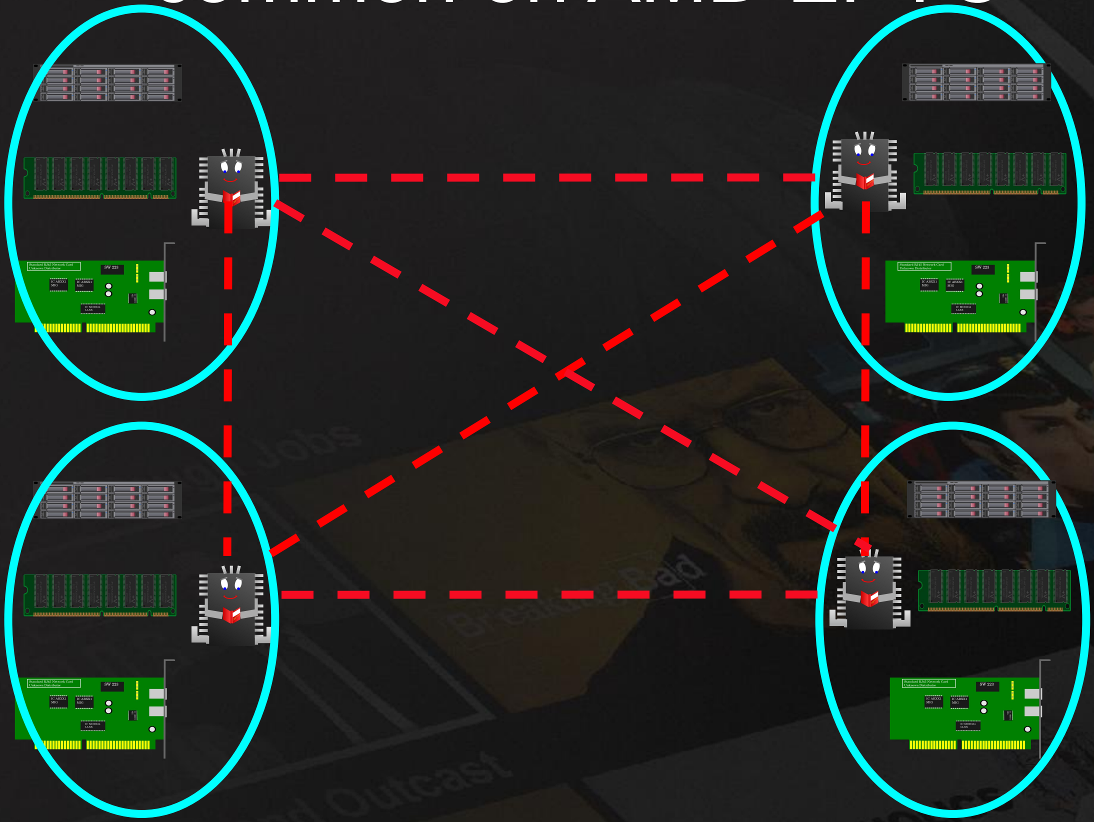
4 Node configurations are common on AMD EPYC



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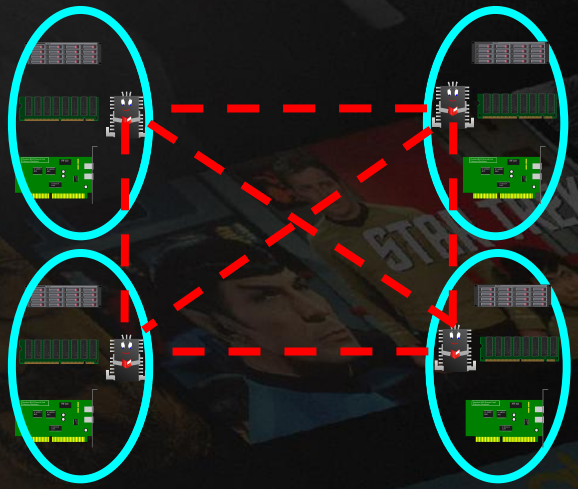
Cross-Domain costs

Latency Penalties:

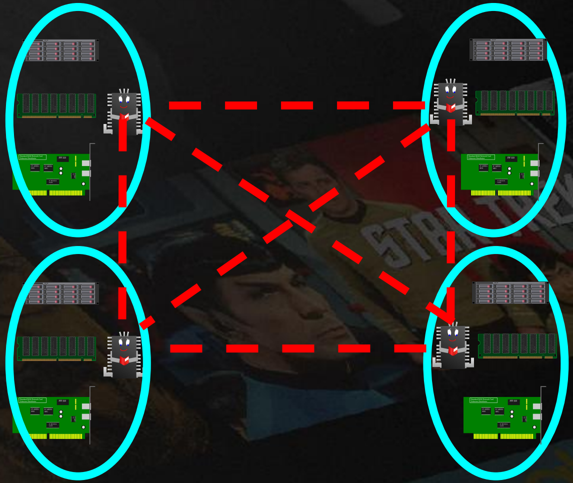
- 12-28ns



Cross-Domain costs

Bandwidth Limit:

- AMD Infinity Fabric
  - ~47GB/s per link
  - ~280GB/s total

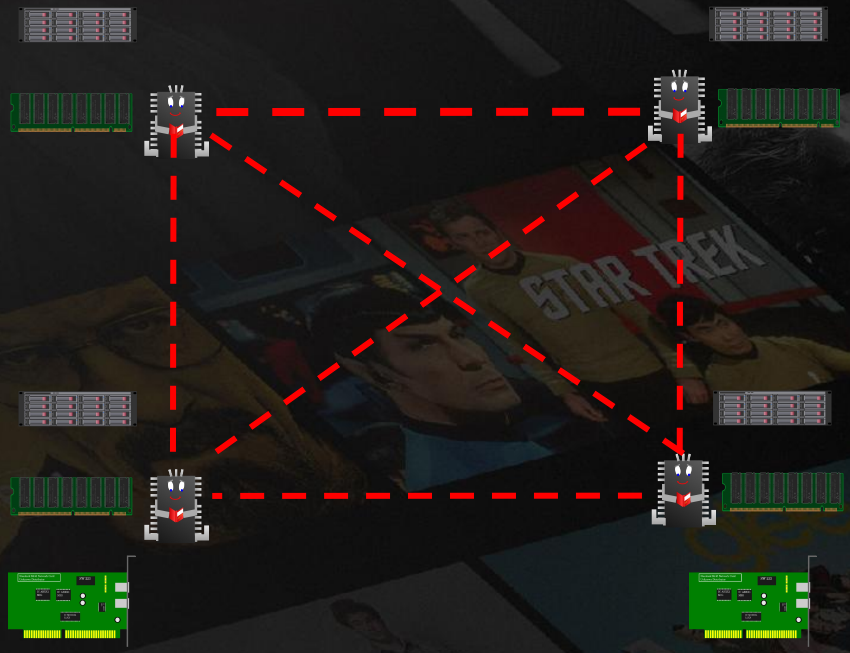


Strategy: Keep as much of our 200GB/sec of bulk data off the NUMA fabric is possible

- Bulk data congests NUMA fabric and leads to CPU stalls when competing with normal memory accesses.

4 Nodes, worst case

Steps to send data:



4 Nodes, worst case

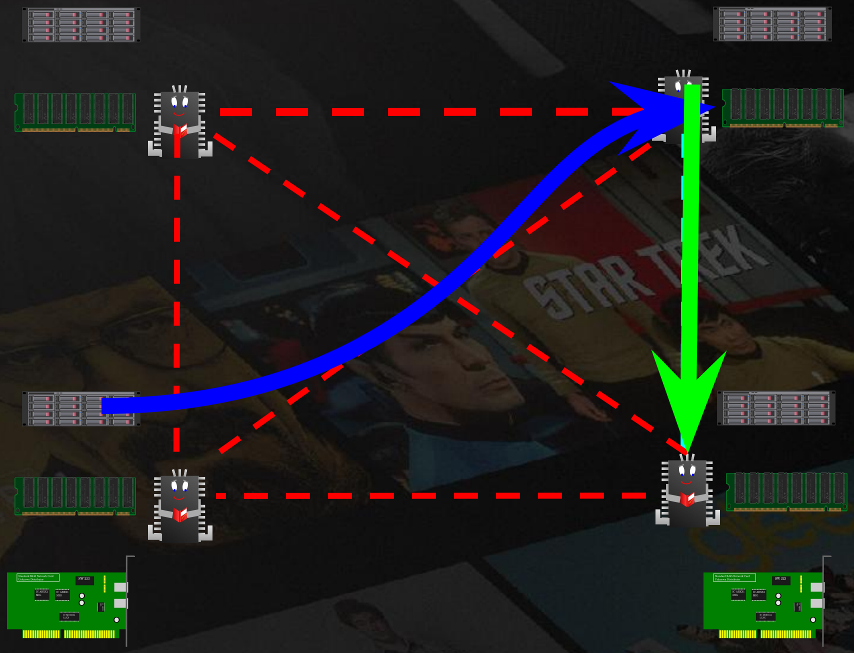
Steps to send data:

- DMA data from disk to memory
    - First NUMA bus crossing

4 Nodes, worst case

Steps to send data:

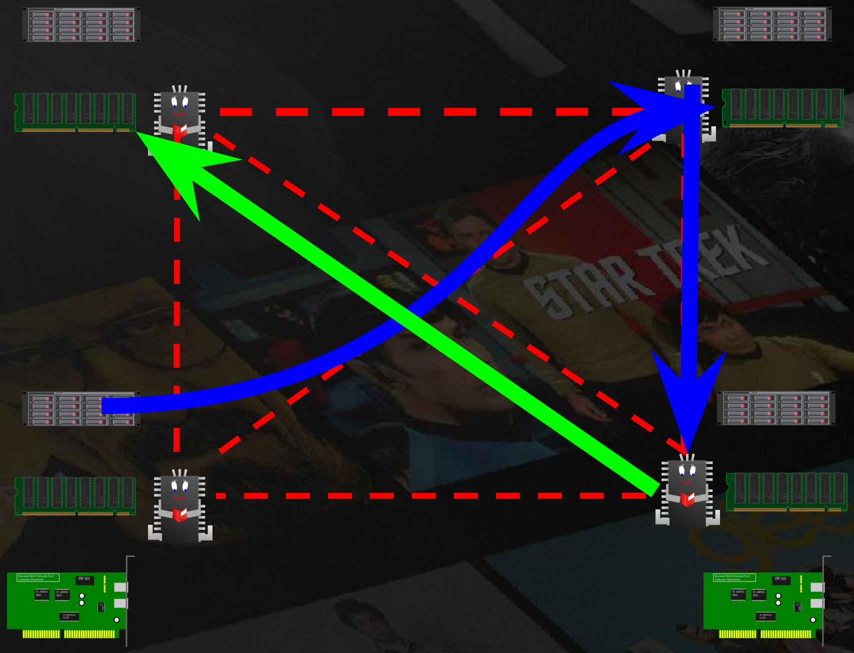
- DMA data from disk to memory
    - First NUMA bus crossing
- CPU reads data for encryption
    - Second NUMA crossing



4 Nodes, worst case

Steps to send data:

- DMA data from disk to memory
    - First NUMA bus crossing
- CPU reads data for encryption
    - Second NUMA crossing
- CPU writes data for encryption
    - Third NUMA crossing



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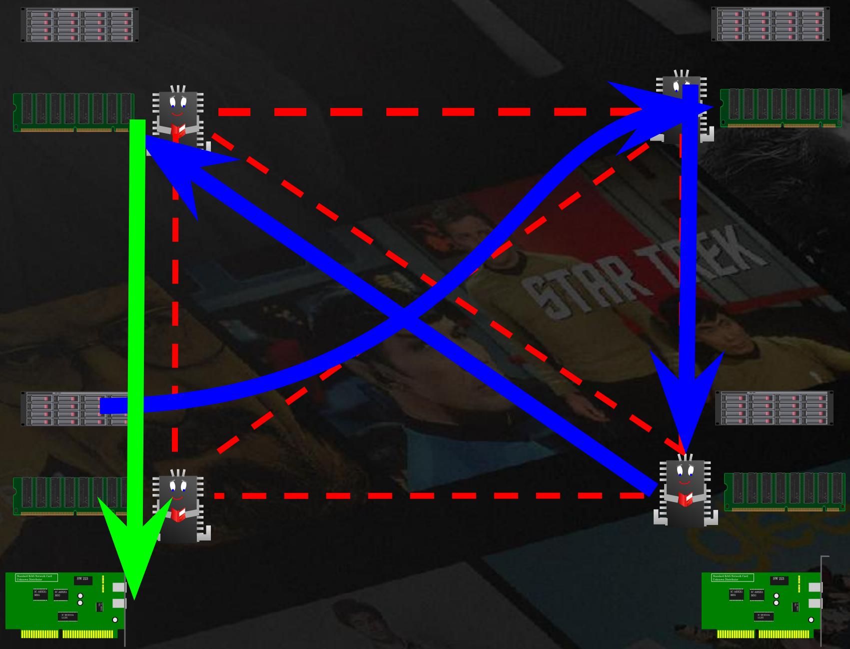
4 Nodes, worst case

Steps to send data:

- DMA data from disk to memory
  - First NUMA bus crossing
- CPU reads data for encryption
  - Second NUMA crossing
- CPU writes data for encryption
  - Third NUMA crossing
- DMA data from memory to network
  - Fourth NUMA crossing



Worst Case Summary:

- 4 NUMA crossings
- 200GB/s of data on the NUMA fabric
  - Fabric saturates, cannot handle the load.
  - CPU Stalls, saturates early

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Best Case Summary:

- 0 NUMA crossings
- 0GB/s of data on the NUMA fabric

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How can we get as close as possible to the best case?

- Constrained to use 1 IP address per host
- Must use lagg(4) LACP network bonding

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Impose order on the chaos.. *somehow*:

- Disk centric siloing
  - Try to do everything on the NUMA node where the content is stored
- Network centric siloing
  - Try to do as much as we can on the NUMA node that the LACP partner chose for us

Network centric siloing

- Associate network connections with NUMA nodes
- Allocate local memory to back media files when they are DMA'ed from disk
- Allocate local memory for TLS crypto destination buffers & do SW crypto locally
- Run kTLS workers, RACK / BBR TCP pacers with domain affinity
- Choose local lagg(4) egress port

All of this is upstream!

4 Nodes, worst case with siloing

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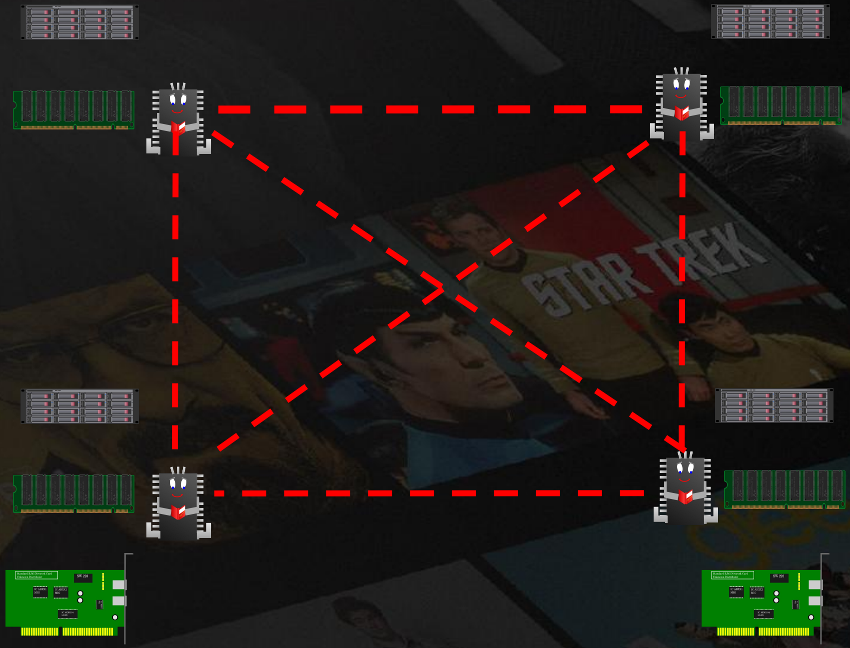

4 Nodes, worst case with siloing

Steps to send data:

- DMA data from disk to memory
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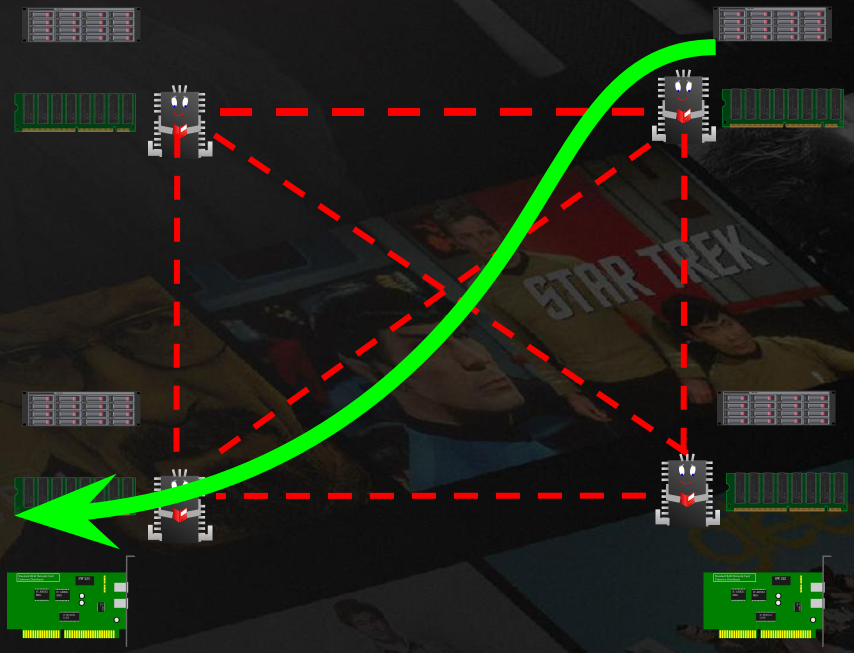

4 Nodes, worst case with siloing

Steps to send data:

- DMA data from disk to memory
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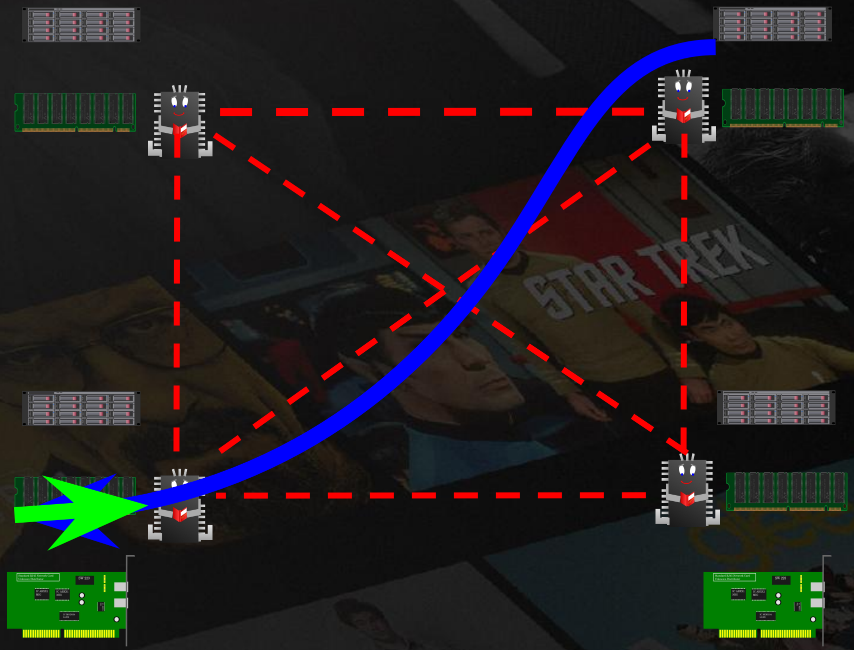
- CPU reads data for encryption



4 Nodes, worst case with siloing

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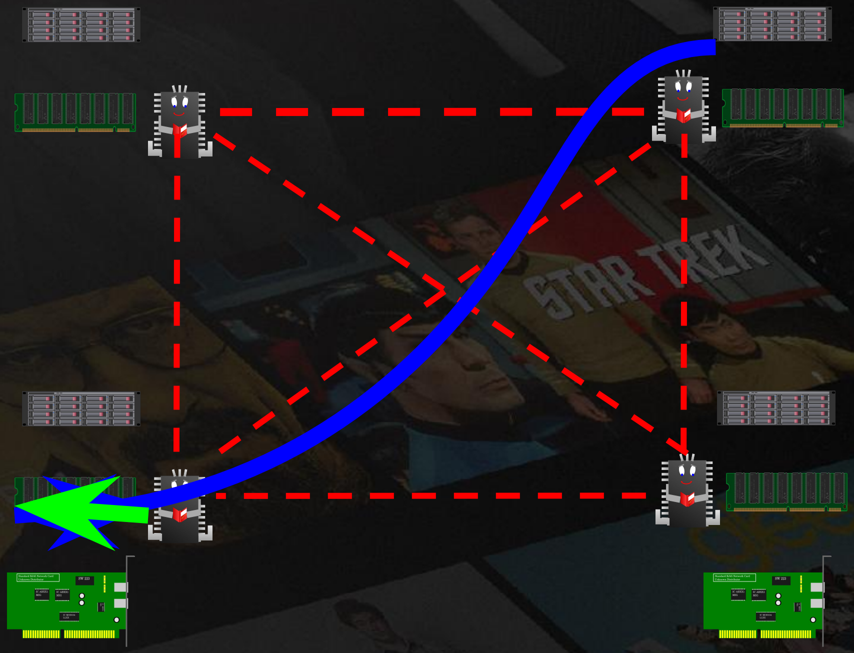

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4 Nodes, worst case with siloing

Steps to send data:

- DMA data from disk to memory
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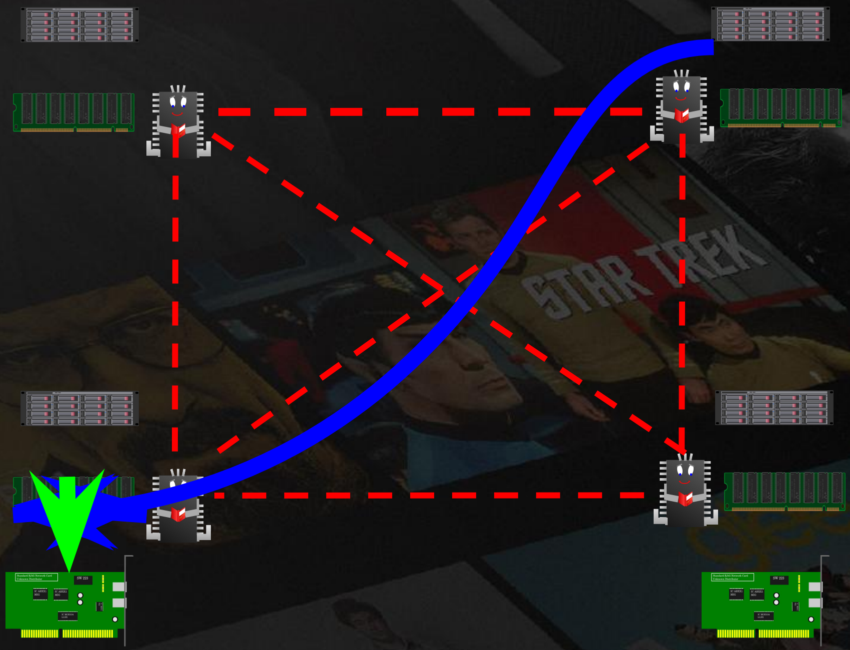
- CPU reads data for encryption
- CPU writes data for encryption
- DMA data from memory to network



Worst Case Summary:

- 1 NUMA crossing on average
  - 100% of disk reads across NUMA
- 50GB/s of data on each NUMA fabric link
  - Much less than the 280GB/sec of Inifinity fabric bandwidth

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Real Life is *Messy*

- NICs on only 2 of the 4 NUMA nodes
- Differing number of NVME on each node
- Hacks to “pretend” we have NICs in all 4 domains
- Impacts worst and average cases

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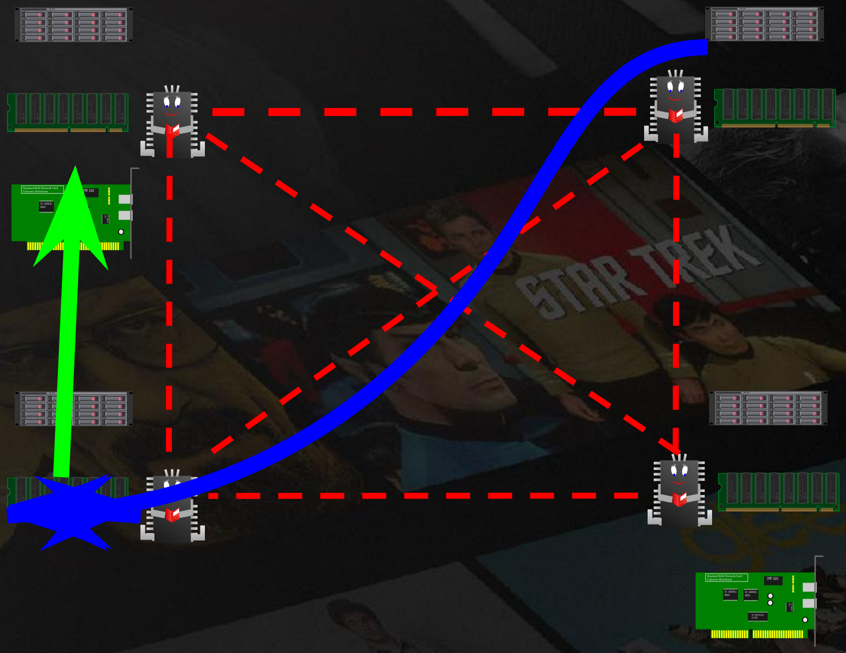
4 Nodes,worst case with siloing: messy

Steps to send data:

- DMA data from disk to memory
  - First NUMA bus crossing
- CPU reads data for encryption
- CPU writes data for encryption
- DMA data from memory to network



Worst Case Summary:

- 2 NUMA crossing on average
  - 100% of disk reads across NUMA
  - 100% of network writes across NUMA
- 100GB/s of data on the NUMA fabric
  - Less than the 280GB/s of Inifinity fabric bandwidth

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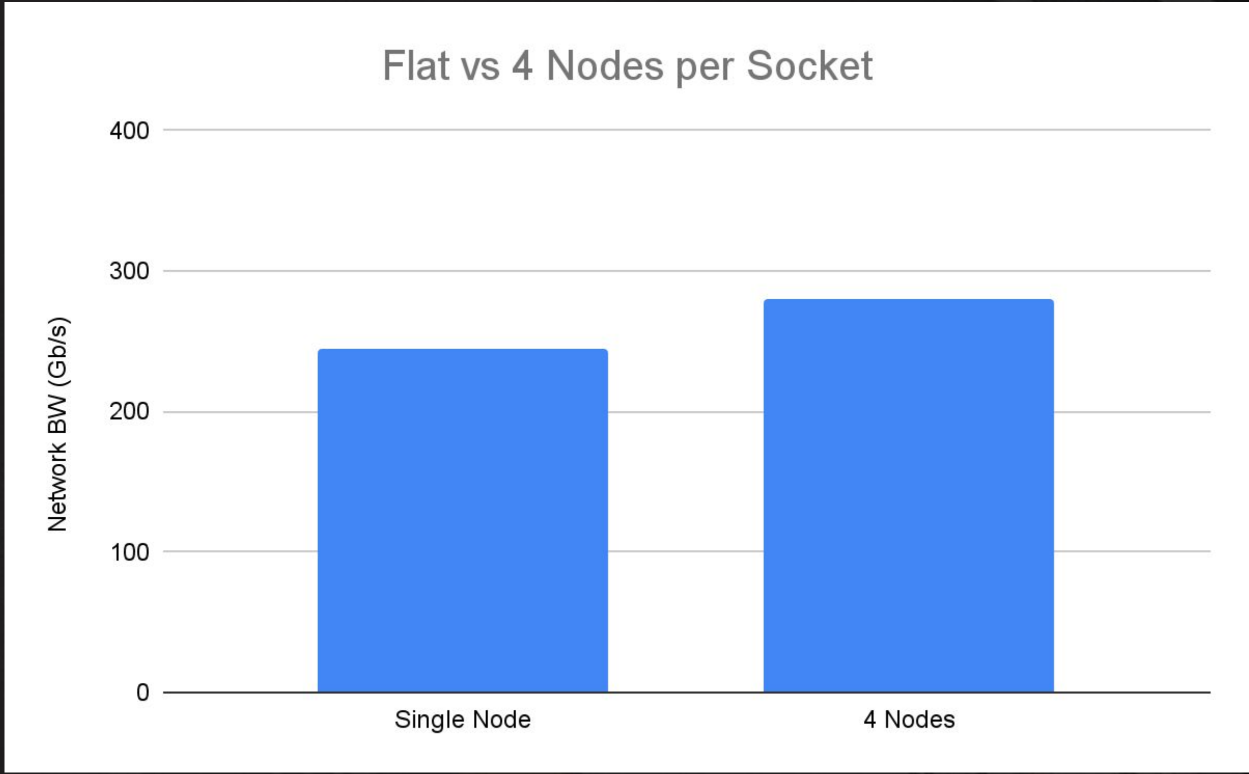
Average Case Summary:

- 1.25 NUMA crossings on average
  - 75% of disk reads across NUMA
  - 50% of NIC transmits across NUMA due to unbalanced setup
- 62.5 GB/sec of data on NUMA fabric

Performance: 1 vs 4 nodes



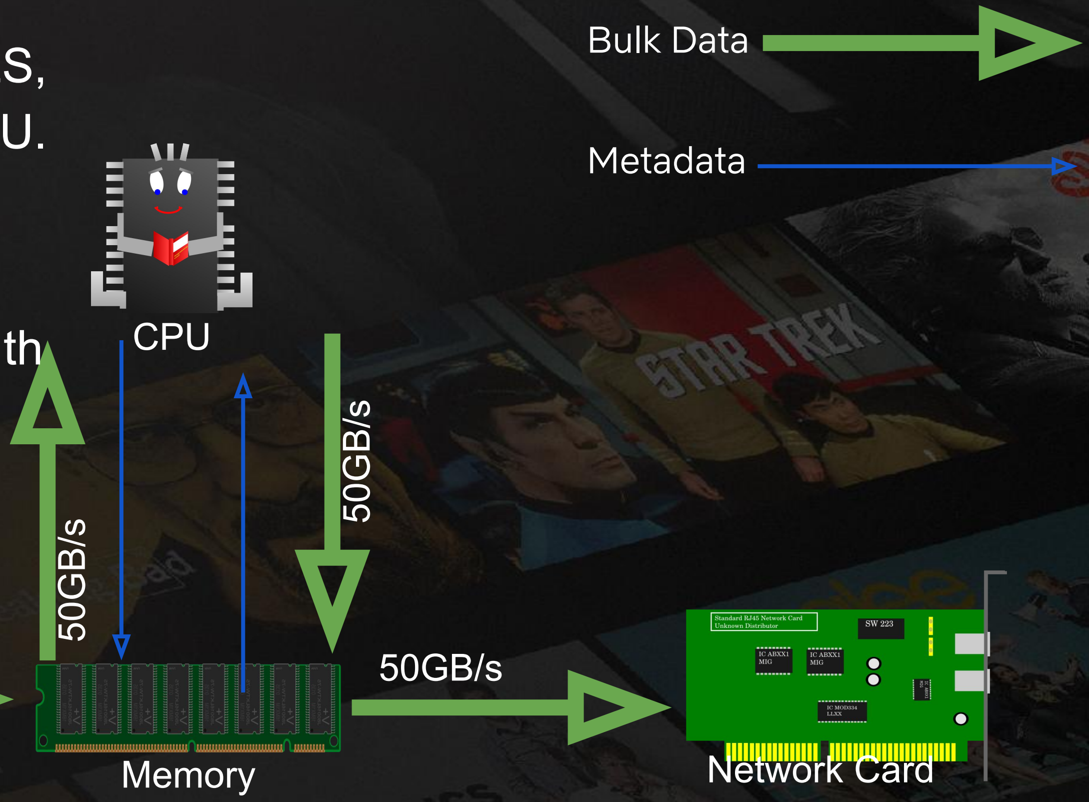
Would NIC based kTLS offload help for 400Gb/s ?

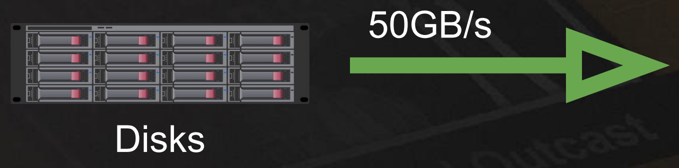
Netflix 400Gb/s Video Serving Data Flow

Using sendfile and software kTLS, data is encrypted by the host CPU.

400Gb/s == 50GB/s

~200GB/sec of memory bandwidth and ~64 PCIe Gen 4 lanes are needed to serve 400Gb/s





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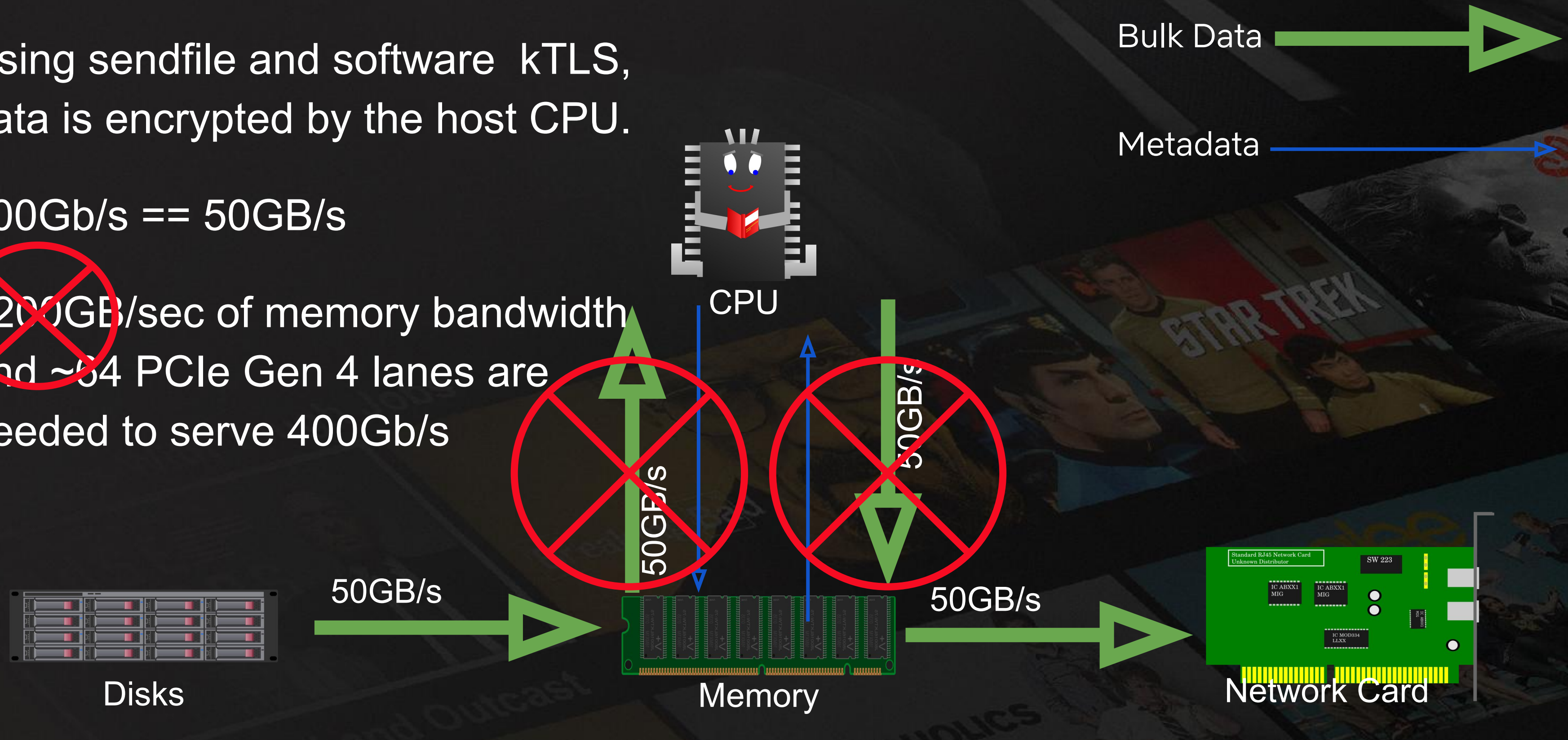

Netflix 400Gb/s Video Serving Data Flow

Using sendfile and NIC kTLS, data is encrypted by the NIC.

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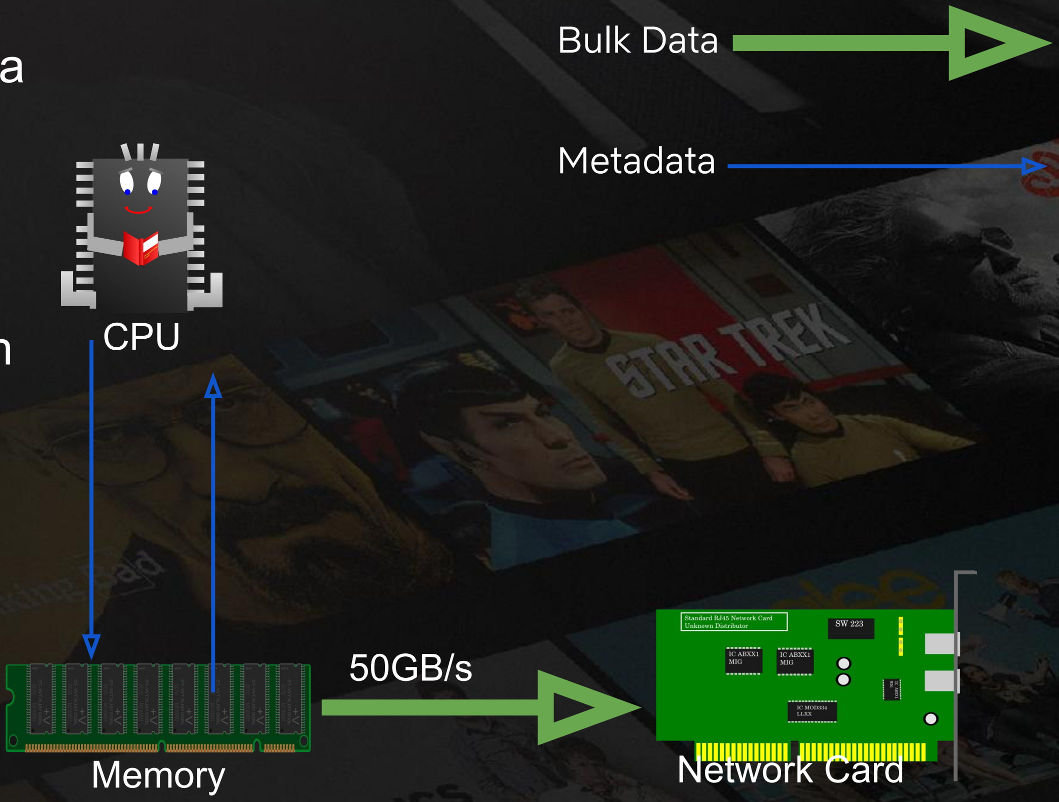
~100GB/sec of memory bandwidth and ~64 PCIe Gen 4 lanes are needed to serve 400Gb/s



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What is NIC kTLS?:

- Hardware Inline TLS
- TLS session is established in userspace.
- When crypto is moved to the kernel, the kernel passes crypto keys to the NIC
- TLS records are encrypted by NIC as the data flows through it on transmit
    - No more detour through the CPU for crypto
    - This cuts memory BW requirements in half!

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Mellanox ConnectX-6 Dx

- Offloads TLS 1.2 and 1.3 for AES GCM cipher
- Retains crypto state within a TLS record
  - Means that the TCP stack can send partial TLS records without performance loss
- If a packet is sent out of order (eg, a TCP retransmit), it must re-DMA the record containing the out of order packet

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CX6-DX: In-order Transmit

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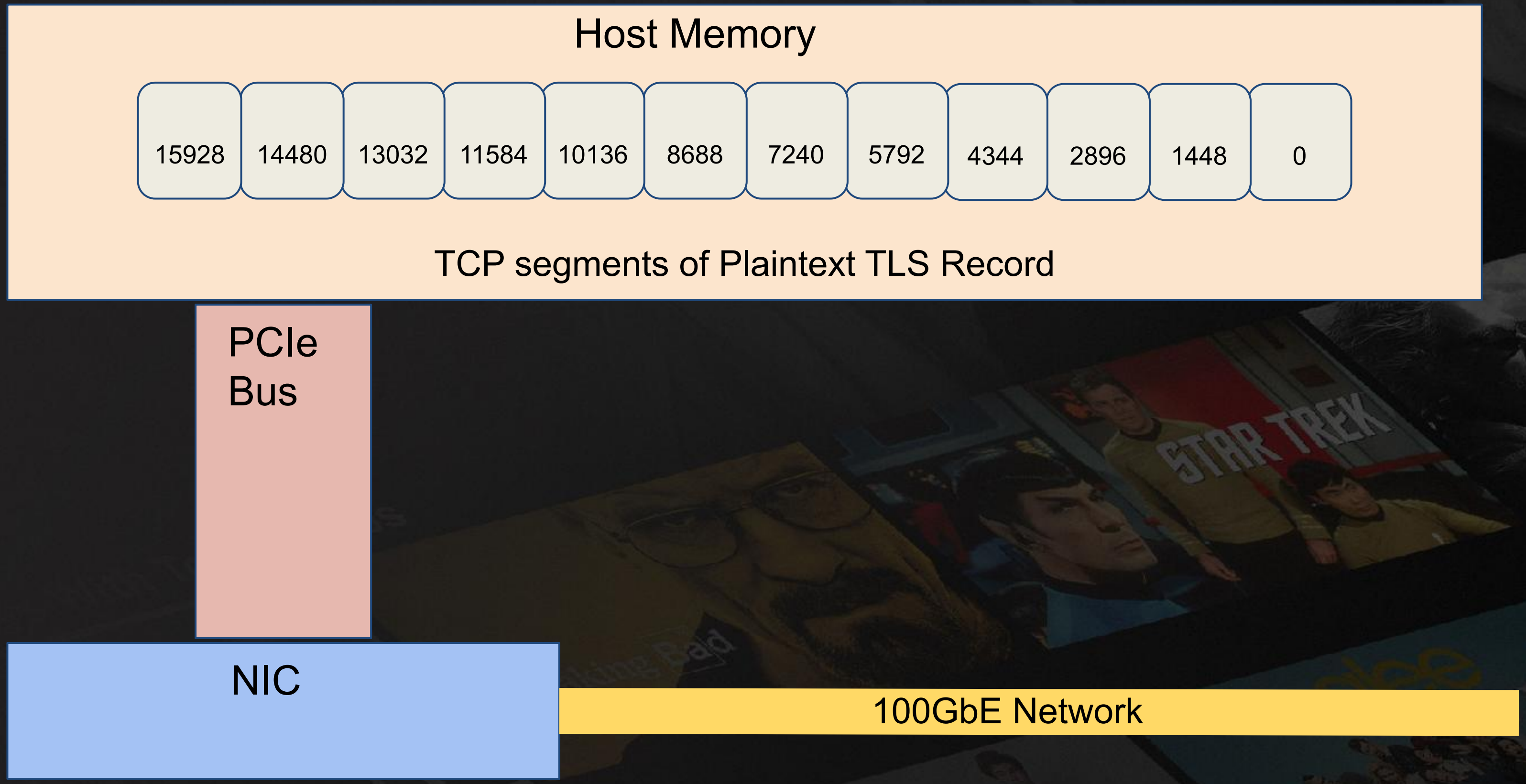
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TCP segments of Plaintext TLS Record
PCIe Bus
NIC
100GbE Network

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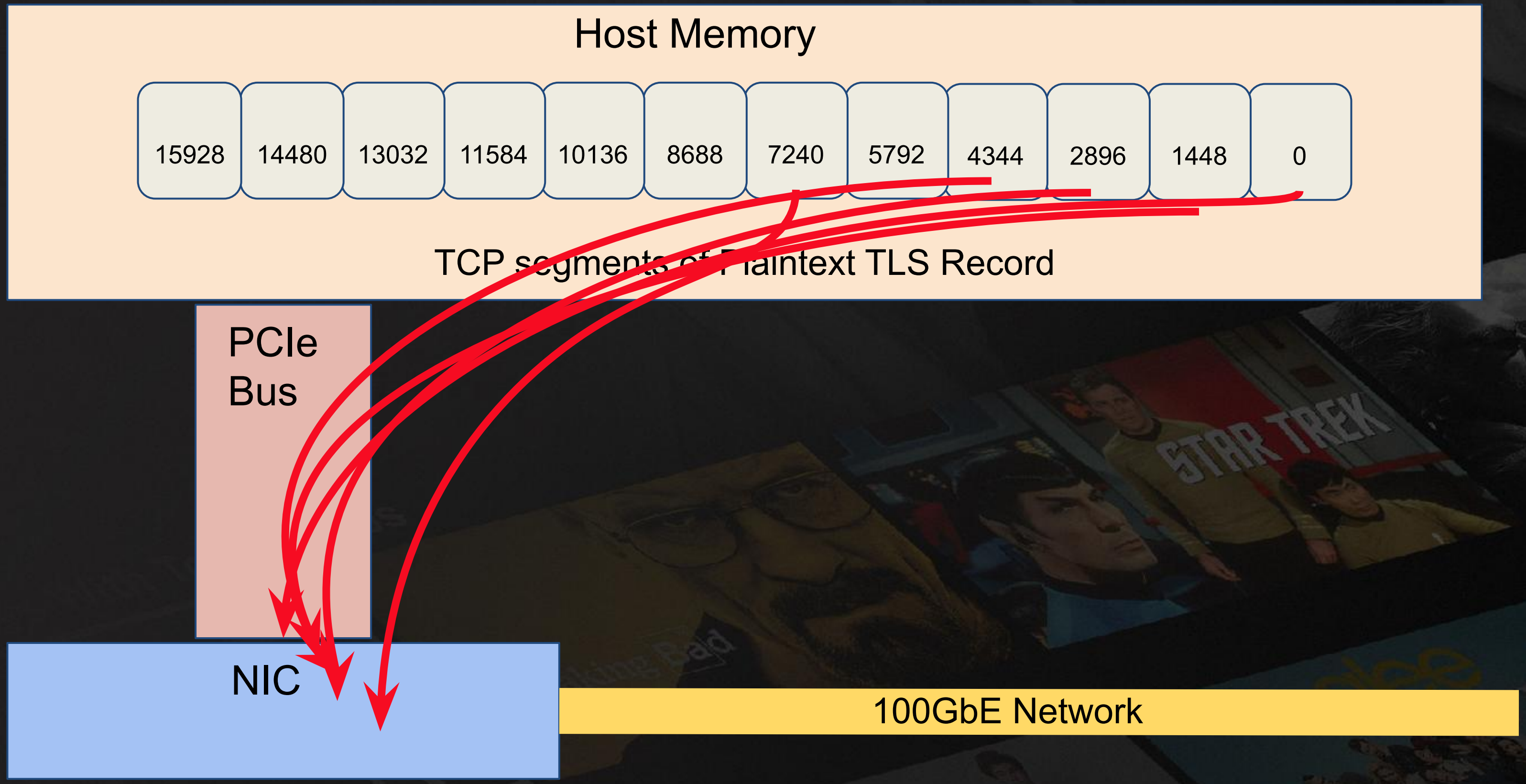
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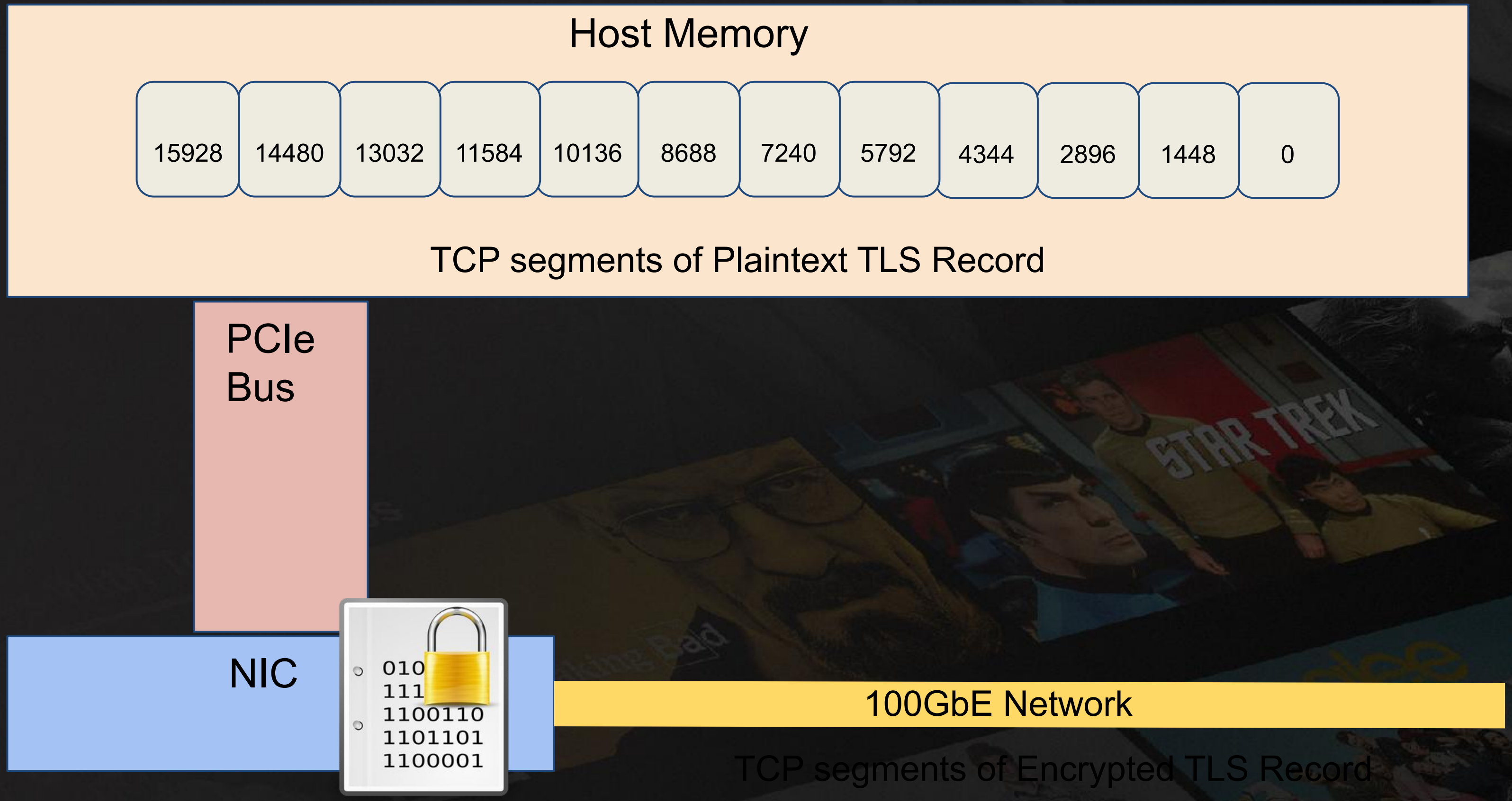
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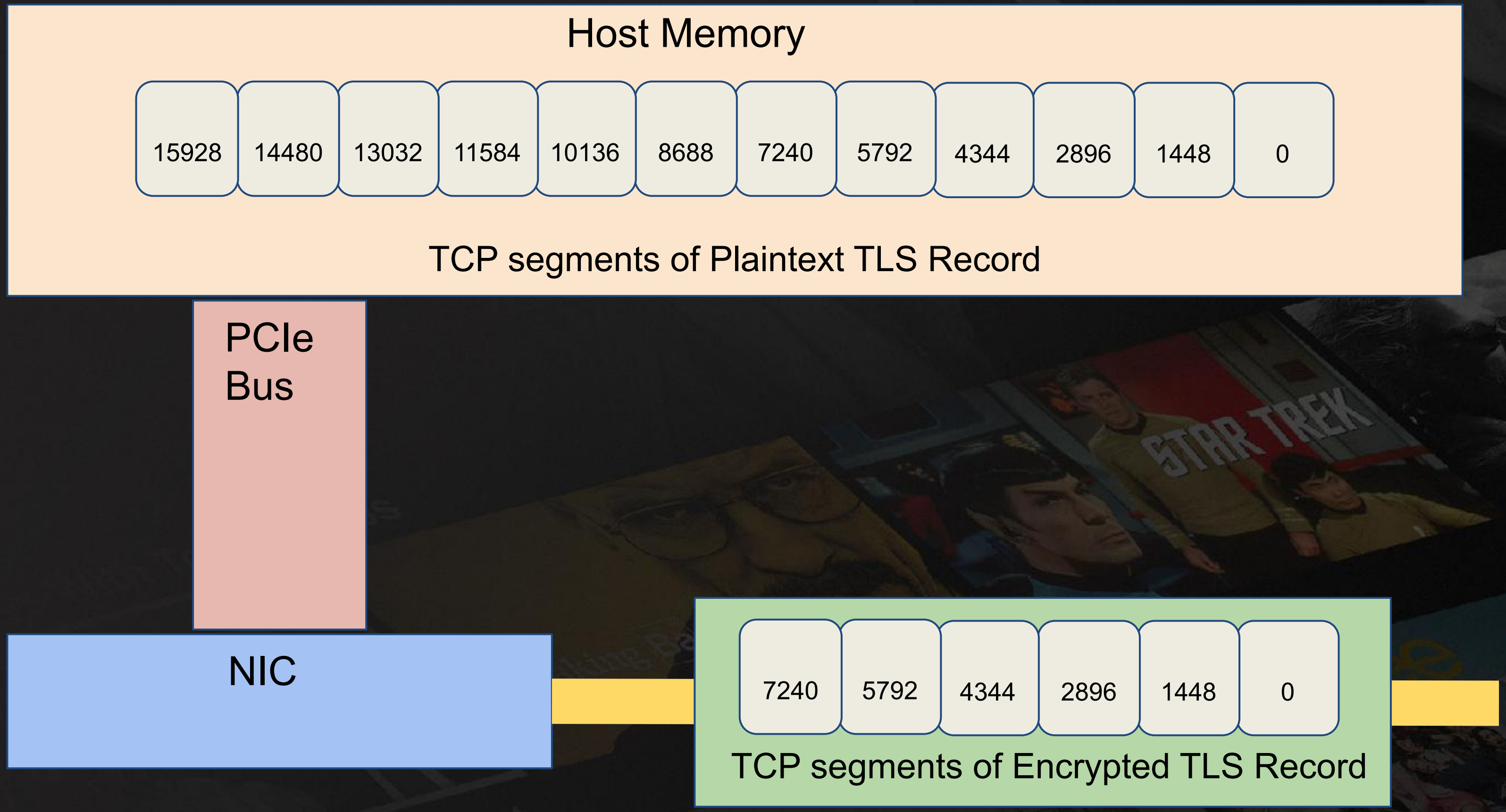

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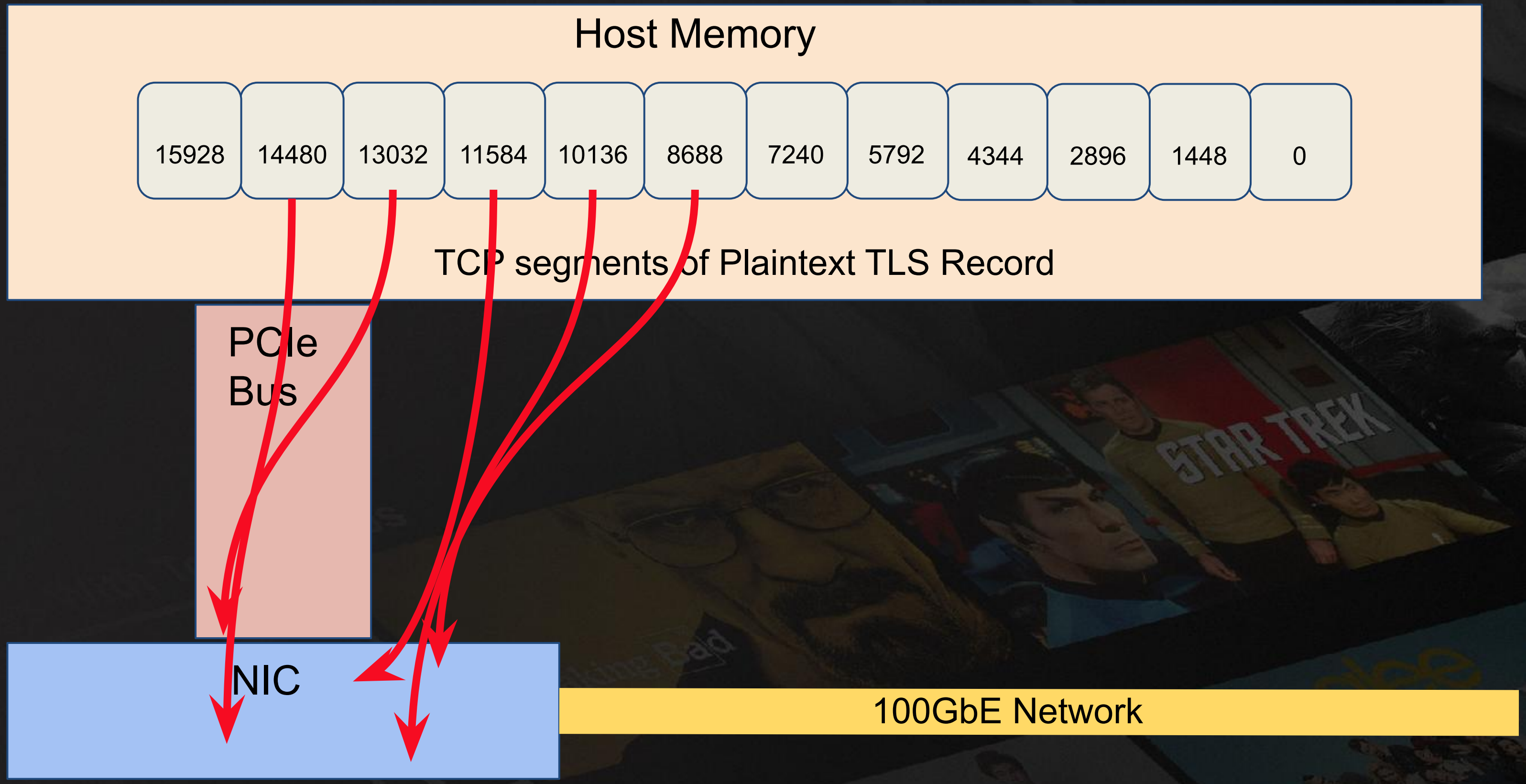
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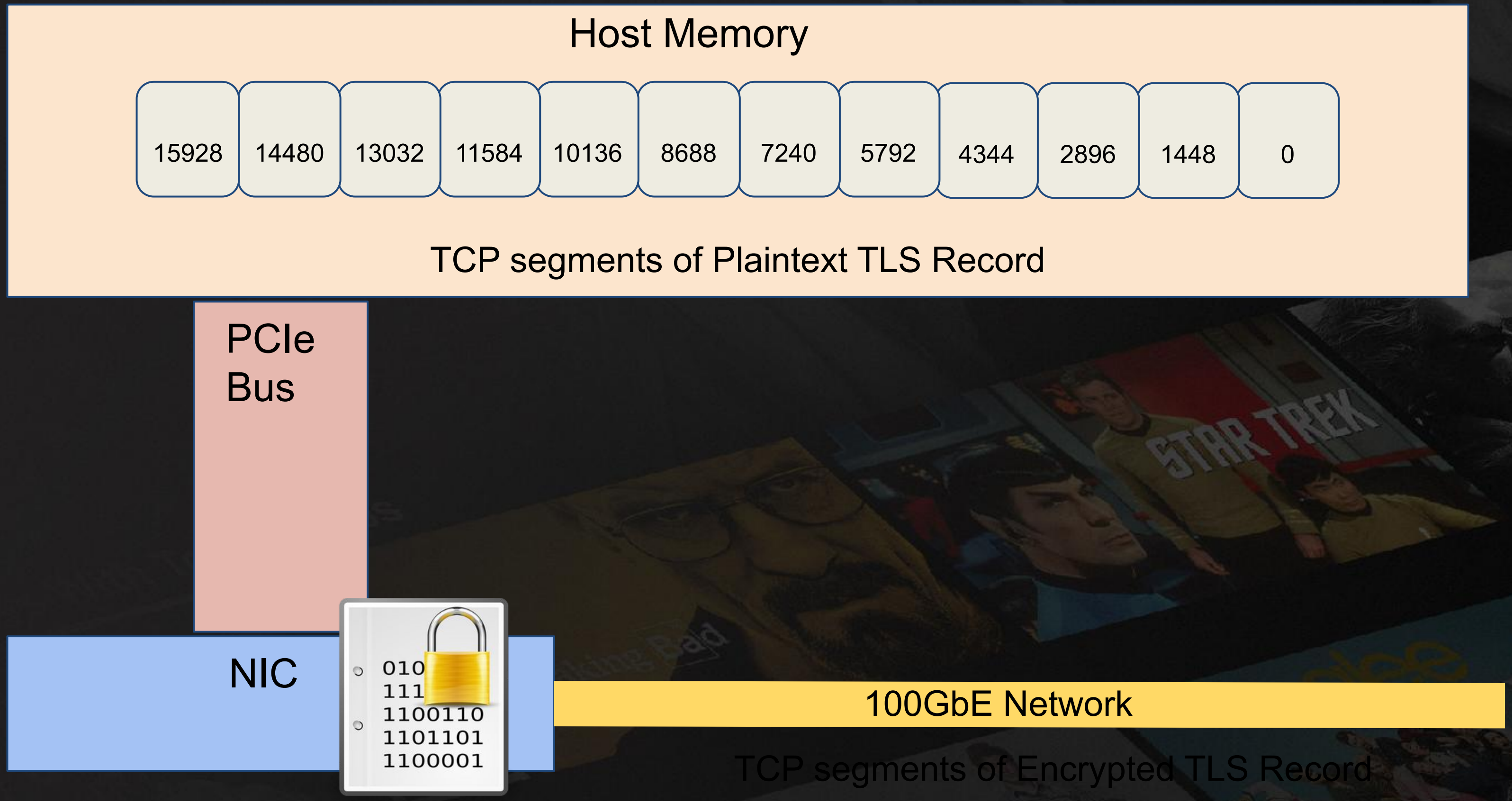
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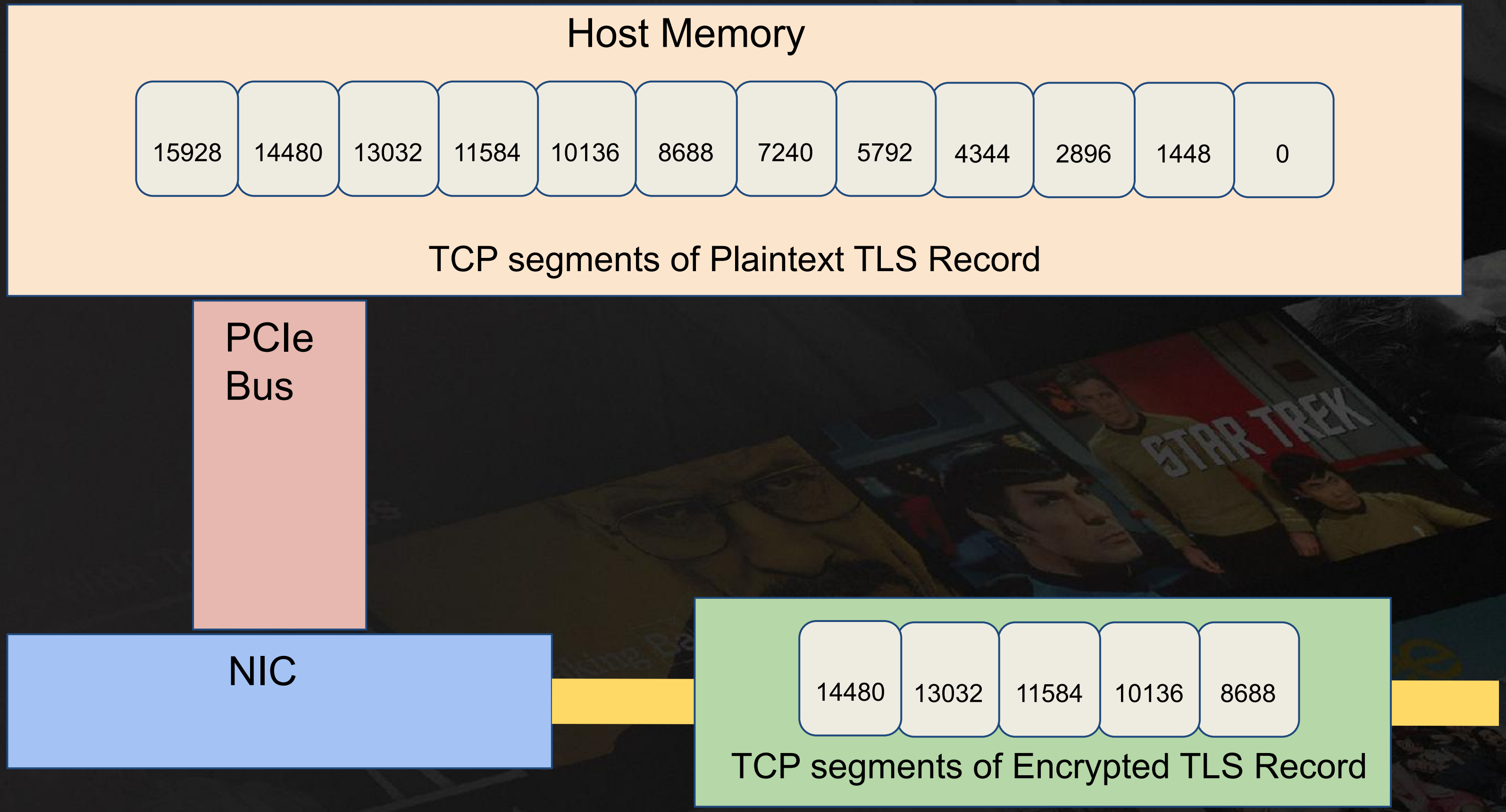
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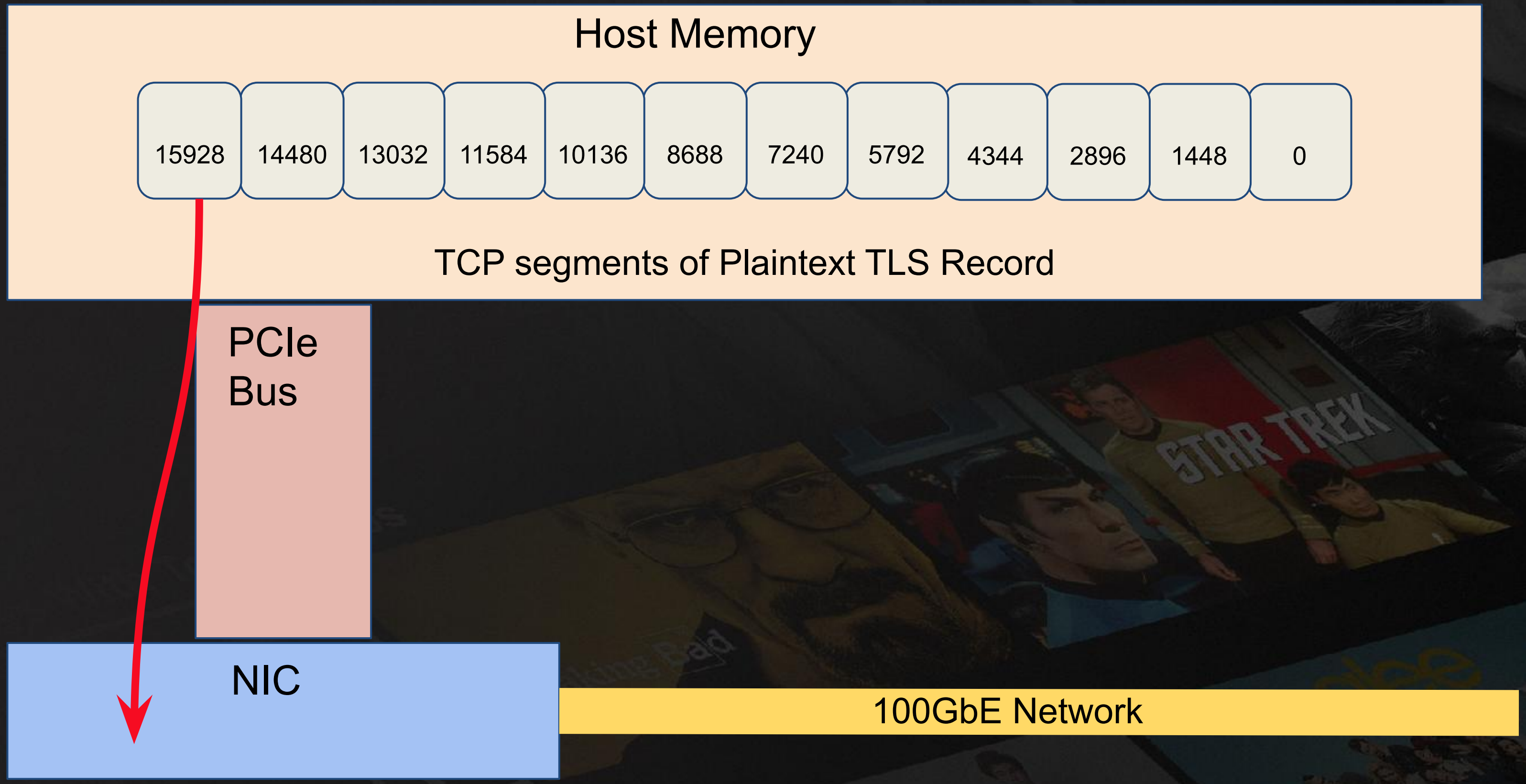
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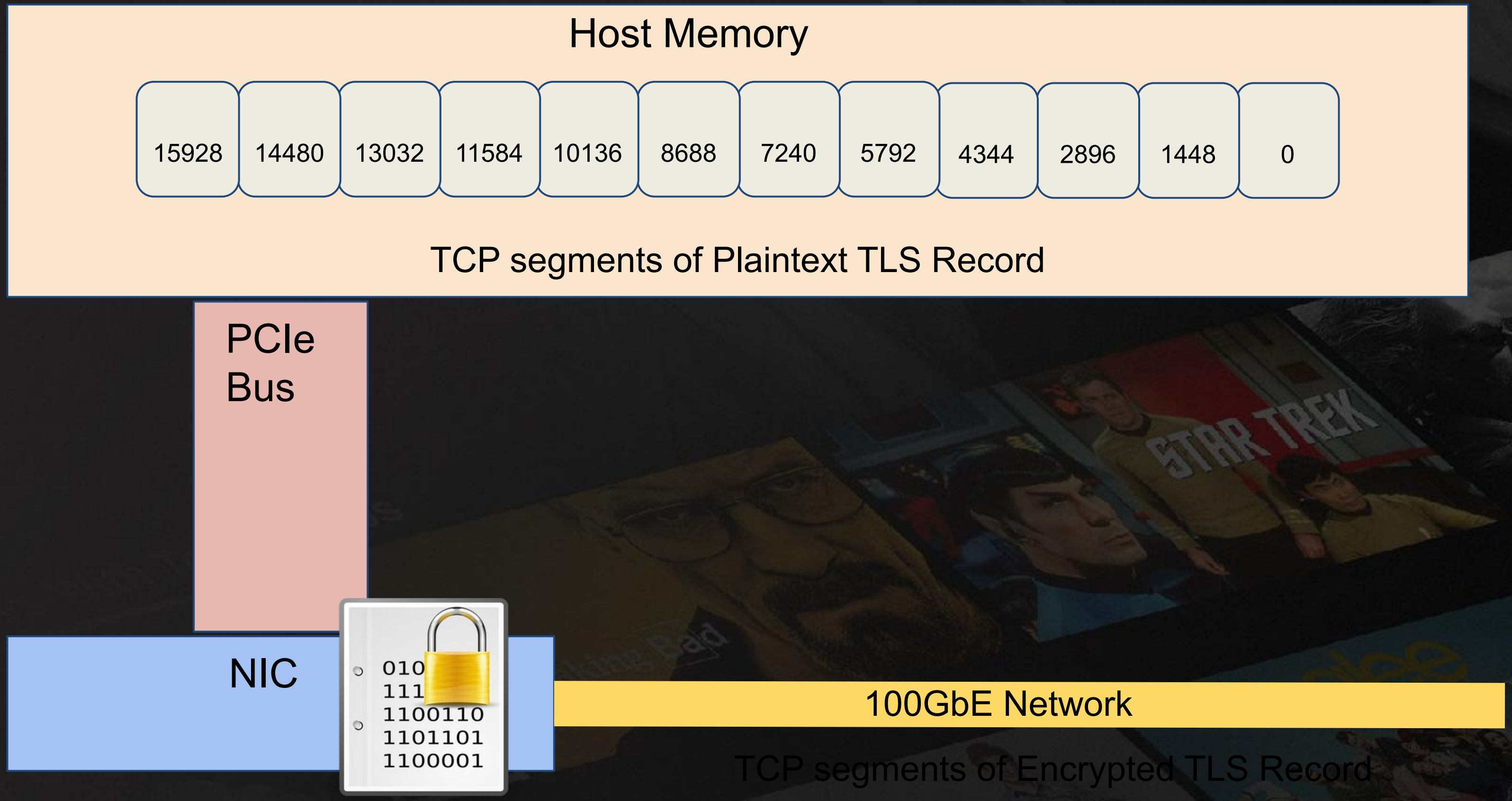
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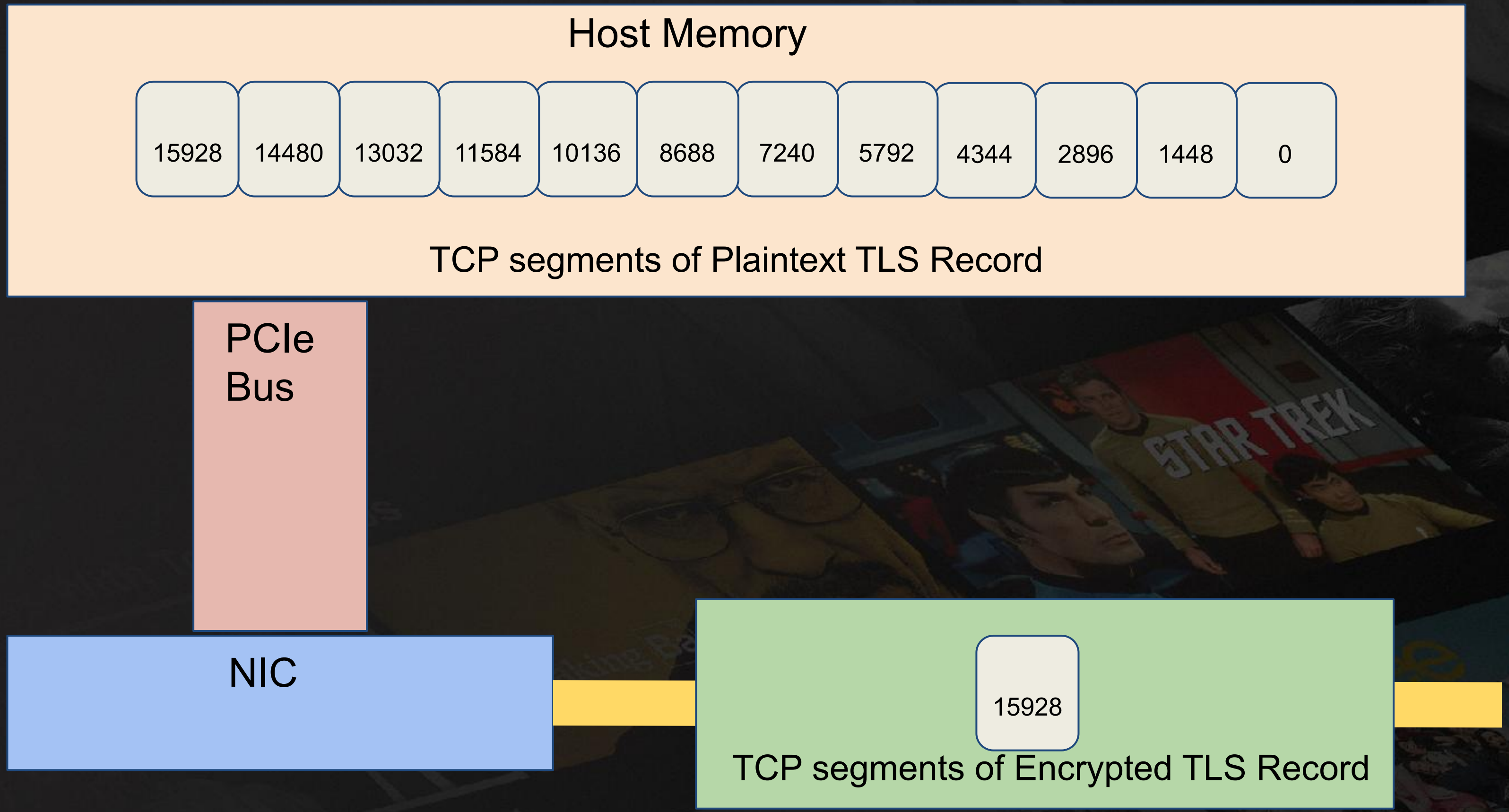
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CX6-DX: TCP Retransmit

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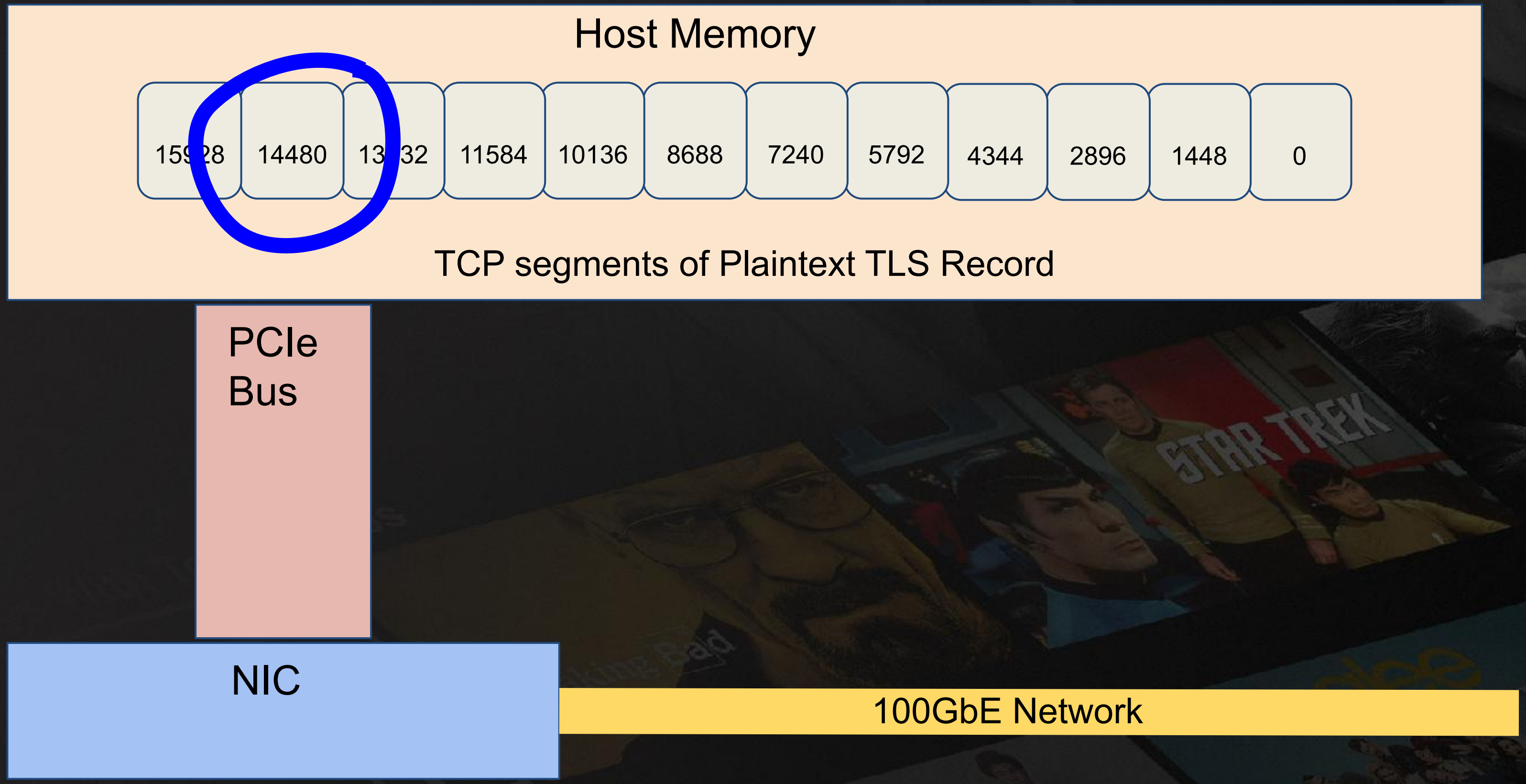

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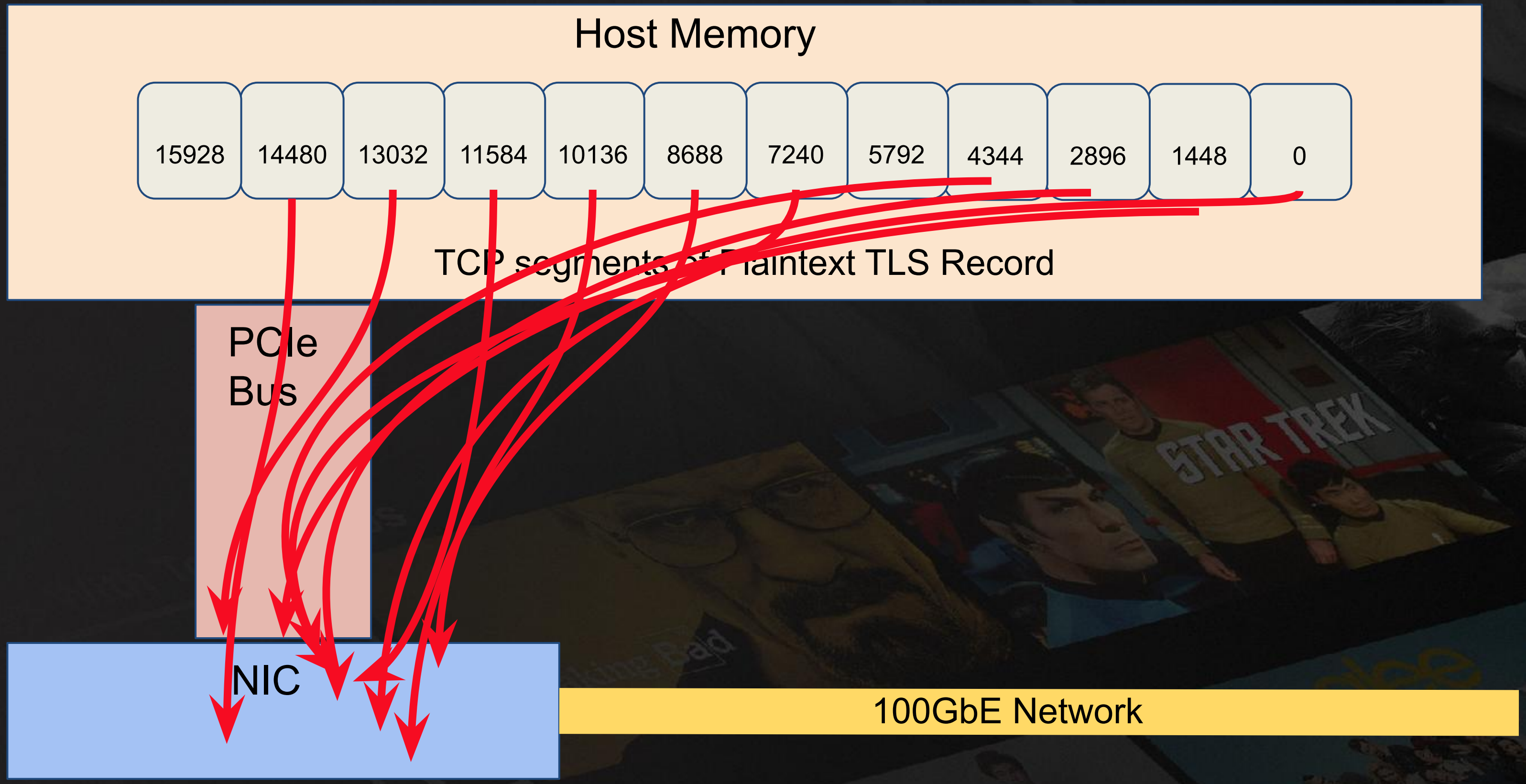
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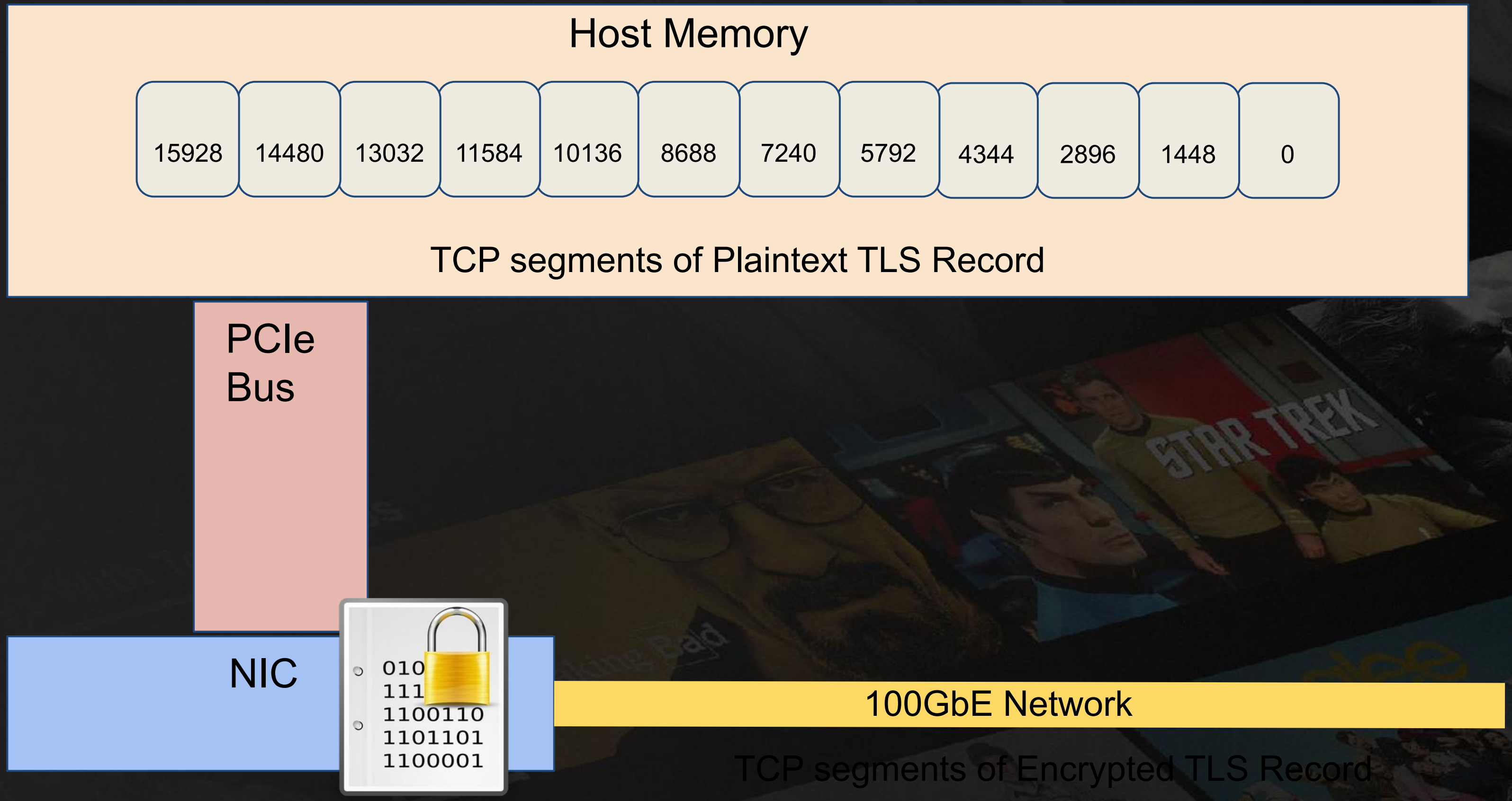
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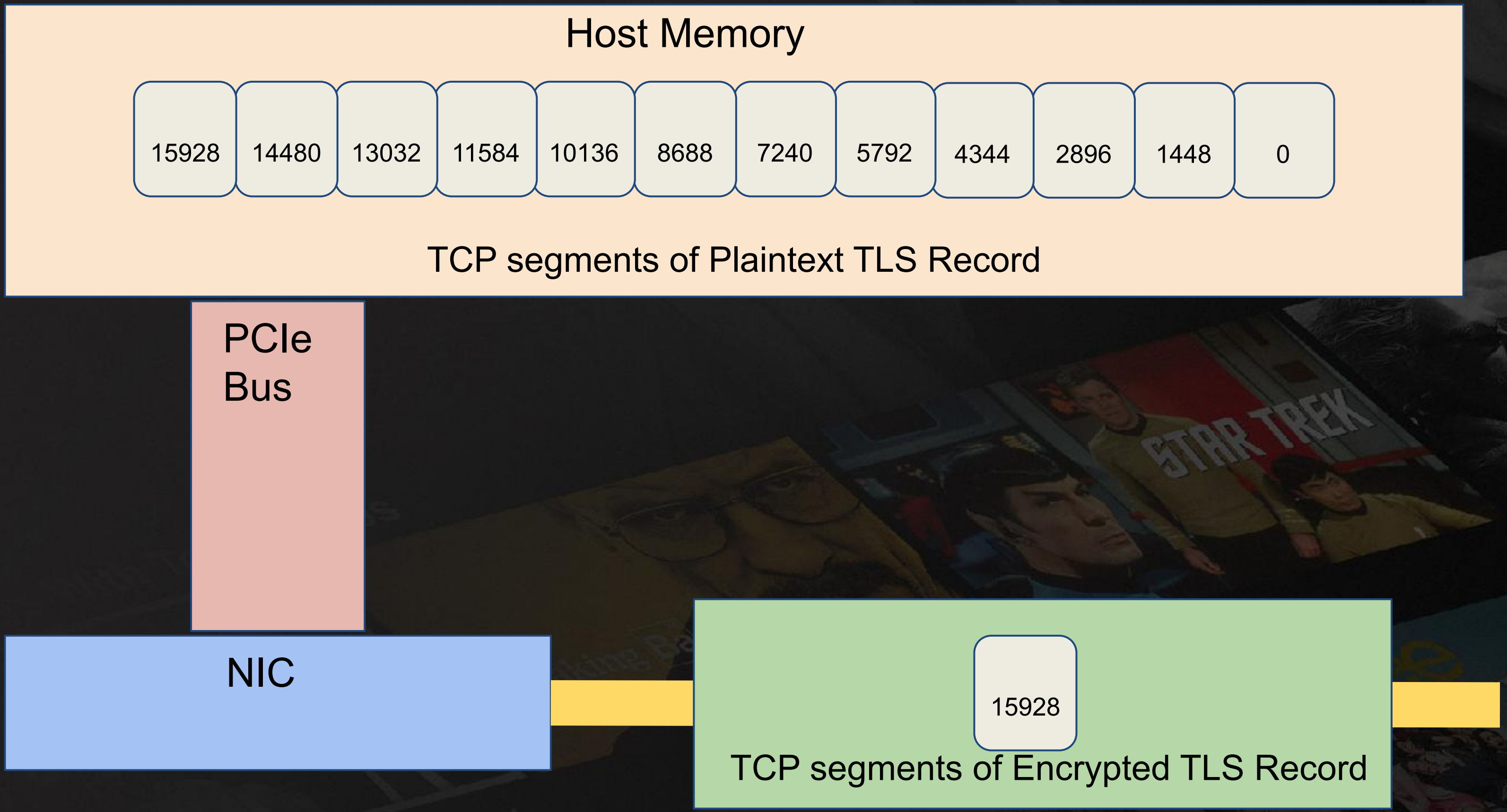
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CX6-DX: Initial Results

Peak:125Gb/s per NIC, (~250Gb/s total)
Sustained:75Gb/s per NIC, (~150Gb/s total)

- Pre-release Firmware

CX6-DX: Initial performance

- NIC stores TLS state per-session
- We have a lot of sessions active
  - (~400k sessions for 400Gb/s)
  - Performance gets worse the more sessions we add
- Limited memory on-board NIC
  - NIC pages in and out to buffers in host RAM
  - Buffers managed by NIC

PCIe Relaxed Ordering

- Allows PCIe transactions to pass each other
    - Should eliminate pipeline bubbles due to “slow” reads delaying fast ones.
    - May help with “paging in” TLS connection state
- Enabled Relaxed Ordering
    - Didn’t help
    - Turns out CX6-DX pre-release firmware hardcoded Relaxed Ordering to disabled

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CX6-DX: Results from next firmware

- Firmware update enabled Relaxed Ordering on NIC
- Peak results improved:

160Gb/s per NIC (~320Gb/s total)

- Note that peak and sustained were effectively identical from this fw update forward.
- This is a new record!
- Nearly as fast as SW TLS (per NIC): 160Gb/s vs 190Gb/s, much faster overall

CX6-DX: Results from production fw

- Firmware update added “TLS_OPTIMIZE” setting
- Peak & sustained results improved:

190Gb/s per NIC (~380Gb/s total)!

CX6-DX: What's needed to use of NIC TLS in production at Netflix?

- QoE testing
  - Measure various factors, such as rebuffer rate, play delay, time to quality, etc.
  - Initial results are great
  - Larger, more complete study scheduled soon.

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CX6-DX: What's needed to use of NIC TLS in production at Netflix?

- Track retransmits & move sessions to software
  - Monitor bytes retransmitted for lossy networks
  - Monitor segments retransmitted to protect against attacks

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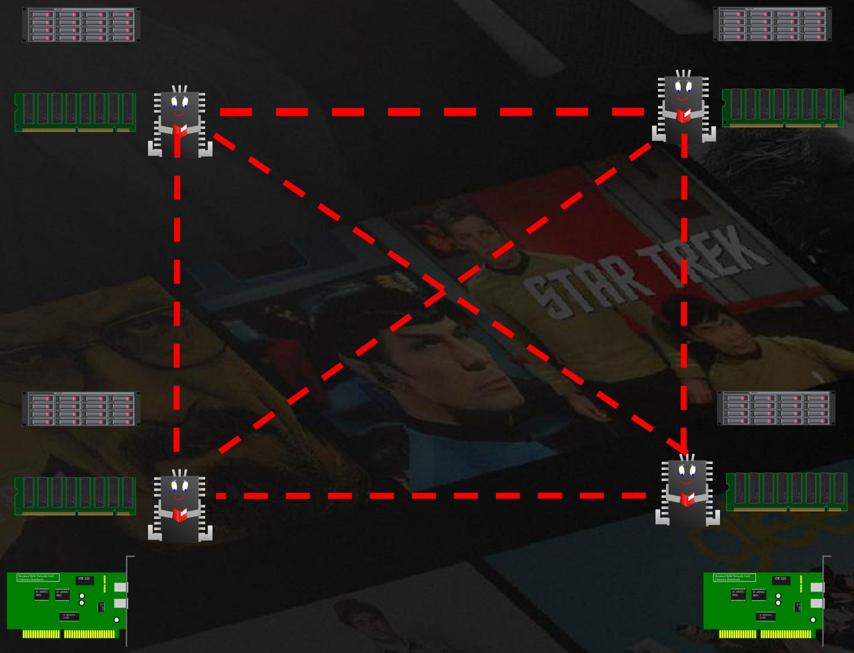
CX6-DX:Mixed HW/SW session perf?

- Moving a non-trivial percentage of conns to SW has unanticipated BW cost.
- Setting SW switch threshold to 1% bytes retransmitted moves ⅓ of conns to SW
- Max stable BW moves from 380Gb/s to 350Gb/s with roughly ⅓ of connections in SW
  - Performance impact is more than expected

4 Nodes, worst case with siloing + NIC kTLS

Steps to send data:



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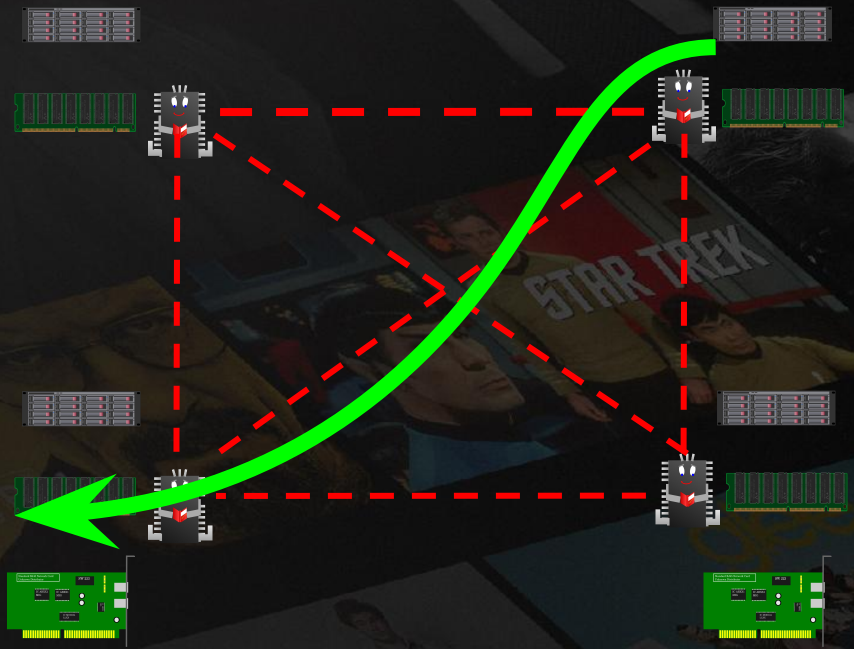
4 Nodes, worst case with siloing + NIC kTLS

Steps to send data:

- DMA data from disk to memory
  - First NUMA bus crossing



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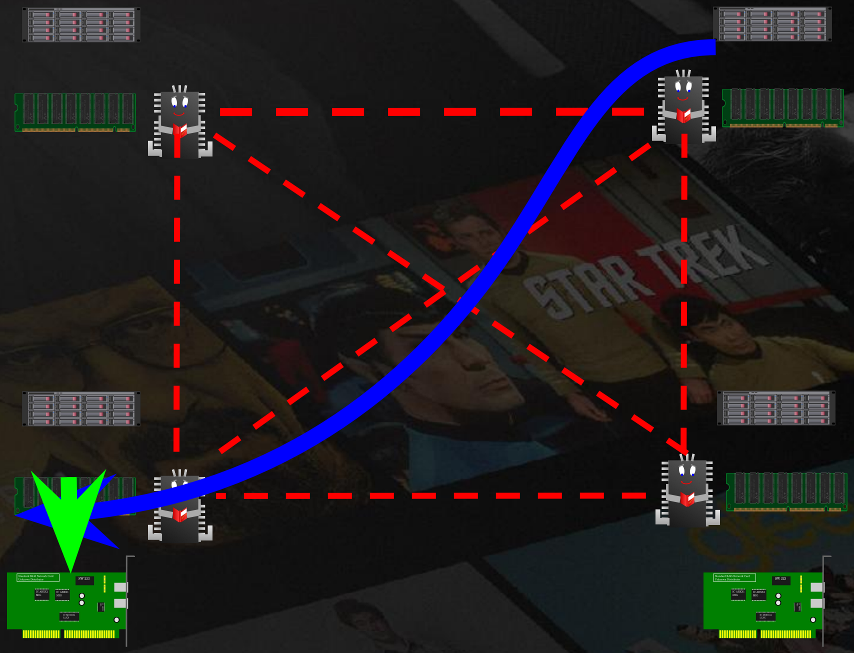
4 Nodes, worst case with siloing + NIC kTLS

Steps to send data:

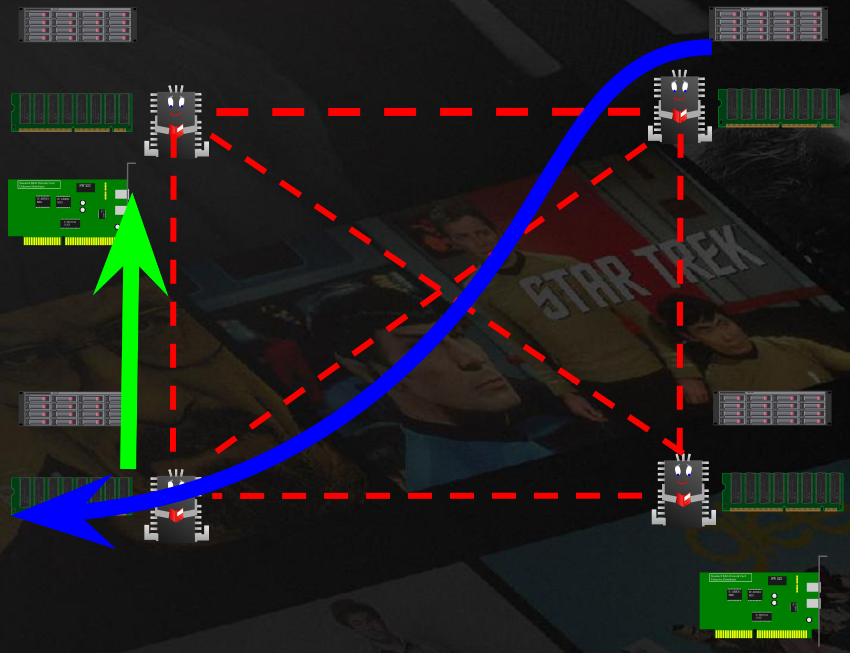
- DMA data from disk to memory
  - First NUMA bus crossing
- DMA data from memory to network



4 Nodes, worst case with siloing + NIC kTLS

Steps to send data:

- DMA data from disk to memory
    - First NUMA bus crossing
- DMA data from memory to network



Worst Case Summary:

- 2 NUMA crossing on average
  - 100% of disk reads across NUMA
  - 100% of network writes across NUMA
- 100GB/s of data on the NUMA fabric
  - Less than the 280GB/s of Inifinity fabric bandwidth

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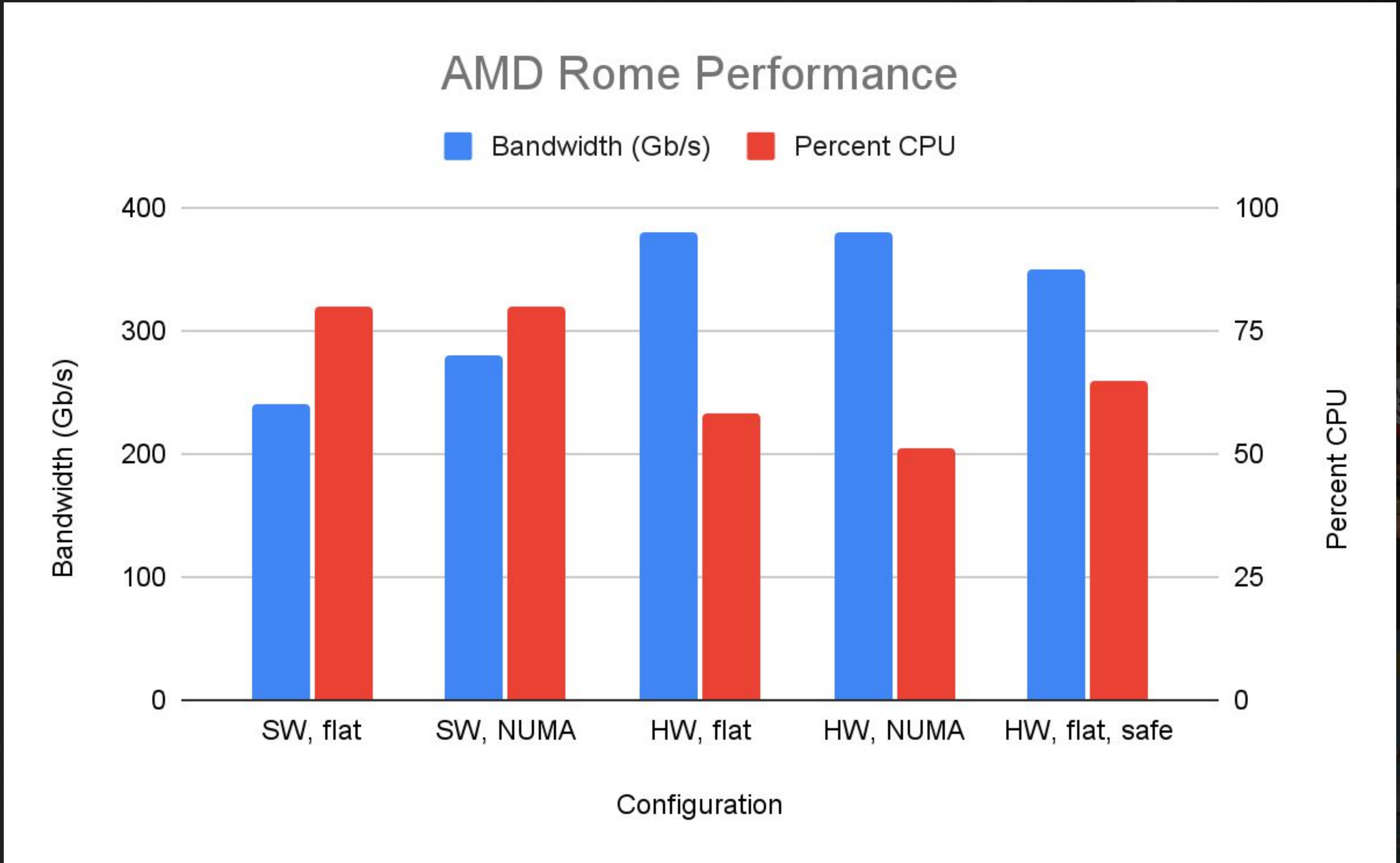
Average Case Summary:

- 1.25 NUMA crossings on average
  - 75% of disk reads across NUMA
  - 50% of NIC transmits across NUMA due to unbalanced setup
- 62.5 GB/sec of data on NUMA fabric


AMD Rome Performance
Bandwidth (Gb/s)
Percent CPU
400
300
200
100
0
100
75
50
25
0
Bandwidth (Gb/s)
Percent CPU
SW, flat
SW, NUMA
HW, flat
HW, NUMA
HW, flat, safe
Configuration

Other platforms? Ampere Altra

- "Mt. Snow"
  - Q80-30: 80 3.0GHz Arm Neoverse-N1 cores
  - 8 channels of 256GB DDR4-3200
  - 128 Lanes Gen4 PCIe
  - 16x WD SN720 2TB NVMe
  - 2 Mellanox CX6-DX NICs

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Other platforms? Ampere Altra

- Minimal access to system counters
    - No way to see memory BW usage
    - No way to see IO bandwidth or latency
    - Leads to feeling like you’re driving blind

Other platforms? Ampere Altra

- Poor performance with SW kTLS:
  - CPU limited at 180Gb/s

- Poor initial performance with NIC TLS
  - PCIe limited at 240Gb/s
    - Very low CPU utilization
    - NICs saturated, and we see lots of output drops

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Ampere: PCIe Extended Tags

- Poor initial performance with NIC TLS: 240Gb/s
- Very low CPU utilization
- NICs saturated, and we see lots of output drops
- Seems like a PCIe problem

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Ampere: PCIe Extended Tags

- PCIe is more of a network than a bus
- Number of outstanding DMA reads is limited by the number of PCIe “tags”
- PCIe tag space is 5-bits by default, allowing for 32 DMAs to be in-flight at the same time
- PCIe extended tags increase the tag space to 8 bits, allowing 256 DMA reads in flight at the same time
- Like increasing TCP window size.

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Ampere: PCIe Extended Tags

- After enabling extended tags, we see a bandwidth improvement:

240Gb/s -> 320Gb/s

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Other platforms? Intel Ice Lake Xeon

- 8352V CPU
  - 36 cores, 2.1GHz
  - 8 channels 256GB DDR4-3200 (running at 2933)
  - 64 Lanes Gen4 PCIe
  - 20x Kioxia 4TB NVMe (PCIe Gen4)
  - 2 Mellanox CX6-DX NICs

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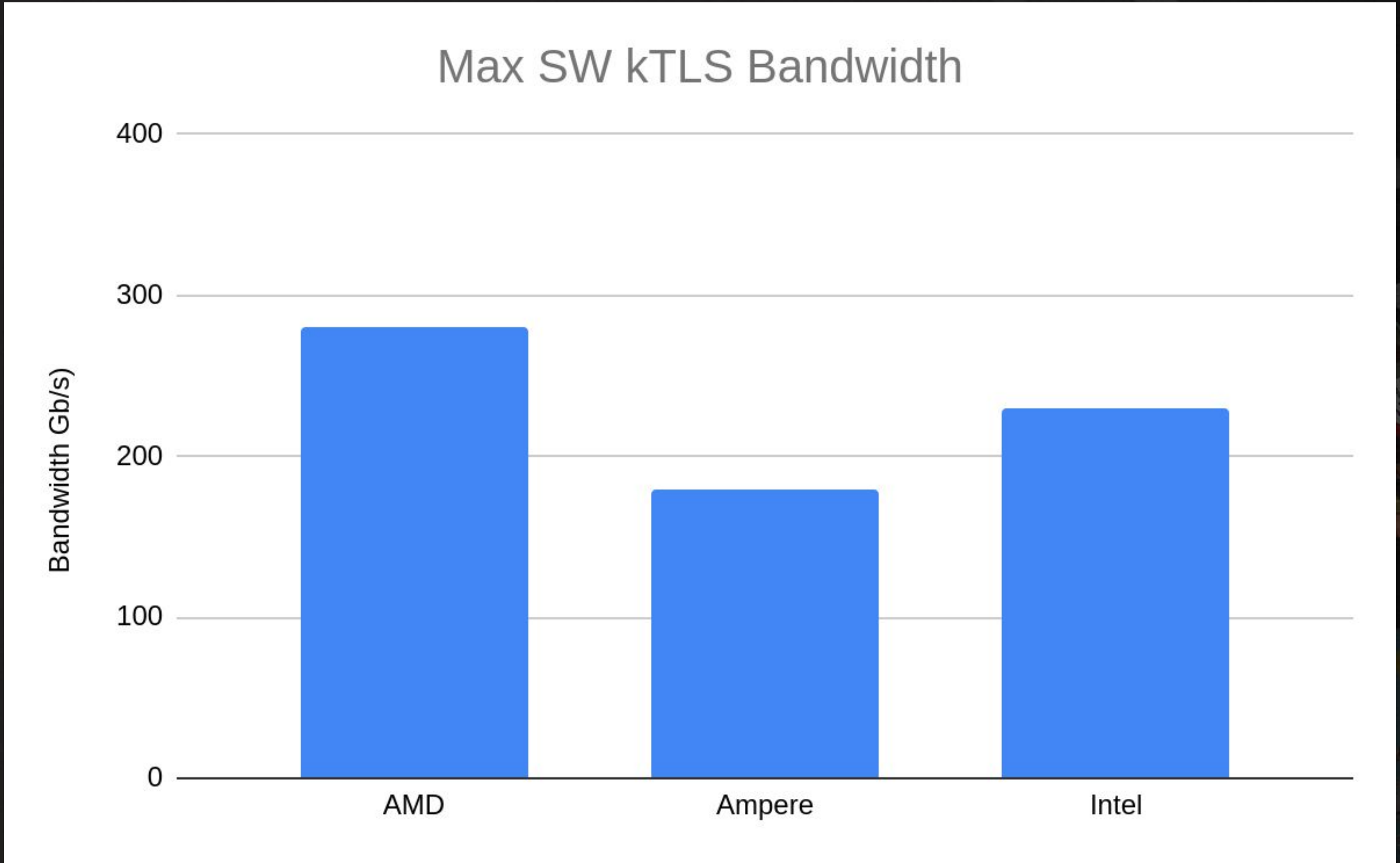
Intel Ice Lake Xeon

- 230Gb/s SW kTLS
  - Limited by memory BW

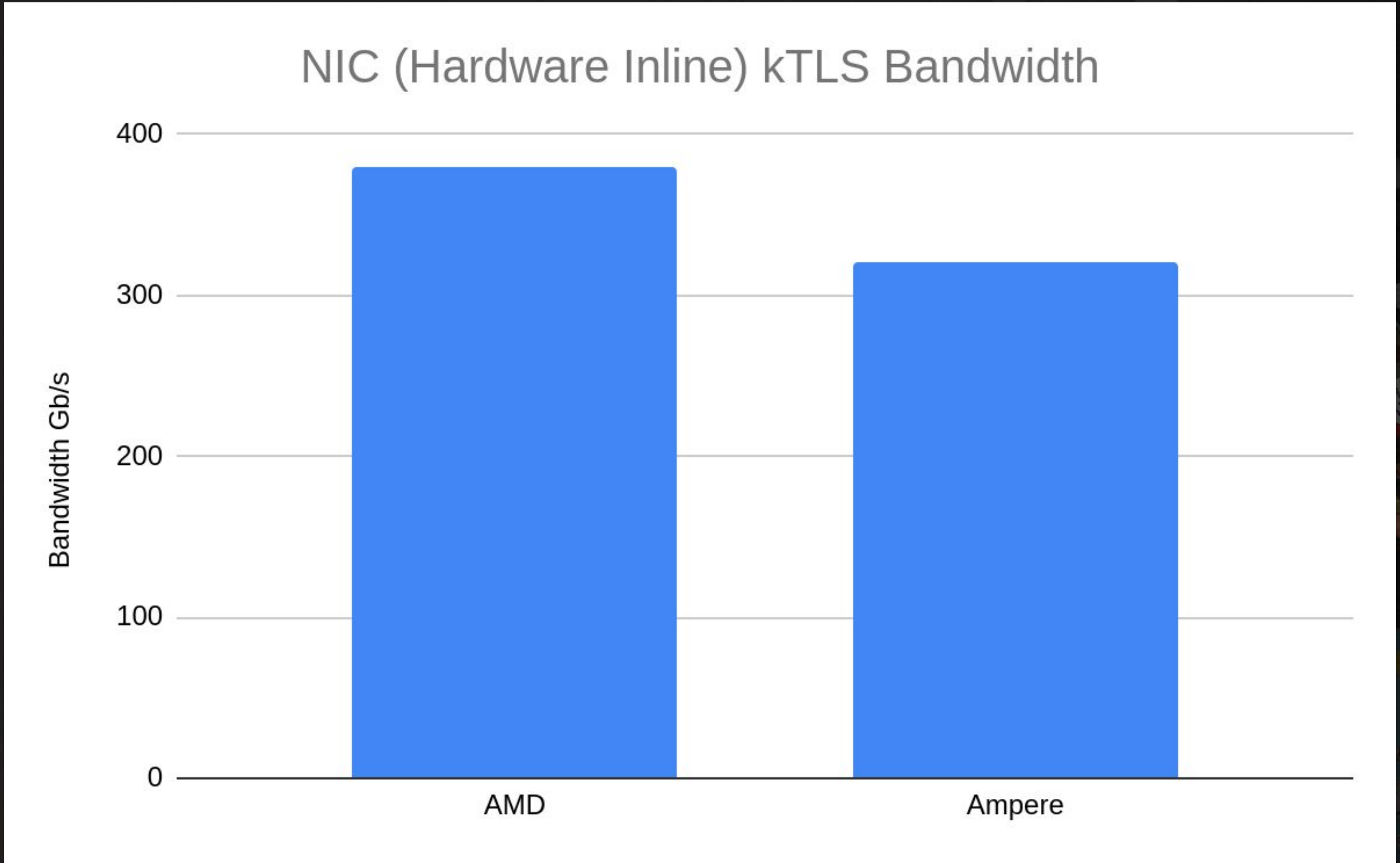
Intel Ice Lake Xeon (WIP)

- 230Gb/s SW kTLS
  - Limited by memory BW
    - 8352V runs memory at 2993, others SKUs run at 3200
      - Would expect the same performance as AMD from that
- BIOS locked out PCIe Relaxed ordering, so no NIC KTLS results yet



Max SW kTLS Bandwidth
Bandwidth Gb/s)
400
300
200
100
0
AMD
Ampere
Intel

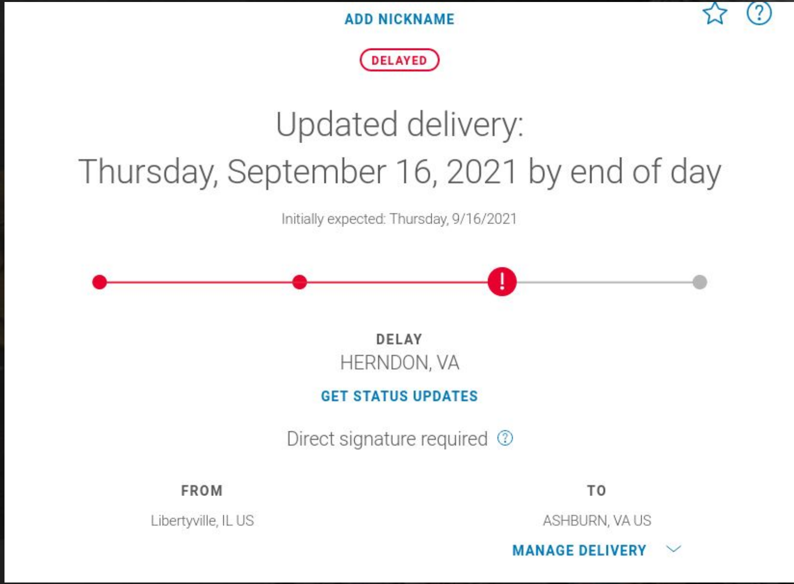
NETFLIX



NIC (Hardware Inline) kTLS Bandwidth
400
300
200
100
0
Bandwidth Gb/s
AMD
Ampere

But wait, there's …. not … more..

- 800Gb prototype sitting on datacenter floor due to shipping exception 😞
- Something to talk about next year?



Many thanks to:

- Warren Harrop & the Netflix Open Connect hardware team for putting together the testbed.
- FreeBSD developers for making such an awesome OS

Slides at:

https://people.freebsd.org/~gallatin/talks/euro2021.pdf

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Disk centric siloing

- Associate disk controllers with NUMA nodes
- Associate NUMA affinity with files
- Associate network connections with NUMA nodes
- Move connections to be “close” to the disk where the contents file is stored.
- After the connection is moved, there will be 0 NUMA crossings!

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Disk centric siloing problems

- No way to tell link partner that we want LACP to direct traffic to a different switch/router port
  - So TCP acks and http requests will come in on the "wrong" port
- Moving connections can lead to TCP re-ordering due to using multiple egress NICs
- Some clients issue http GET requests for different content on the same TCP connection
  - Content may be on different NUMA domains!

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Disk centric siloing problems

- Different numbers of NVME drives on each domain
  - Node 3 has 3x the number of NVME drives as Node 0
- Content popularity differences can lead to hot and cold disks
- All of this adds up to uneven use of each Numa Node.
  - Output limited by hottest Numa node

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Disk centric siloing problems

- Moving established NIC TLS sessions to a different egress NIC is painful

Disk centric siloing problems

- Moving NIC TLS sessions is expensive
  - Session will be established before content location is known

AMD: NUMA w/NIC kTLS Offload

- Disk Siloing
  - Allocate host pages to back files on NUMA node close to NVME, not NIC
  - Eliminates the 0.75 crossings for 4 domains with NVME
  - Still have the 0.5 crossings on average for remapped NICs

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AMD: NUMA w/NIC kTLS Offload

- Disk Siloing
  - Assumes equal number of NVME on each node
  - Actual machine has:
    - Node 0: 2 NVME
    - Node 1: 6 NVME
    - Node 2: 4 NVME
    - Node 3: 6 NVME

AMD: NUMA w/NIC kTLS Offload

- Disk Siloing
  - Peak of ~300Gb/s
  - Traffic unequal due to more NVME on Node 3
  - Output drops on mce3 (NIC port on Node 3) at 98Gb/s, while mce0 (NIC port on Node 1) is mostly idle at 40Gb/s
  - Tried “remapping” NVME and pretending some drives in different domains

AMD: NUMA w/NIC kTLS Offload

- Disk Siloing
  - Pretended some of Node 3's NVME drives were in Node 1
    - Reached a peak of ~350Gb/s
    - Output still uneven between domains because of uneven popularity of content on different NVME drives
  - Sharding based on network (LACP) far more even