Remote TCP Connection Offload and Applications

Shuo Li*, Steven W. D. Chien*, Tianyi Gao, Michio Honda
University of Edinburgh
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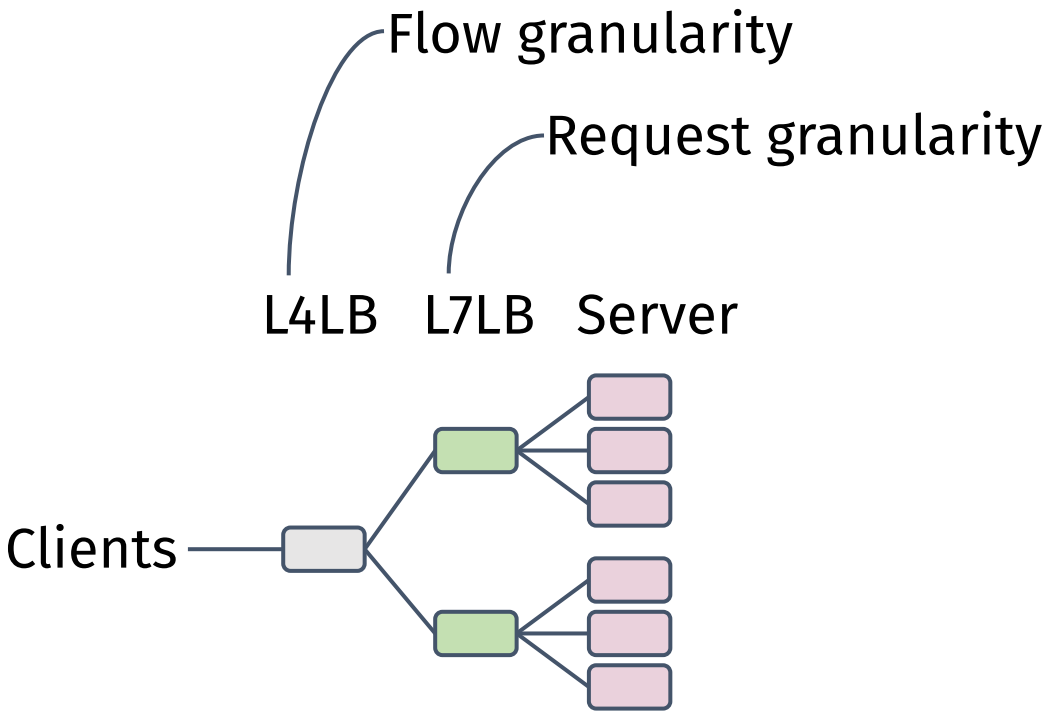
THE UNIVERSITY *of* EDINBURGH
informatics

*Joint first authors

Overview

- Load balancing in datacenters



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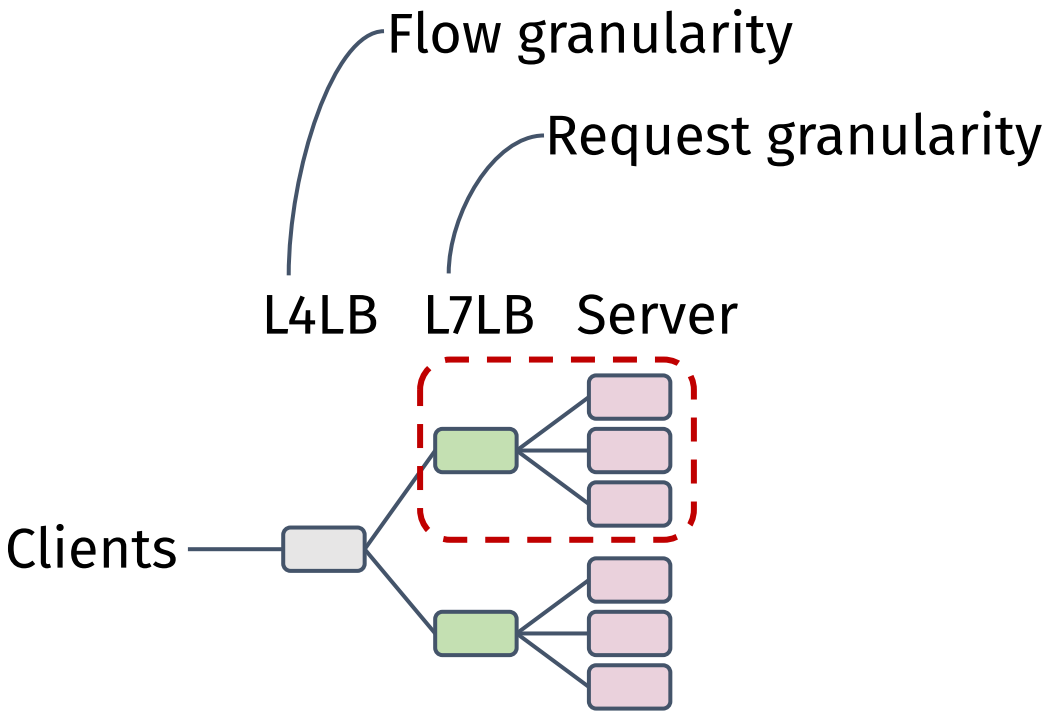

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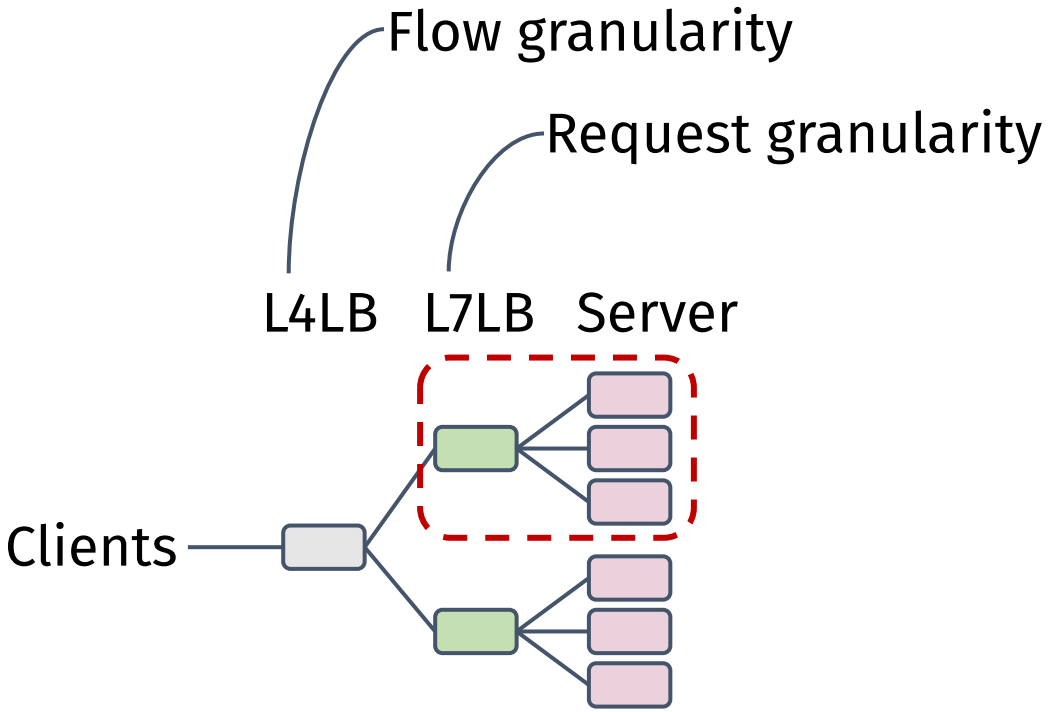
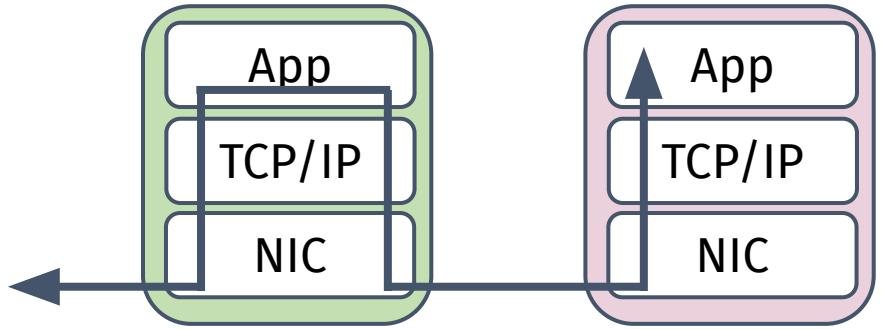
- L7LB datapath





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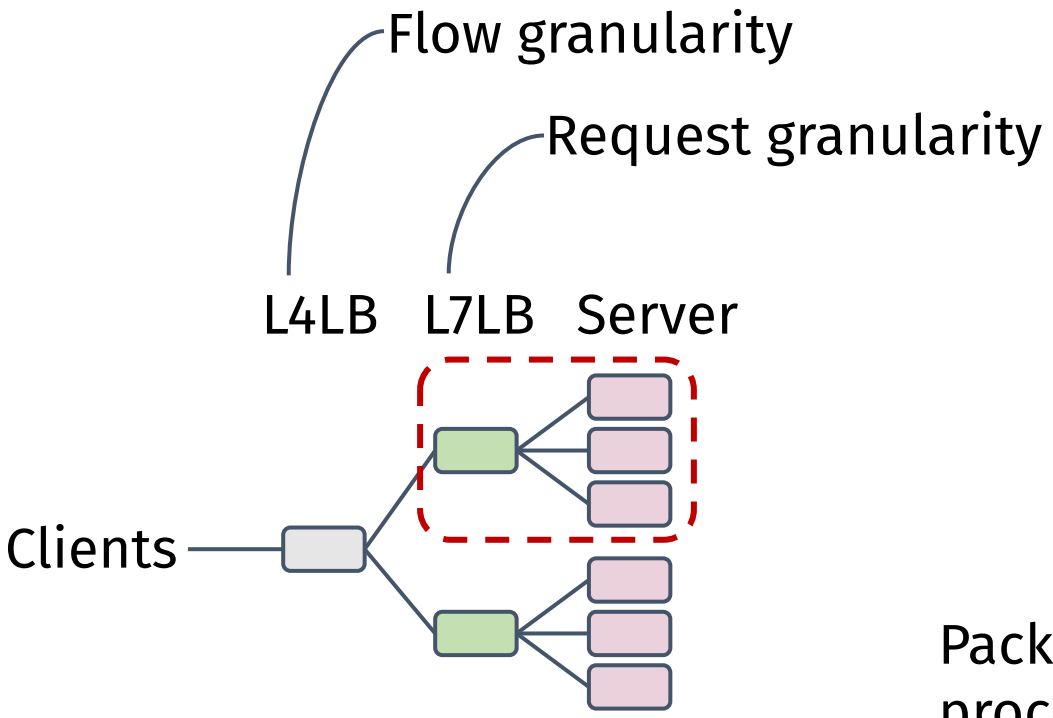
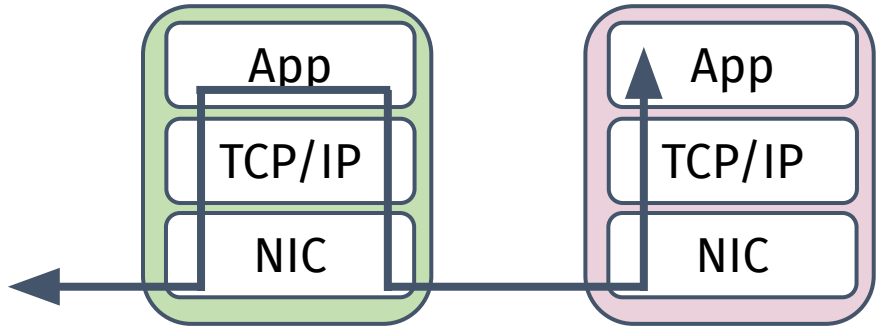
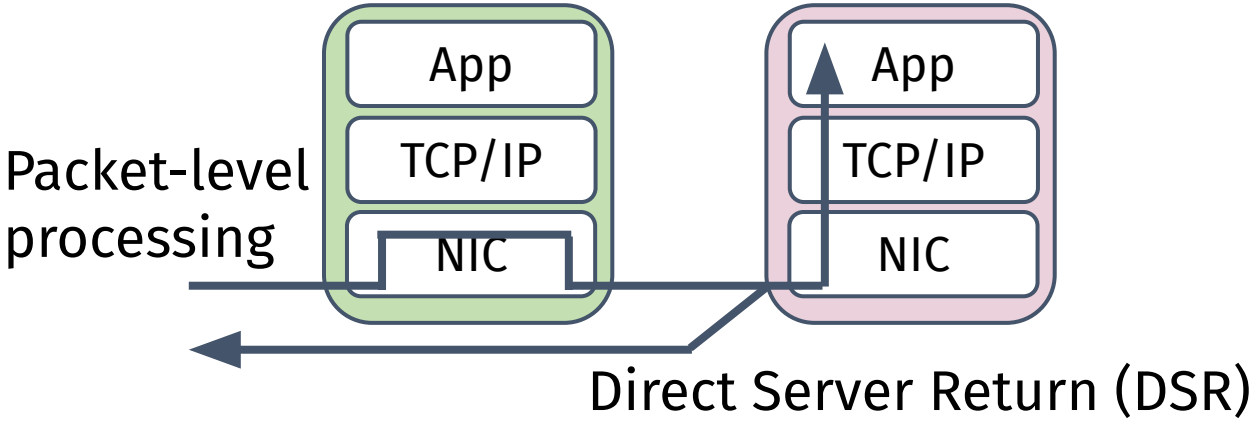


- L7LB datapath



- **XO** datapath



Existing L7LB enhancements

- Flow steering at a programmable switch [1, 2]
  - Hard to deploy

[1] Prism, NSDI'21
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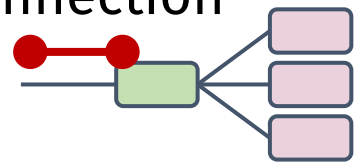
- No Direct Server Retern (DSR) [3]
  - Inefficient
- No TLS support [4]
  - Impractical
- No real app integration [1, 2, 3]
  - Hard to use

[1] Prism, NSDI'21
[2] Capybara, APSys'23
[3] DISC, NSDI'25
[4] Miresga, WWW'25

XO in-action

- L7LB accepts a client connection
- Read the client request

Client TCP
connection



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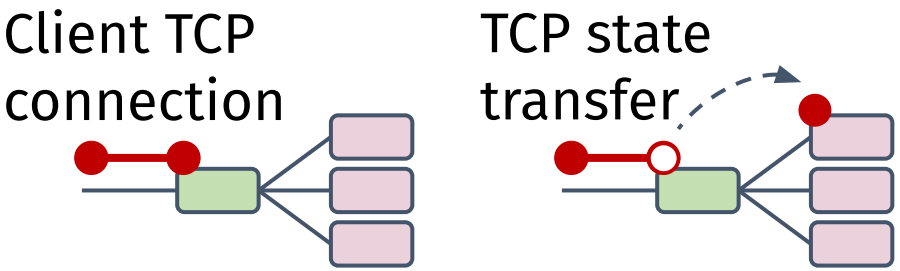
- L7LB migrates the connection to the server



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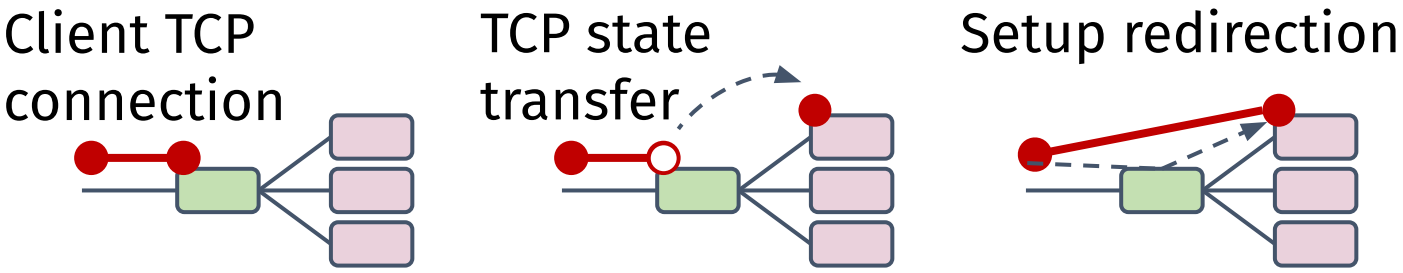

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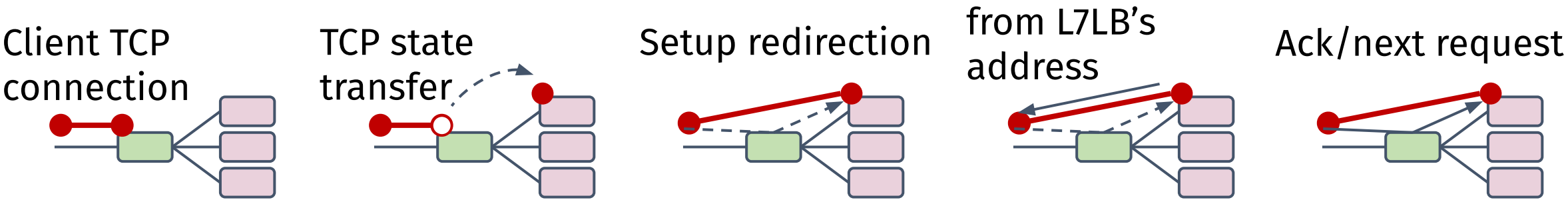
- The server modifies the source address



SW/HW Hybrid packet redirection

- eBPF is fast to setup (good for fast conn. migration) but inefficient
- tc-flower is slow but efficient after migration due to hw offload

	Operation (µs)		Rate (Mpps)		Latency (µs)	
	Insert	Remove	64B	1500B	64B	1500B
eBPF (tc)	4.01	3.77	0.79	0.78	21.06	22.42
eBPF (XDP)	38.31	7.41	6.65	2.07	16.52	18.45
tc (CX5)	476	404	33.01	2.07	8.26	9.89
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- We do hybrid: *SW until HW activated*
  - Install the equivalent flow rule with both eBPF and tc-flower

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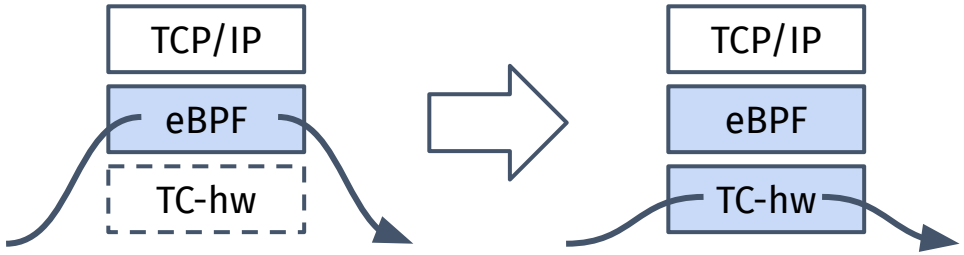
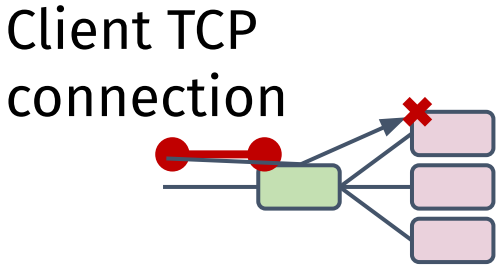


Cancellable queue

- Returning the connection to L7LB needs both SW/HW rule withdrawal



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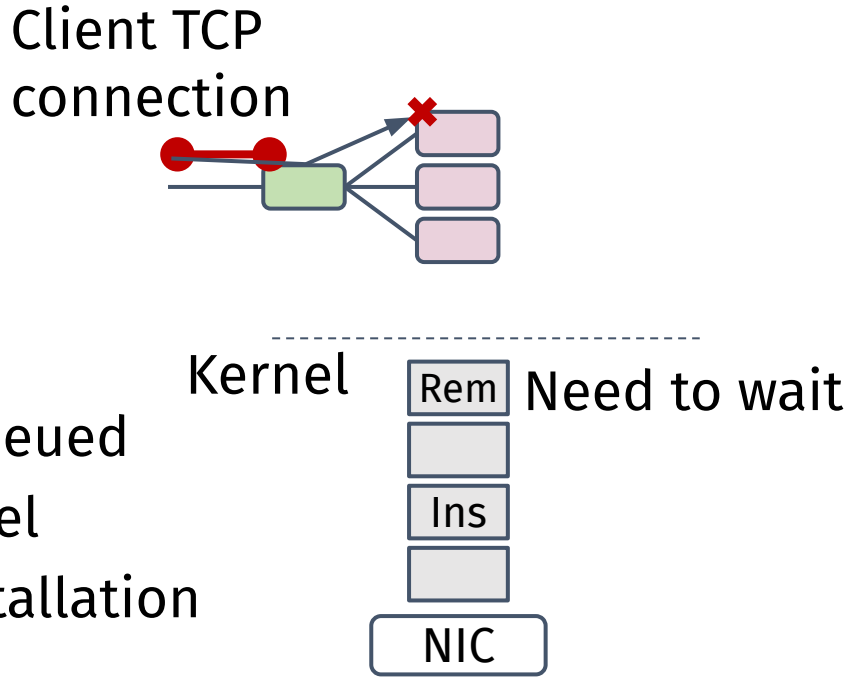

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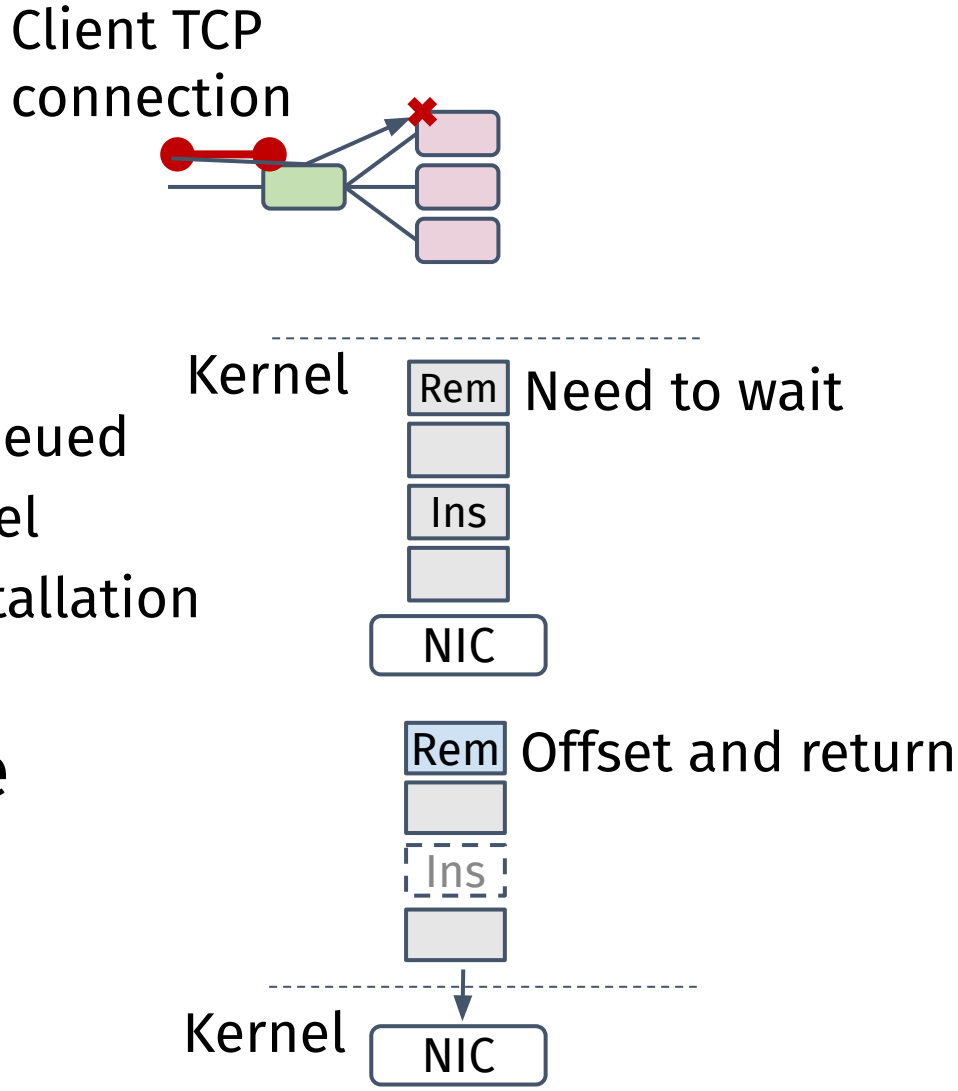
- We move the queue to the user space
  - Offset the pending installation rule

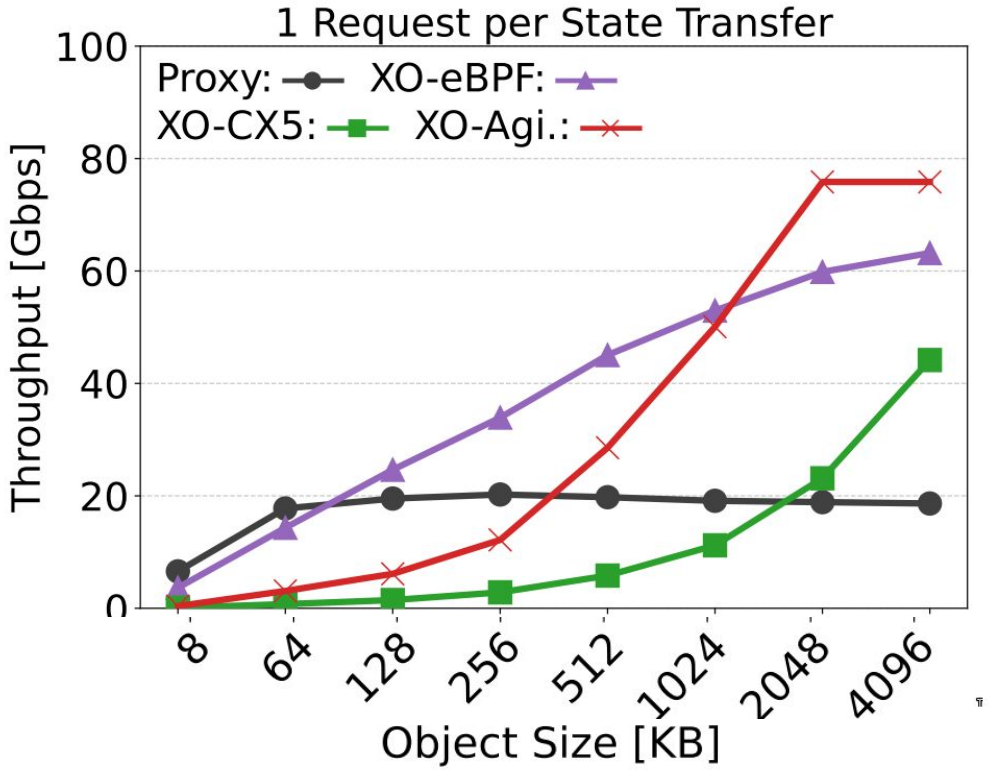


Application porting experience

- XO (or any connection migration-based approaches) needs both L7LB and server app modification - how hard it is?
- Nginx (replicated backend) and Ceph (sharded backend)
- The use of kernel stack eased porting significantly
  - Full file descriptor semantics, threading model etc
  - It’d have been much harder if we opted for kernel-bypass stacks

XO throughput

- 25Gbps L7LB and server links
  - Larger objects or less frequent migrations amortize the connection migration costs



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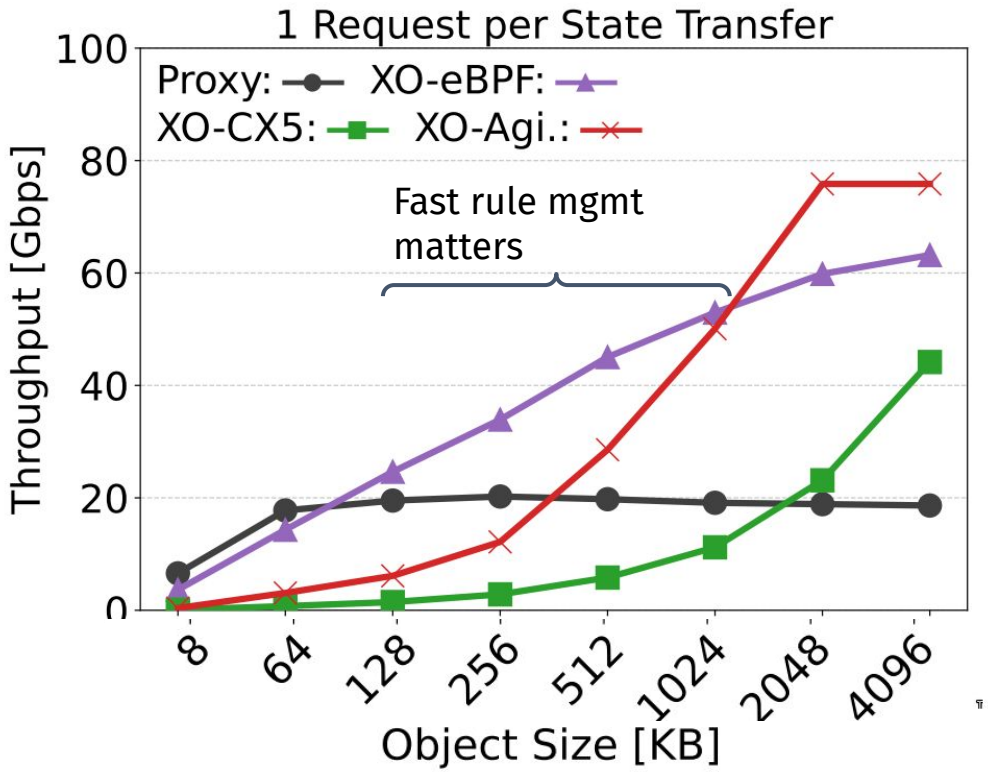

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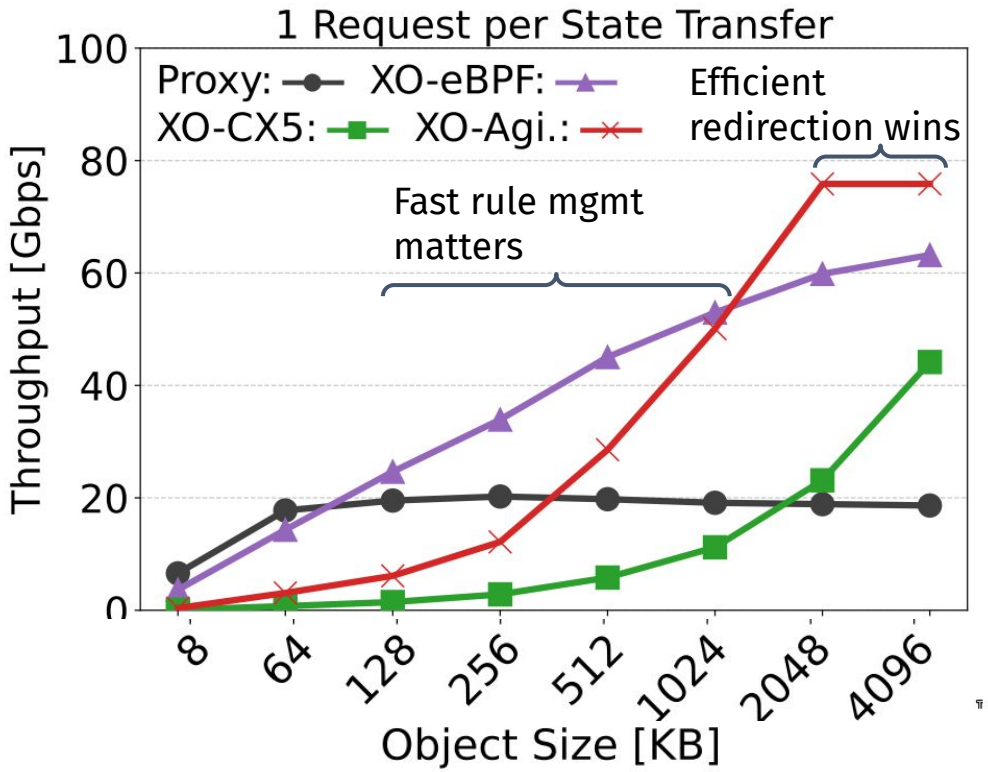

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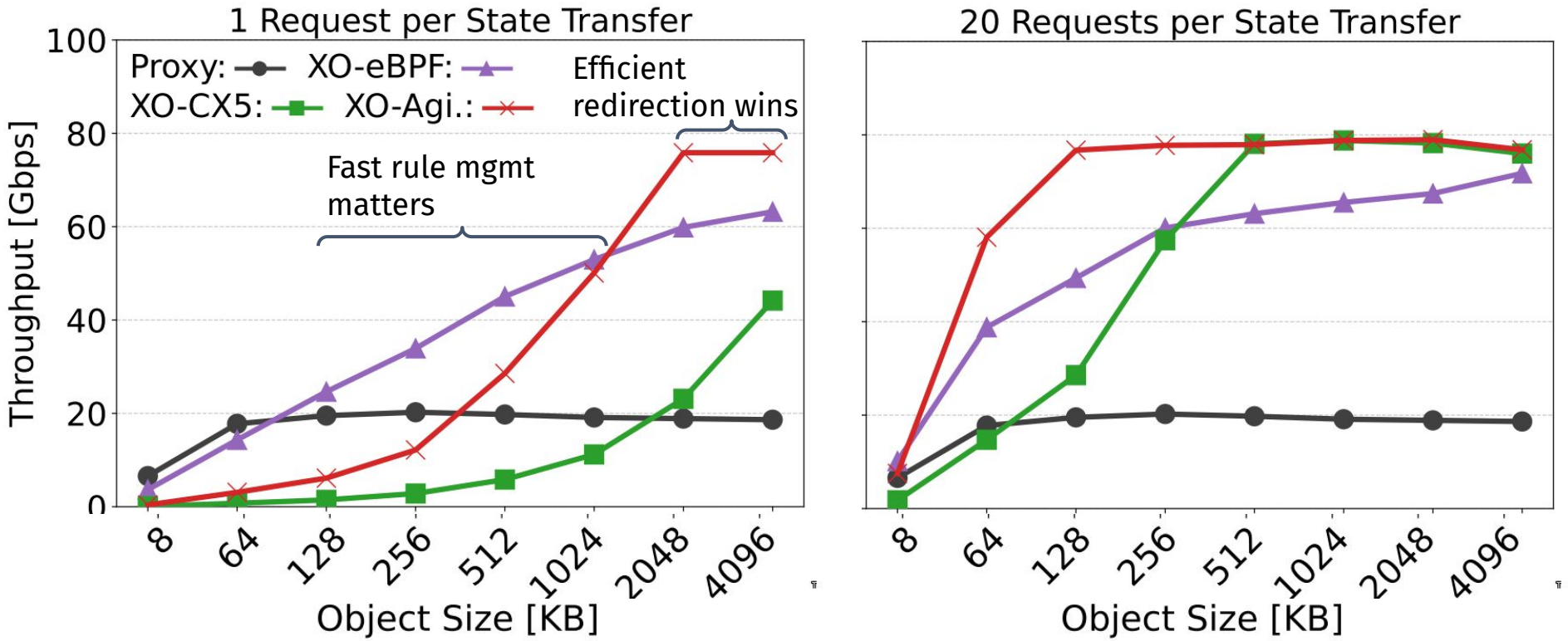
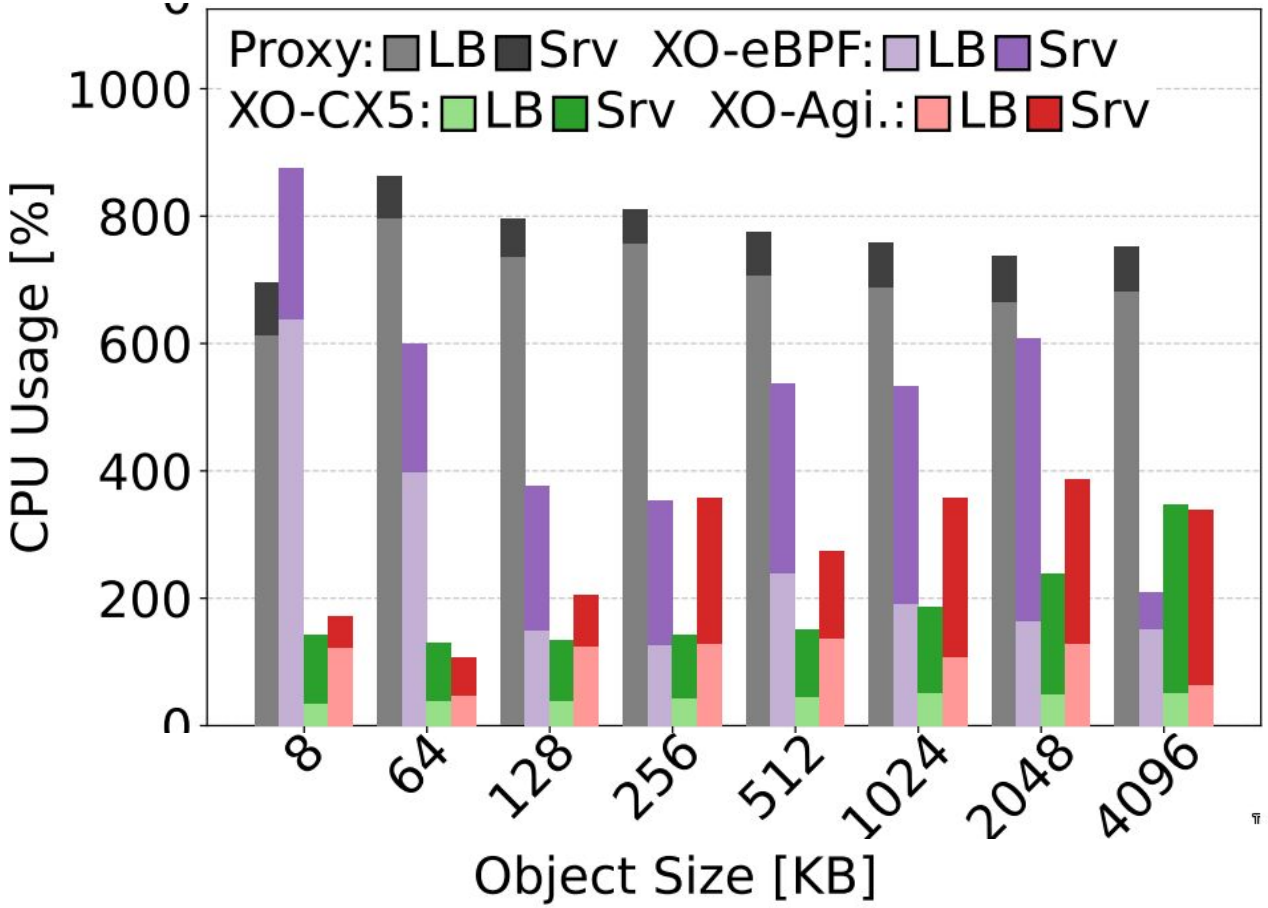


XO CPU usage

- 25Gbps L7LB and server links
  - L7LB CPU usage decreases despite higher throughput



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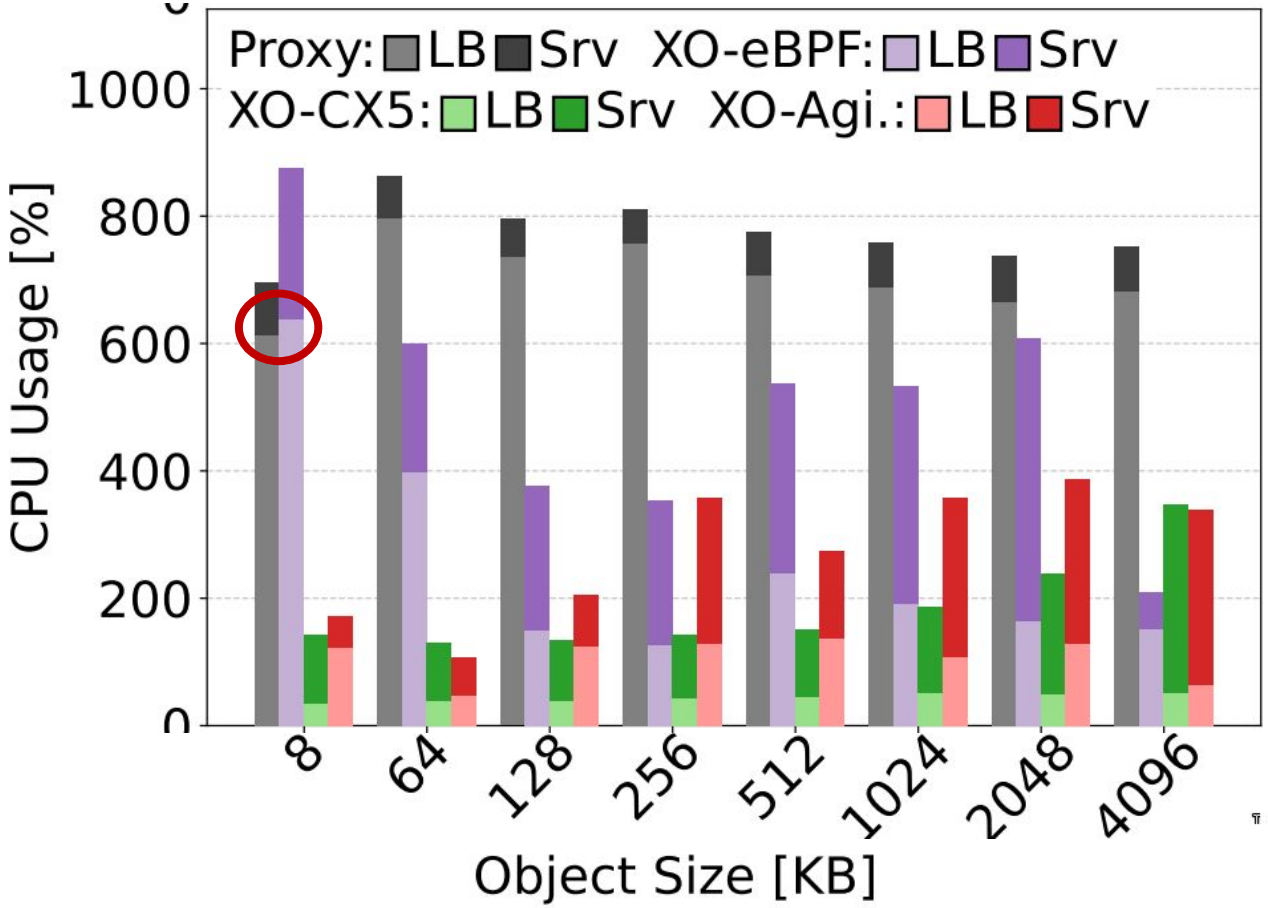

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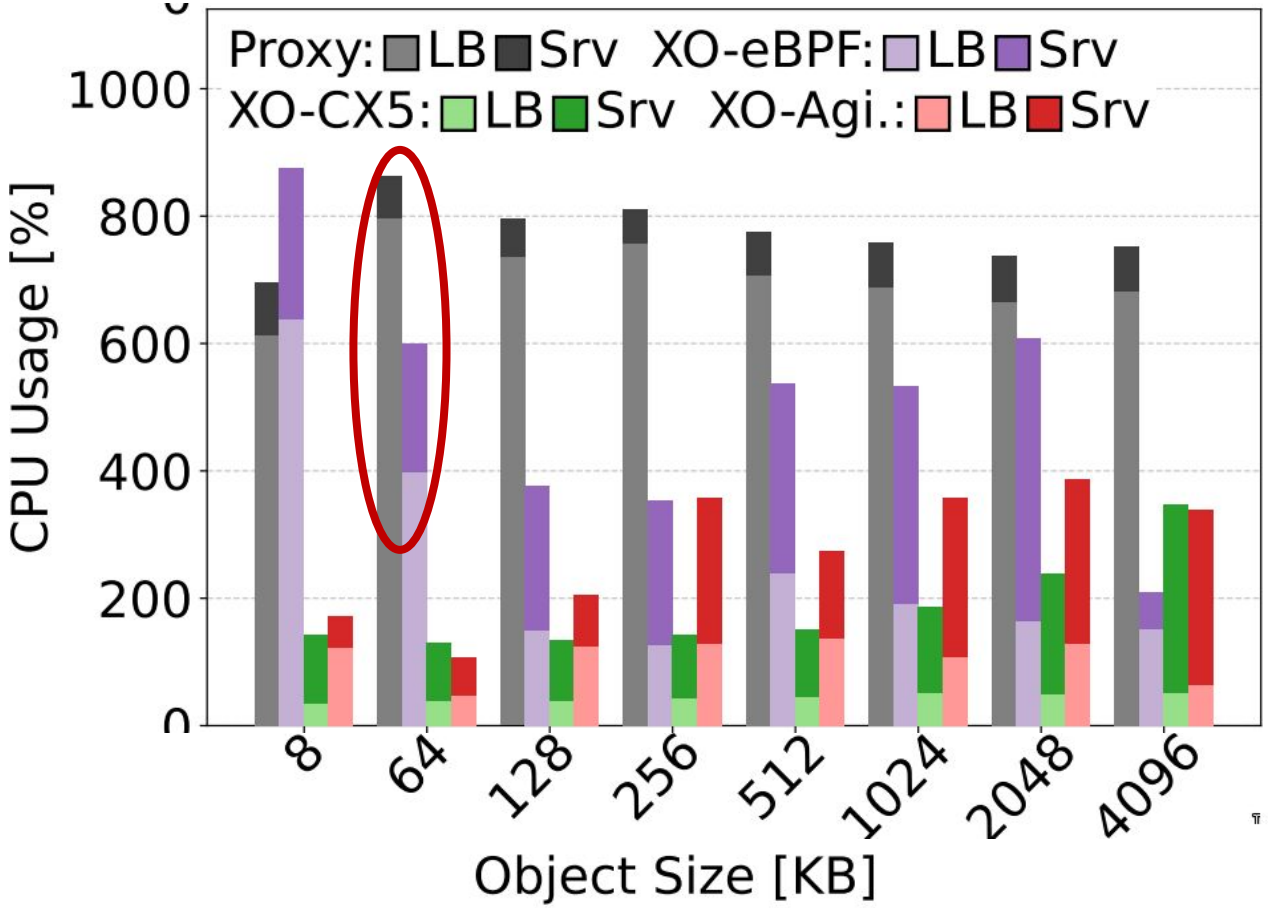

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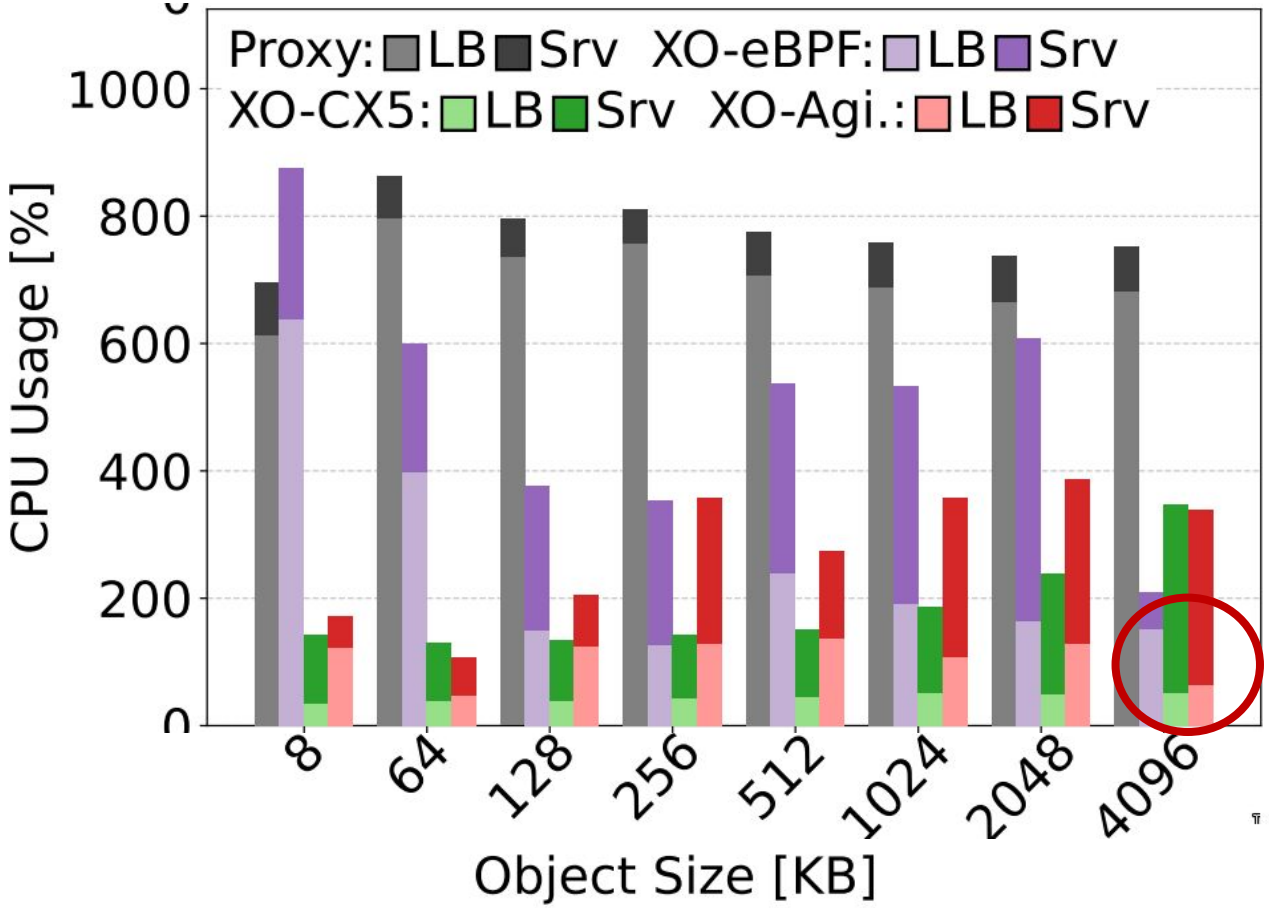

Connection migration latency

Operation	Latency [µs]	
(L) Block flow	4	
(L) Serialize TLS	2	
(L) Serialize TCP	11	
(L->S)State transferring to the server	148	
(L) Sending RPC: BEGIN_OFFLOAD		
(S) Restore TCP		39
(S) Restore TLS		15
(S) Install source IP rewrite rule		5
(L) Received RPC: SERVER_READY		
(L) Install redirection rule and unblock	4	
(L) Send RPC: L7LB_READY	56	
Total	**225**	

State transfer can be faster (if we modify the stack)

- Connection serialization takes 13 syscalls, each locking the socket

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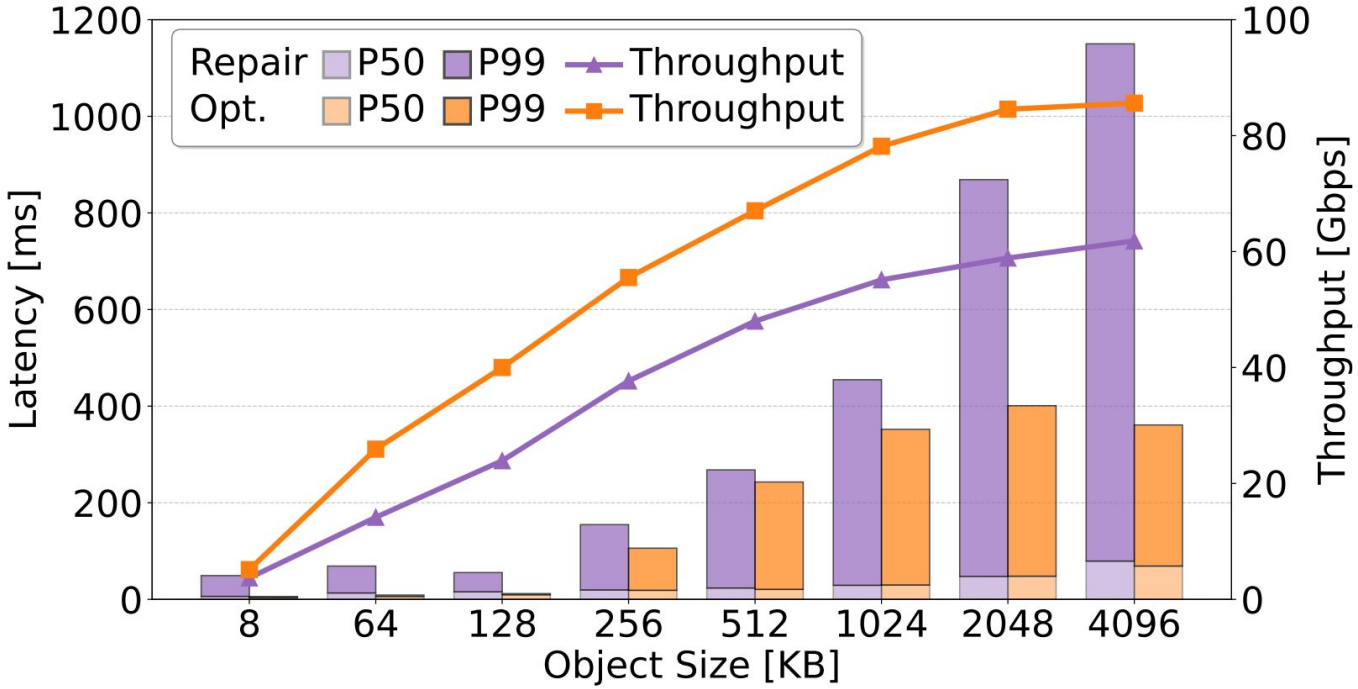
- We implement consolidated serialization or deserialization call to amortise syscall and socket locking costs



XO-nginx performance

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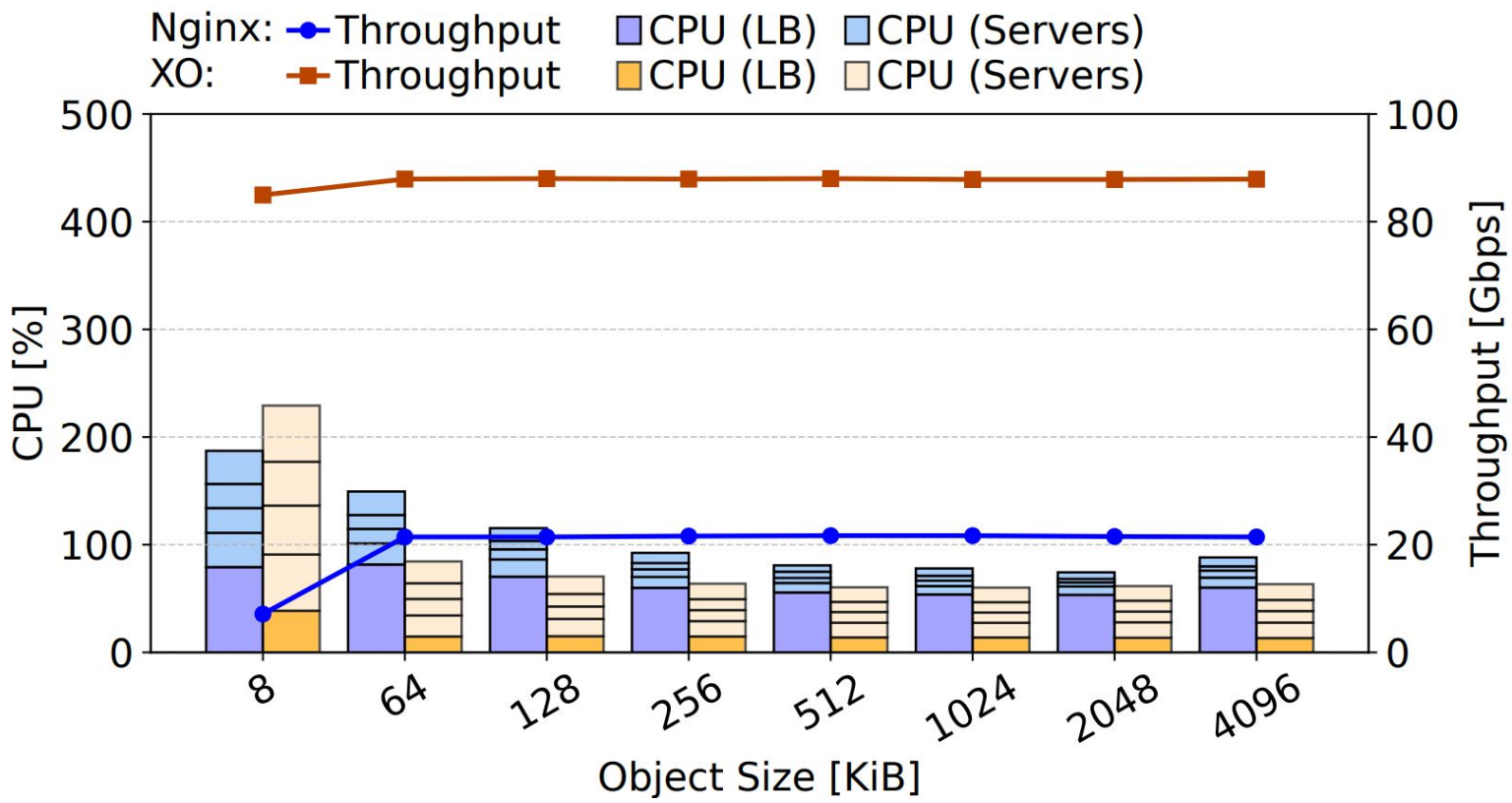
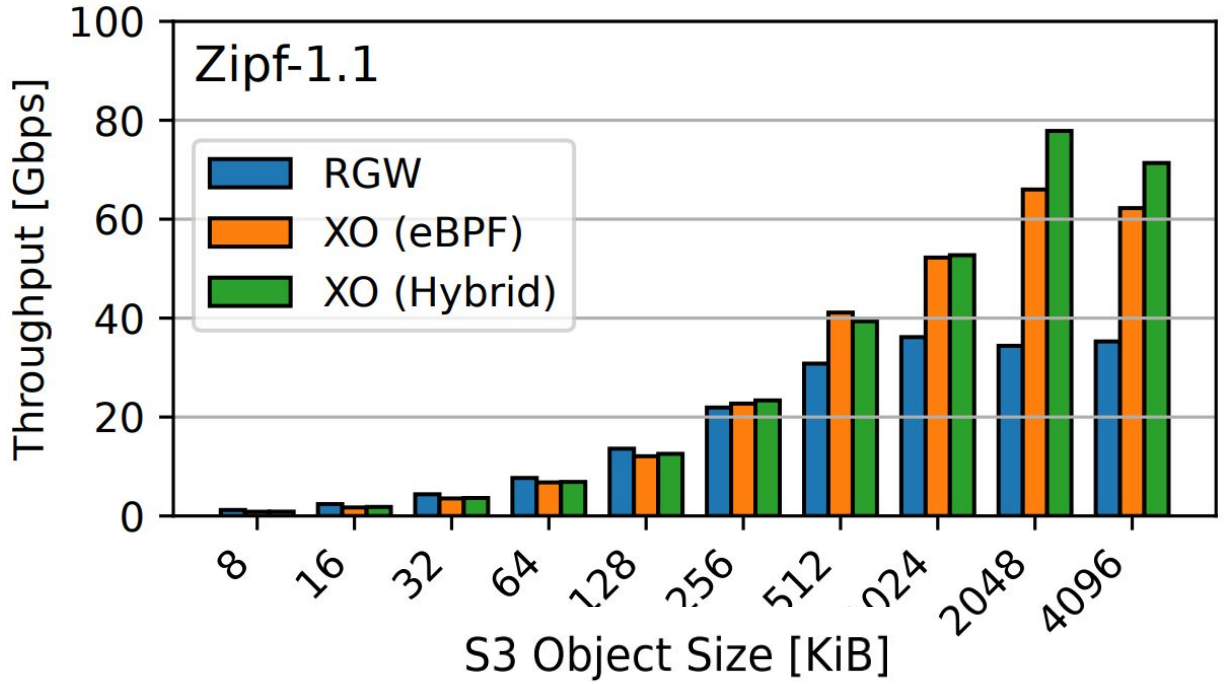
  - Better BW utilization
  - Reduced L7LB CPU usage



XO-Ceph performance

- 100Gbps L7LB and server links
  - Better throughput with 256KiB or larger objects
    - Typical Ceph depoloyments hosts many larger data*



*https://ceph.io/en/news/blog/2025/benchmarking-object-part2/

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  - Currently not restored (i.e., slow-start)
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  - We have eBPF-only option
- Congestion window, RACK state etc
  - Currently not restored (i.e., slow-start)
  - Future work will (carefully) restore it: Important for long-RTT flows
- Concurrent requests
  - Packet level buffering/replication as with HA/TCP [NSDI'25]
    - At most awnd per connection
    - Trivial with eBPF

Summary

- XO: Remote TCP Connection Offload (from L7LB to the servers)
  - Ingress: Lightweight packet-level redirection at the host
  - Egress: Direct Server Return
  - Real app integration: Nginx and Ceph
  - Reduced L7LB CPU and BW usage and better server resource utilization
- Details and more results in the paper
- Code: https://github.com/uoenoplab/xo
  - AE confirmed it works with xl170 nodes on Cloudlab