Tagger: Practical PFC Deadlock Prevention in Data Center Networks

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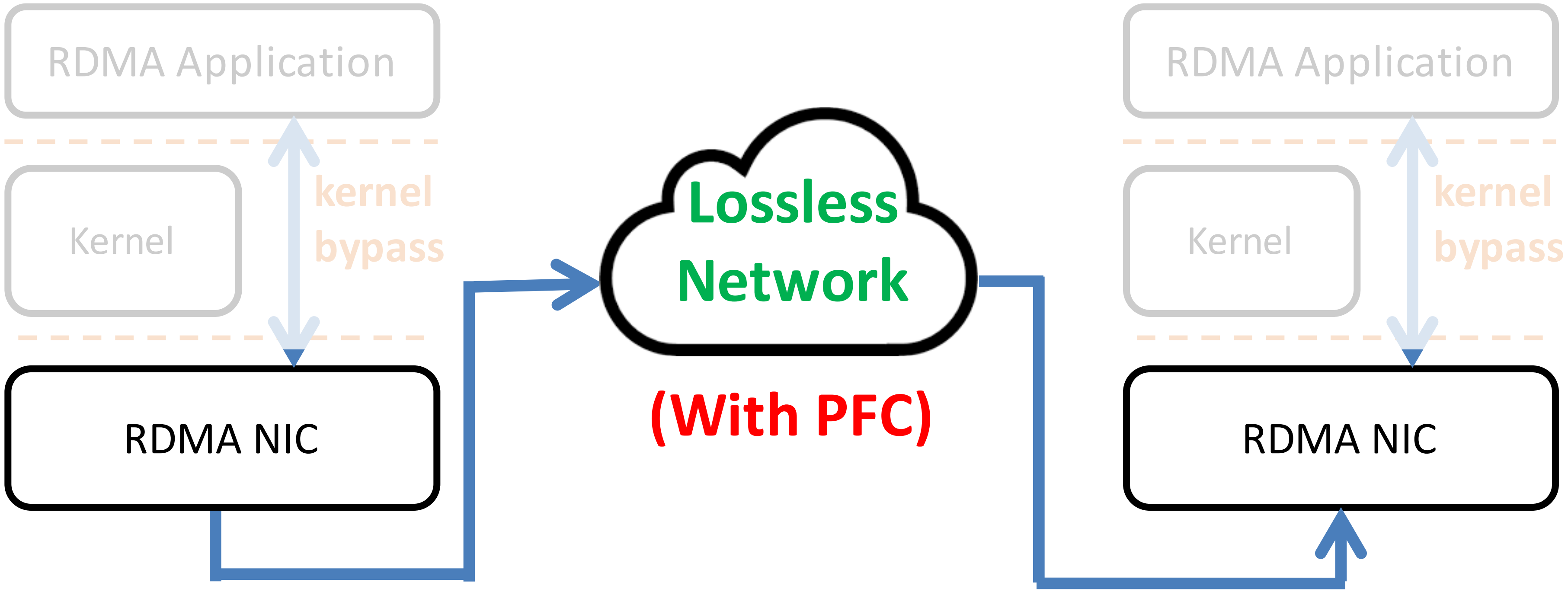
* Work done while at Microsoft

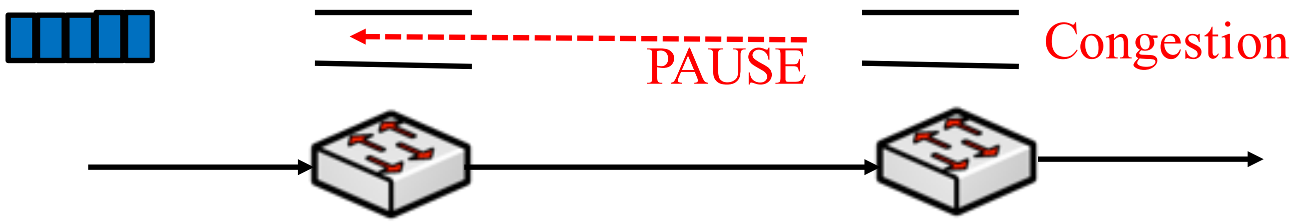
RDMA is Being Widely Deployed

RDMA: Remote Direct Memory Access

- ❖ High throughput, low latency with low CPU overhead
- ❖ Microsoft, Google, etc. are deploying RDMA



Priority Flow Control (PFC)

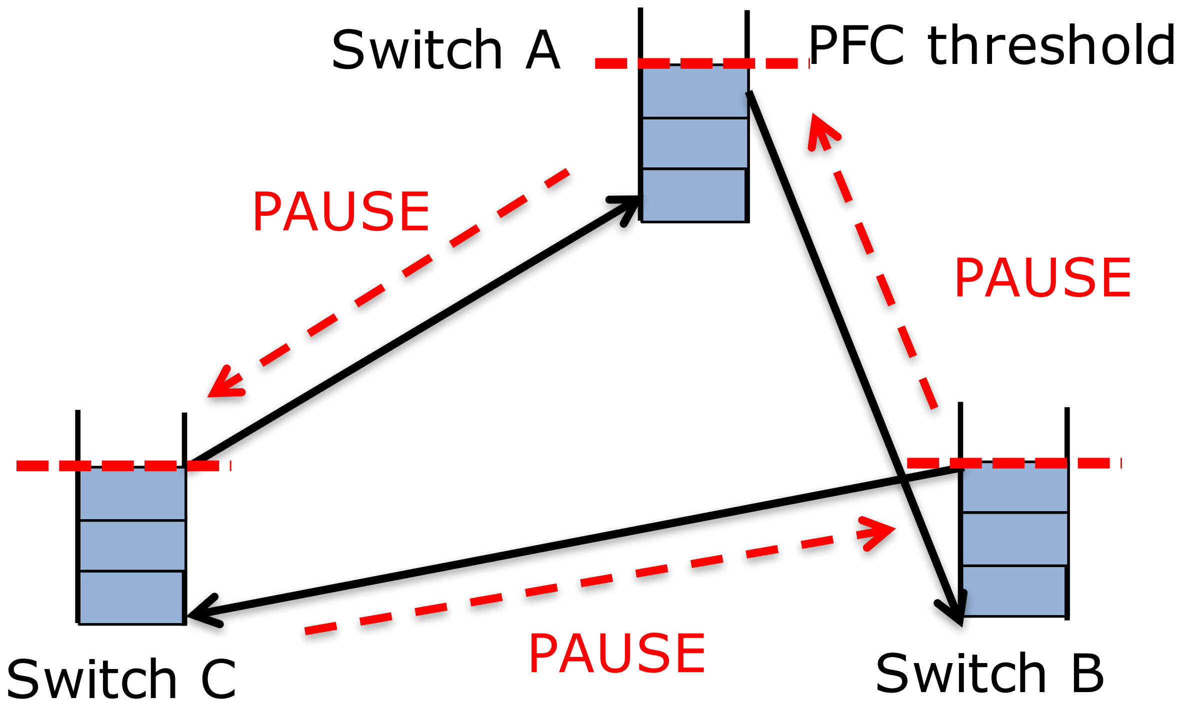


PFC threshold: 3pkts

PAUSE upstream switch when PFC threshold reached

❖ Avoid packet drop due to buffer overflow

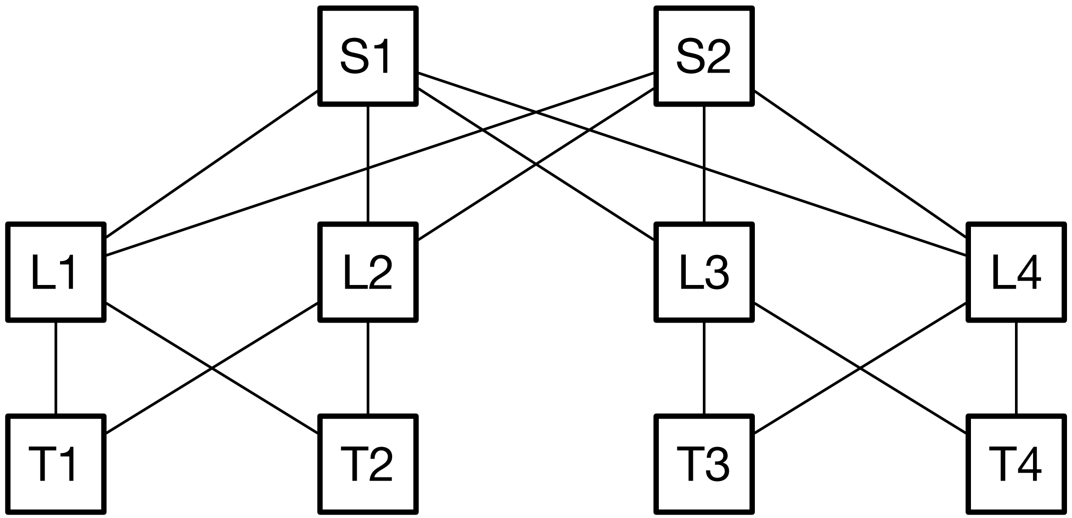
A Simple Illustration of PFC Deadlock



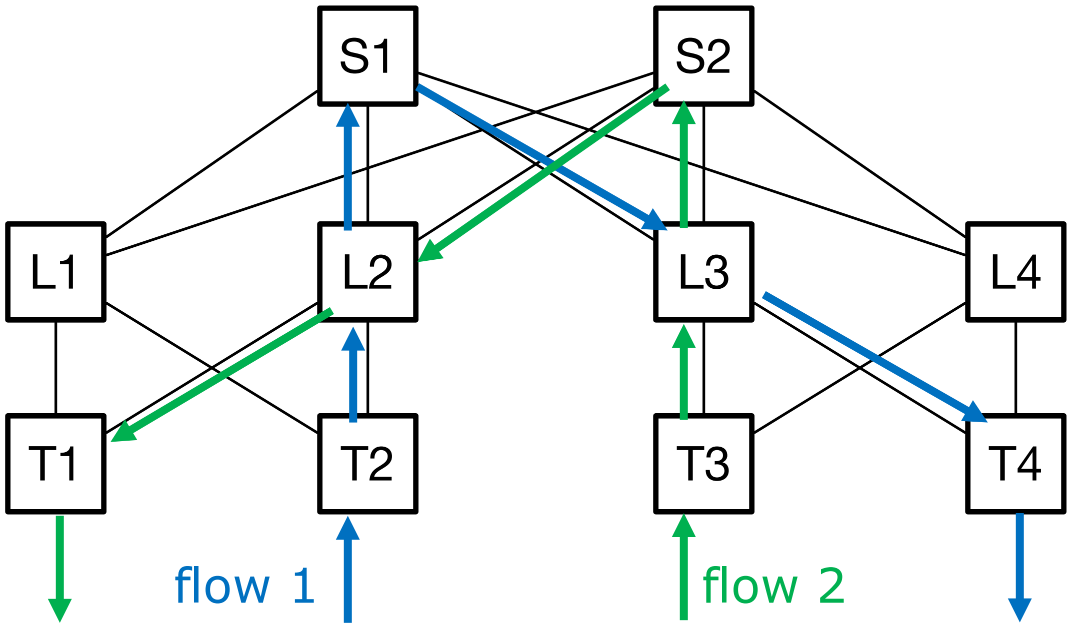
Due to Cyclic Buffer Dependency (CBD) A->B->C->A

Not just a theoretical problem, we have seen it in our datacenters too!

CBD in the Clos Network

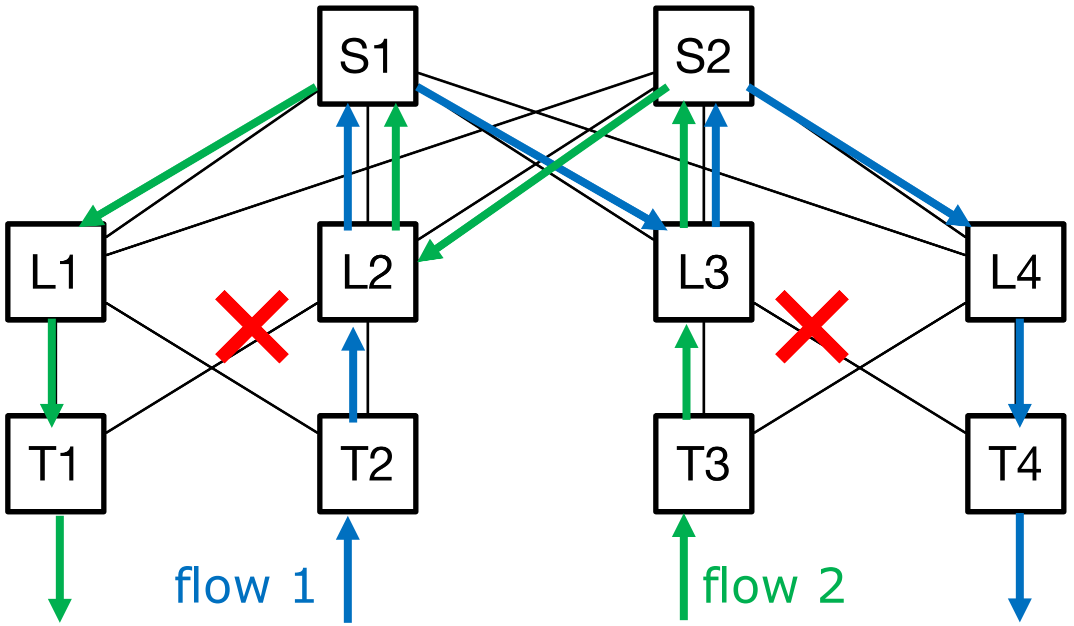


CBD in the Clos Network



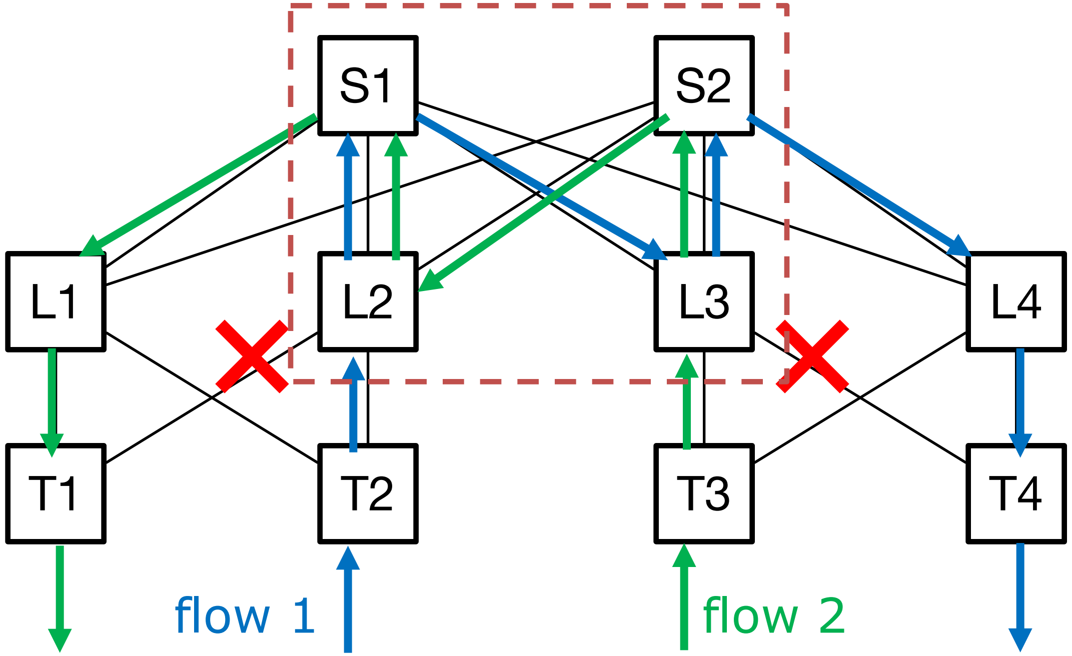
consider two flows initially follow shortest UP-DOWN paths

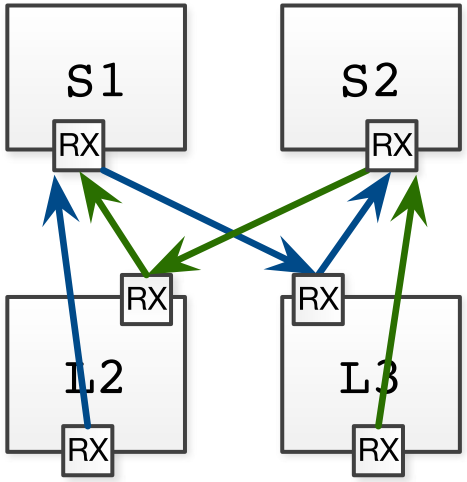
CBD in the Clos Network



due to link failures, both flows are locally rerouted to non-shortest paths

CBD in the Clos Network





buffer dependency graph

these two **DOWN-UP bounced** flows create CBD

CBD: L2->S1->L3->S2->L2

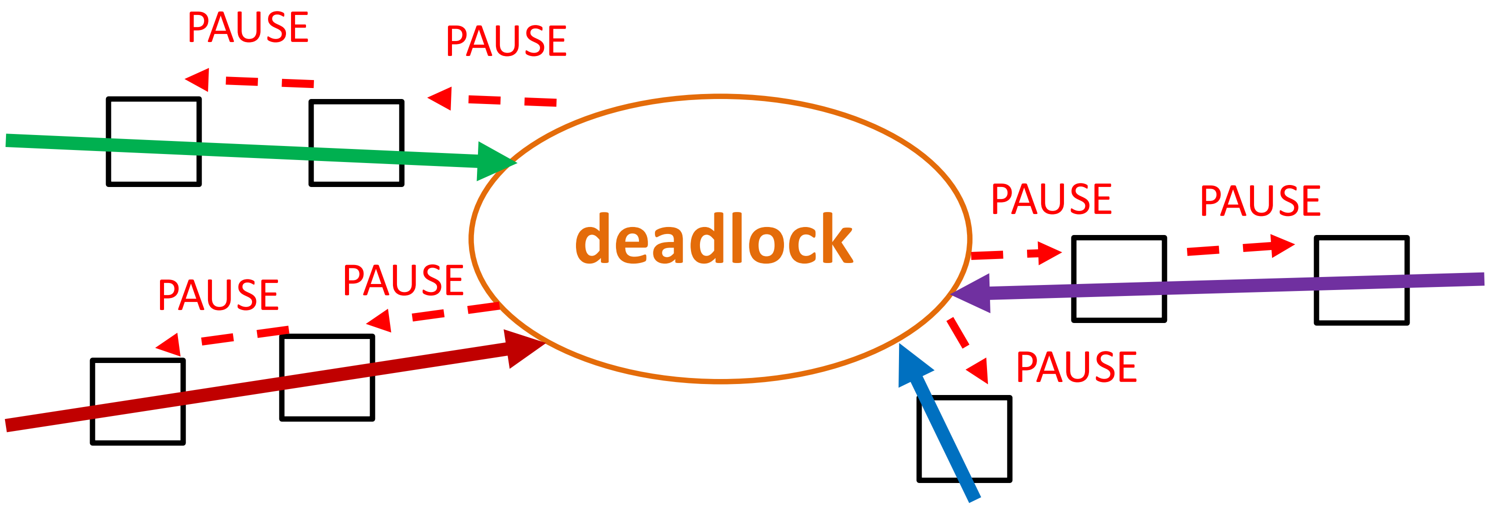
Real in Production Data Centers?

Packet reroute measurements in more than 20 data centers:

~100,000 DOWN-UP reroutes!

Handling Deadlock is Important

- **#1:** transient problem → **PERMANENT** deadlock
  - Transient loops due to link failures
  - Packet flooding
  - …
- **#2:** small deadlock can cause large deadlock



Three Key Challenges

What are the challenges in designing a practical deadlock prevention solution?

- No change to existing routing protocols or hardware
- Link failures & routing errors are unavoidable at scale
- Switches support at most 8 limited lossless priorities
  (and typically only two can be used)

The Existing Deadlock Prevention Solutions

- #1: deadlock-free routing protocols
  - not supported by commodity switches (**fail challenge #1**)
  - not work with link failures or routing errors (**fail challenge #2**)

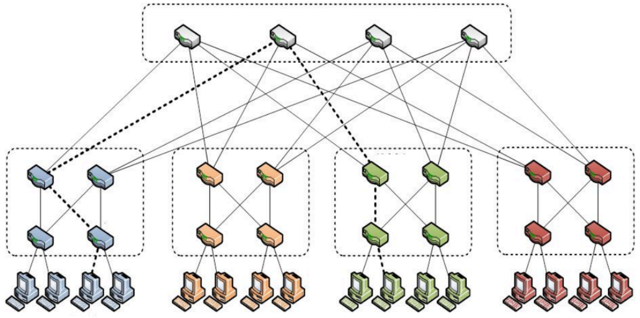
- #2: buffer management schemes
  - require a lot of lossless priorities (**fail challenge #3**)

Our answer: **Tagger**

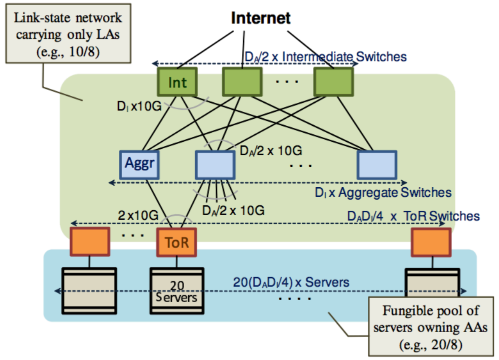
TAGGER DESIGN

Important Observation

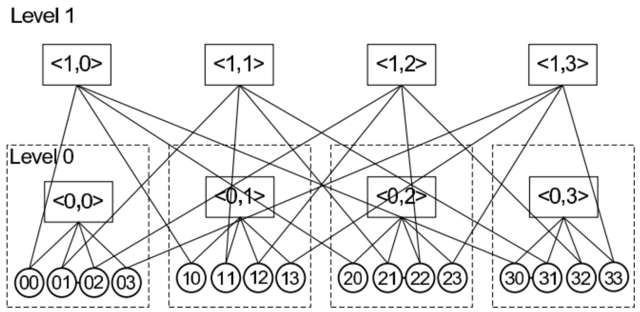
Fat-tree [Sigcomm'08]



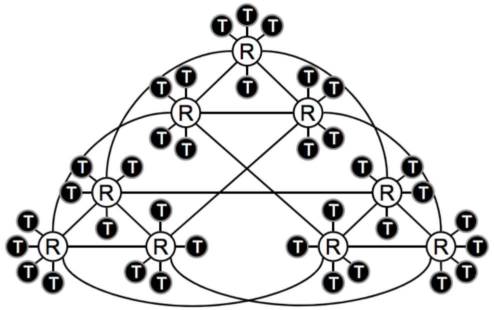
VL2 [Sigcomm'09]



BCube [Sigcomm'09]



HyperX [SC'09]



desired path set: all shortest paths

desired path set: dimension-order paths

Takeaway: In a data center, we can ask operator to supply a set of **expected lossless paths (ELP)**!

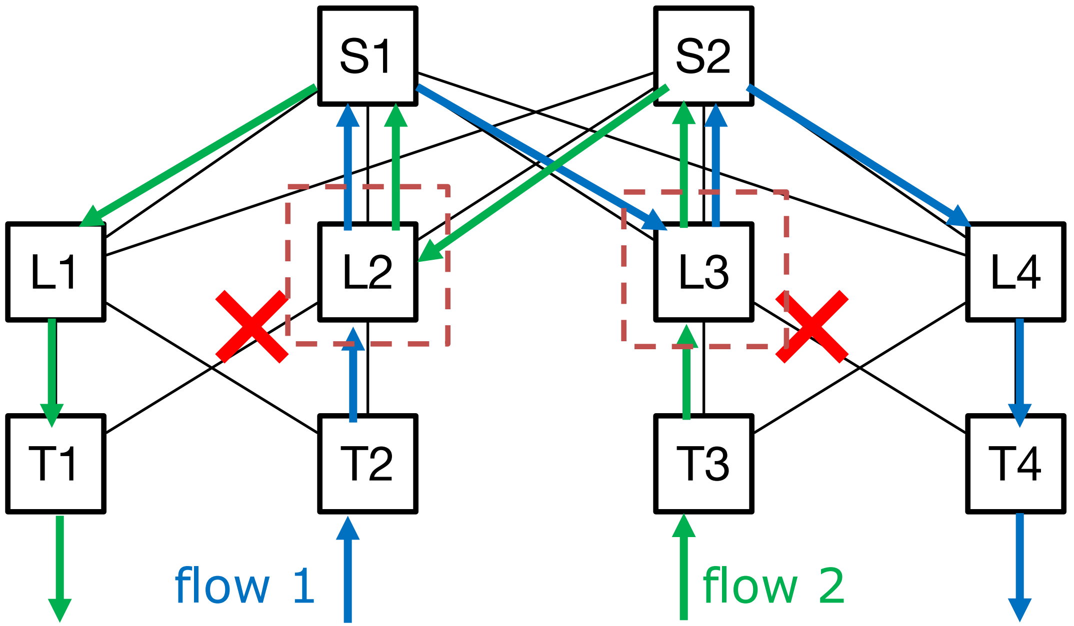
Basic Idea of Tagger

1. Ask operators to provide:
   - topology & expected lossless paths (ELP)

2. Packets carrying tags when in the network

3. Pre-install match-action rules at switches for tag manipulation and packet queueing
   - packets travel over ELP: lossless queues & CBD never forms
   - packets deviate ELP: lossy queue, thus PFC not triggered

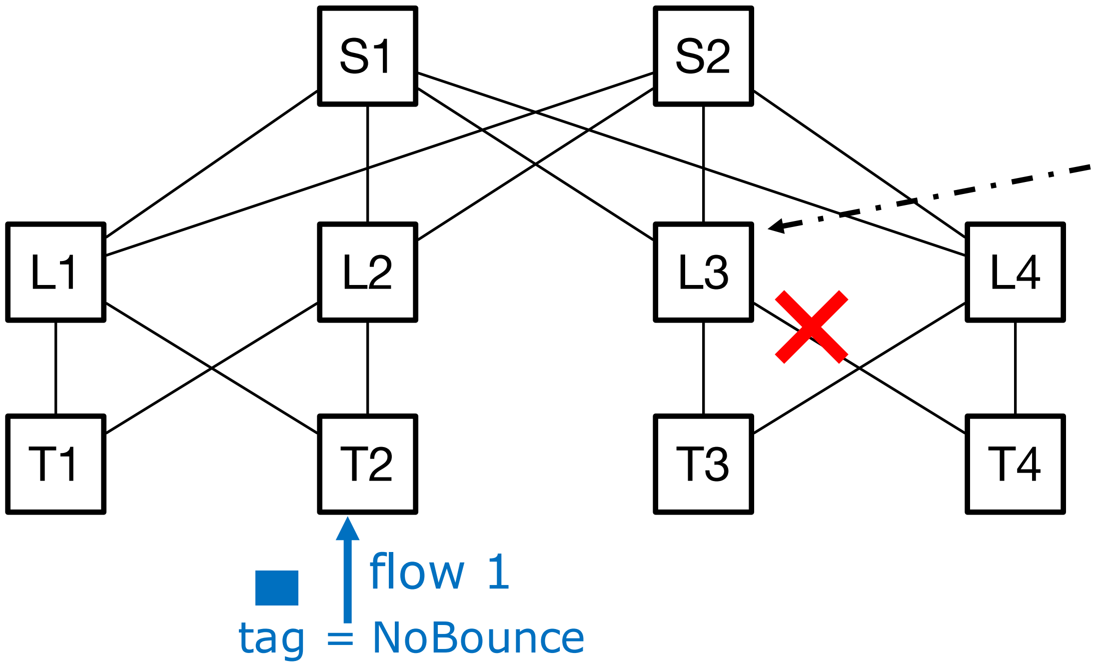
Illustrating Tagger for Clos Topology



Root cause of CBD:
packets deviate UP-DOWN routing!

ELP = all shortest paths (CBD-free)

Illustrating Tagger for Clos Topology



match

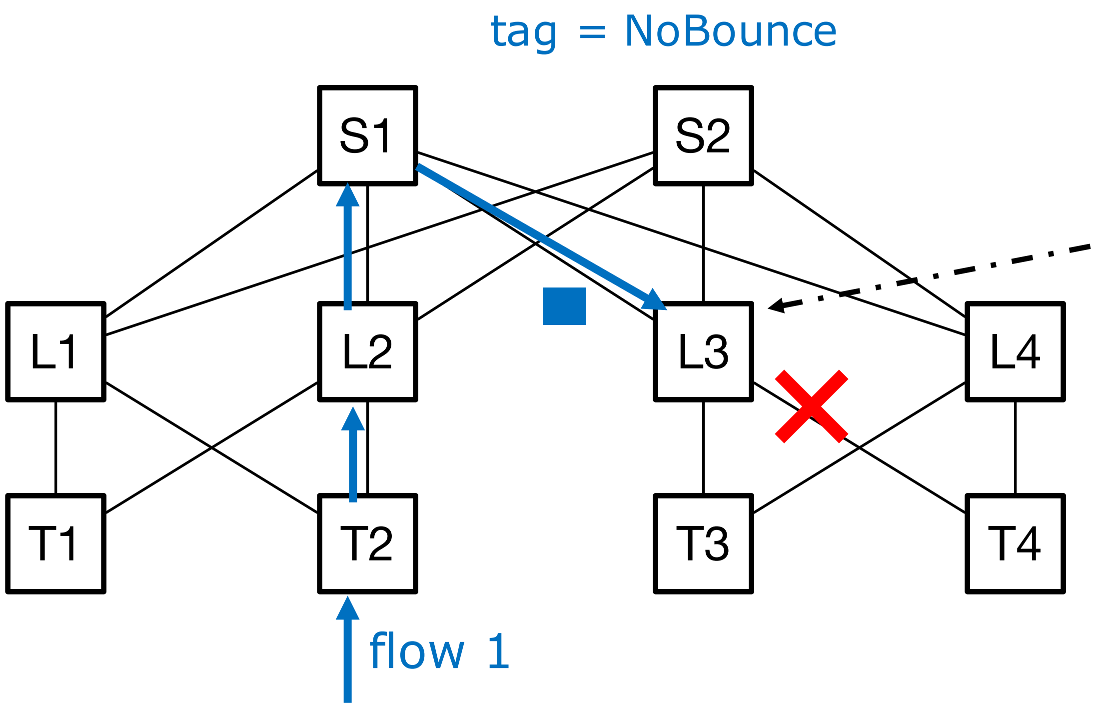
action

Tag	InPort	OutPort	NewTag
NoBounce	S1	S2	Bounced
…	…	…	…

match-action rules installed at switches

- Under Tagger, packets carry tags when travelling in the network
- Initially, tag value = NoBounce
- At switches, Tagger pre-install match-action rules for tag manipulation

Illustrating Tagger for Clos Topology



match

action

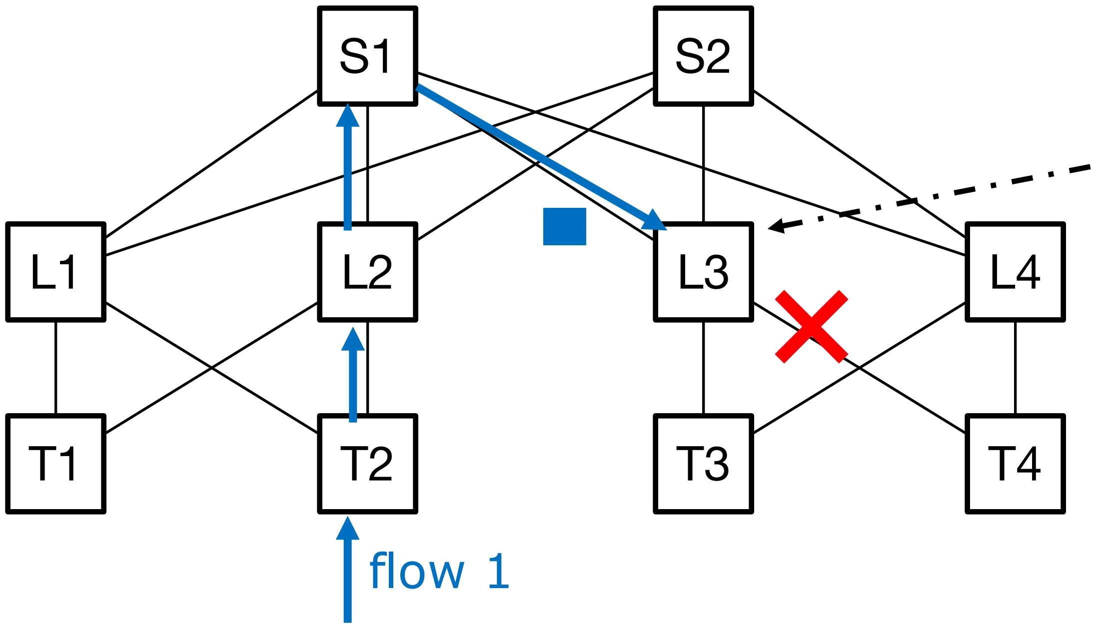
Tag	InPort	OutPort	NewTag
NoBounce	S1	S2	Bounced
…	…	…	…

match-action rules installed at switches

Packet received by switch L3

Illustrating Tagger for Clos Topology

tag = ~~NoBounce~~ Bounced



match

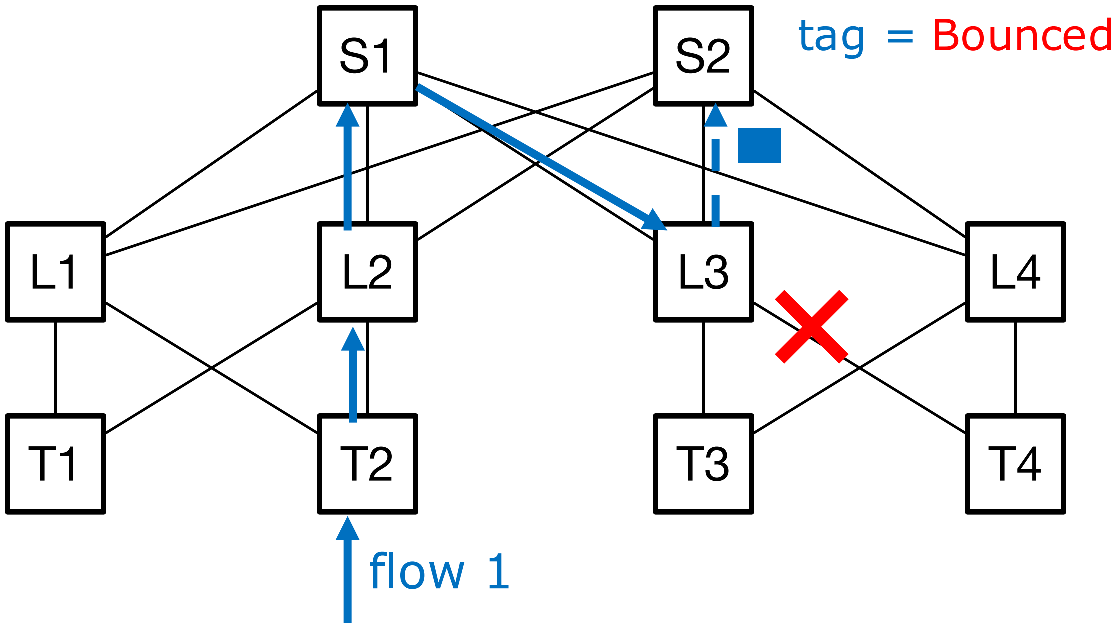
action

Tag	InPort	OutPort	NewTag
NoBounce	S1	S2	Bounced
…	…	…	…

down-up bounce observed!

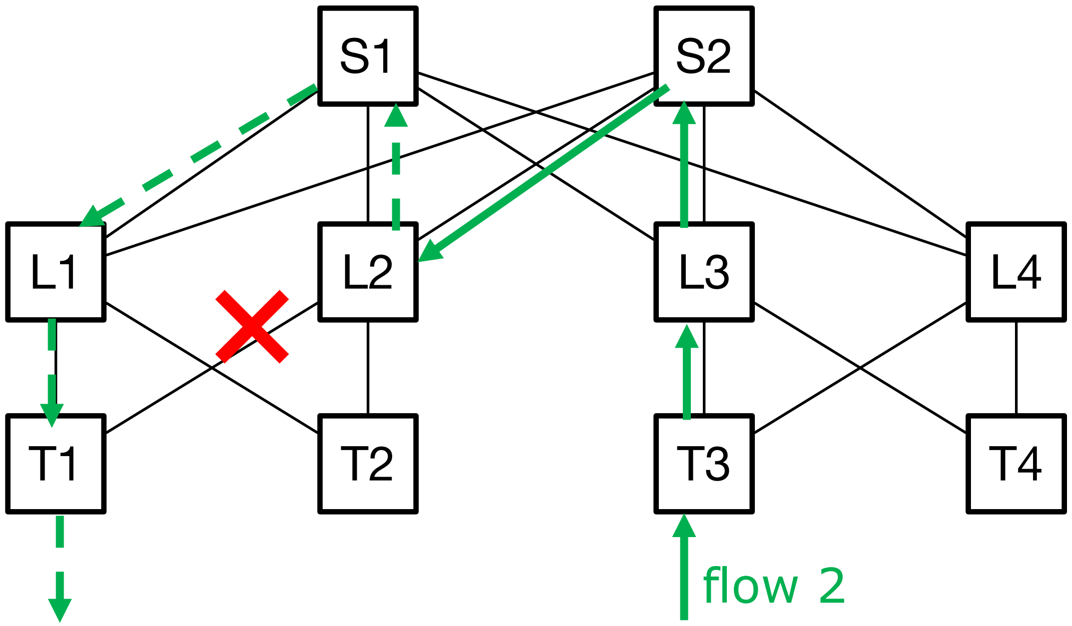
rewrite tag once DOWN-UP bounce detected

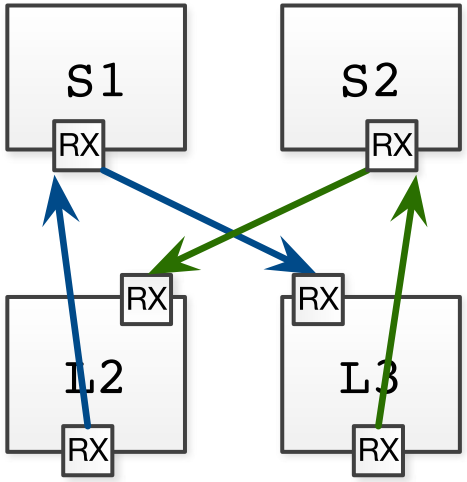
Illustrating Tagger for Clos Topology



- S2 knows it is a bounced packet that deviates ELP → placed in the lossy queue
- No PFC PAUSE sent from S2 to L3 → buffer dependency from L3 to S2 removed

Illustrating Tagger for Clos Topology



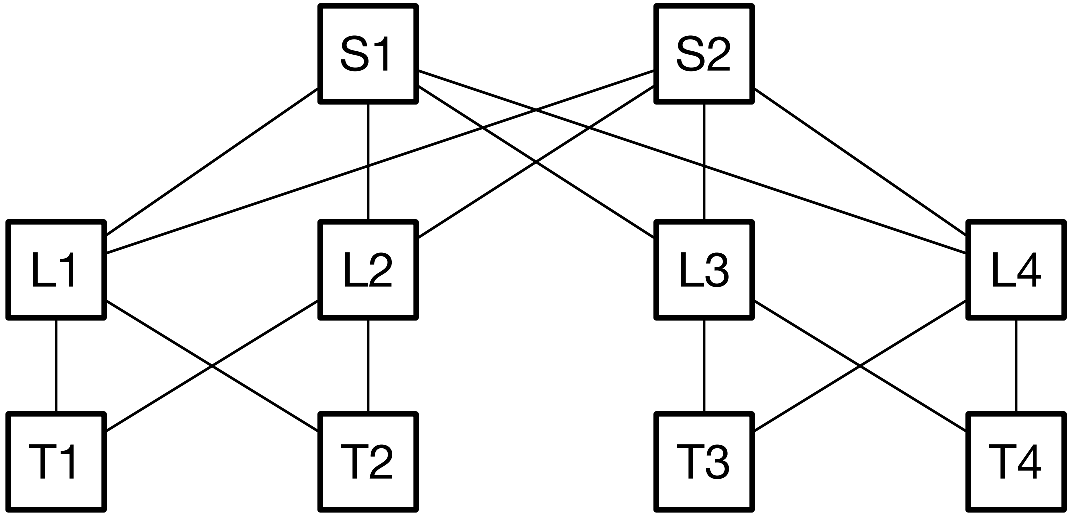


buffer dependency graph

~~CBD: L2->S1->L3->S2->L2~~

- Tagger will do the same for packets of flow 2
- 2 buffer dependency edges are removed → CBD is eliminated

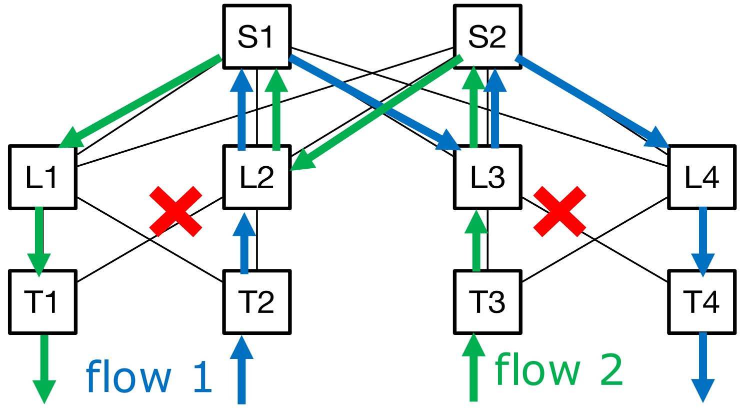
What If ELP Has CBD?



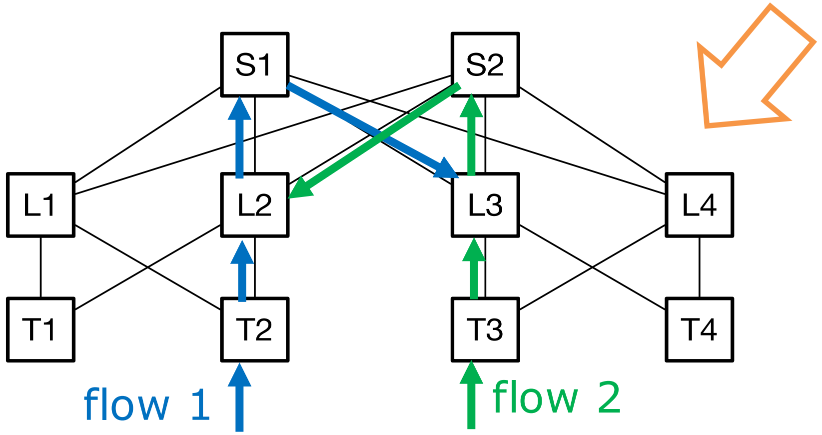
ELP = shortest paths + 1-bounce paths

(ELP has CBD now!)

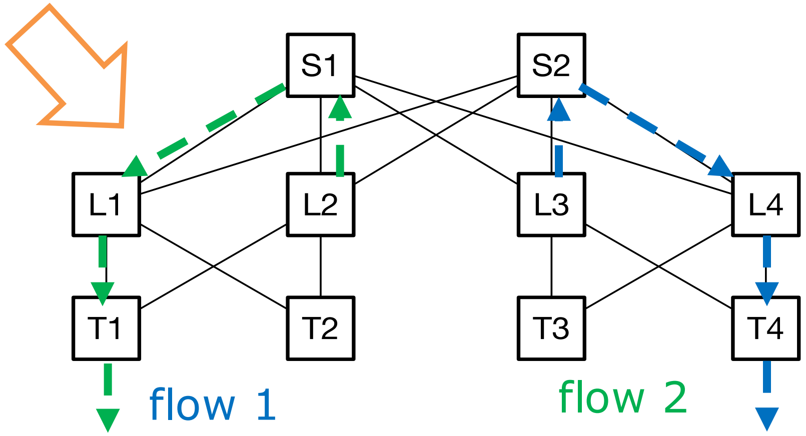
Segmenting ELP into CBD-free Subsets



two bounced paths are in ELP now

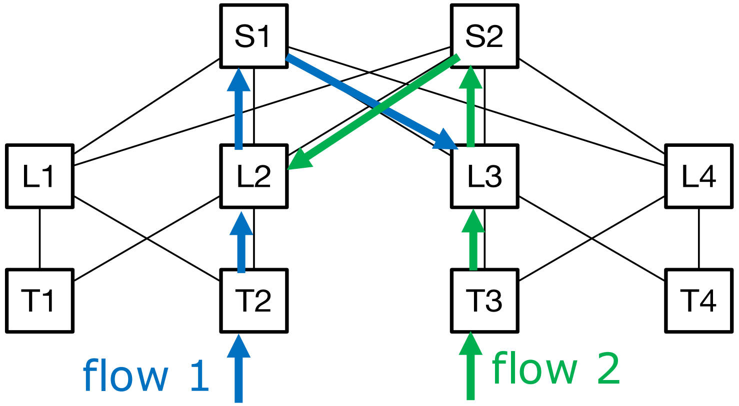


path segments before bounce
(only have UP-DOWN paths, no CBD)

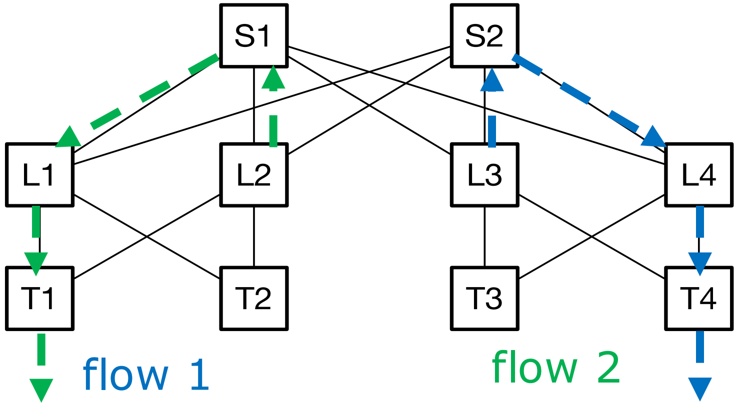


path segments after bounce
(only have UP-DOWN paths, no CBD)

Isolating Path Segments with Tags

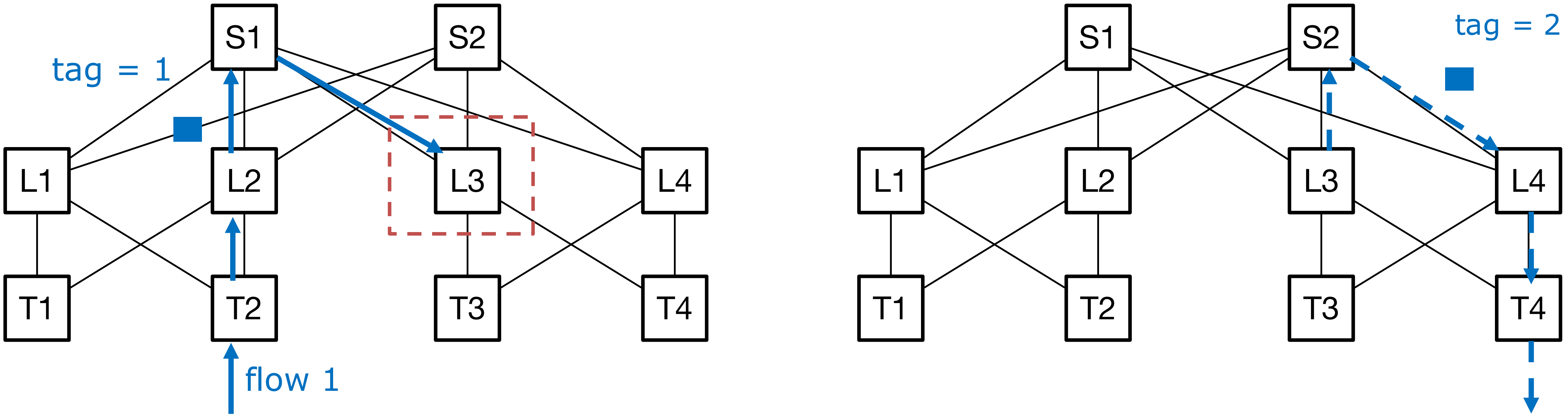


tag 1 → path segments before bounce



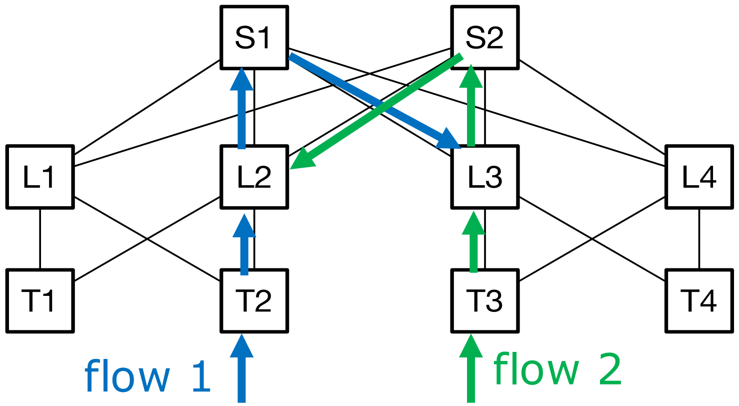
tag 2 → path segments after bounce

Isolating Path Segments with Tags

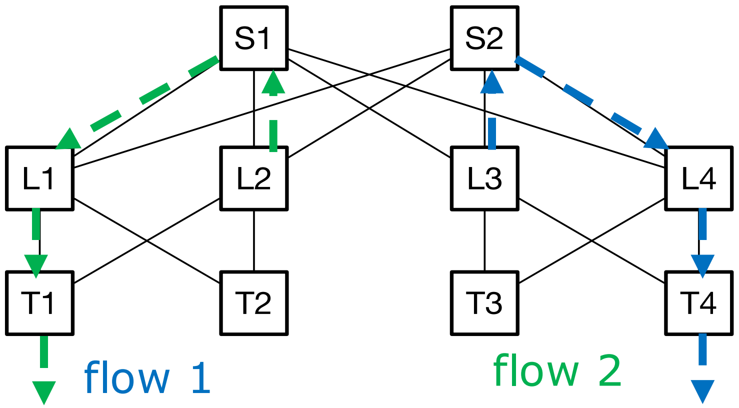


Adding a rule at switch L3: (Tag = 1, Inport=S1, OutPort = S2) -> NewTag = 2

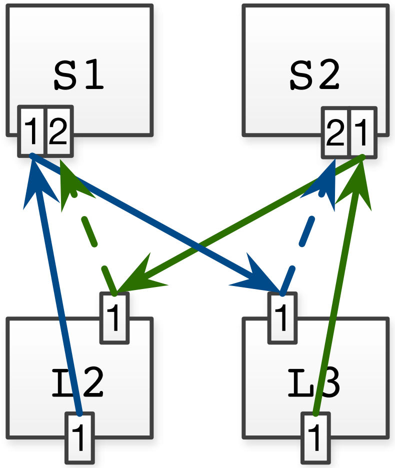
No CBD after Segmentation



tag 1



tag 2

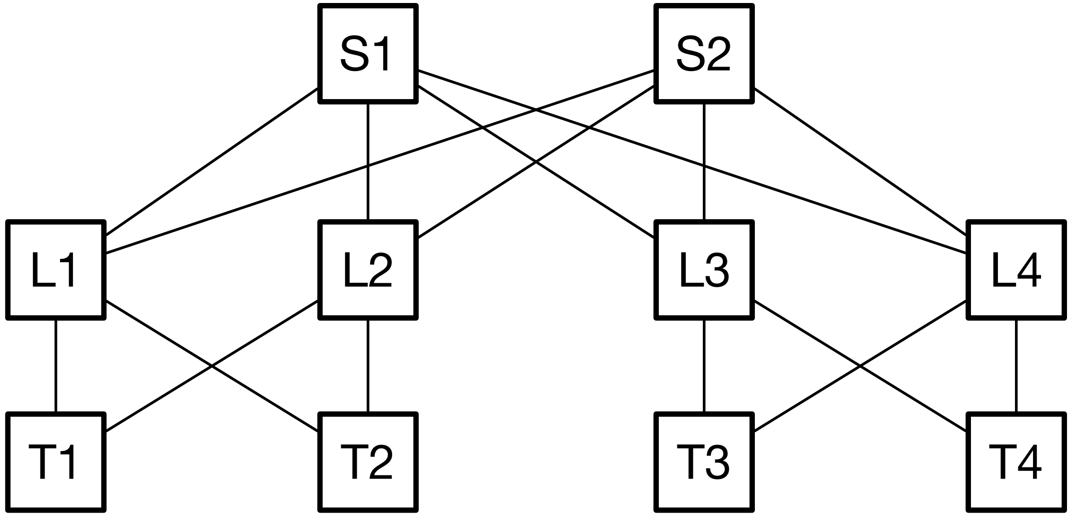


buffer dependency graph

packets with tag i → i-th lossless queue

~~CBD: L2->S1->L3->S2->L2~~

What If k-bounce Paths all in ELP?



solution: just segmenting ELP into k CBD-free subsets based on number of bounced times!

ELP = shortest up-down paths + ~~1-bounce paths~~
k-bounce paths

Summary: Tagger Design for Clos Topology

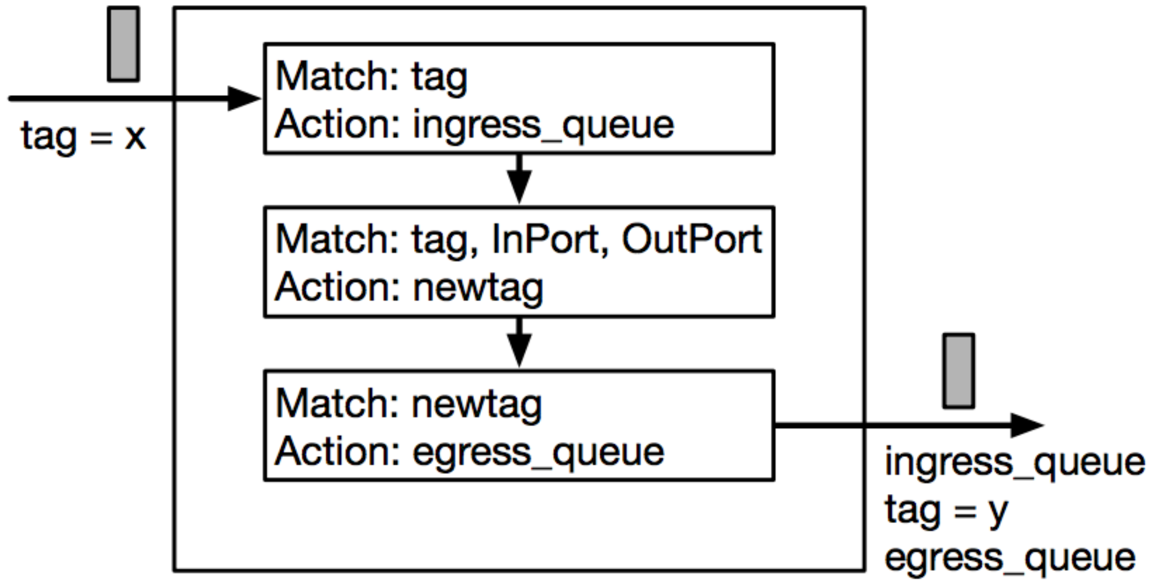
1. Initially, packets carry with tag = 1

2. pre-install match-action rules at switches:
   - DOWN-UP bounce: increase tag by 1
   - Enqueue packets with tag i to i-th lossless queue (i <= k+1)
   - Enqueue packets with tag i to lossy queue(i > k+1)

For Clos topology, Tagger is optimal in terms of # of lossless priorities.

How to Implement Tagger?

- DSCP field in the IP header as the tag carried in the packets
- build 3-step match-action pipeline with basic ACL rules available in commodity switches



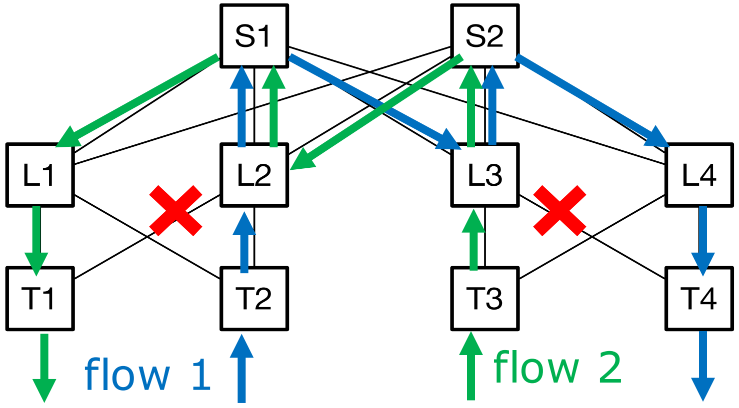
Tagger Meets All the Three Challenges

1. Work with existing routing protocols & hardware
2. Work with link failures & routing errors
3. Work with limited number of lossless queues

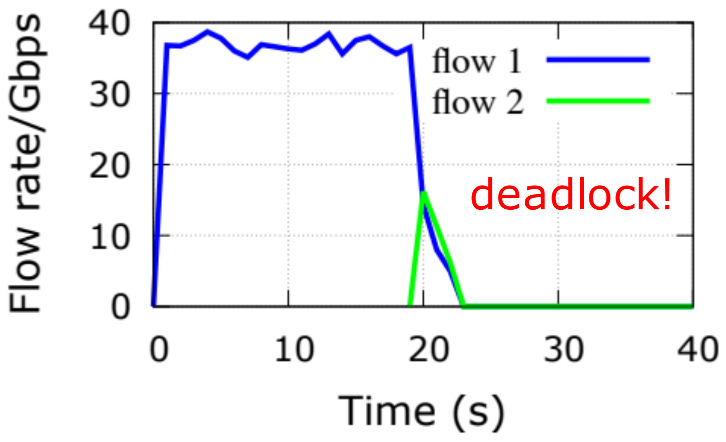
More Details in the Paper

- Proof of Deadlock freedom
- Analysis & Discussions
  - Algorithm complexity
  - Optimality
  - Compression of match-action rules
  - …

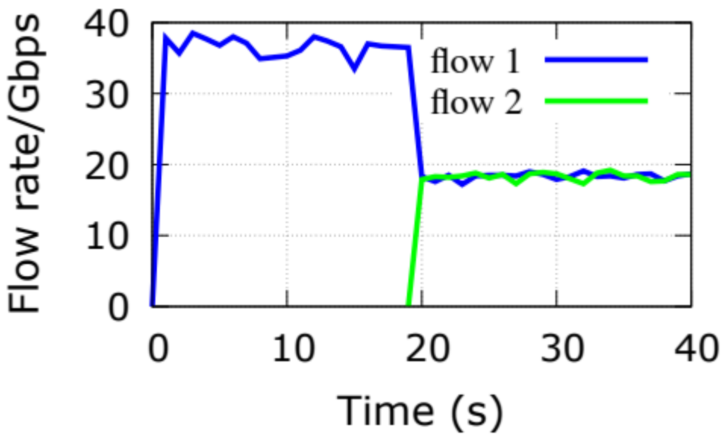
Evaluation-1: Tagger prevents Deadlock



Scenario: two flows forms CBD



(a) Without Tagger



(b) With Tagger

Tagger avoids CBD caused by bounced flows, and prevents deadlock!

Evaluation-2: Scalability of Tagger

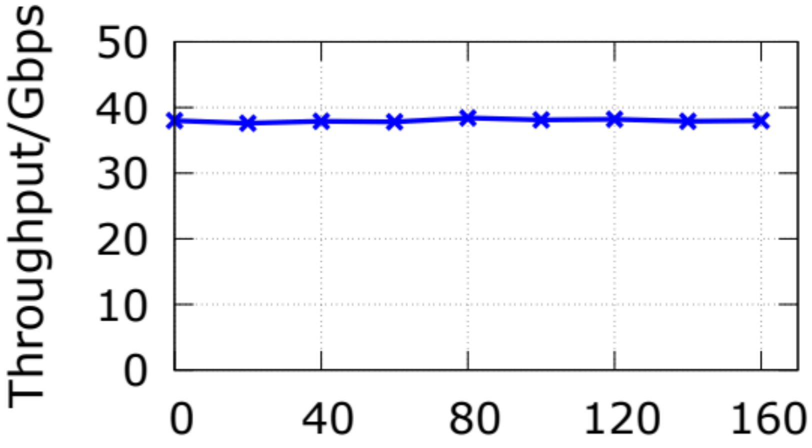
Switches	Ports	Longest ELP	Lossless Priorities	Max Rules
100	32	5	2	40
500	64	6	3	76
1,000	64	6	3	88
2,000	64	7	3	98
2,000 (*)	64	7	4	135

* last entry includes additional 20,000 random paths.

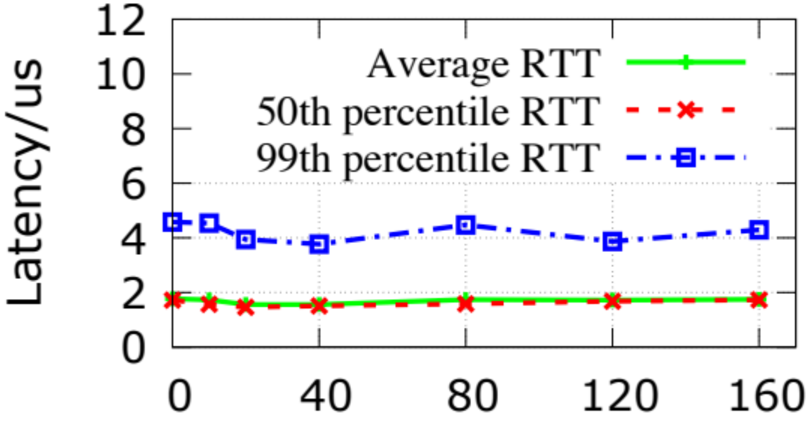
Match-action rules and priorities required for Jellyfish topology

Tagger is scalable in terms of number of lossless priorities and ACL rules.

Evaluation-3: Overhead of Tagger



(a) Throughput



(b) Latency

Tagger rules have no impact on throughput and latency

Conclusion

- Tagger: a tagging system guarantees deadlock-freedom
  - **Practical**:
    - ➢require no change to existing routing protocols
    - ➢implementable with existing commodity switching ASICs
    - ➢work with limited number of lossless priorities
  - **General**:
    - ➢work with any topologies
    - ➢work with any ELPs

Thanks!