deTector: a Topology-Aware Monitoring System for Data Center Networks

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Data Center Network Monitoring

- Failures are the norm rather than exception
  - Typical first year for a new cluster (Jeff Dean, Google)
    - 8 network maintenances
    - 15 router reloads/failures
    - 26 rack failures/moves
    - Dozens of blips of DNS
    - 1000 individual machine failures
- SLA violation (99.999%)
  - Packet losses and latency spikes
  - Difficult to troubleshoot (up to days to fix the issues)

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A network monitoring system for rapid failure recovery

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  - Packet losses and latency spikes
  - Difficult to troubleshoot (up to days to fix the issues)

Challenges

- Clean failures
  - Easy to detect, e.g., server down.
- Gray failures
  - Not reported by the device (SNMP/CLI)
- Low-rate losses
  - Covered up by ECMP
- Transient failures
  - Difficult to play back and pinpoint

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Exhaustive detection

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  - Difficult to play back and pinpoint

Existing Solutions

- Existing systems
  - Passive: CLI/SNMP
  - Active: Pingmesh, NetNORAD

- Limitations
  - Fail to detect at least one type of losses
  - High overhead
  - Can not pinpoint failures without other tools (e.g., tracert)

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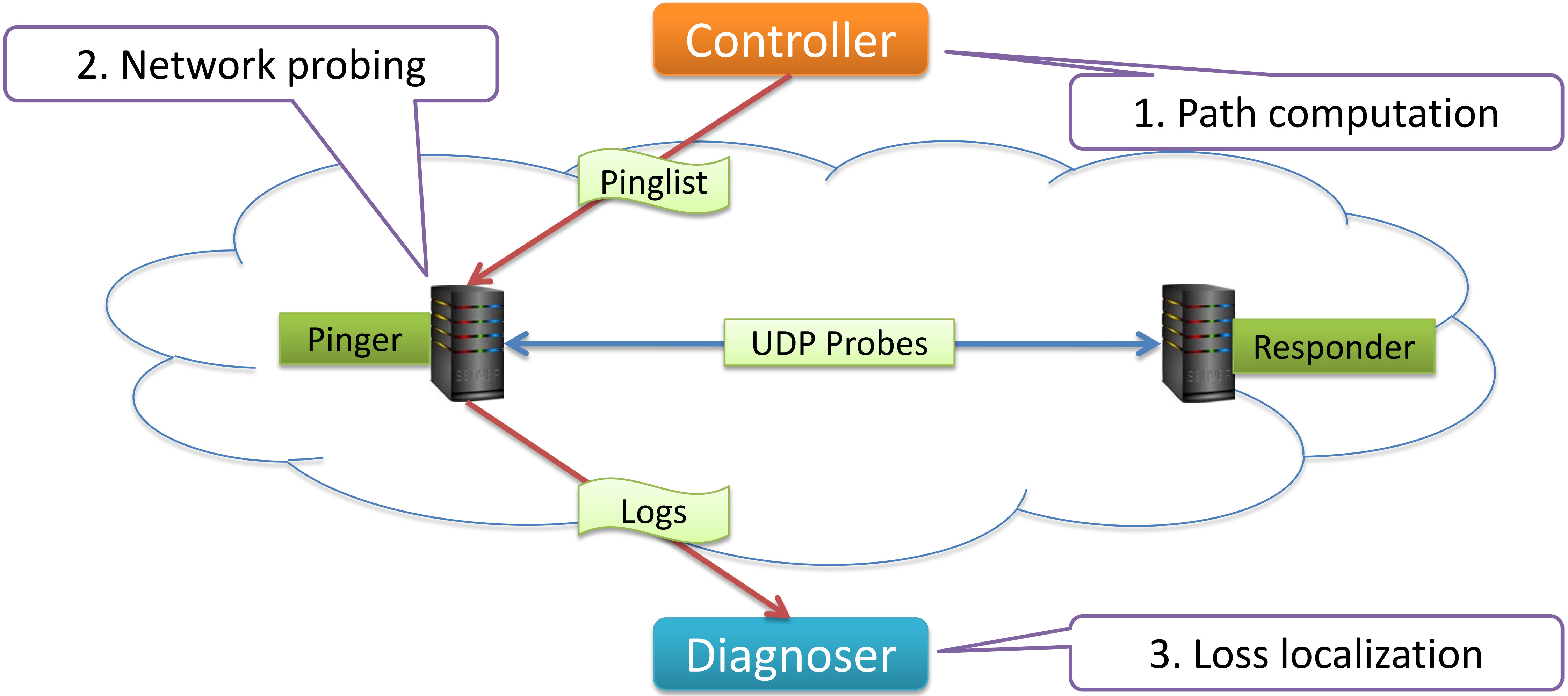
Can we design a better network monitoring system by exploiting network topology?

deTector in One Slide



Phase I: Path Computation

Path Selection Problem

	Link 1	Link 2	Link 3
Path 1	1	1	0
Path 2	1	0	1
Path 3	0	0	1

- Given a routing matrix, select probing paths to send probes:
  - path number minimizing
  - α-coverage
  - β-identifiability

α-coverage

Each link is covered by at least α paths

	Link 1	Link 2	Link 3
Path 1	1	1	0
Path 2	1	0	1
Path 3	0	0	1

- Ensure even and enough path coverage of each link
- w[link]: track the number of paths through it.
- If w[link] > α, then the link has enough paths through it.

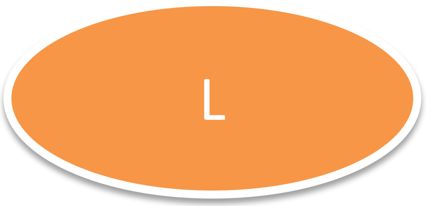
β-identifiability

	1,2	1	2
	Link 1	Link 2	Link 3
Path 1	1	1	0
Path 2	1	0	1
Path 3	0	0	1

- Any β failed links can be identified correctly
- Probe matrix: path1 + path2

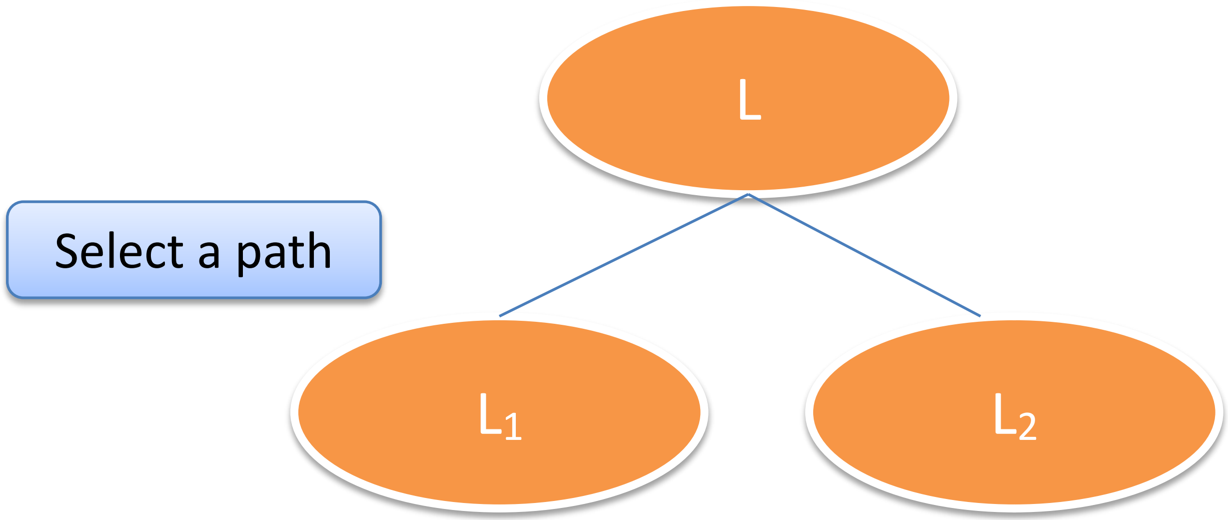
  1-identifiability but not 2-identifiability

Algorithm for 1-identifiability



- Select the minimum number of paths so that each link has a different set of probe paths.
- Greedily select the path which splits the largest number of link sets in each iteration.

Algorithm for 1-identifiability



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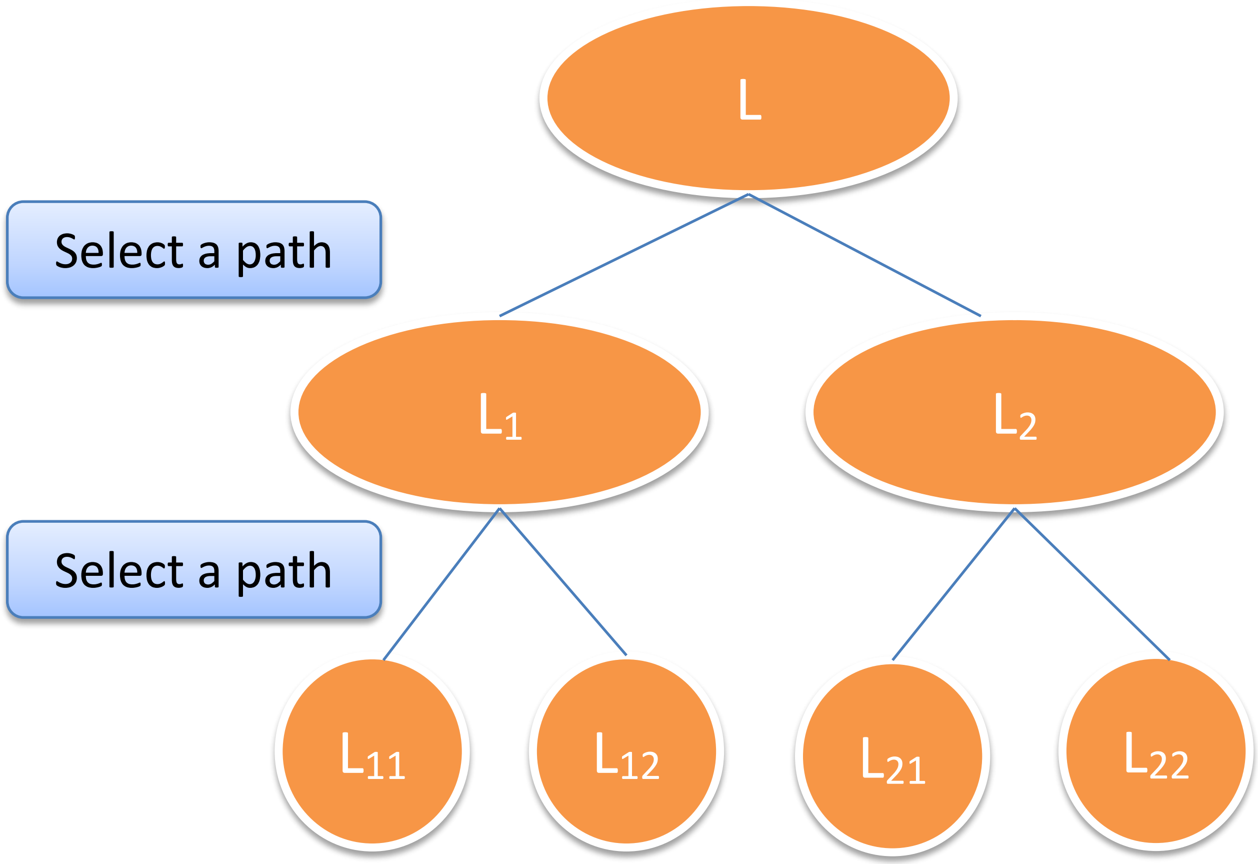

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1-identifiability => β-identifiability

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Physical links

- Extend routing matrix with virtual links.
- If a virtual link is down, we say its corresponding physical links have failed.

1-identifiability => β-identifiability

	Link 1	Link 2	Link 3	Link 12	Link 13	Link 23
Path 1	1	1	0	1	1	1
Path 2	1	0	1	1	1	1
Path 3	0	0	1	0	1	1

Physical links OR Virtual links

- Extend routing matrix with virtual links.
- If a virtual link is down, we say its corresponding physical links have failed.

Probe Matrix Construction (PMC) Algorithm

- Extend the routing matrix with virtual links
- Define a score for each path

$$score(path) = \sum_{link \in path} w[link] - \#\text{ of link sets on } path$$

Quantify coverage

Quantify identifiability

- Select a path with minimal score in each iteration
- Stop when achieving α-coverage and β-identifiability

PMC Algorithm

- Achieve 63% approximation ratio.
- Time complexity $O(n^2)$ where n is the number of paths.
- A Fattree(64) DCN has more than 2^{32} paths, running time > 24 hours

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Optimizations for speedup

Optimization I: Routing Matrix Decomposition

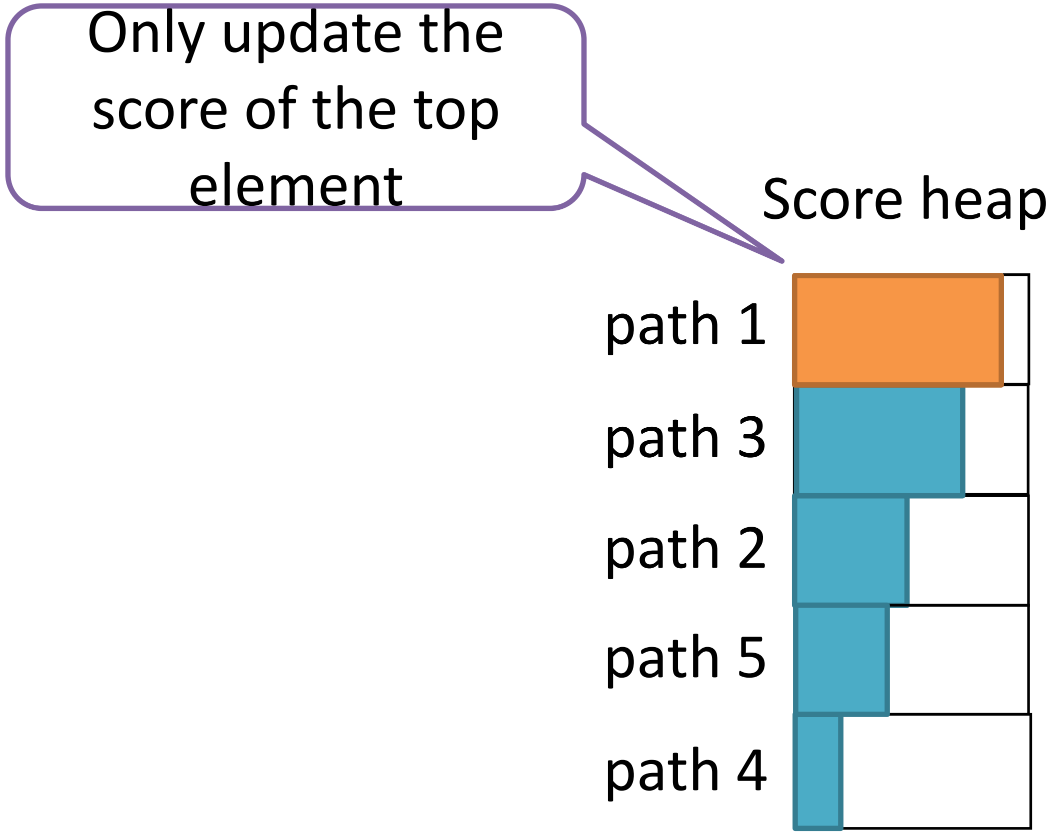
1	1	0	0	0
1	0	1	0	0
0	1	1	0	0
0	0	0	1	0
0	0	0	1	1

Share no links and paths

1	1	0
1	0	1
0	1	1

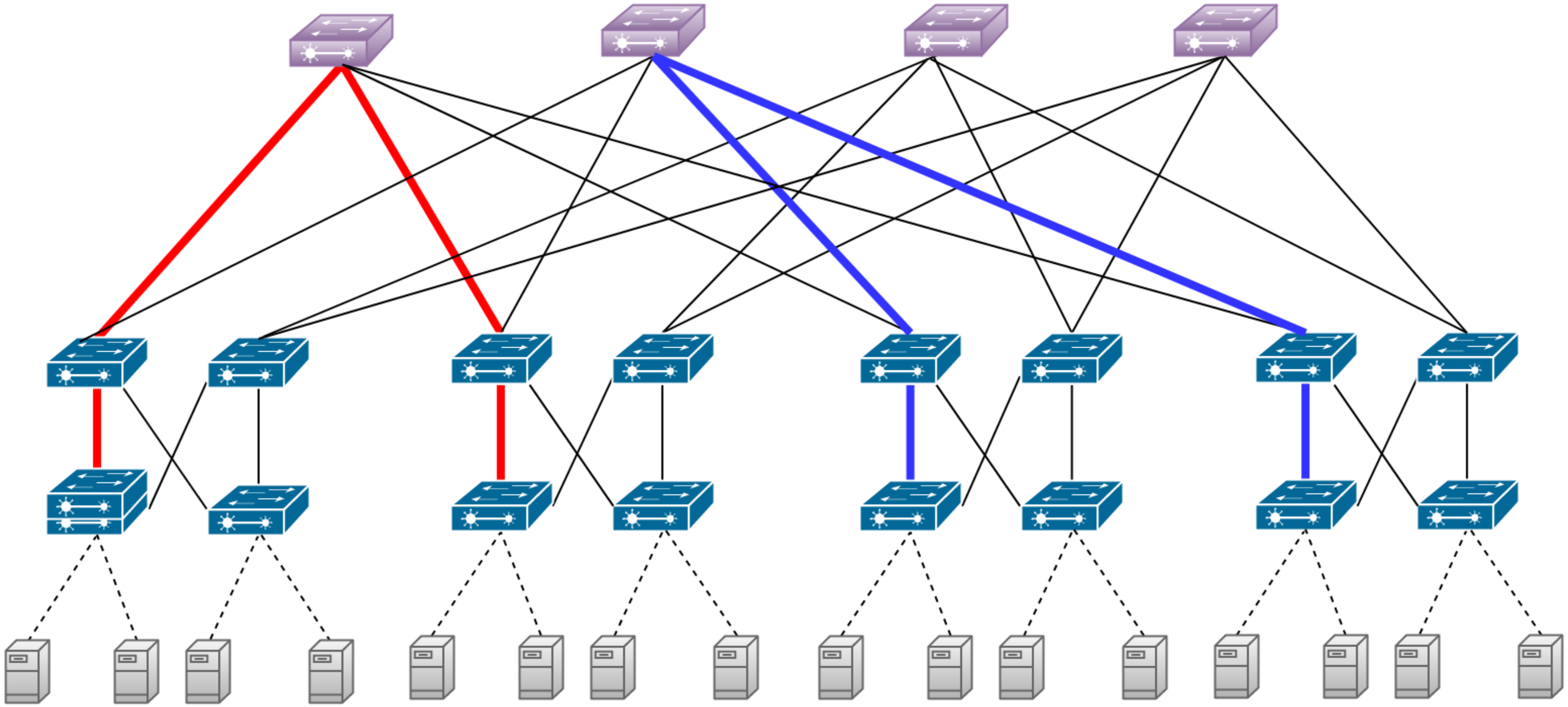
1	0
1	1

Optimization II: Lazy Update



- Defer the score update of a path as much as possible until we have to.
- Correctness guaranteed by the submodularity of the objective function.

Optimization III: Symmetry Reduction



Most DCN topologies are symmetric!

PMC Algorithm Results of Fattree

- Running time on one Xeon E5-2620 CPU

From days to seconds

DCNs	# of nodes	# of links	# of original paths	Strawman	Decomposition	Lazy update	Symmetry reduction
Fattree(12)	612	1296	184,032	231.458	5.216	0.506	0.126
Fattree(24)	4,176	10,368	11,902,464	> 24h	1381.226	23.254	0.280
Fattree(72)	99,792	279,936	8,703,770,112	> 24h	> 24h	> 24h	17.054

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- The number of probe paths

The optimal needs at least 52428 paths

DCNs	# of original paths	# of selected paths w (α, β)		
		(1, 0)	(1, 1)	(3, 2)
Fattree(32)	66,977,792	4,096	7,680	12,288
Fattree(64)	4,292,870,144	32768	61,440	98,304

Phase II: Network Probing

Network Probing

- UDP probes: varying packet length, DSCP, source port
- Source routing: IP-in-IP encapsulation and decapsulation
- Responders: simply echo probes back

Phase III: Loss Localization

Loss Localization Problem

	Link 1	Link 2	Link 3	Loss measurements
Path 1	1	1	0	4
Path 2	1	0	1	1
Path 3	0	0	1	3

- Given the probe matrix and loss measurements, select the least number of links to explain the observation.
- NP-hard

Packet Loss Localization (PLL) Algorithm

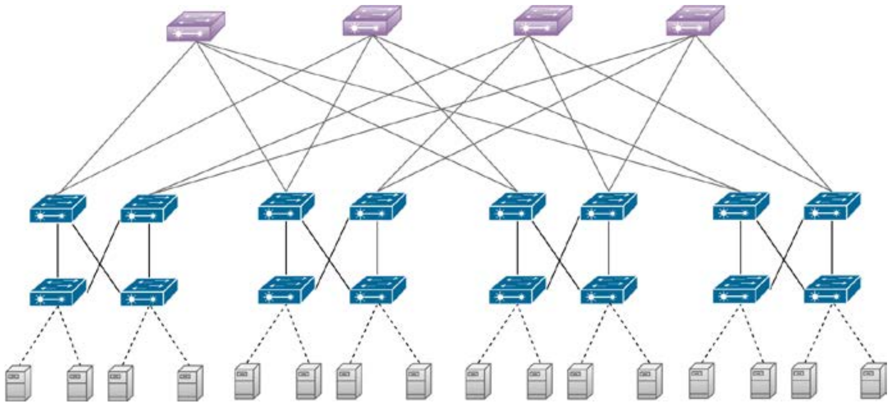
- In each iteration we select a link that can explain the largest number of probe losses until all are explained
  – If a link lies in the packet path, then the link can explain the loss.

- Two simple improvements
  – Matrix decomposition to speedup computation
  – Use threshold to filter false positives
    - The ratio of # of lossy paths over # of all probe paths through the link

Experiment

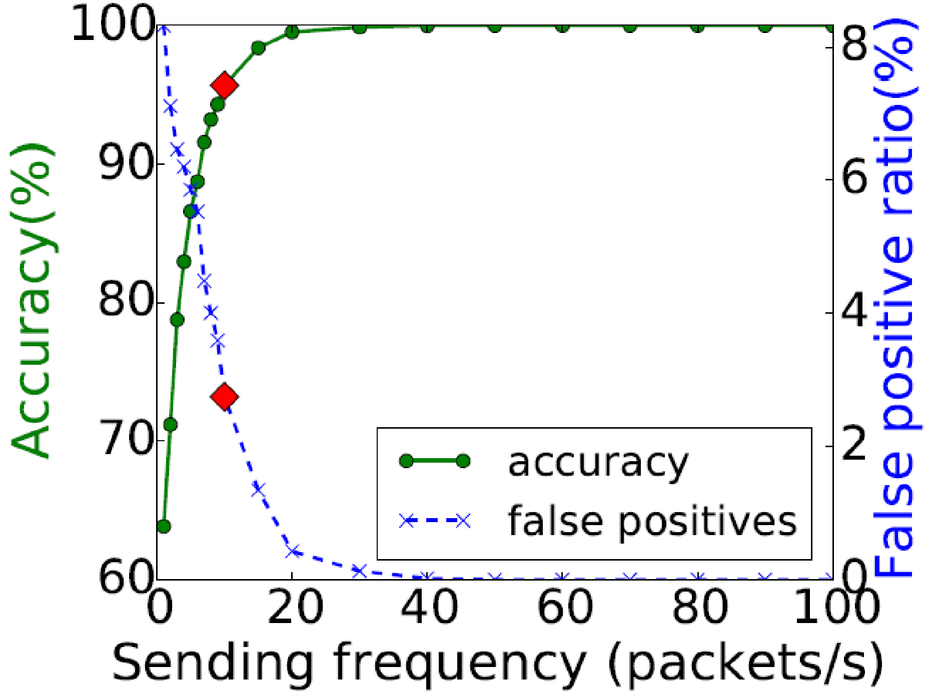
- A 4-ary Fattree testbed with 20 SDN switches
- Install OpenFlow rules to emulate losses caused by various failures
  - Full packet loss: link down etc.
  - Deterministic partial loss: packet blackhole etc.
  - Random partial loss: bit flips etc.
- Performance metric
  - Accuracy
  - False positive ratio

ONetSwitch

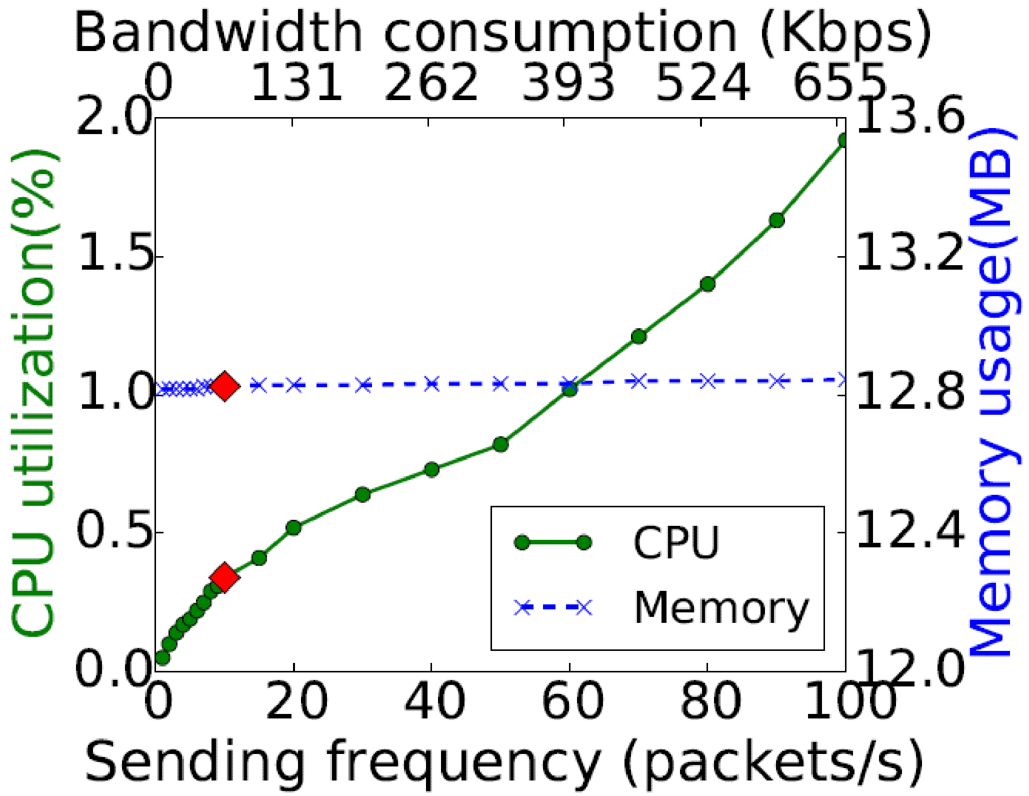


Experiment

- Sensitivity test of sending frequency



Accuracy and false positives



Overhead of pingers

Experiment

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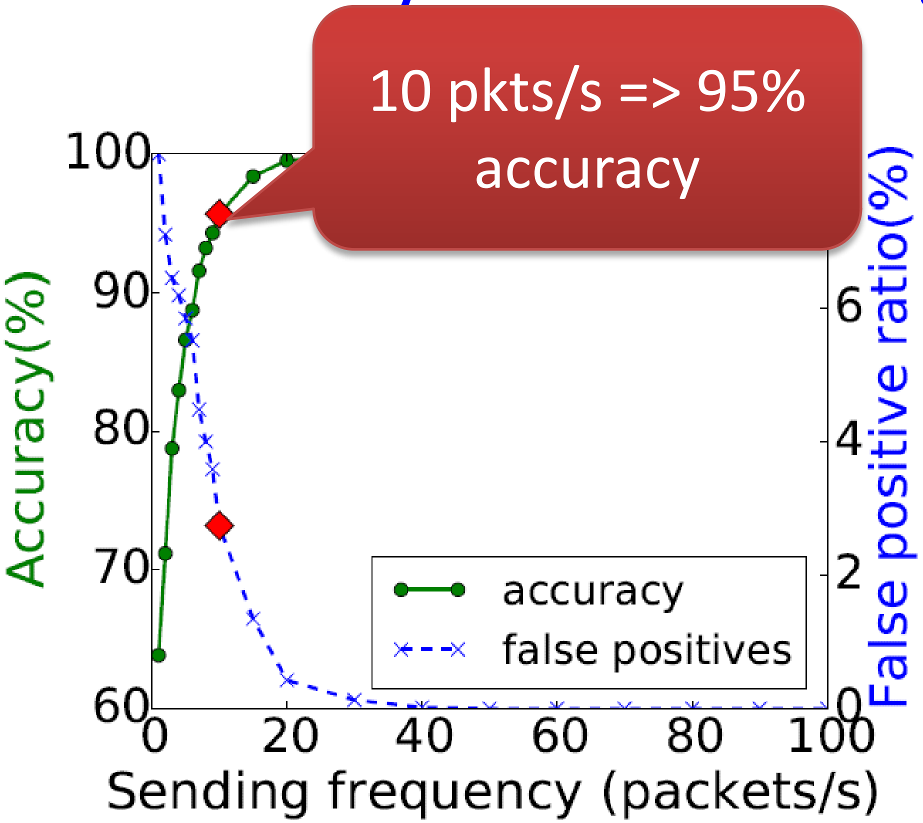

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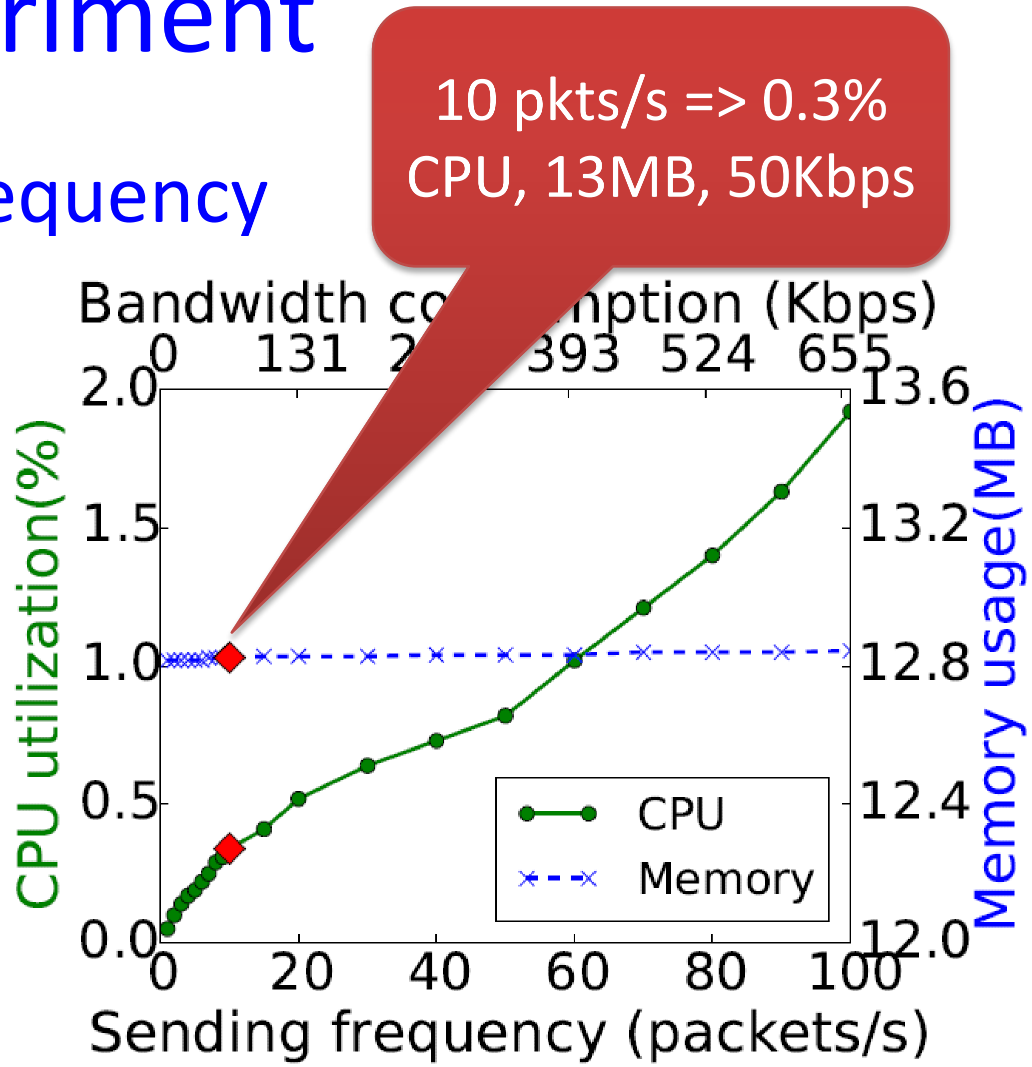
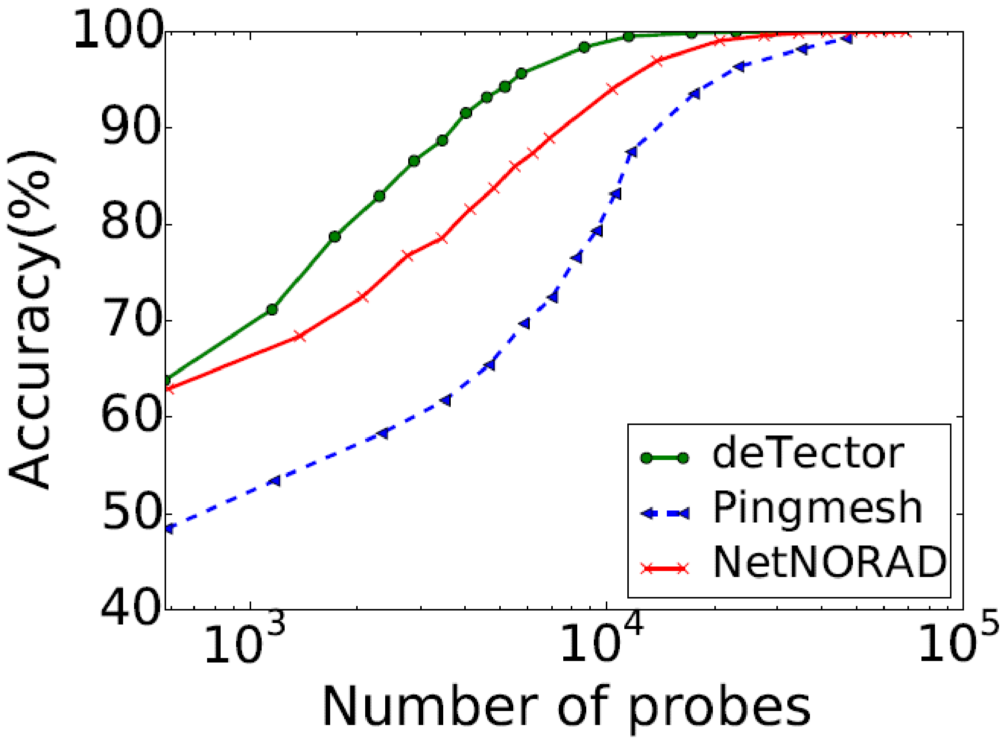
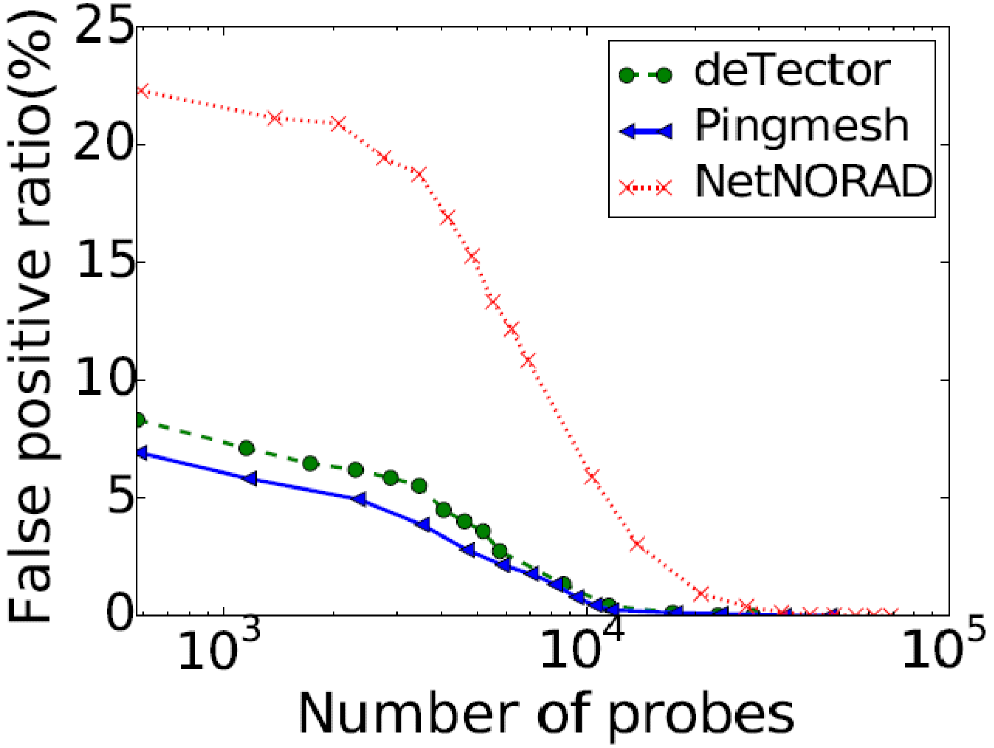


Overhead of pingers

Experiment

- Accuracy and false positives of three monitoring systems





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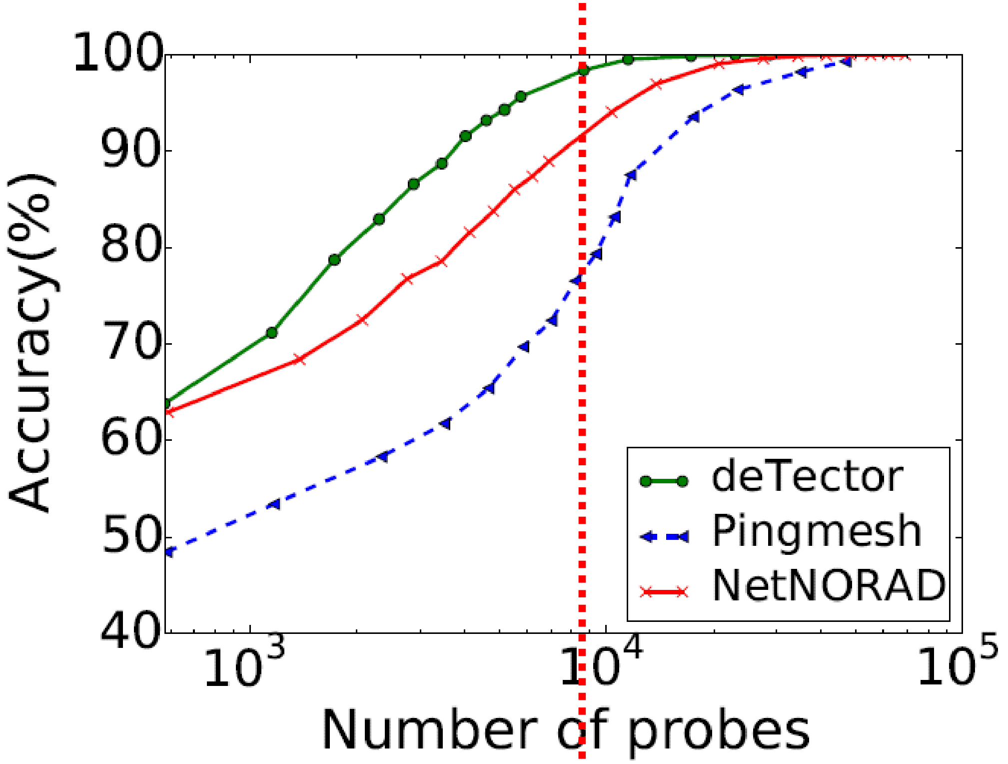

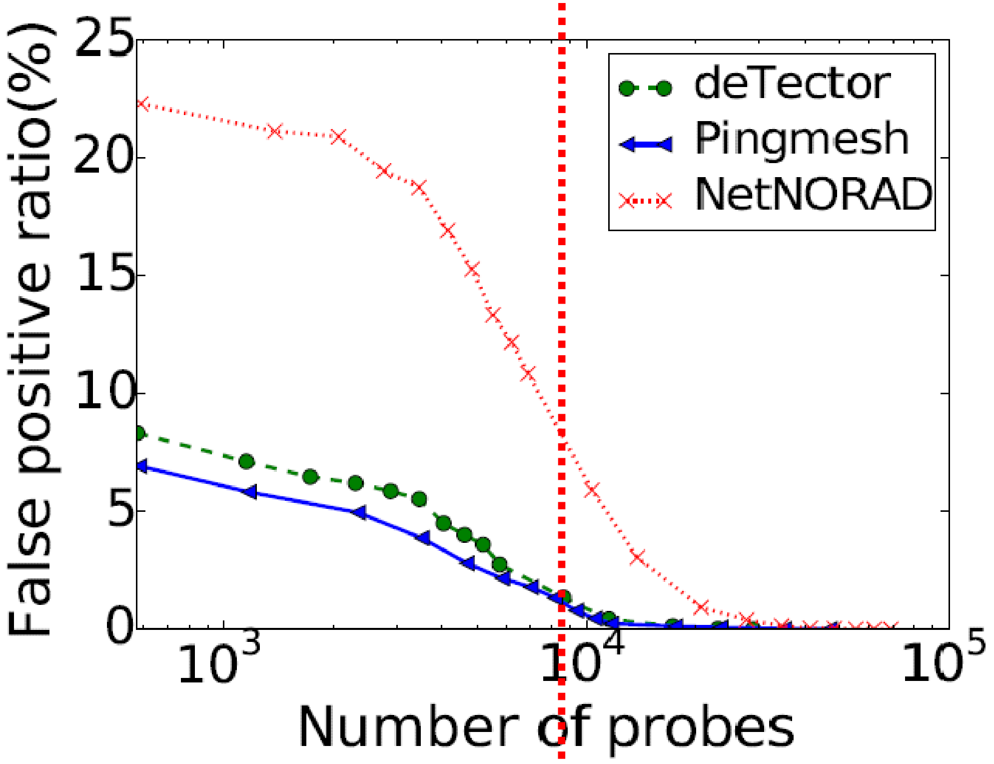

Same # of probes, 98%, 89%, 78% accuracy respectively

Same # of probes, 1%, 8%, 1% false positives respectively

Simulation

- Accuracy in a 18-radix Fattree, with probe matrices of different levels of α-coverage and β-identifiability

(α, β)	# of paths	Accuracy (%) with # of failed links				
		1	5	10	20	50
$(1, 0)$	729	30.56	30.87	30.30	30.26	29.19
$(2, 0)$	1485	58.43	57.43	57.08	56.81	57.11
$(3, 0)$	2187	68.22	70.61	69.89	70.40	70.14
$(1, 1)$	1269	94.74	93.37	94.21	93.43	90.29
$(1, 2)$	1512	99.26	99.06	99.02	98.77	95.92
$(1, 3)$	2349	99.63	99.63	99.67	99.62	98.07

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Identifiability is more effective than coverage for failure localization.

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2-identifiability is enough.

Summary

- The core of deTector is a carefully designed probe matrix, enabling fast and accurate loss detection and localization.
- deTector is practically deployable.
- Discussions
  - Packet entropy: limited destination IP addresses
  - Loss diagnosis: do not know why packets are dropped
  - Beyond deTector: apply probe matrix to optimize in-band techniques

Thanks