A Robust System for Accurate Real-time Summaries of Internet Traffic

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Big Picture

- Operators and researchers want to understand the traffic on Internet links.

- Generic measurement system goals:
  - Produce answers which match user questions
  - Be accurate in measurements
  - Scale to high network speeds (OC-768, 10GigE, …)
  - Be robust for all traffic mixes (DDoS, worm, flash crowd, …)

Typical Operational Measurement Questions

- What is the application breakdown in packets & bytes?
- How much traffic came from or went to a particular subnet?
- What are the best ISPs to peer with to decrease my costs based on the actual traffic of my customers?
- Where is the best place to deploy a new web cache?
- Which of my web servers has the most unique clients?
- Which of my hosts seem to be spam servers?

Flow Measurement

- How do we answer these questions?
- Current operational traffic measurement:
  - Typically collected on routers
  - Packet sampling employed on high-speed links
  - Flow-based
    - For each tuple of: protocol, source & destination IP addresses and ports
    - Count: # packets, # bytes
- Generally, people aggregate flows to make summaries keyed by specific fields (e.g. just source IP address)

Flow aggregation *(by source ip)*

Src. IP Addr.	Dest. IP Addr	Proto	Src. Port	Dest. Port	Packet Count	Byte Count	Flow Count
6.1.1.93	1.82.0.1	UDP	53	53	2	497	
6.1.0.14	4.44.0.1	TCP	80	2223	4	646	
6.3.0.27	1.95.0.1	TCP	1214	62772	125	187008	
6.1.1.93	4.71.0.6	TCP	49200	80	3	565	
6.1.0.28	1.82.0.1	TCP	49199	80	5	647	
6.1.1.93	1.95.0.1	TCP	49198	80	5	647	
6.1.1.93	4.71.0.6	TCP	49196	80	6	708	
6.1.2.59	7.88.0.1	TCP	51643	80	6	817	

6.1.1.93					16	2417	**4**

Large-Scale Malicious Traffic

- Denial-of-service attacks, worm spread and port scanning can overwhelm flow measurement systems

- Fields in the flow key take on a much larger range than in normal traffic:
  - Spoofed source DoS = random source IP address
  - Typical Internet worm = random destination IP address
  - Port scanning = walk of large # of ports and addresses

- In these situations every single packet may result in a separate flow

Outline

- Background
- **Traffic Summaries**
- System Overview and Algorithms:
  - Count flows
  - Identify important entries
  - Adapt sampling rates
- Conclusions

Traffic Summaries

- Most users have a well-defined set of reports and aggregations they normally want.
- Can we do better than Adaptive NetFlow with the Flow Counting Extension (or similar flow-based reporting) when the user specifies the desired aggregations in advance?

- Yes!
  - Smaller, more specific reports.
  - More precise estimates, including tight lower-bounds.
  - Isolation of damage from DoS, worms and scanning.

Traffic Summaries

- Provided reports are of "hogs" (or "heavy-hitters")
  - All aggregates contributing significant numbers of packets, bytes or flows are reported

- Operator configures desired aggregations
- For example:
  - Source IP addresses – top sources by pkts, bytes or flows
  - Protocol/Ports – for determining top applications

Traffic Summaries – "Hog" Reports

Key type:

- source IP address
- destination IP address
- src. Port and Protocol
- dst. Port and Protocol
- AS matrix
- dst. network prefix
- …

X

Counter type:

- Packet hogs
- Byte hogs
- Flow hogs
- Out-degree hogs
- In-degree hogs
- …

Robustness & Isolation

- Robustness – system should degrade gracefully in the face of unexpected load, continuing to provide accurate answers with bounded error.

- Isolation – results of each separate summary should be similar to what it would be if that summary was the only one being computed.
  - i.e. traffic mixes which cause one table to rapidly fill should not interfere with the accuracy of the other tables

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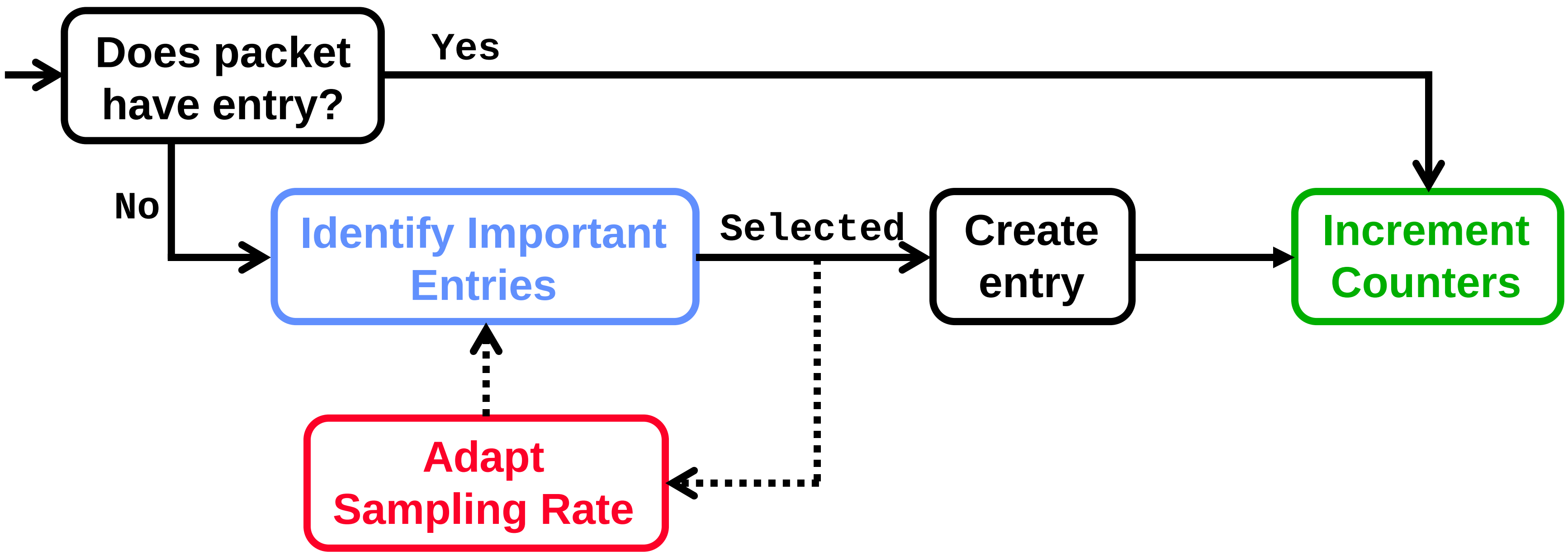
Why is this hard?

- The most straightforward way of generating a hog report would be to keep a table indexed by the each key in the traffic with a simple counter for the measured value.
  - Tables can easily get very large, holding entries which will never be part of the final hog report.
  - Counting flows (or in-/out- degree) can not be done with simple counters alone, since more state is required to track the unique members of a set.

System Overview



- Basic logical control flow is replicated for each desired summary table.
- The actual design shares computation and information to improve both system efficiency and the accuracy of counters.

Algorithms – Flow Counting

- Generic goal: given a stream of items, count the number of unique items.

- Our goal: given a stream of packets belonging to specific flows, count the number of unique flows.

- Caveat: we need to do this operation for *many* entries (100,000s) in parallel
  - e.g. for each different source IP address that will be reported, we must track how many flows had that address

Algorithms – Flow Counting

- Three general approaches:
  - Keep a table of all flows and aggregate by key-type when needed
    - Exact answers, but infeasible for most real-time applications
    - Generally used in existing deployments
  - Individual flow counting data structure per key-type table entry
  - Global data structure and simple counter per key-type table entry

Per Entry Flow Counting Algorithms

- Multiresolution bitmaps (MRB)
  - Memory requirements are logarithmic in maximum number of flows
  - A couple kilobytes is sufficient to give 3% average error for hundreds of millions of flows

- Triggered bitmaps (TRB)
  - Most entries will have a small number of flows
    - Start with a small direct bitmap.
    - When it fills, dynamically switch to a MRB.
  - Saves memory in the typical case but the accuracy is less than using MRB from the beginning

Per Entry Flow Counting Algorithms

- List-triggered bitmaps (LTRB)
  - Again, most entries will have a small number of flows
    - For each entry, maintain a small list (2 – 4) of the actual flow ids seen
    - When the list fills, switch to MRB. Populate the MRB with the exact set of seen flow ids.

  - Accuracy is the same as MRB, while achieving space savings similar to TRB.

Global Flow Counting Algorithms

- Tuple set membership:
  - Maintain a set of all flows previously counted.
  - On all packets, check its flow in the set:
    - If present, the flow has already been counted
    - If not present, the flow is new, update the counts for all table entries involving this packet
  - Provides exact counts, but memory usage explodes

- Bloom filter tuple set:
  - Use a bloom filter to approximate set membership with fixed false-positive rates
  - Significantly smaller memory requirements

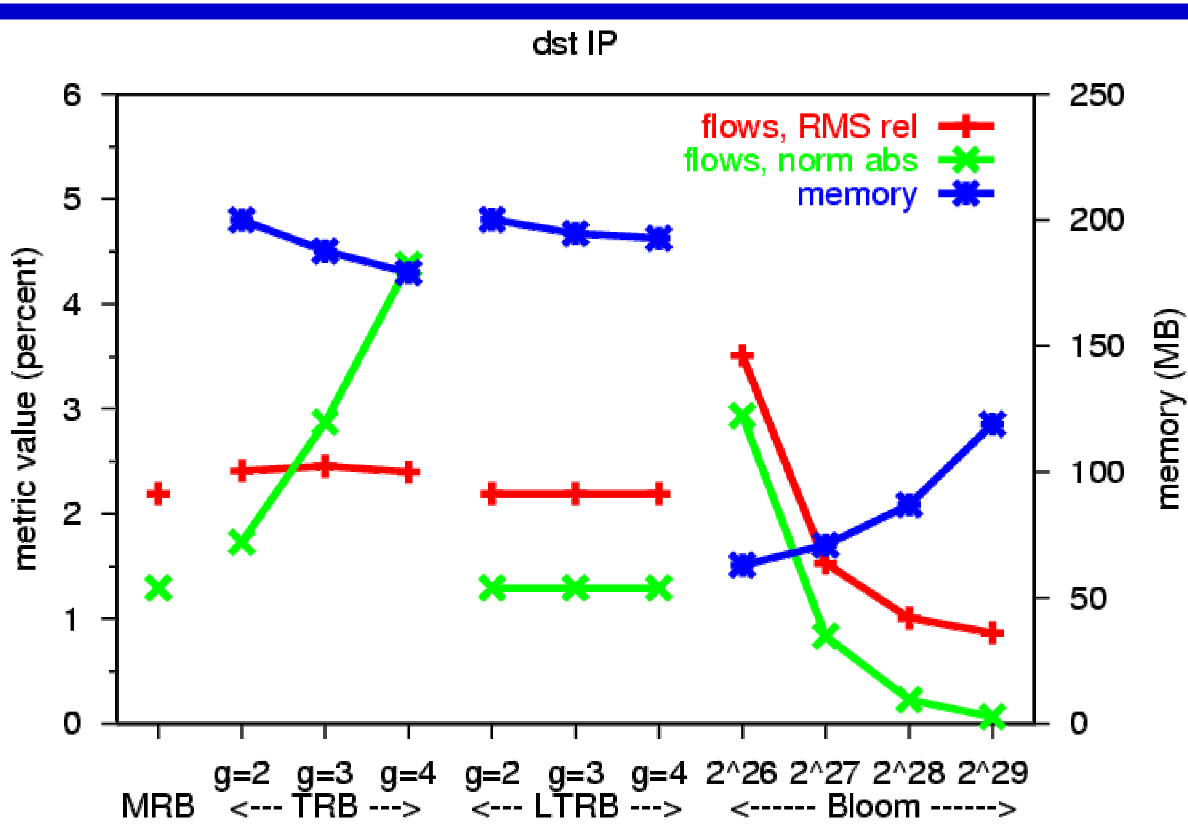
Global Flow Counting Algorithms

- Bloom filter:
  - False-positives can lead to under-estimation of flow counts
    - Every reported count is a lower-bound
  - Some false-positives can be detected by combining information from multiple summary tables
    - e.g., if the bloom filter says that we have already seen the flow associated with a packet, but there is no entry in the destination IP address table when there should be, then we know this is a new flow

Experimental Setup
(For all data in this presentation)

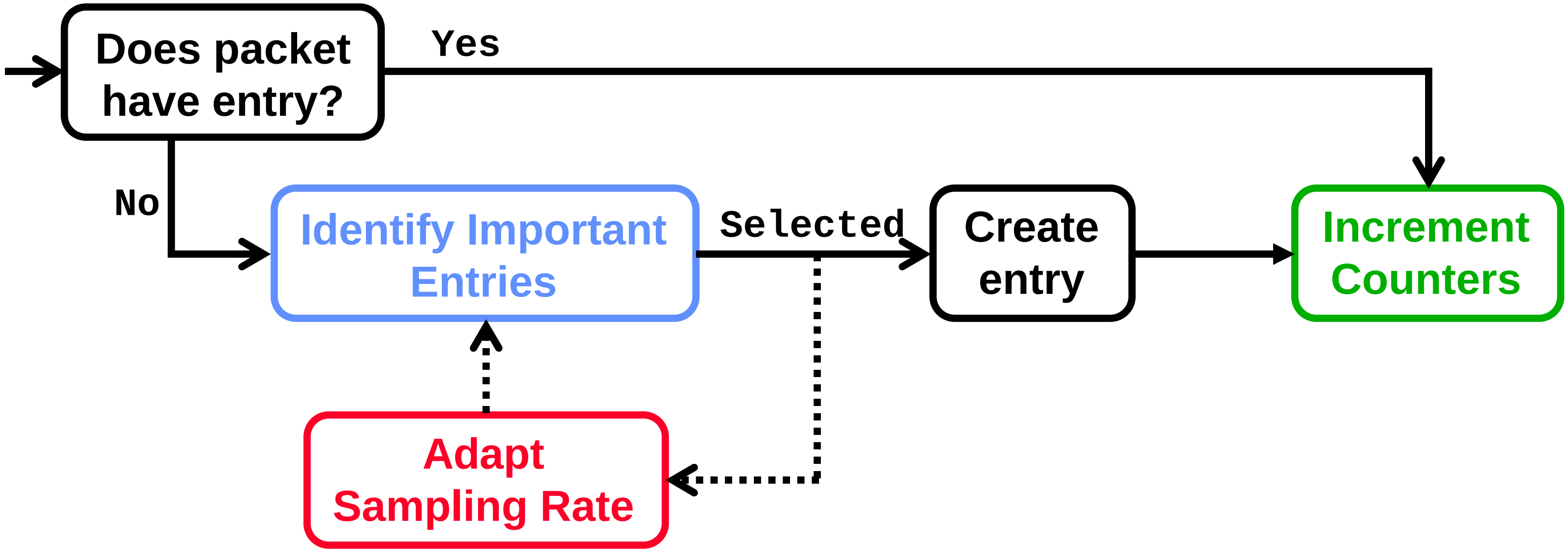
- Packet traces allow testing with different algorithms and seeds
- OC-48 trace (5 minute portion):
  - 22.5M packets (75 kpps), 12.8GB (342 Mbps), 1.21M flows
- Simulated DDoS:
  - Fixed destination IP address and port, 44 byte TCP SYN packets
  - Random source IP addresses and source ports
  - 10M packets (33 kpps), 400MB (12 Mbps), 10M flows
- Additional datasets used in paper
- Same software runs in real-time on monitor boxes

Picking a Counting Algorithm



- MRB (multiresolution bitmap) memory usage is 1062 MB.
- TRB (triggered bitmap), LTRB (list-triggered bitmap), Bloom (bloom filter)

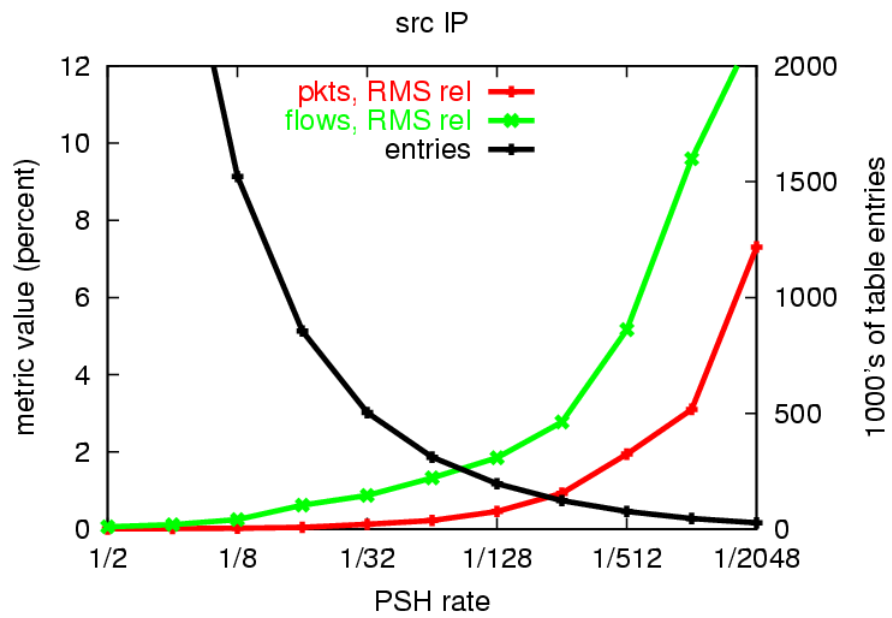
System Overview

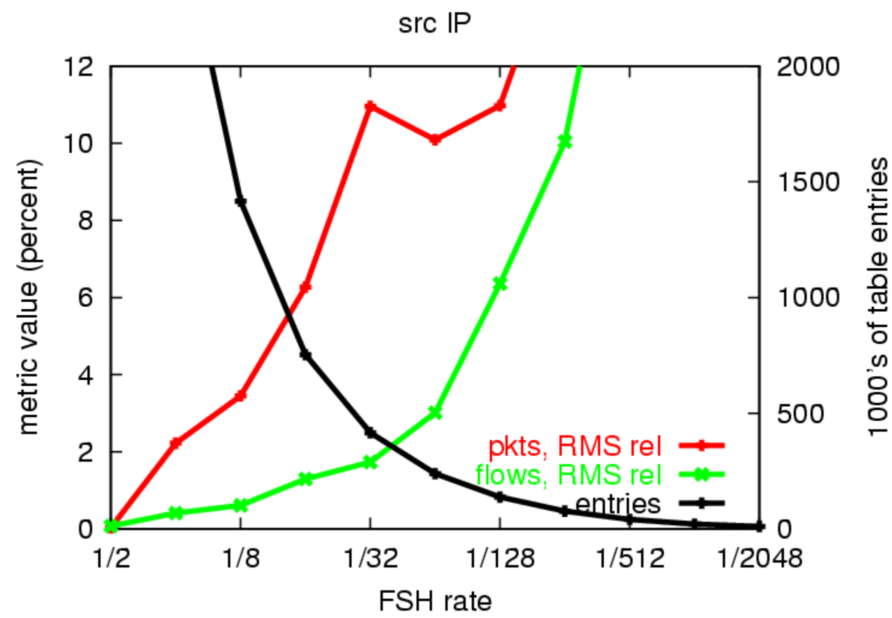


Algorithms – Identifying Important Entries

- Packet sample and hold (PSH) ensures there are table entries for anything with a large number of packets
  - For each packet, if there is already an entry in the table, increment the packet count
  - If there is not an entry, probabilistically sample this packet and create an entry in the table when sampled
- Flow sample and hold (FSH) ensures there are table entries for anything which will have a large number of flows
  - For each packet, if there is already an entry in the table, update the associated flow count using previous techniques
  - If there is not an entry, sample this *flow* by checking if Hash(flowID) < f (sampling fraction) and create an entry in the table

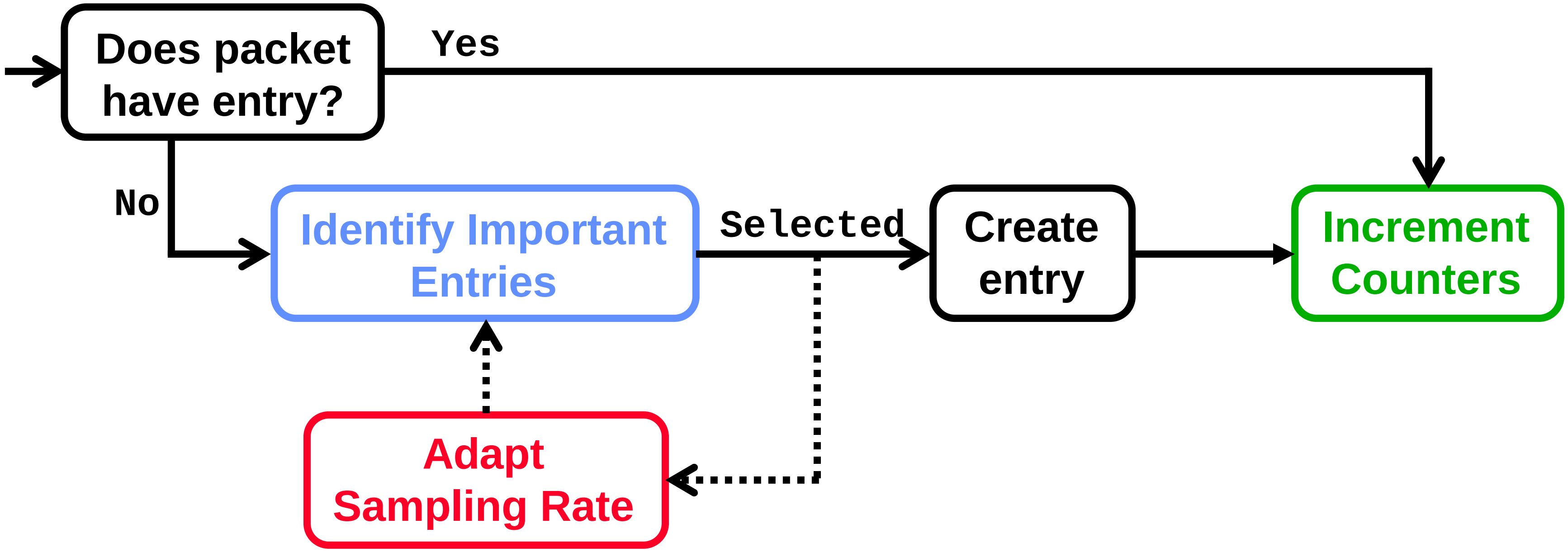
Why both PSH & FSH (& DSH…)?





- Full tuple set table, so all error due to sampling
- PSH can use lower sampling rates and keep packet count errors low
- FSH can use lower sampling rates and keep flow count errors low
- Use both to keep total sampling low with low error

System Overview

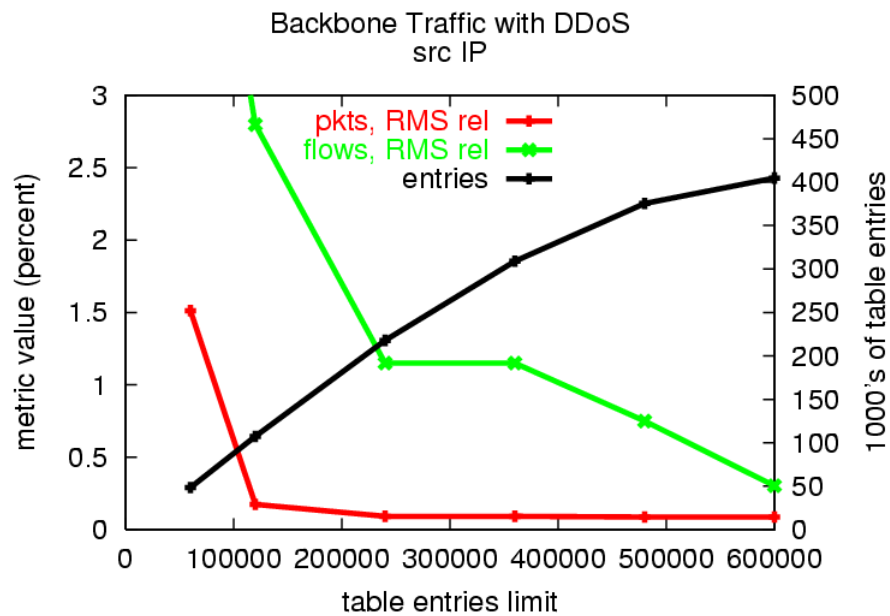


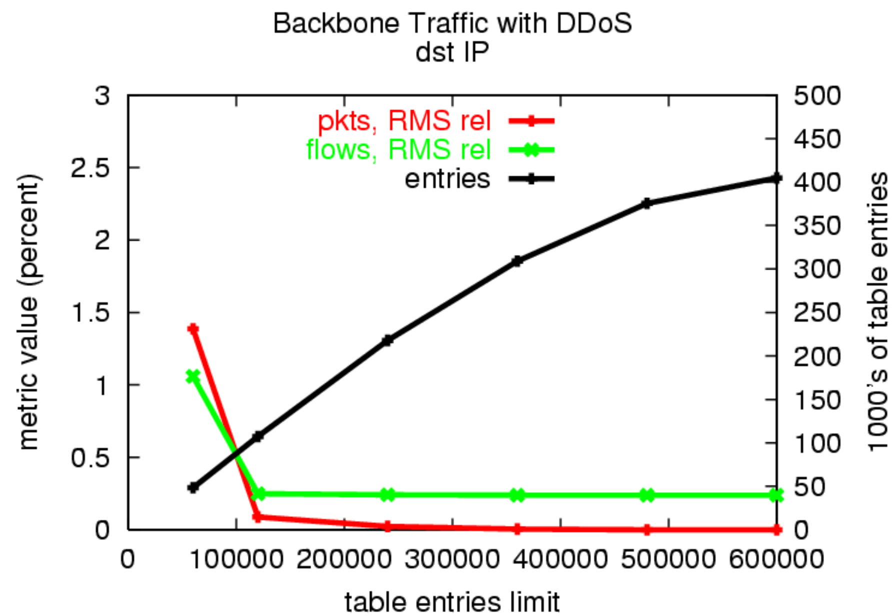
Algorithms – Adapting Sampling Rate

- Observe which tables and samplers (PSH, FSH) are contributing to memory consumption and dynamically adjust the sampling rates for each.

- Details in paper/technical report.

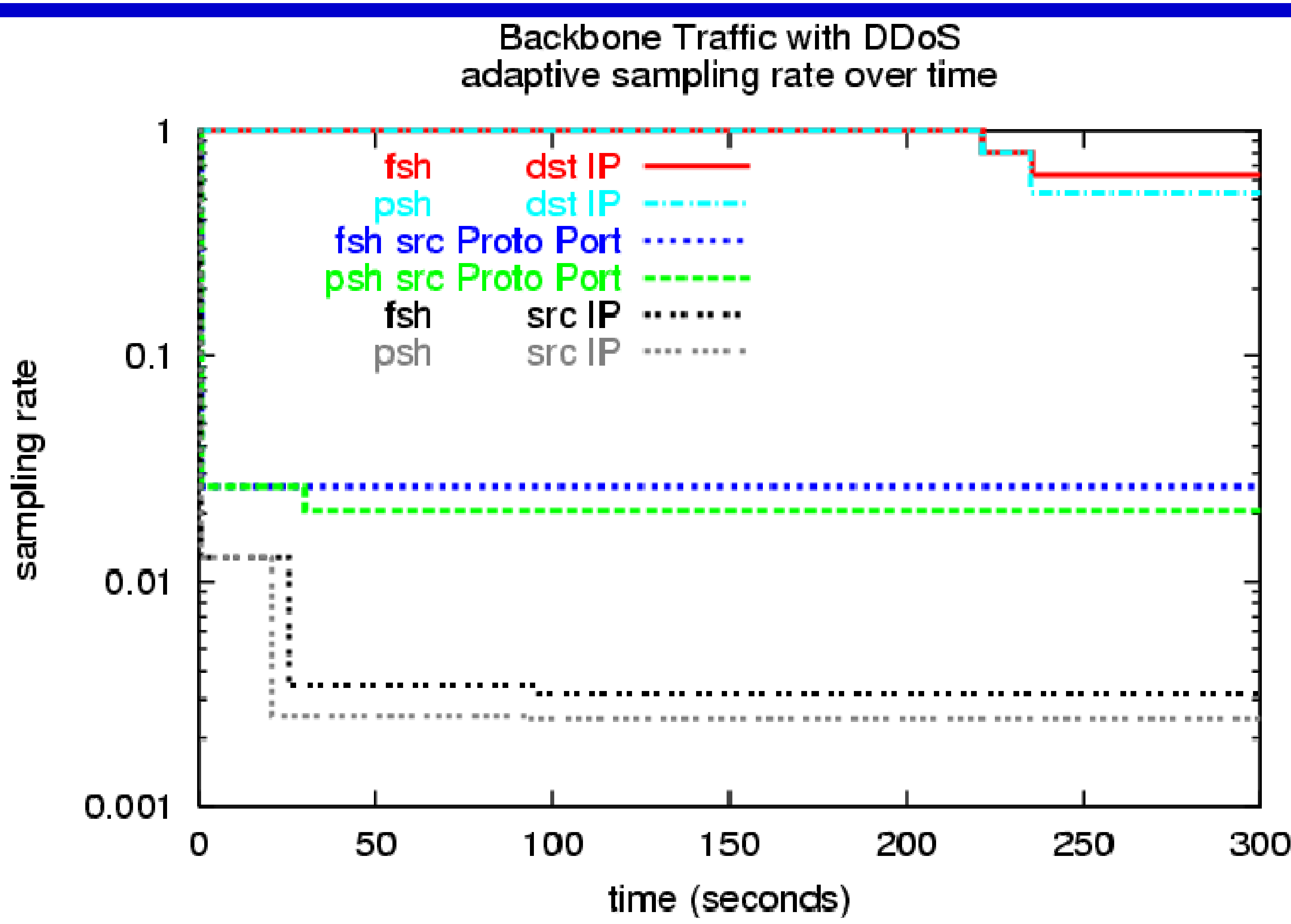
Adaptivity – Robustness/Isolation during DDoS Attack





- Recall DDoS attack is spoofing source addresses and not the destination addresses.
- We expect such an attack to over-fill the source IP address table, reducing accuracy.
- However we wish to ensure that other tables are not adversely affected.

Adaptivity – Robustness/Isolation during DDoS Attack



Conclusions

- Producing traffic summaries, rather than collecting all flows and forcing the user to aggregate:
  - significantly decreases memory usage and reporting bandwidth
  - significantly increases accuracy of results
- Novel algorithms:
  - Flow sample and hold (FSH) allows online streaming identification of “flow hogs”
  - Bloom filter tuple set counting and list-triggered bitmaps (LTRB) efficiently solve “flow counting” for 100,000s of counters
- Adaptive controls:
  - provide robustness against malicious/unexpected traffic
  - allow isolation between independent reports

Questions?

Extended Technical Report

- http://www.caida.org/outreach/papers/2005/tr-2005-01/

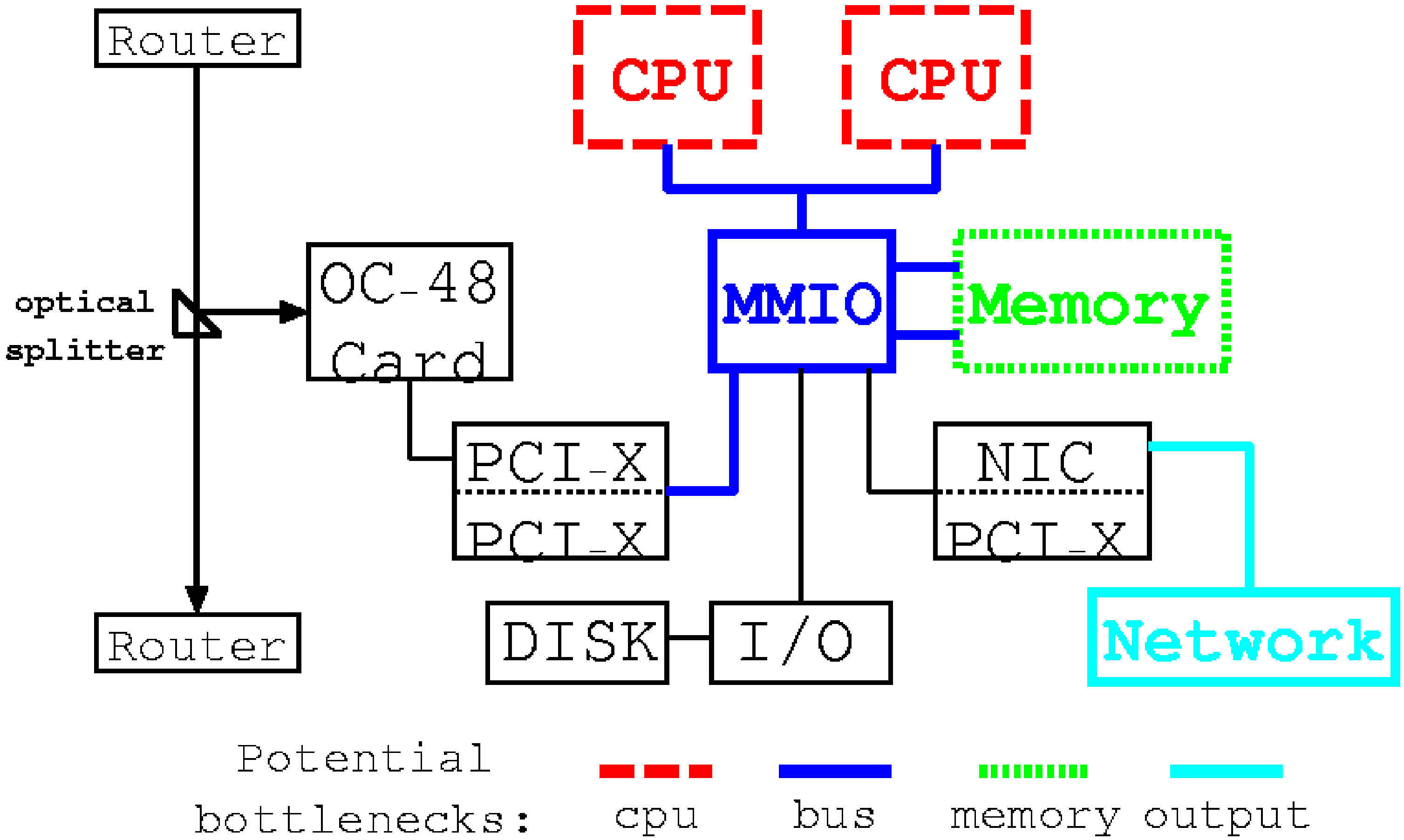
Traffic Summaries – Global Traffic Counters

- # of packets
- # of bytes
- # of active flows (5-tuples)
- # of active source IP addresses
- # of active destination IP addresses
- …

Traffic Summary Isolation

- We would prefer that the separate aggregation reports were independent and isolated:
  - Traffic which causes one table to rapidly fill should not interfere with the accuracy of the other tables
- To solve this, we:
  - Adjust the sampling rates independently for each report
  - Dynamically adapt memory consumption for each separate table to ensure high fidelity for all

Bottlenecks



Picking a Counting Algorithm