FleXam: Implementing Security Applications in OpenFlow Controller

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Anti-Outline

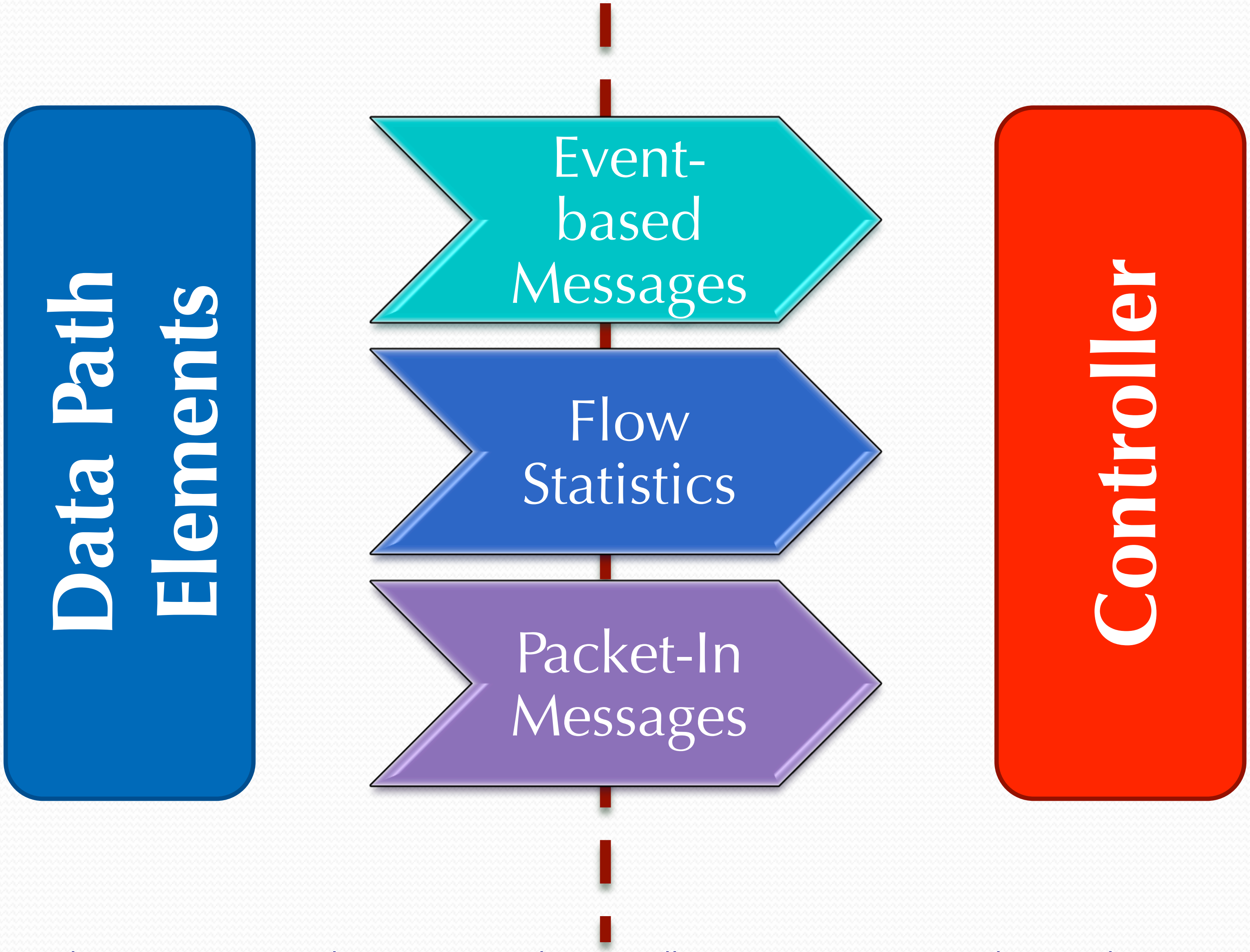
- First, what this paper is not about:
  - Unlike what the title might suggest, the focus of this work is not security!
- What is it about then?
  - Simple observation
  - Simple question
  - Simple extension to OpenFlow
  - Simple example as a case study

To Summarize:
The paper is not about *security*; and,
it is very *simple*! ☺

Observation

- It might be desirable to implement security (or similar) services as SDN controller applications
  - Works for some (e.g. small) networks
  - Can reduce cost and complexity
- Need packet level information
  - Botnet detection: connection patterns, packet contents
  - Port scan detection: packet header, inter-arrival times
  - Worm detection: packet contents

Separation of Controller and Data Path



Controller Information Channels

- **Event-based Messages**
  - Generated by switches
  - Information about network structure, and topology changes
- **Flow Statistics**
  - Collected by switches; pulled by the controller
  - Flow level information
- **Packet-In Messages**
  - Generated by switches
  - Flow level information; limited packet level

Packet Level Information in OpenFlow

- Lack of packet level information is not intrinsic in SDN
  - But a side-effect of how OpenFlow works
- OpenFlow is mainly designed to deal with flows rather than individual packets
- Still, we can access packet level information to some extent.

Packet Level Information in OpenFlow

- **Option 1:** Do not install flow rule
  - Every packet of the flow will be sent to the controller

- **Option 2:** Divert packets to a monitoring device
  - Suggested in original OpenFlow white paper

Limitations …

- **Option 1:** install no rule
  - Controller sits on the packet delivery path
    - Potential bottleneck
    - Increased packet delivery times
  - Switch may buffer the packet
    - Only parts of each packet may reach the controller
- **Option 2:** divert traffic to monitoring device
  - High network overhead
  - Unnecessary overhead
    - E.g. need packet header, receive full packet
  - Complex monitors required
    - Increased network cost and complexity

A Question

- Existing information channels either
  - Provide no packet level information
  - Need to relay all packets

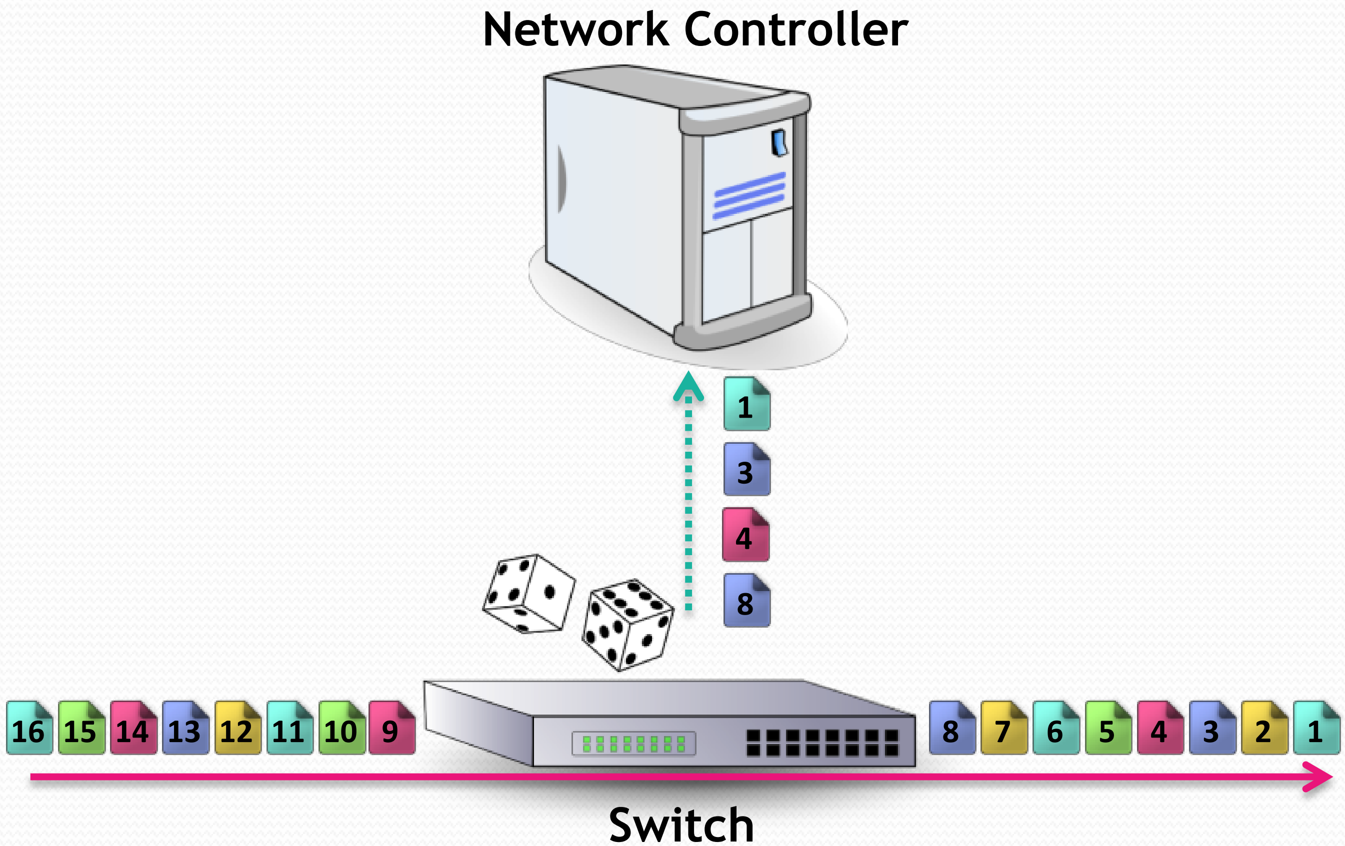
Question:
Is there a simple mechanism to create a tunable channel for packet level information?

FleXam: Flexible Sampling in OpenFlow

- Per-flow sampling as a new information channel
  - Gives the controller access to packet-level information
- The controller defines
  - Which flows need to be sampled
  - Inside a given flow how samples are selected
  - What part of each packet is selected
  - Where the samples are sent to
- Simple, yet flexible
  - … for different applications

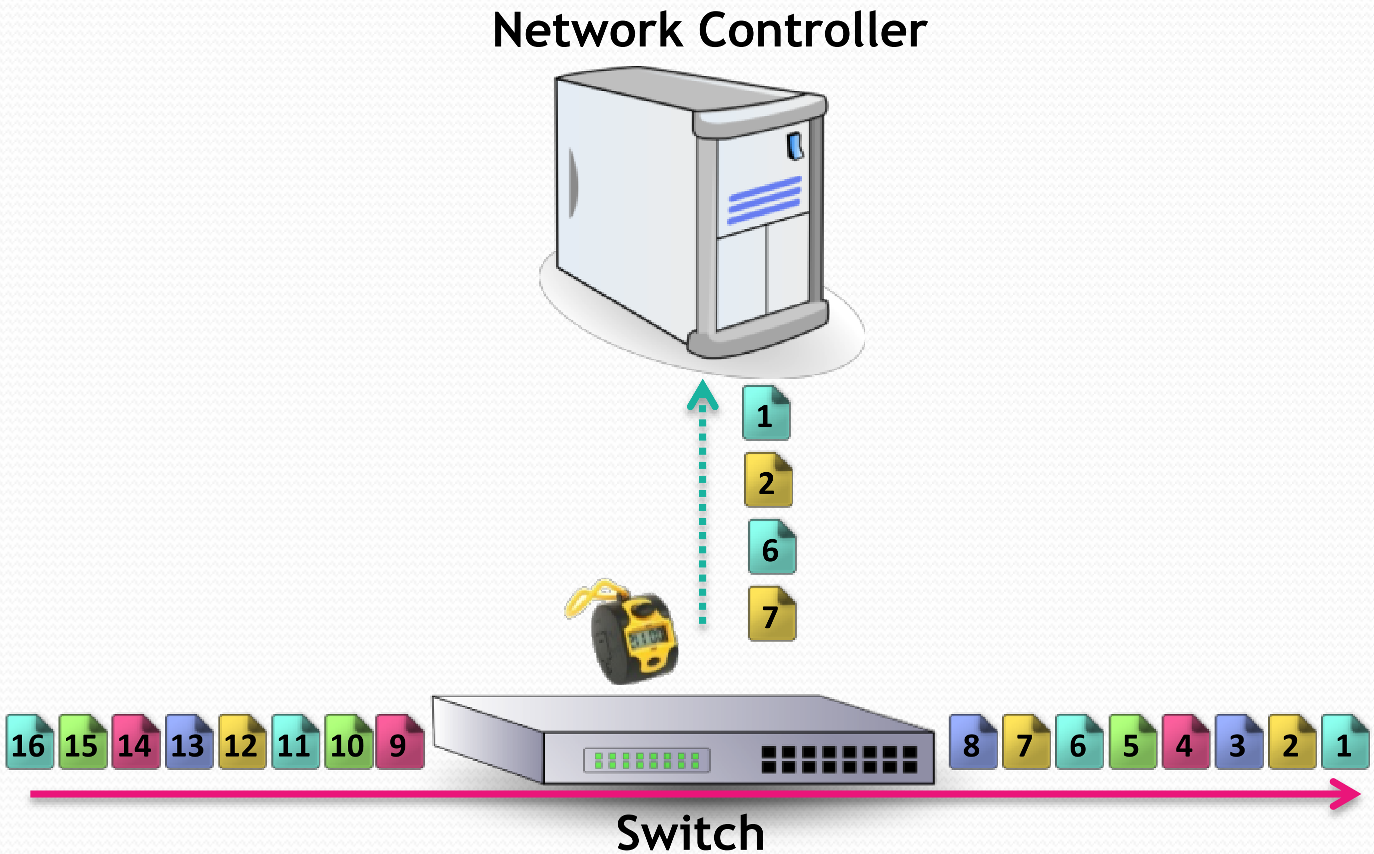
Stochastic Sampling in FleXam

- Select each packet with a fixed probability of ρ and forward to the control plane



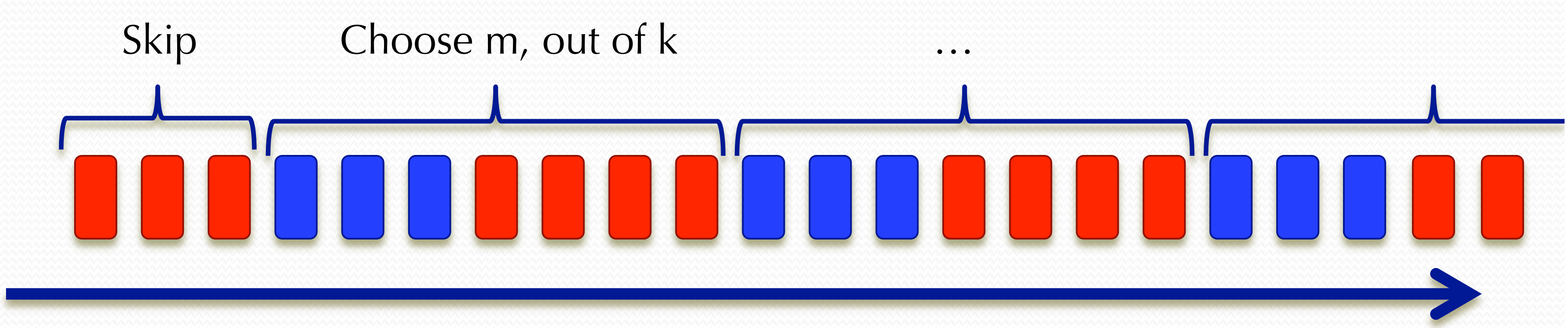
Deterministic Sampling in FleXam

- Select m consecutive packets out of every k consecutive packets, skipping the first δ



Deterministic Sampling – Cont'd

- *m=1*: normal one out of *k packets*
- *m>1, k=∞*: only the first m packets
  - Suitable for applications such as traffic classification
- δ > *0*: exclude short flows
  - Suitable for elephant flows



OpenFlow Specification

- New action: OFPAT_SAMPLING
  - Can be easily added to current OpenFlow implementations
  - No overhead for flows with no sampling
- Six parameters
  - *scheme*: which packet parts should be sent
  - m, k, and δ: deterministic sampling parameters
  - ρ: stochastic sampling parameter
  - *destination*: where should be sent to

Switch Implementation

- Stochastic sampling:
  - Generate a random number
  - Select the packet if it is less than ρ
- Deterministic sampling:
  - Reuse Received Packets Counter
    - No need to new counter
  - Select packet if:

$$((\text{Received\_Packet\_Counter} - \delta)\ \%\ k) < m$$

- Both can be executed in the data path at line rate

Applications

- Various potential applications
  - Traffic classification
  - Quality of service
  - Diagnostics and troubleshooting

- In depth look at …
  - Port scan detection; and
  - Elephant flow detection

- Accuracy vs. load trade-off

Case Study: Port Scan Detection

- Example of FleXam used for security applications
- Threshold Random Walk algorithm
  - Assume the probability of a failed connection is
    - Relatively low for a benign host
    - High for attacker hosts
  - Maintaining an attacker likelihood ratio for each host
    - Increase it when a new connection fails
    - Decrease it when a new connection succeeds
  - Mark a connection successful if we observe
    - At least two packets from a UDP connection
    - A non TCP_SYN packet from a TCP connection

Evaluation Setup

- Developed an OpenFlow switch simulator
  - Provides an API similar to NOX
- Based on the dataset used by Mehdi et al. [2]
  - Separate attack and benign datasets
  - More details in the paper
- We created 20 different trials
  - Inserting the attack data at different times inside benign data

Effect of Sampling on Port Scan Detection

- **Flow-shortening:** only small fraction of flow packets are observed
  - Small flows: probably see only one packet
  - If only see SYN packet
    - Mark connection as failed
    - Decreases accuracy with false positives
- **Flow-reduction:** only some flows are observed
  - Uniform per-packet sampling
    - Miss many short flows, especially attack flows that are single packets
  - Miss some failed connections
    - Decreases accuracy with false negatives

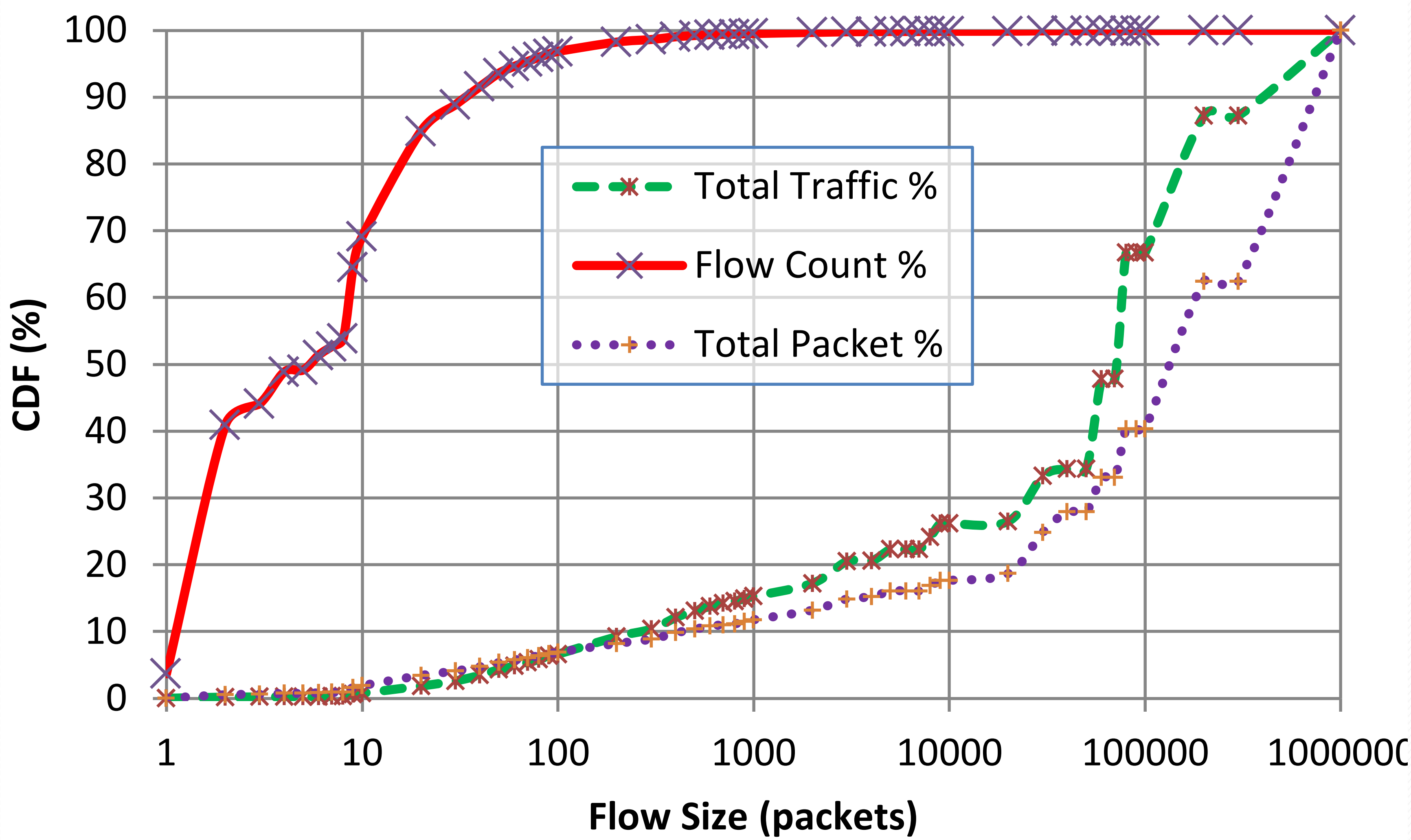
Resolving Flow-Shortening Problem

- Receive a sampled packet from a new connection
  - TCP non SYN packet → mark connection as successful
  - UDP packet or TCP_SYN packet:
    - Ask the switch to send the next packet of this flow: Install an exact match flow rule with deterministic sampling with $m=1$ and $k=\infty$
      - If receive any packet later on, mark connection as successful
      - Otherwise, mark it as failed after a timeout

Resolving Flow-Reduction Problem

- Small number of flows carry most of the traffic
- In our traffic data:
  - Flows with more than 50 packets
    - 6% of total flows
    - Carry 96% of total packets
    - Carry 95% of total bytes
- Identify and exclude large (elephant) flows from sampling
  - Spend sampling budget on small flows

Resolving Flow-Reduction Problem

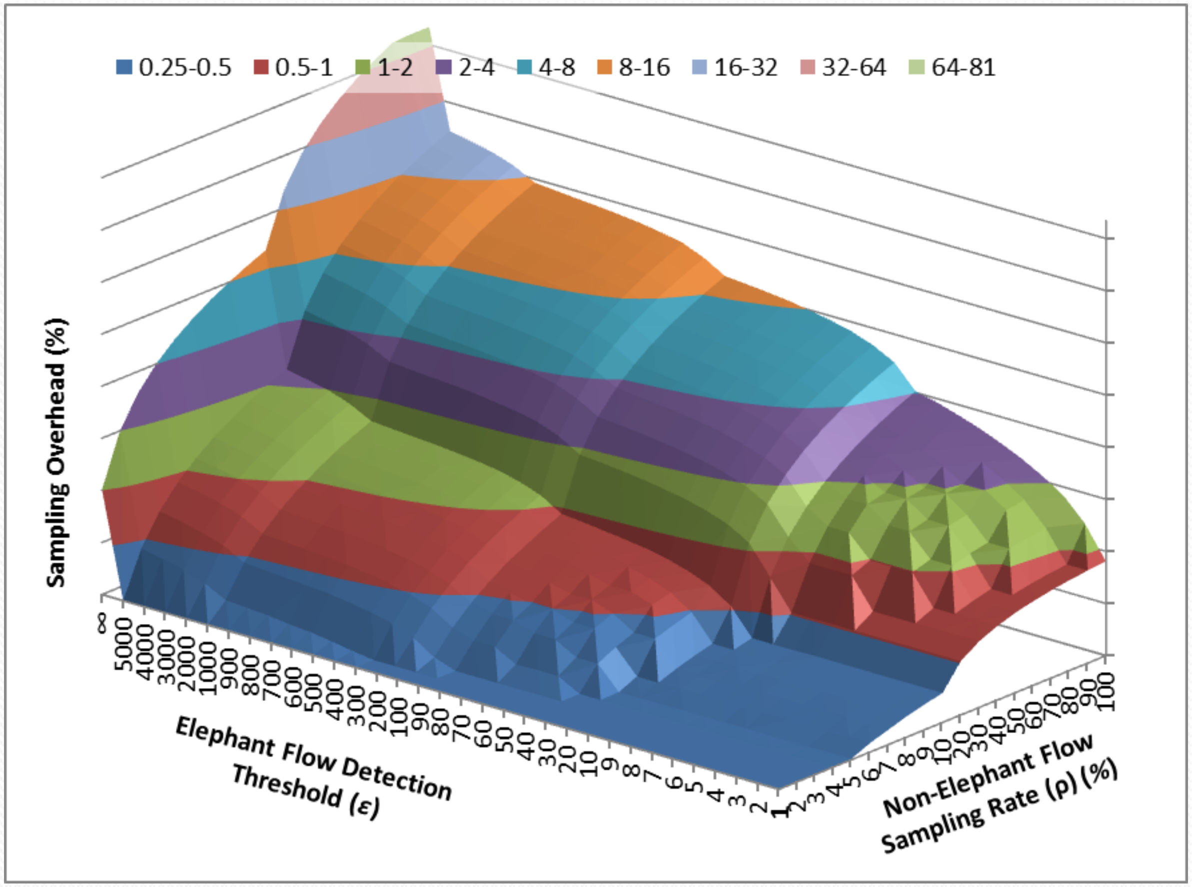


Elephant Flow Detection

- Sample all unknown traffic with a given rate of ρ
- Identify elephant flows
  - If more than ε samples received from a given flow
- Exclude elephant flows from sampling
  - Install an exact match flow rule to route them, without any sampling action
- No need to complicated switch modifications

Network Overhead

- Overhead is low for a wide range of values
  - E.g. it is less than 0.4% for $\rho<10$ and $\varepsilon<10$

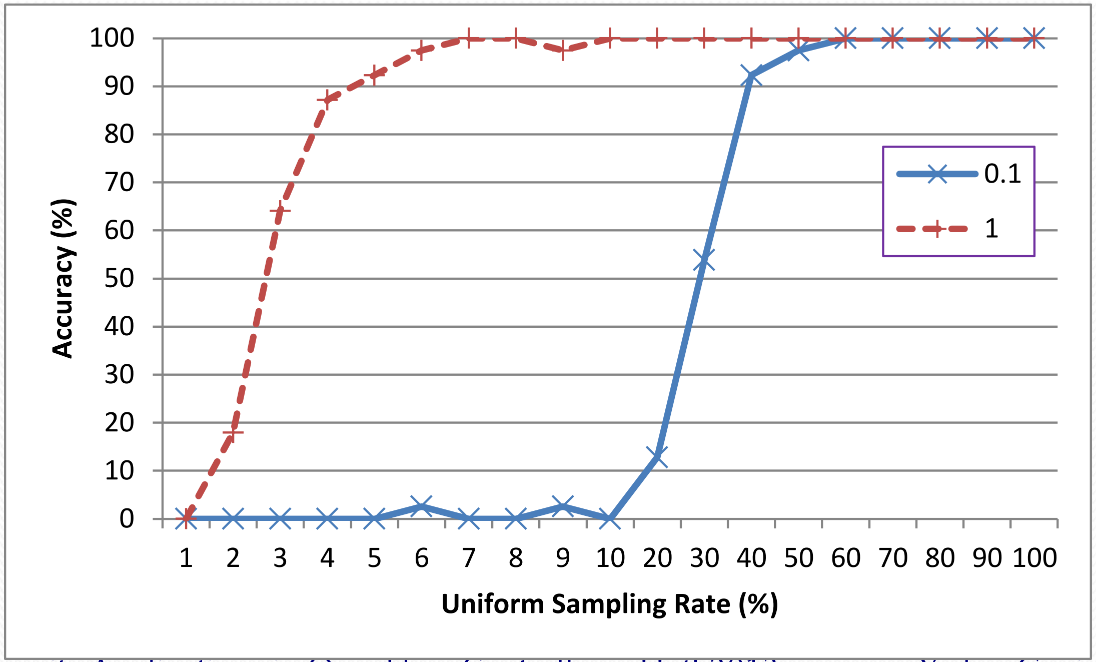


Accuracy

- Attack rates of 10, 100 and 1000 packets/s
  - All scanners were detected for any pairs of (ρ , ε)
- For 100% accuracy in other two cases:
  - (ρ =50%, ε =3) has overhead of 0.7% for an attack rate of 0.1 pps
  - (ρ =5%, ε =4) has overhead of 0.25% for an attack rate of 1 pps

Uniform Sampling Accuracy and Overhead

- Minimum sampling rate (and overhead) for 100% accuracy:
  - 60% for attack rate of 0.1 pps
  - 7% for an attack rate of 1 pps
  - 1% for higher attack rates (10, 100, and 1000 pps)



Overhead Comparison

- Network overhead for 100% accuracy

Method	Attack Rate				
	0.1	1	10	100	1000
Our Method	**0.7%**	**0.25%**	**0.1%**	**0.1%**	**0.5%**
Uniform Sampling	60%	7%	1%	1%	1%
Mehdi et al. [2]	1.1%	1.2%	2%	9%	47%
Reactive OpenFlow Routing (No port scan detection)	**0.7%**	0.8%	1.5%	8.7%	47%

FleXam and Network Cost/Complexity

- In small networks
  - The controller could also be the monitoring device
  - Eliminating the need for a separate monitoring device
    - Significant reductions in cost and complexity

- For large networks
  - Samples can be directed to different monitoring devices
  - Reduce the load of monitoring devices by only sending the traffic they are interested in, and not all traffic

- Network overhead is tunable by the controller
  - Change parameters in real time, if needed

Conclusion

- Proposed FleXam
  - Flexible sampling extension for OpenFlow
  - Enables the controller to access packet-level information
  - Flexible for different applications
  - Yet simple enough to be implemented entirely in switch data-path and operate at line rate
- Demonstrated how to implement port scan detection with FleXam
  - An example of security applications that need access to packet-level information
- Other applications remain as future work

Thank You!

Questions?