FERMILAB-SLIDES-18-122-CD

GoldenEye: stream-based network packet inspection using GPUs

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The 43nd IEEE Conference on Local Computer Networks

October 4, 2018

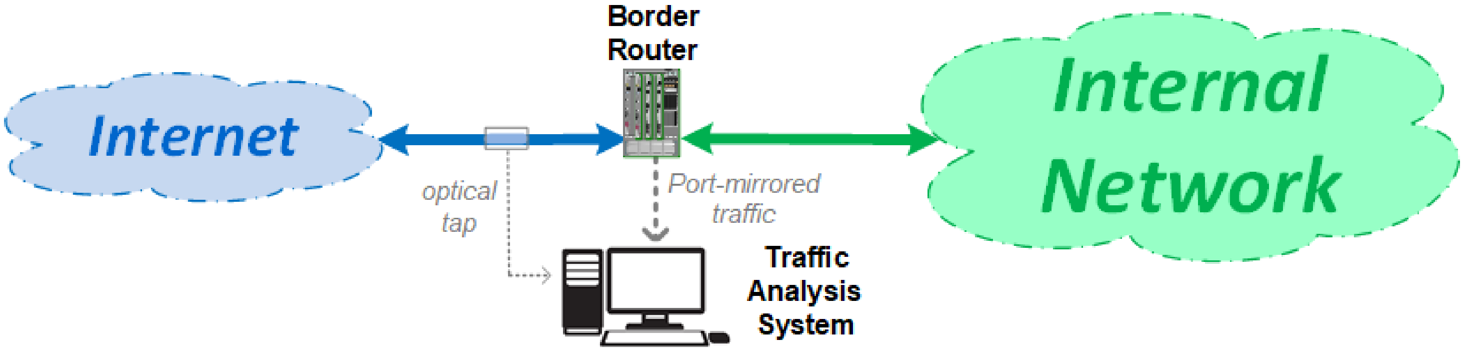
This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Outline

- Motivation of GPU-based traffic analysis
- Framework of GPU-based traffic analysis
- Performance evaluation
- Conclusion & future work

Network Traffic Analysis

- Network traffic analysis tools provides indispensable information for
  - Operation & management
  - Performance troubleshooting
  - Network security
  - Statistical purpose



- Basic functions:
  - Profile traffic activities
  - Scan traffic content for suspicious patterns signatures

Task Overview

Stateful packet processing

- Track and maintain the states of network functions:
    - TCP connections
    - Sub-string matches in intrusion detection systems

Timely response

- Fast and reliable network data processing at a link speed

Protect traffic integrity

- Packet shouldn’t be lost in processing cycle

Challenges in data and state management

Data Management Challenges and Solutions

Challenges:

- High-speed networks
  - 10/25/40GE-connected serves
  - 100GE backbone technologies are commonplace

Millions of packets generated & transmitted per second

- Complex packet analysis algorithms
  - Algorithms are increasingly complex as security threats become more sophisticated
  - Need a flexible and programmable computing platform

Data Management Solutions

Solutions:

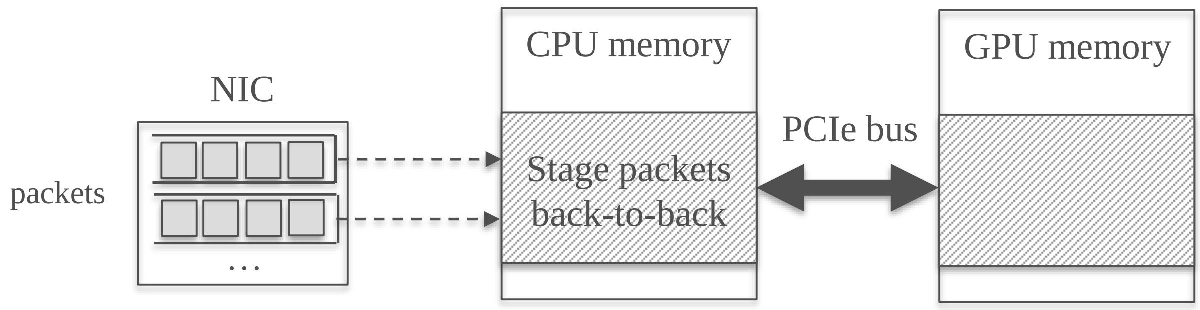
- Heterogeneous data management
- GPU-centric computing
  - GPU is specialized for data-parallel, large-throughput computations
  - Thousands of cores for massively parallelism
  - Tolerance of memory latency

Features	NPU/ASIC	CPU	GPU
High compute power	Varies	✗	✓
High memory bandwidth	Varies	✗	✓
Easy programmability	✗	✓	✓
Data-parallel execution model	✗	✓	✓

Packet Processing on Heterogeneous Architectures

Data processing flow:

- CPU receives packets from NIC, parses headers and *batches* them in an input buffer.
- When a specified batch size or a preset time limit is reached, the input buffer is transferred to the GPU memory via PCIe.
- A set of GPU kernels are then launched to perform tasks such as IP address matching, cryptographic operations, and deep packet inspection.
- The results are transferred back to the CPU memory to guide further actions.



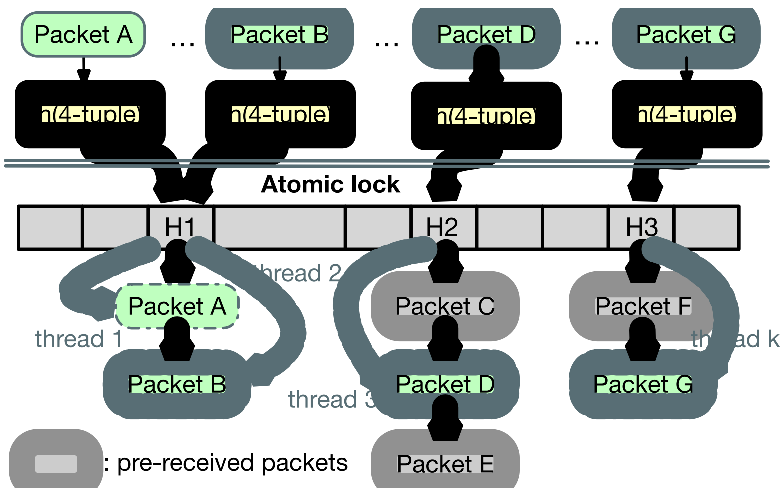
Packet batching can be a feasible way to improve GPU utilization, but it increases difficulties in stateful packet processing…

State Management Challenges

Challenge 1: flow management & stream reassembly

- Stateful network functions must both track the states of network connections and scan network packets at a per-flow level.
- Flow state management and stream-reassembly require state synchronization when dealing with packets from the same connection.
- Limited data parallelism when less simultaneous TCP connections are present.

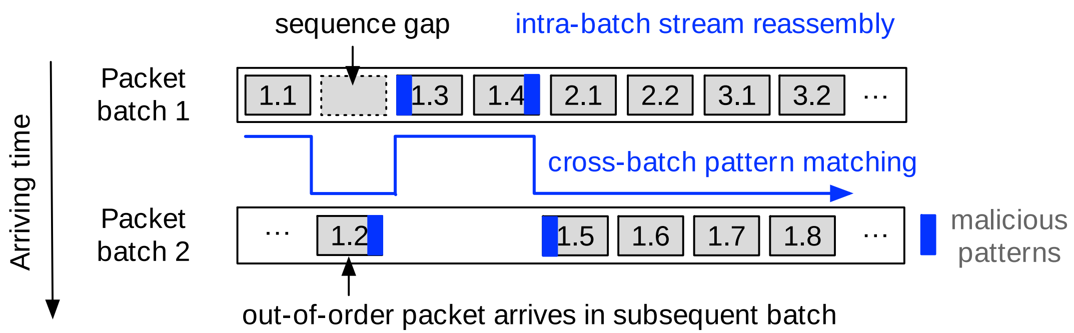
Conventional hash-based approach requires atomic locks with packets from the same TCP flow connection, and is prone to ambiguity caused by hash-key collision.



State Management Challenges

Challenge 2: Inter-batch state connection

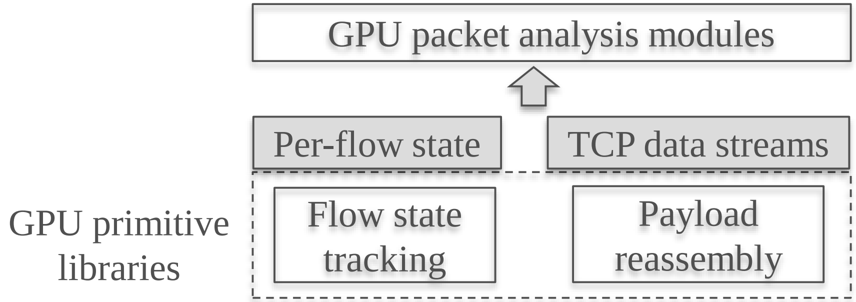
- Stateful packet inspection must detect signatures that straddle packet boundaries.
- GPU's batch-processing mechanism requires maintaining connection states and tracking potential sub-matches across input batches.



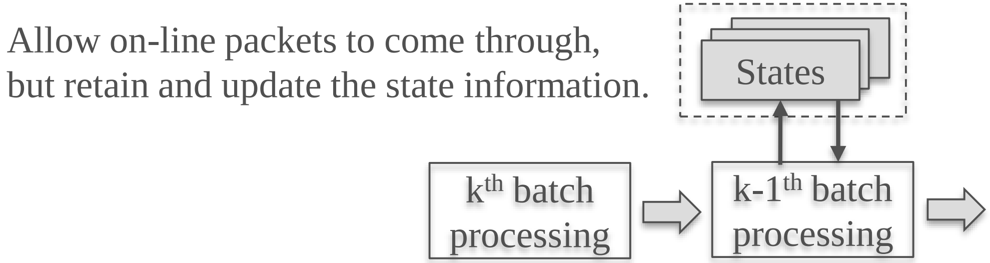
Stateful packet inspection must detect and memorize the sub-matches across input batches.

State Management Solutions

- Parallel flow management and stream processing via GPU sort and prefix-scan
  - Sort and prefix-scan are extremely fast on GPU (over ten billions of elements/sec).



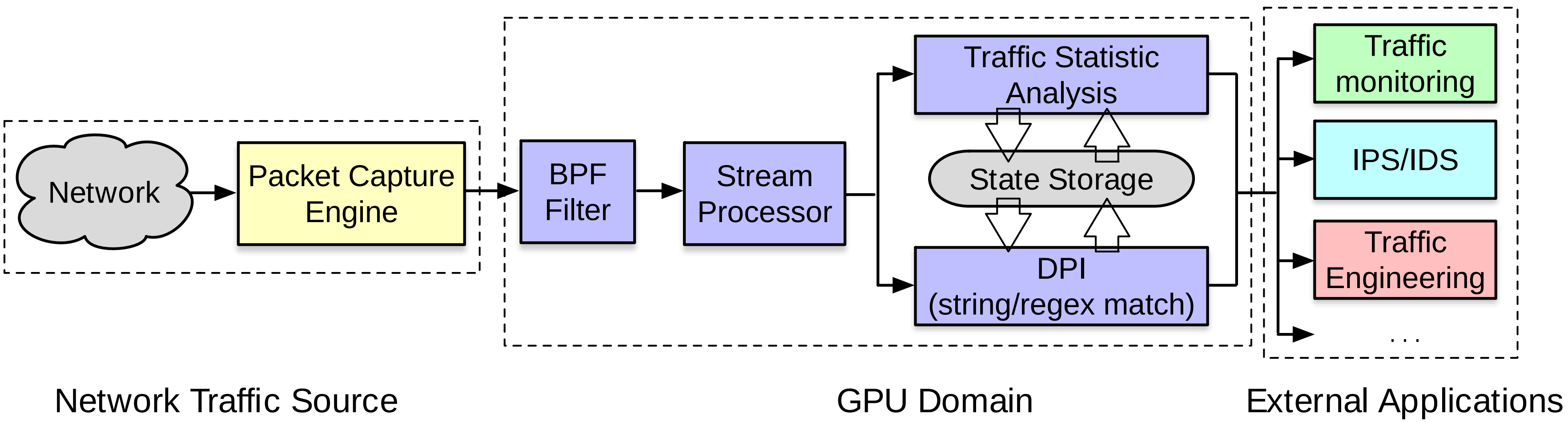
- Inter-batch network function state connection
  - Developed a buffer-free, cross-packet/batch pattern matching algorithm.
  - Combine the state and context information with packets in subsequent batches.



GoldenEye Network Traffic Analysis Framework

GoldenEye Modules

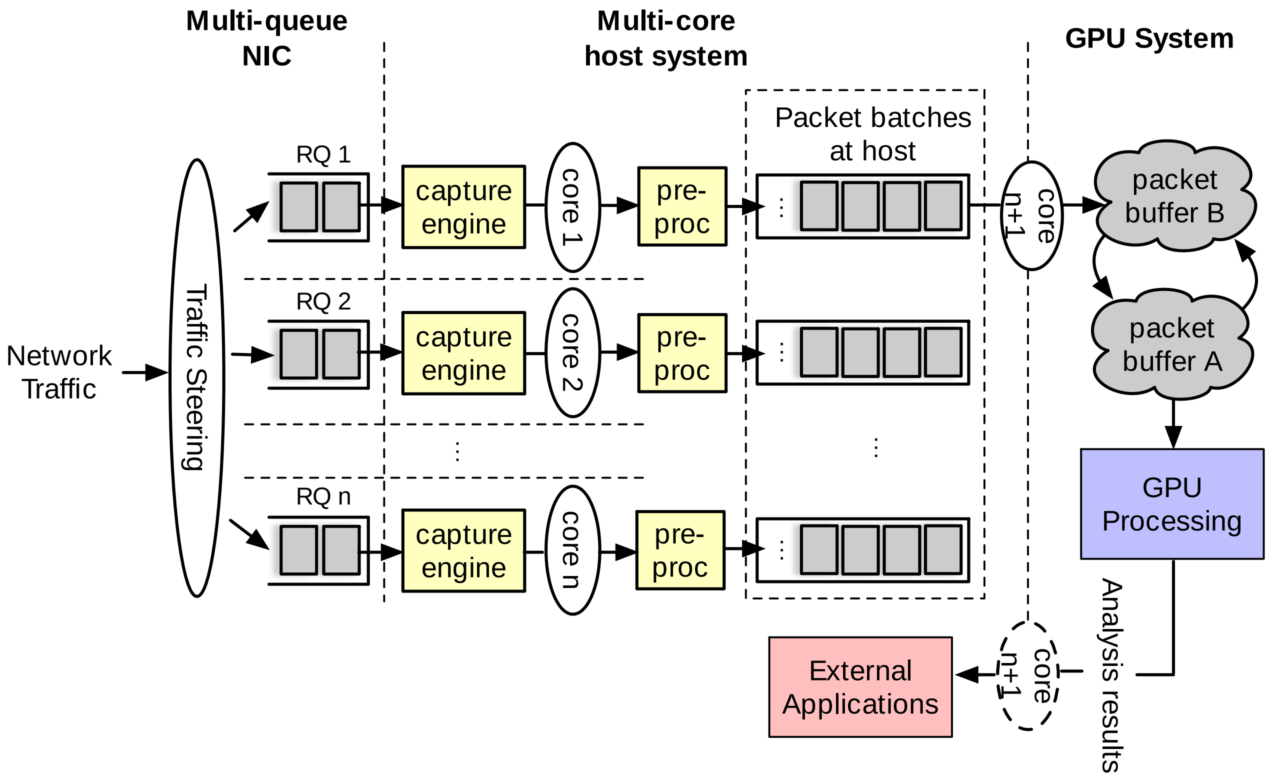
- Packet capture & pre-processing
- BPF filter
- Stream processor
- Traffic statistic summary
- Deep packet inspection
- State buffer



Packet Capture and Processing on Multicore Systems

Logics:

- Multithreading packet capturing and pre-processing
- Queue packets for batch processing
- Dual-buffer for concurrent data transfer and GPU computing



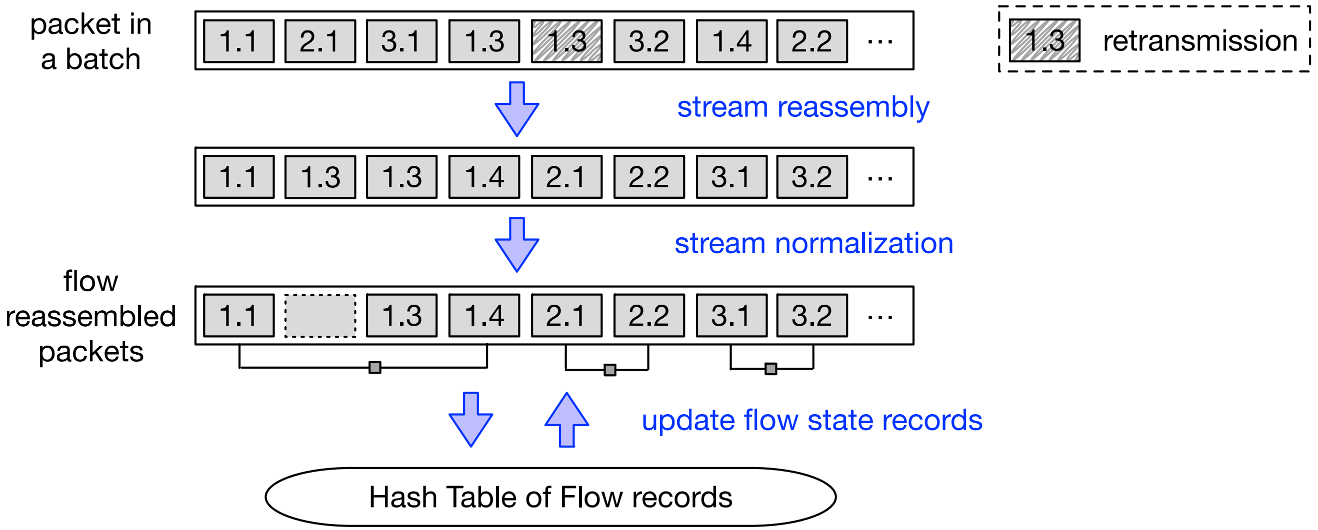
GPU-centric Stream Processor

Tasks:

- Monitor the states of TCP connections.
- Reassemble TCP packets into bi-directional byte-streams.

Implementations:

- Stream reassembly: sort packets into streams by their TCP 4-tuples and sequences.
- Flow state tracking: compare the stream states against existing connections.
- Stream normalization: rescan flow-reassembled packets and remove retransmission.



Traffic Statistical Analysis

<u>Main strategy</u>:

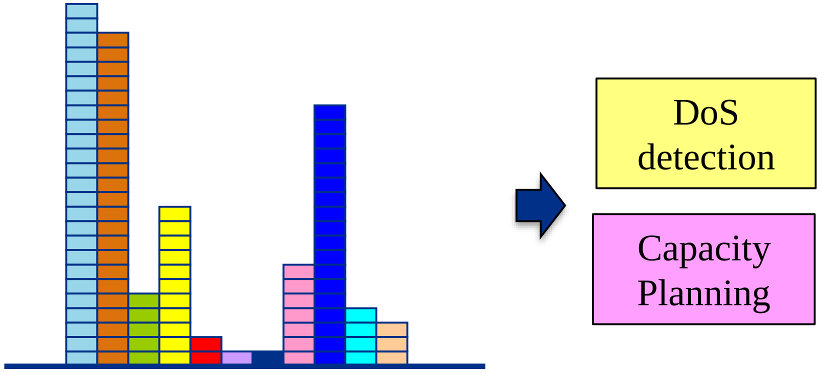
- Similar to the TCP flow management function, GoldenEye's statistical aggregation module is built with a set of primitive GPU sort and prefix-scan operations.

<u>Example use cases:</u>

- Host traffic monitoring

Src IP	Src Port	Dest IP	Dest Port	Proto	Pkt Sent	Byte Sent
131.2.3.0	80	10.1.2.4	998	TCP	32	16484
10.1.2.4	998	131.2.3.0	80	TCP	121	179841

- Heavy-hitter Detection



Stream-based Deep Packet Inspection

Tasks:

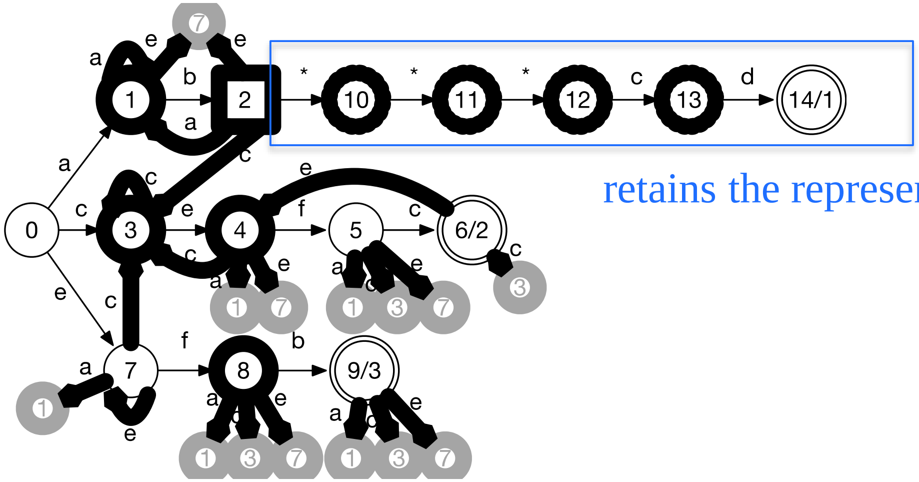
- Intra-batch pattern matching:
  - Perform pattern matching over stream-reassembled packets in the same batches.

- Inter-batch pattern matching:
  - Detect and reconstruct signature patterns that straddle batch boundaries.

Intra-batch Signature Matching

General pattern matching algorithm: hybrid-FA[1]

- HFA compresses the states of DFA by keeping any subset whose expansion would cause state explosion in an NFA form.



retains the representation in an NFA form

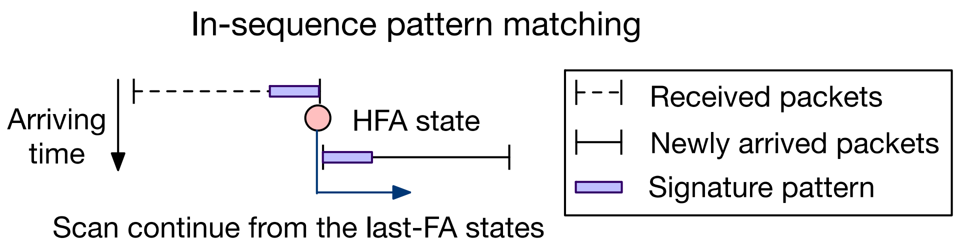
Implementation of intra-batch pattern matching:

- Each GPU thread takes one packet.
- Perform cross-packet detection at a per-flow basis.

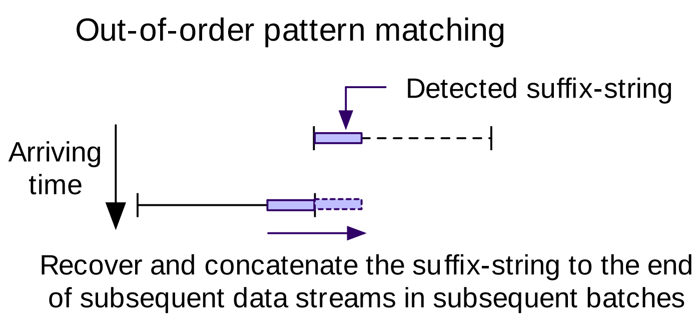
[1] Michela Becchi, Patrick Crowley, “A hybrid finite automaton for practical deep packet inspection”, 2007 ACM CoNEXT conference.

Inter-batch Signature Matching

- In-sequence pattern matching
  - Matching process of subsequent stream fragments will continue from the last FA-states of the previous fragments.



- Out-of-order pattern matching
  - Look for regex-suffixes in out-of-order streams.
  - Recover the string of previous matches and concatenate it to stream fragments that arrive latter to fill the hole.



Out-of-order Pattern Matching

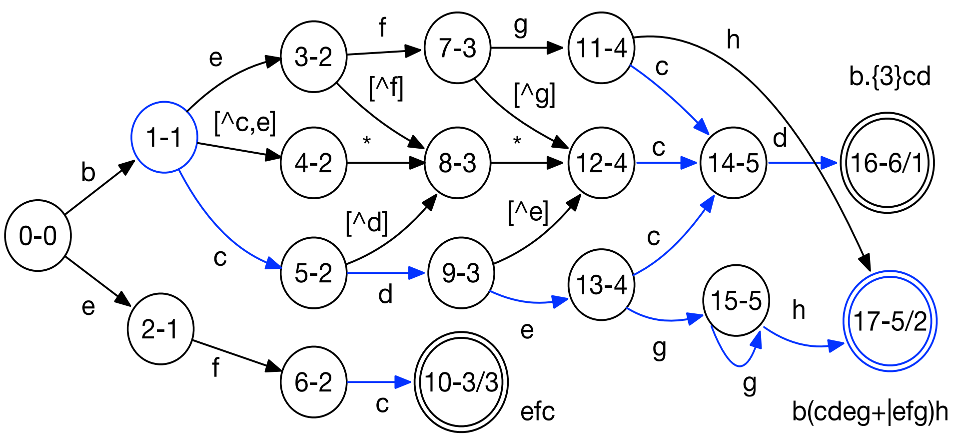
Suffix-regex detection: search streams with all potential initial states

- Parallel among both out-of-order stream fragments and the possible initial states of a search

Suffix-string reconstruction:

- Retain the first and the last FA-states of any partial-matches
- Reconstruct sub-regexes by relating states to their “depths” in the original regexes

Example: search suffix-regexes in the stream of “cdegggh”



Optimization w/ Chained Expression

Logics:

- Speed up DPI with string-based filters
- Reduce memory consumptions by breaking complex regexes into chained pieces

Strategy:

- Convert a regex into one of the three forms: <str><regex>, <regex><str>, or <regex><str><regex>.
- Process packet streams first through the string-filter.
- The regex engine will not be triggered until the string guarded by its side happens.

Performance Evaluation

Testbed systems:

- Dual Intel E5-2650 v4 CPU (12 cores per socket)
- NVIDIA K40 GPU

Traffic trace:

- Traffic source
  - Intrusion detection dataset created by Canadian Institute of Cybersecurity (CICIDS)
  - Science data flow mirrored from the border router at Fermilab (Fermilab)

- Traffic pattern

	Trace size	# of packets	# of TCP connections	Mean packet-size
Fermilab	9.8 GB	8.7×10^6	54.78×10^3	1118-byte
CICIDS	17.1 GB	44.34×10^6	1.10×10^6	386-byte

Regex datasets:

- 104 and 192 spyware and malware signatures snapshot from Snort 2.9.7.2

Performance Evaluation

Memory footprint

- Stream reassembly

Traffic Trace	Default	
	Buffer & reassembly	GoldenEye
Fermilab	307.81 MB	44.20 MB
CICIDS	186.32 MB	48.05 MB

- Chained regex FAs

Regex	Chained Regex			DFA		HFA	
	string-filter	regex engine					
malware	25.62 MB	5510 states	5.46 MB	exploded	N/A	~2×10^6 states	~2 GB
spyware	26.64 MB	3637 states	3.74 MB	~7×10^6 states	~7 GB	~1×10^6 states	~1 GB

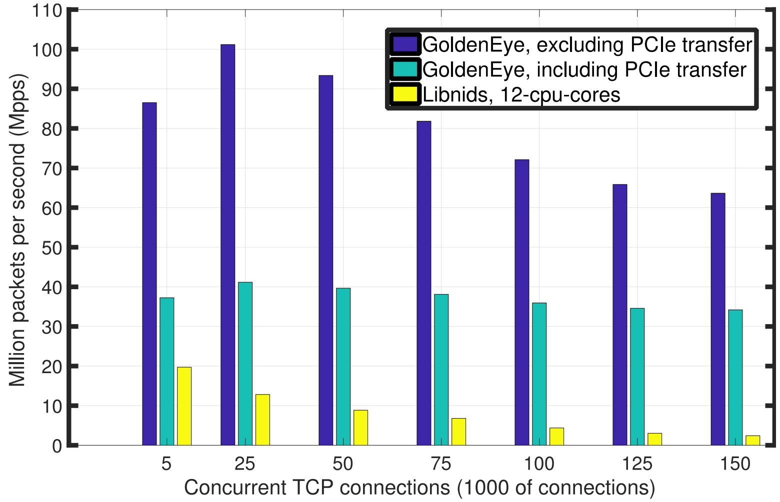
Performance Evaluation

Flow tracking & TCP reassembly

- Performance with real traffic

	Fermilab	CICIDS
GoldenEye wo/ PCIe transfer	623.30 Gbit/s	335.73 Gbit/s
GoldenEye w/ PCIe transfer	552.30 Gbit/s	232.487 Gbit/s
Libnids[1] (12 CPU cores)	186.65 Gbit/s	31.102 Gbit/s

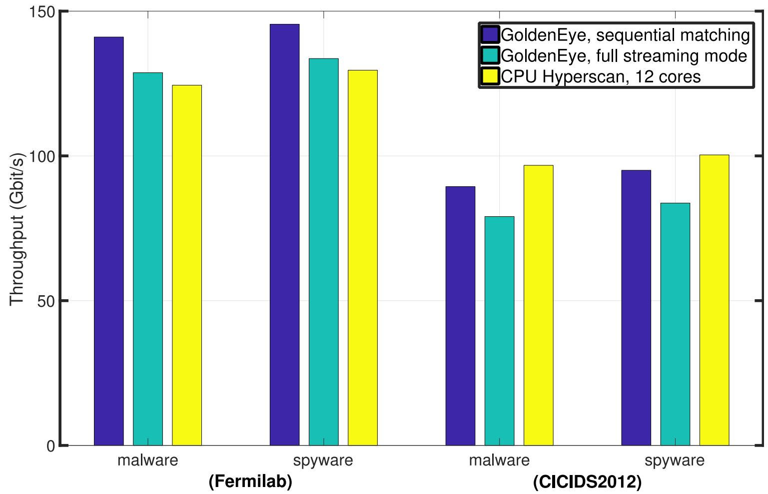
- Scalability to the number of concurrent TCP connections



[1] R. Wojtczuk, “Libnids. http://libnids. sourceforge. net.”

Performance Evaluation

Stream-based regex matching



Consolidate DPI application

Regex	Fermilab	CICIDS
malware	105.55 Gbit/s	62.13 Gbit/s
spyware	108.69 Gbit/s	64.95 Gbit/s

Hyperscan: “a high-performance multiple regex matching library” https://01.org/hyperscan

Conclusion & Future Works

GoldenEye:

- Provides a fast, memory efficient packet processing framework for GPU platforms, capable of statistical and stream-based payload analysis.
- Reassemble TCP streams in GPU and match signature patterns across packets, without requiring system to buffer and rescan packets or limit scanning to a fixed window of historical data.

Future Directions:

- Continue to add new features to support ever complex network tasks.
- Combine our packet processing functions with advanced learning algorithms to build behavior-based network automate detection.