GoldenEye: stream-based network packet inspection using GPUs

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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:
  o TCP connections
  o 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
  o 10/25/40GE-connected serves
  o 100GE backbone technologies are commonplace

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

{ Millions of packets generated & transmitted per second }
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

<table>
<thead>
<tr>
<th>Features</th>
<th>NPU/ASIC</th>
<th>CPU</th>
<th>GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>High compute power</td>
<td>Varies</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>High memory bandwidth</td>
<td>Varies</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Easy programmability</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Data-parallel execution model</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
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...*
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.

![Diagram showing packet batch 1 and 2 with sequence gap, intra-batch stream reassembly, cross-batch pattern matching, and out-of-order packet arrival.]

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).

```
GPU packet analysis modules
```

```
Per-flow state          TCP data streams
Flow state tracking    Payload reassembly
```

- 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.

```
Allow on-line packets to come through, but retain and update the state information.
```

```
k^{th} batch processing  k-1^{th} batch processing
```

4/18/2019 GoldenEye: stream-based network packet inspection using GPUs, IEEE LCN 2018
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

Multi-queue NIC

Traffic Steering

Network Traffic

Multi-core host system

Packet batches at host

GPU System

packet buffer B

packet buffer A

Analysis results

External Applications

GPU Processing

Fermilab
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

Main strategy:
- 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.

Example use cases:
- Host traffic monitoring

<table>
<thead>
<tr>
<th>Src IP</th>
<th>Src Port</th>
<th>Dest IP</th>
<th>Dest Port</th>
<th>Proto</th>
<th>Pkt Sent</th>
<th>Byte Sent</th>
</tr>
</thead>
<tbody>
<tr>
<td>131.2.3.0</td>
<td>80</td>
<td>10.1.2.4</td>
<td>998</td>
<td>TCP</td>
<td>32</td>
<td>16484</td>
</tr>
<tr>
<td>10.1.2.4</td>
<td>998</td>
<td>131.2.3.0</td>
<td>80</td>
<td>TCP</td>
<td>121</td>
<td>179841</td>
</tr>
</tbody>
</table>

- Heavy-hitter Detection
Stream-based Deep Packet Inspection

Tasks:

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

• Inter-batch pattern matching:
  o 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.

Implementation of intra-batch pattern matching:
- Each GPU thread takes one packet.
- Perform cross-packet detection at a per-flow basis.

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 “cdeggh”

[Diagram of a graph representing the out-of-order pattern matching process]
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
  o Intrusion detection dataset created by Canadian Institute of Cybersecurity (CICIDS)
  o Science data flow mirrored from the border router at Fermilab (Fermilab)
• Traffic pattern

<table>
<thead>
<tr>
<th></th>
<th>Trace size</th>
<th># of packets</th>
<th># of TCP connections</th>
<th>Mean packet-size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermilab</td>
<td>9.8 GB</td>
<td>$8.7 \times 10^6$</td>
<td>$54.78 \times 10^3$</td>
<td>1118-byte</td>
</tr>
<tr>
<td>CICIDS</td>
<td>17.1 GB</td>
<td>$44.34 \times 10^6$</td>
<td>$1.10 \times 10^6$</td>
<td>386-byte</td>
</tr>
</tbody>
</table>

Regex datasets:
• 104 and 192 spyware and malware signatures snapshot from Snort 2.9.7.2
Performance Evaluation

Memory footprint
- Stream reassembly

<table>
<thead>
<tr>
<th>Traffic Trace</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Buffer &amp; reassembly</td>
</tr>
<tr>
<td>Fermilab</td>
<td>307.81 MB</td>
</tr>
<tr>
<td>CICIDS</td>
<td>186.32 MB</td>
</tr>
</tbody>
</table>

- Chained regex FAs

<table>
<thead>
<tr>
<th>Regex</th>
<th>Chained Regex</th>
<th>DFA</th>
<th>HFA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>string-filter</td>
<td>regex engine</td>
<td></td>
</tr>
<tr>
<td>malware</td>
<td>25.62 MB</td>
<td>5510 states</td>
<td>exploded</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>spyware</td>
<td>26.64 MB</td>
<td>3637 states</td>
<td>~7×10^6 states</td>
</tr>
</tbody>
</table>
Performance Evaluation

Flow tracking & TCP reassembly

- Performance with real traffic

<table>
<thead>
<tr>
<th></th>
<th>Fermilab</th>
<th>CICIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GoldenEye wo/ PCIe</td>
<td>623.30 Gbit/s</td>
<td>335.73 Gbit/s</td>
</tr>
<tr>
<td>transfer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GoldenEye w/ PCIe</td>
<td>552.30 Gbit/s</td>
<td>232.487 Gbit/s</td>
</tr>
<tr>
<td>transfer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Libnids(^1) (12 CPU cores)</td>
<td>186.65 Gbit/s</td>
<td>31.102 Gbit/s</td>
</tr>
</tbody>
</table>

- Scalability to the number of concurrent TCP connections

Performance Evaluation

Stream-based regex matching

Consolidate DPI application

<table>
<thead>
<tr>
<th>Regex</th>
<th>Fermilab</th>
<th>CICIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>malware</td>
<td>105.55 Gbit/s</td>
<td>62.13 Gbit/s</td>
</tr>
<tr>
<td>spyware</td>
<td>108.69 Gbit/s</td>
<td>64.95 Gbit/s</td>
</tr>
</tbody>
</table>

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