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FPGA-Enhanced Real-Time Analysis of Network Traffic

Yu-Kuen Lai, Drixter Velayo Hernandez, Hsiang-Lun Hua, Bo-Shun Huang
Computer Networks & Systems Research Lab
Department of Electrical Engineering
Chung-Yuan Christian University, Chungli, Taiwan

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Outline

- **Motivation**
  - Common Network Traffic Measurement Tasks
  - Challenges
- **General Backgrounds**
  - Sketch-based Data Stream Algorithms
  - Flow-size/Flow-length Distribution
- **High-Speed Real-Time Processing**
  - Estimating Weibull Model Parameters
  - CAIDA 2007 DDoS
  - Witty Worm
- **Summary**
- **Q&A**

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Common Measurement Tasks

- Heavy Hitter Detection
- Shannon Entropy
  - One of the effective methods for Network Anomaly Detection
- **Flow Size/Length Distribution Estimation plays a fundamental role in**
  - Understanding network behavior
  - Optimizing performance
  - Managing resources, and
  - Detecting anomalies

Bohan Zhao, Xiang Li, Boyu Tian, Zhiyu Mei, and Wenfei Wu. 2021. DHS: Adaptive Memory Layout Organization of Sketch Slots for Fast and Accurate Data Stream Processing. In *Proceedings of the 27th ACM SIGKDD Conference on Knowledge Discovery & Data Mining*. ACM, Virtual Event Singapore, 2285 – 2293. https://doi.org/10.1145/3447548.3467353

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Challenges

- **Packet arrives at a rapid rate**
- **Per-Flow Traffic Measurement is challenging**
  - Memory space
  - Processing time
- **Key space**
  - IPv4 address of 32-bit
  - High distinct number of flows
- **How to process and compute statistics on packet streams in real-time?**
- **Typical Implementation**
  - Software-based
  - Off-line approaches

A. K. Marnerides, A. Schaeffer-Filho, and A. Mauthe, “Traffic Anomaly Diagnosis in Internet Backbone Networks,”
B. Computer. Networks, vol. 73, no. C, pp. 224–243, Nov. 2014.

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Sketch-based Data Stream Algorithms

- **A probabilistic data structure**
- **"Processing a long stream of data items in one pass using small memory space" [Kumar et al., IMC 03]**
- **Widely used in networking and data stream processing**
  - Capable of summarizing large amounts of data
  - Update/Query operations in a memory-efficient manner
- **Especially useful in scenarios of**
  - Infeasible to store all data due to resource constraints
  - High-speed Network Monitoring
  - Anomaly Detection, and Traffic Engineering

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Flow Size/Length

- **Flow**
  - Flow is defined by selected attributes of layer 3-4 packet header.
  - For example, by 5-tuple of:

  {IP_Src, IP_Dest, TCP_SrcP, TCP_DestP, Proto}
- **Flow Size**
  - The total amount of data transferred within a flow
  - In terms of the number of **bytes**
- **Flow Length**
  - The total amount of **packets** transferred within a flow

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Security and Anomaly Detection

- Sudden Increase in Large/Small Flows
- Changes in Flow Length Distribution
  - DDoS attacks
    - Attackers generate large numbers of short flows to overload web servers or services
  - Network scanning
    - Numerous short flows could be a sign of network scanning
- Changes in Flow Size Distribution
  - Some malware or Worms may generate large flows
  - Attackers overwhelm network bandwidth with large amounts of data

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- **Can we do high-level coarse-grained estimation to track Changes of Flow Length and Flow Size?**
- **At wire-speed of 100Gbps and beyond?**

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Statistical Model of Flow Size/Length Distribution

- **Highly-skew, Long-tail distribution**
  - Lognormal, Pareto and Weibull are commonly used for the long-tail network traffic modeling [2] [24]

- **Due to the complexity of Internet traffic, single distribution can not be fitted accurately** [26]
- **Weibull distribution is a flexible model**
  - Can accommodate various shapes
    - Including the exponential and Rayleigh distributions as special cases
  - Tracking the change of the parameter
    - Real-time estimation of Weibull shape parameter is useful in traffic monitoring and anomaly detection [4]

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Weibull and Log-Normal Model for Flow Length/Size Distribution

PARAMETER ESTIMATION

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Weibull Model

- **The probability density function of a Weibull random variable**
  - $\boldsymbol{\alpha}$: Shape
  - $\boldsymbol{\beta}$: Scale
  - $\boldsymbol{\delta}$: Location

$$f(x) = \frac{\alpha}{\beta}(\frac{x-\delta}{\beta})^{\alpha-1}e^{-((x-\delta)/\beta)^{\alpha}}$$

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Method of Moments

- **A technique for estimating the parameters of statistical distributions**
- **By equating the *population moments* to the *sample moments***
- **Particularly useful for distribution models of**
  - Weibull
  - Log-Normal

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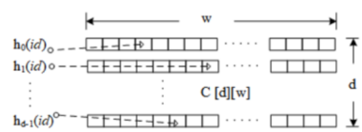
Estimating the First Moment m_1

$$\frac{m_1}{\sqrt{(cm_2)}} = \frac{\Gamma(1+\frac{1}{\alpha})}{\Gamma(1+\frac{2}{\alpha}) - \Gamma^2[1+\frac{1}{\alpha}]}$$

- **Take the *Flow Length* as an example:**
- **Assuming the flow *id* is the source IP address**
- **Packet counts of flows are updated in the counter of *C[d][w]***
- **The total packets count of all IP flows is the total sum of each row**

$$m_1 = \mu = \frac{1}{n}\sum_{id=0}^{n-1} x_{id}$$



$$\sum_{id=0}^{n-1} x_{id} = \sum_{i=0}^{w-1} C[0][i]$$

- **The first frequency moment F_1**

$$F_1 = \sum_{i=0}^{w-1} C[0][i]$$

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Zeroth Frequency Moment F_0

$$m_1 = \mu = \frac{1}{n}\sum_{id=0}^{n-1} x_{id}$$

- **The distinct count of the observed flows: n**
- **Can be estimated by using the sketch-based algorithms**

$$n \approx \hat{F}_0$$

  - FM sketch [#flajolet_probabilistic_1983]
  - HyperLogLog [#flajolet_hyperloglog_2007]

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Estimation of the Sample Moments

- **Get a function with only the shape parameter α**

$$\frac{m_1}{\sqrt{(cm_2)}} = \frac{\Gamma(1+\frac{1}{\alpha})}{\Gamma(1+\frac{2}{\alpha}) - \Gamma^2[1+\frac{1}{\alpha}]}$$

- **The first moment about the origin**

$$\hat{m}_1 = \frac{F_1}{\hat{F}_0}$$

- **The second moment about the mean**

$$c\hat{m}_2 = \frac{\hat{F}_2}{\hat{F}_0} - (\frac{F_1}{\hat{F}_0})^2$$

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FPGA Functional Simulations

- Count-Min Sketch
  - cm_d = 7
  - cm_w = 65536
- FM Sketch PCSA
  - fm_n = 512
  - fm_bits = 32
- **Trace: MAWI, 200403201400.dump.gz**

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200403201400.dump.gz_obsT10_flow_length_sip_2024-08-18

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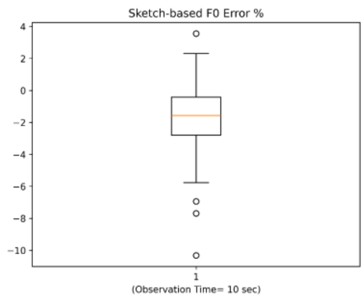
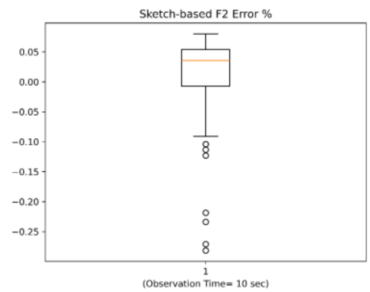
Relative Error
Estimated F_0 & F_2

- F0
  - Median: -2%
  - Q1-Q3: ~ -3%





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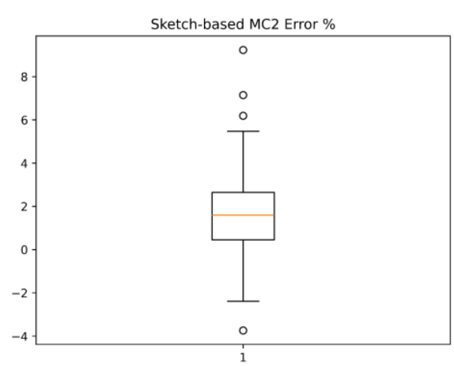
Relative Error
Second Moment about the Mean

- MC2
  - Median: 1.8%
  - Q1-Q3: ~ 3%



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Synthetic DDoS Network Traffic

- **CAIDA+MAWI**
- **CAIDA 2007 DDoS Trace (Attacking):**
  - The attacker sent many ICMP Echo request packets to the Victim
  - Randomly created source IP addresses
  - Four DDoS attacking traffic are selected from the CAIDA 2007 DDoS trace (to-victim).
    - 20070804_140436.pcap
    - 20070804_140936.pcap
    - 20070804_141436.pcap
    - 20070804_141936.pcap
- **MAWI DITL 2019 Trace (Background)**
  - https://mawi.wide.ad.jp/mawi/ditl/ditl2019/201904091800.html

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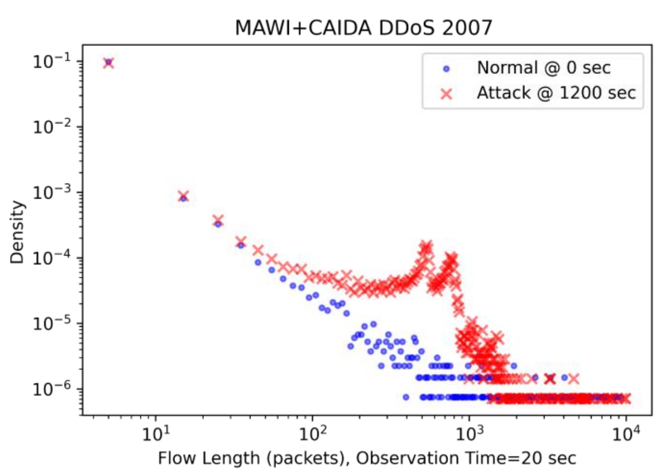
CAIDA 2007 DDoS Flow Length Distribution



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WITTY WORM

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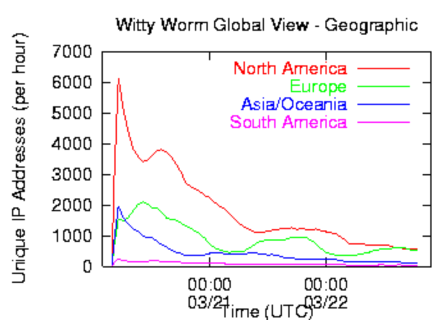
Witty Worm Outbreak

- **March 19, 2004, Approximately at 8:45pm PST**
  - UTC time at 3:45 AM on March 20, 2004
- **Infected 12,000 machines in 45 mins**
- **Targeting several Internet Security Systems (ISS) products**
  - Buffer overflow vulnerability



https://www.caida.org/archive/witty/

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Witty Worm Characteristics

- **The infecting host sends**
  - 20,000 **UDP** packets
  - Random destination IP address
  - Random size between 796 and 1307 bytes
  - from **source port 4000**

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MAWI 2004 Data Set Witty Worm

- **Outbreak begins at UTC Time 3:45 AM on March 20, 2004**
- **Captured by the daily 15-min traces**

MAWI Trace 2004	UTC Time 2004	
200403181400.dump.gz	03/18，05:00:01 AM	
200403191400.dump.gz	03/19，05:00:01 AM	
200403201400.dump.gz	03/20，05:00:01 AM	*****
200403211400.dump.gz	03/21，05:00:01 AM	****
200403221400.dump.gz	03/22，05:00:01 AM	**
200403231400.dump.gz	03/23，05:00:01 AM	*
200403241400.dump.gz	03/24，05:00:01 AM	*
200403251400.dump.gz	03/25，05:00:01 AM	
200403261400.dump.gz	03/26，05:00:01 AM	

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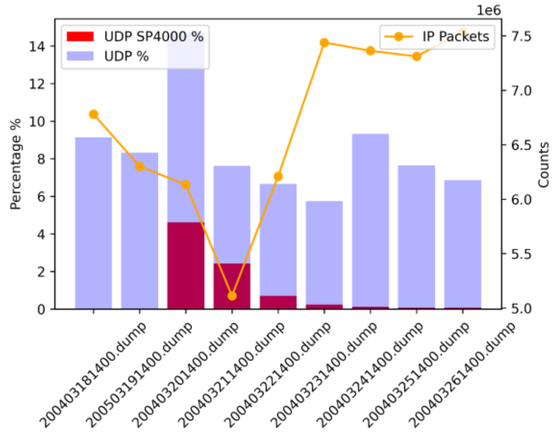
MAWI Traces

- During the Witty Worm Outbreak
- ~5% UDP Source Port 4000 Packets



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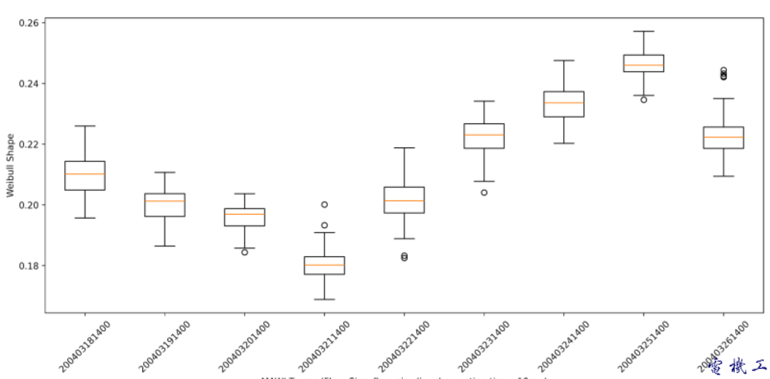
Estimated Weibull Shape

- **Shape Parameter Decreases**
  - The tail of the distribution becomes heavier (longer)
  - Variability in the data increases, meaning there's less predictability in the size of any given flow



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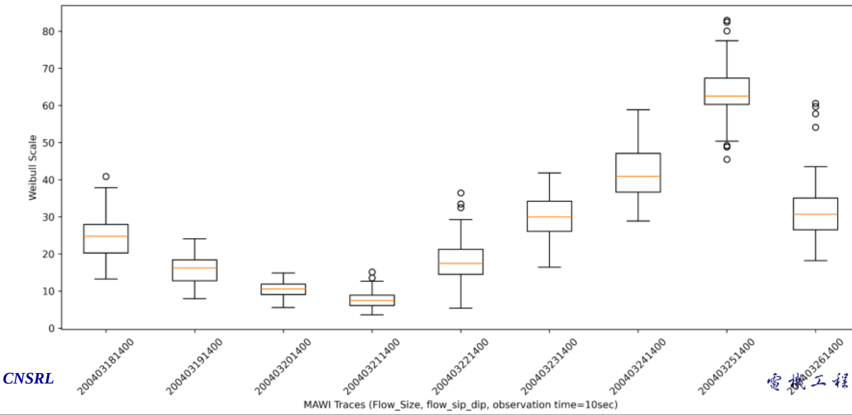
Estimated Weibull Scale

- **Scale Parameter Decreases**
  - The distribution becomes more concentrated near zero
  - The peak of the distribution shifts towards the origin



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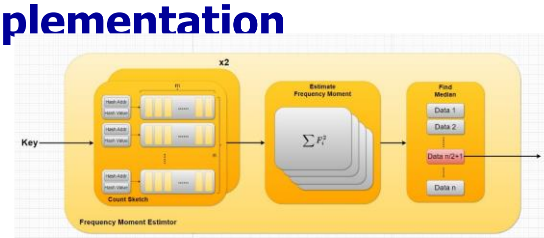
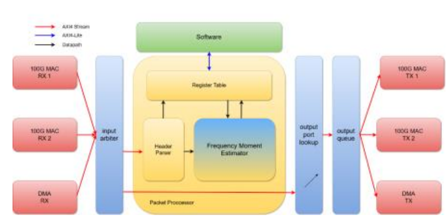
Sketch-based FPGA Implementation



- **F_2 Estimation**
  - AMS-Cormode Sketch base on Count-sketch [5]
- **F_0 Estimation**
  - FM Sketch, Probabilistic Counting with Stochastic Averaging (PCSA) [6]
- **NetFPGA PLUS Framework**
- **Xilinx Alveo U200 FPGA**



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[5] Graham Cormode and Marios Hadjieleftheriou. 2009. Finding the frequent items in streams of data. *Commun. ACM* 52, 10 (2009), 97–105. https://doi.org/10.1145/1562764.1562789

[6] Philippe Flajolet and G. Nigel Martin. 1985. Probabilistic counting algorithms for data base applications. *J. Comput. Syst. Sci.* 31, 2 (1985), 182–209. http://portal.acm.org/citation.cfm?id=5215

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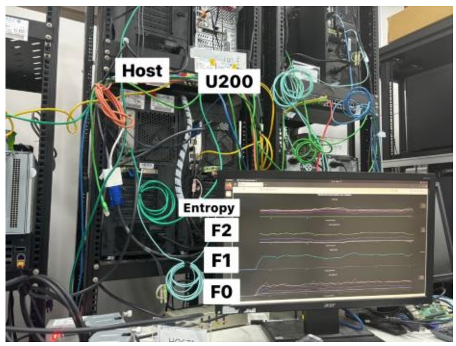
Xilinx FPGA Demo

- Replays the synthetic trace from a 2-port 100Gbps NIC
- Observation time of 30 seconds



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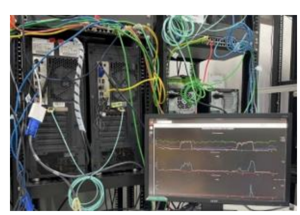
Summary

- **Real-time online processing**
  - exceeding 100Gbps line speed
- **For less than 132K bytes of memory space**
  - Count Sketch: 128K Bytes
  - FM Sketch PCSA: 4K Bytes
- **Flow-Length/ Flow-Size Distribution**
  - Weibull Parameter Estimation
  - Log-Normal Parameter Estimation
- **Sketch-based Implementation**
  - Xilinx Alveo U200 FPGA /w NetFPGA PLUS Framework
- **Suitable to implement on the high-speed network equipment**



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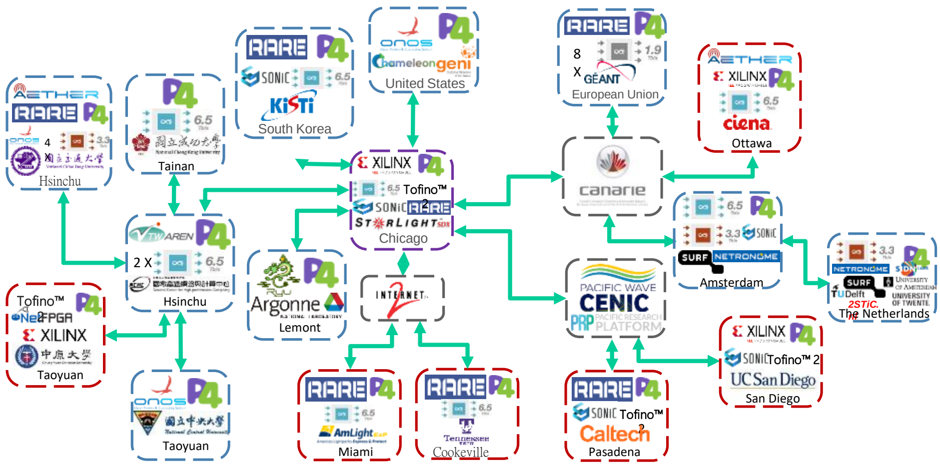
International P4 Experimental Networks (iP4EN)



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