MoonGen
A Scriptable High-Speed Packet Generator

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January 31st, 2016
FOSDEM 2016

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Outline

Hardware vs. Software Packet Generators

Architecture of MoonGen

Hardware Timestamping on Commodity NICs

Precise Rate Control

Example Measurements
Source: www.spirent.com
Challenges for software packet generators

- Hardware packet generators are
  - Precise
  - Accurate
  - Fast
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- Software packet generators
  - Run on cheap commodity hardware
  - Flexible
Challenges for software packet generators

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- Software packet generators
  - Run on cheap commodity hardware
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- Key challenges for software packet generators
  - Rate control
  - Timestamping
Design goals

Design goal of MoonGen
Combine the advantages of both approaches while avoiding their disadvantages.
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Combine the advantages of both approaches while avoiding their disadvantages.

- **Fast:** DPDK for packet I/O, explicit multi-core support
- **Flexible:** Craft all packets in user-controlled Lua scripts
- **Timestamping:** Utilize hardware features found on modern commodity NICs
- **Rate control:** Hardware features and a novel software approach
Architecture

Userscript
- Userscript master
- Userscript slave
  - Lua VM

MoonGen Core
- config API
- data API
- DPDK
- NIC
  - Port
    - $Q_0$ ...
    - $Q_n$

Userscript
- Lua VM
  - spawn
- Lua VM

MoonGen
- Userscript
- Lua VM
- Userscript
- Lua VM

HW
- NIC
- NIC
Hardware timestamping

- NICs support PTP for precise clock synchronization
- PTP support requires hardware timestamping capabilities
- These can be (mis-)used for delay measurements
- Typical precision
  - $\pm 6.4$ ns (Intel 10 GbE chips)
  - $\pm 32$ ns (Intel GbE chips)
- Some restrictions
  - Packets must be UDP or PTP L2 protocol
  - Minimum UDP packet size is 84 bytes
Software rate control in existing packet generators

- Software tries to push single packets to the NIC
- Queues cannot be used, no batch processing
- NICs work with an asynchronous push-pull model
- This can lead to micro-bursts
- Unreliable, imprecise, and bad performance
Modern NICs support rate control in hardware

- Limited to constant bit rate and bursty traffic
- Precision controlled by the hardware
- High performance as queues can be used, but inflexible
Software rate control based on invalid packets

- Fill gaps with invalid packets \( p^i \) (e.g. bad CRC)
- NIC in the DuT drops invalid packets without side-effects
- Combines advantages of both approaches
- Precision limited by byte rate (0.8 ns per byte) and minimum packet size (33 byte)
- High performance & high precision

\[ Q_{\text{memory}} \quad Q_{\text{NIC}} \quad \overrightarrow{\text{Wire}} \]
Does it work?

- Test setup: forward packets with Open vSwitch
- Measure the latency of the device under test

![Graph showing latency vs. offered load](image-url)
Does it work?

- Compare both rate control approaches
- Maximum deviation: 2%
Does it matter?

- Compare CBR with Poisson traffic
- Different response from the device under test

![Graph showing latency vs. offered load for CBR and Poisson MoonGen with median and 25/75th percentile]

Latency [\(\mu s\)]

Offered load [Mpps]

- CBR MoonGen (Median)
- CBR MoonGen (25/75th perc.)
- Poisson MoonGen (Median)
- Poisson MoonGen (25/75th perc.)
Example: Linux NAPI

- Open vSwitch on Linux
- Uniform distribution caused by interrupt throttling

![Graph showing latency distribution](image-url)
Example: Linux Virtualization (VirtIO)

- Open vSwitch forwarding through a VM
- Long tail distribution, typical for VMs

![Latency vs Probability Diagram]

- Probability [%]
- Latency [µs]

- 100 µs
- 150 µs
- 200 µs
- 250 µs
- 300 µs
- 350 µs
Example: Hardware Switch

- AS5712-54X 10/40 GbE OpenFlow switch
- Bimodal distribution caused by more input than output ports
  - Some packets are forwarded directly (cut-through switch)
  - Some packets are blocked by another flow and buffered
Summary

- Speeds of 10 Gbit/s per CPU core (64 byte packets)
- Sub-microsecond precision and accuracy
- Execute user-defined script code for each packet
- Easy to use
Q & A

Try MoonGen yourself!

https://github.com/emmericp/MoonGen

Questions?
[Backup slide] Performance I: Lua can be faster than C

- UDP packets from varying source IP addresses

- Pktgen-DPDK needs a complicated main loop that covers all possibilities
- MoonGen can use a tight inner loop
Generate random UDP packets on 2 10 Gbit NICs
8 calls to Lua’s standard `math.random` per packet
CPUs artificially clocked down to 1.2 GHz
Generate random UDP packets on 2 10 Gbit NICs
- 8 calls to Lua’s standard `math.random` per packet
- CPUs artificially clocked down to 1.2 GHz

![Graph showing packet size vs rate for 1, 2, and 3 cores]
[Backup Slide] Rate control: 500 kpps

![Graph showing the probability distribution of inter-arrival times for MoonGen (hardware), Pktgen-DPDK, and zsend.]
Backup Slide] Rate control: 1,000 kpps

![Graph showing probability distribution for inter-arrival time in microns]

- **MoonGen (hardware)**
- **Pktgen-DPDK**
- **zsend**
### HW/SW rate control details

<table>
<thead>
<tr>
<th>Rate</th>
<th>Software</th>
<th>Bursts</th>
<th>±64 ns</th>
<th>±128 ns</th>
<th>±256 ns</th>
<th>±512 ns</th>
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<tbody>
<tr>
<td>500 kpps</td>
<td>MoonGen</td>
<td>0.02%</td>
<td>49.9%</td>
<td>74.9%</td>
<td>99.8%</td>
<td>99.8%</td>
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<td></td>
<td>Pktgen-DPDK</td>
<td>0.01%</td>
<td>37.7%</td>
<td>72.3%</td>
<td>92%</td>
<td>94.5%</td>
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<tr>
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<td>zsend</td>
<td>28.6%</td>
<td>3.9%</td>
<td>5.4%</td>
<td>6.4%</td>
<td>13.8%</td>
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<tr>
<td>1000 kpps</td>
<td>MoonGen</td>
<td>1.2%</td>
<td>50.5%</td>
<td>52%</td>
<td>97%</td>
<td>100%</td>
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<tr>
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<td>Pktgen-DPDK</td>
<td>14.2%</td>
<td>36.7%</td>
<td>58%</td>
<td>70.6%</td>
<td>95.9%</td>
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<td>zsend</td>
<td>52%</td>
<td>4.6%</td>
<td>7.9%</td>
<td>24.2%</td>
<td>88.1%</td>
</tr>
</tbody>
</table>
Effects of bad rate control

- Interrupt rate of an Open vSwitch packet forwarder

- Micro-bursts confuse dynamic interrupt throttling
- This affects latency (cannot be measured with zsend)
Hardware timestamping precision and accuracy

- Measure latencies of cables of various length
- Calculate encoding time $k$ and propagation speed $v_p$

Result for fiber cable: $k \approx 311\,\text{ns}$, $v_p = 0.72c \pm 0.056c$
Effects of invalid packets

- Median latency of an Open vSwitch packet forwarder
- Packet rate controlled by hardware vs. invalid frames

Minor modifications to the DuT (e.g. an active SSH session) result in a deviation of up to 15% with the same rate control mechanism.