MoonGen: A Scriptable High-Speed Packet Generator

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ABSTRACT
We present MoonGen, a flexible high-speed packet generator. MoonGen is able to saturate 10 GbE links with minimum sized packets using only a single CPU core by running on top of the packet processing framework DPDK. This new kind of packet generator moves the whole packet generation logic into user-controlled Lua scripts, thereby ensuring high flexibility. In addition, we utilize hardware features of Intel NICs that have not been used for packet generators previously. A key feature is the measurement of latency with sub-microsecond precision and accuracy by using hardware timestamping capabilities of modern commodity NICs. We address timing issues with software-based packet generators and apply methods to mitigate those problems with both hardware support on commodity NICs and with a novel method to control the inter-packet gap. Features that were previously only possible with hardware-based solutions are now provided by MoonGen on commodity NICs. MoonGen can also be used as a framework for general-purpose packet processing. MoonGen is available as free software under the MIT license at https://github.com/emmericp/MoonGen.

1. INTRODUCTION
Tools for traffic generation are essential to quantitative evaluations of network performance. Hardware-based solutions for packet generation are expensive and in many cases inflexible. Existing software solutions often lack performance or flexibility and come with precision problems [2].

The state of the art in packet generation, which is discussed further in Section 2, motivated us to design MoonGen. Our novel software packet generator is flexible, fast, and precise without relying on special-purpose hardware.

Moving the whole packet generation logic into user-controlled Lua scripts ensures flexibility. We build on the JIT compiler LuaJIT [17] and the packet processing framework DPDK [12]. Our architecture and its implementation are described in detail in Section 3. This combination allows us to send 14.88 Mpps, line rate at 10 GbE with minimum sized packets, from a single CPU core while executing script code for each packet. Explicit support for multi-core architectures allows us to load multiple 10 GbE interfaces at once.

MoonGen is controlled through its API instead of configuration files. We explain the API in Section 4, presenting code examples for typical use cases. The API allows for applications beyond packet generation as it makes DPDK packet processing facilities available to Lua scripts.

Section 5 evaluates the performance and shows that running scripts for each packet is feasible. Multi-core scaling is also addressed.

Our packet generator can measure latencies with sub-microsecond precision and accuracy. This is achieved by using hardware features of Intel commodity NICs that are intended for synchronization of clocks across networks. Latency measurements are evaluated in Section 6.

Modern 10 GbE NICs also feature hardware support for generating constant bit-rate (CBR) traffic by controlling the inter-departure times of packets. We compare existing software implementations to the hardware-assisted approach of MoonGen in Section 7. Section 8 discusses a new mechanism introduced by MoonGen for generating complex traffic patterns without additional hardware support.

MoonGen is available as free software under the MIT license [5]. Section 9 describes how to use the published code to reproduce all experiments in this paper.

2. STATE OF THE ART
Packet generators face a tradeoff between complexity and performance. This is reflected in the available packet generators: Barebone high-speed packet generators with limited capabilities on one hand and feature-rich packet generators that do not scale to high data rates on the other hand. While high-speed packet generators often only send out pre-crafted Ethernet frames (e.g. pcap files), more advanced packet generators are able to transmit complex load patterns by implement-
ing and responding to higher-layer protocols (e.g. web server load tester). Consequently, there is a lack of fast and flexible packet generators. Besides mere traffic generation, many packet generators also offer the possibility to capture incoming traffic and relate the generated to the received traffic.

The traditional approach to measure the performance of network devices uses hardware solutions to achieve high packet rates and high accuracy. Especially their ability to accurately control the sending rate and precise timestamping are important in these scenarios. Common hardware packet generators manufactured by IXIA, Spirent, or XENA are tailored to special use cases, e.g. performing RFC 2544-compliant device tests. They send predefined traces of higher-layer protocols, but avoid complex hardware implementations of protocols. Therefore, these hardware appliances are on the fast-but-simple end of the spectrum of packet generators. They are focused on well-defined and reproducible performance tests for comparison of networking devices via synthetic traffic. However, the high costs severely limit their usage.

NetFPGA is an open source FPGA-based NIC that can be used as a packet generator. Although costs are still beyond commodity hardware costs, it is used more often in academic publications. For example, in 2009, Covington et al. described an open-source traffic generator based on NetFPGA with highly accurate inter-packet delays. The OFLOPS framework by Rotos et al. is able to measure latencies with nanosecond accuracy via a NetFPGA.

Software packet generators running on commodity hardware are widespread for different use cases. Especially traffic generators that emulate realistic traffic, like Harpoon, suffer from poor performance on modern 10GbE links. We focus on high-speed traffic generators that are able to saturate 10GbE links with minimum sized packets. Bonelli et al. implement a software traffic generator, which is able to send 12 million minimum sized packets per second by using multiple CPU cores. Software packet generators often rely on frameworks for efficient packet transmission to increase the performance further. Less complex packet generators can be found as example applications for high-speed packet IO frameworks: zsend for PF_RING and pktgen for netmap. Wind River Systems provides Pktgen-DPDK and netmap for DPDK. The load generator features a Lua scripting API that can be used to control the parameters of the generator, but the scripts cannot modify the packets themselves. Further, existing tools for packet generation like Ostinato have been ported to DPDK to improve their performance. Previous studies showed that software solutions are not able to precisely control the inter-packet delays. This leads to micro-bursts and jitter, a fact that impacts the reproducibility and validity of tests that rely on a precise definition of the generated traffic.

Ostinato is the most flexible software packet solution of the investigated options as it features configuration through Python scripts while using DPDK for high-speed packet IO. However, its scripting API is limited to the configuration of complex options, the scripts cannot be executed for each packet. Precise timestamping and rate control is also not supported.

One has to make a choice between flexibility (software packet generators) and precision (hardware packet generators) with the available options. Today different measurement setups therefore require different packet generators. For example, precise latency measurements currently require hardware solutions. Complex packet generation (e.g. testing advanced features of network middleboxes like firewalls) requires flexible software solutions. We present a hybrid solution with the goal to be usable in all scenarios.

3. IMPLEMENTATION

We identified the following requirements based on our goal to close the gap between software and hardware solutions by combining the advantages of both. MoonGen must...

(R1) be implemented in software and run on commodity hardware.

(R2) be able to saturate multiple 10GbE links with minimum sized packets.

(R3) be as flexible as possible.

(R4) support precise and accurate timestamping and rate control in hardware.

The following building blocks were chosen based on these requirements.

3.1 Packet Processing with DPDK

Network stacks of operating systems come with a high overhead. We found the performance too low to fulfill requirement (R2). Packet IO frameworks like DPDK, PF_RING ZC, and netmap circumvent the network stack and provide user space applications exclusive direct access to the DMA buffers to speed up packet processing. All of them have been used to implement packet generators that fulfill requirement (R2).

MoonGen is based on DPDK, which supports a wide range of NICs by multiple vendors (currently Intel, Emulex, and Mellanox), is well-documented, fast, and available under the BSD license. PF_RING ZC was not considered further as some parts of this framework,
which are needed for high-speed operation mode, re-
quire purchasing a license. In netmap user space ap-
plications do not have direct access to the NIC’s regis-
ters. This is a safety precaution as a misconfigured NIC
can crash the whole system by corrupting memory [20].
This restriction in netmap is critical as it is designed to
be included in an operating system: netmap is already
part of the FreeBSD kernel [19]. However, MoonGen
needs to access NIC registers directly to implement re-
quirement (R4).

3.2 Scripting with LuaJIT

MoonGen must be as flexible as possible (R3). There-
fore, MoonGen moves the whole packet generation logic
into user-defined scripts as this ensures the maximum
possible flexibility. LuaJIT was selected because related
work shows that it is suitable for high-speed packet pro-
cessing tasks [6] without impacting the overall perfor-
ance (R2).

Its fast and simple foreign function interface allows
for an easy integration of C libraries like DPDK [17].
LuaJIT may introduce unpredictable pause times due
to garbage collection and compilation of code during run
time. This can lead to exhausted receive buffers or
starving transmission buffers.

We disable garbage collection by default in MoonGen
to avoid pause times. Typical scripts in MoonGen do
not rely on dynamic allocation in the transmit logic
and run for a predetermined time. Nevertheless, scripts
can explicitly start the garbage collector if necessary, e.g.
between test runs of a longer experiment.

Pause times introduced by the JIT compiler are in
the range of “a couple of microseconds” [18] and can be
handled by the NIC buffers. The currently supported
NICs feature buffer sizes in the order of hundreds of
kilobytes [9, 10, 11]. For example, the smallest buffer on
the X540 chip is the 160kB transmit buffer, which can
store 128 µs of data at 10GbE. This effectively conceals
short pause times.

3.3 Hardware Architecture

Understanding how the underlying hardware works is
important for the design of a high-speed packet genera-
tor. The typical operating system socket API hides im-
portant aspects of networking hardware that are impor-
tant for the design of low-level packet processing tools.

A central feature of modern commodity NICs is sup-
port for multi-core CPUs. Each NIC supported by
DPDK features multiple receive and transmit queues
per network interface. This is not visible from the
socket API of the operating system as it is handled by
the driver [8]. For example, both the X540 and 82599
10GbE NICs support 128 receive and transmit queues.
Such a queue is essentially a virtual interface and they
can be used independently from each other. [10] [11]

Figure 1: MoonGen’s architecture

Multiple transmit queues allow for perfect multi-core
scaling of packet generation (up to the number of avail-
able queues and CPU cores). Each configured queue can
be assigned to a single CPU core in a multi-core packet
generator. Receive queues are also statically assigned
to threads and the incoming traffic is distributed via
configurable filters (e.g. Intel Flow Director) or hashing
on protocol headers (e.g. Receive Side Scaling). [10] [11]

Commodity NICs also often support timestamping
and rate control in hardware. This allows us to fulfill
(R1) without violating (R4).

MoonGen does not run on arbitrary commodity hard-
ware, we are restricted to hardware that is supported by
DPDK [12] and that offers support for these features.
We currently support hardware features on Intel 82599,
X540, and 82580 chips.

Other NICs that are supported by DPDK but not yet
explicitly by MoonGen can also be used, but without
hardware timestamping and rate control.

3.4 Software Architecture

MoonGen’s core is a Lua wrapper for DPDK that pro-
vides utility functions required by a packet generator.
The MoonGen API comes with functions that config-
ure the underlying hardware features like timestamping
and rate control. About 80% of the current code base
is written in Lua, the remainder in C.

Although our current focus is on packet generation,
MoonGen can also be used to implement arbitrary packet
processing tasks in Lua, e.g. packet forwarding or traffic
analysis.

Figure 1 shows the architecture of MoonGen. It runs
a user-provided script, the userscript, on start-up. This script contains the main loop and the whole packet generation logic.

The userscript will be executed in the master task initially by calling the `master` function provided by the script. This master function must initialize the used NICs, i.e. configure the number of hardware queues, buffer sizes and filters for received traffic. It can then spawn new instances of itself running in slave tasks and pass arguments to them. A slave task runs a specified slave function. It usually receives a hardware queue as an argument and then transmits or receives packets via this queue. Starting a new slave task spawns a completely new and independent LuaJIT VM that is pinned to a CPU core. Tasks only share state through the underlying DPDK library.

All functions related to packet transmission and reception in MoonGen and DPDK are lock-free to allow for multi-core scaling.

MoonGen comes with example scripts that implement basic functionality like sending UDP packets (both IPv4 and IPv6), measuring latencies, measuring inter-arrival times, and generating different inter-departure times like a poisson process and bursty traffic.

4. SCRIPTING API

The best way to understand how to use MoonGen is reading one of the example scripts in the MoonGen repository.

The listings in this section show excerpts from the `hello-world.lua` example script. This script uses two transmission tasks to generate two types of UDP flows and measures their throughput and latencies. It can be used as a starting point for a test setup to benchmark a forwarding device or middlebox that prioritizes real-time traffic over background traffic.

The example code in this section is slightly different from the example code in the repository; it has been edited for brevity. Error handling code like validation of command-line arguments and printing of live statistics (current throughput) is omitted here. The timestamping task has been removed as this example focuses on the basic packet generation and configuration API. Most comments have been removed. The interested reader is referred to our repository for the full example code including timestamping and live reporting of the current throughput.

4.1 Initialization

Listing 1 shows the `master` function. This function is executed in the master task on startup and receives command line arguments passed to MoonGen, the devices and transmission rates to use in this case. It configures one transmit device with two queues and one receiving device with the default settings. The call in line 4 waits until the link on all configured devices is established. It then configures hardware rate control features on the transmission queues and starts 3 slave threads, the first two generate traffic, the last counts the received traffic on the given device. The arguments passed to `dpdk.launchLua` will be passed to the respective functions in the new task. The `loadSlave` function takes the transmission queue to operate on and a port to distinguish background from prioritized traffic.

4.2 Packet Generation Loop

Listing 2 shows the actual packet generation in the `loadSlave` function that is started twice.

```
function loadSlave(queue, port)
    local mem = memory.createMemPool(function(buf)
        buf:getUdpPacket():fill{
            pktLength = PKT_SIZE,
            ethSrc = get MAC from device
            ipSrc = "192.168.1.1",
            udpSrc = "1234",
            udpport = port,
        }
    )
    -- get MAC from device
    while dpdk.running() do
        for _, buf in ipairs(bufs) do
            local pkt = buf:getUdpPacket()
            pkt.ip.src:set(baseIP + math.random() * 255)
            sent = sent + queue:send(pkt)
        end
        printf("%s Port %d: Sent %d pkts", queue, port, sent)
    end
end
```

Listing 2: Transmission slave task

It first allocates a memory pool, a DPDK data structure in which packet buffers are allocated. The MoonGen wrapper for memory pools expects a callback function that is called to initialize each packet. This allows a script to fill all packets with default values (lines 5 to 10) before the packets are used in the transmit loop (lines 17 to 23). The transmit loop only needs to modify a single field in each transmitted packet (line 20) to generate packets from randomized IP addresses.

Line 15 allocates a `bufArray` object, a thin wrapper around a C array containing packet buffers. This is used instead of a normal Lua array for performance reasons.
reasons in MoonGen. It contains a number of packets in order to process packets in batches instead of passing them one-by-one to the DPDK API. Batch processing is an important technique for high-speed packet processing.

The main loop starts in line 17 with allocating packets of a specified size from the memory pool and storing them in the packet array. It loops over the newly allocated buffers (line 18) and randomizes the source IP (line 20). It then enables checksum offloading (line 22) and transmits the packets (line 23).

Note that the main loop differs from a packet generator relying on a classic API. MoonGen, or any other packet generator based on a similar framework, cannot simply re-use buffers because the transmit function is asynchronous. Passing packets to the transmit function merely places pointers to them into a memory queue, which is accessed by the NIC later. A buffer must not be modified after passing it to DPDK. Otherwise, the transmitted packet data may be altered, if the packet was not yet fetched by the NIC.

We therefore have to allocate new packet buffers from the memory pool in each iteration. Pre-filling the buffers at the beginning allows us to only touch fields that change per packet in the transmit loop. Packet buffers are recycled by DPDK in the transmit function, which collects packets that were sent by the NIC earlier. This does not erase the packets’ contents.

### 4.3 Packet Counter

Listing 3 shows how the packet reception API of MoonGen can be used to measure the throughput of the different flows is by counting the incoming packets. Example scripts that do not distinguish between different flows can omit this step and simply use the NIC’s statistics registers that are available via `queue:getRxStats()`.

```lua
function counterSlave(queue)
  local bufs = memory.bufArray()
  local stats = {}
  for i = 1, rx do
    local rx = queue:recv(bufs)
    local port = buf:getUdpPacket().udp:getDstPort()
    stats[port] = (stats[port] or 0) + 1
  end
  bufs:freeAll()
  for k, v in pairs(stats) do
    printf("%s Port %d: Received %d pkts", queue, k, v)
  end
end
```

Listing 3: Packet counter slave task

The task receives packets from the provided queue in a `bufArray` in line 5. It then extracts the UDP destination port from the packet (line 8) and keeps statistics per port. These statistics are printed in the end in line 13 to 15.

This script can easily be adopted for a real test setup by adapting the code to the test setup by changing hardcoded constants like the used addresses and ports. The full script in the repository outputs the current throughput periodically in the transmission and reception loops. A separate timestamping task acquires and prints latency statistics.

### 4.4 Best Practices

We identified the following best practices during our experiments with MoonGen.

A separate script should be written for each experiment setup as this approach is meant to eliminate complex configuration files by writing scripts. Writing a complex configuration system inside a userscript is beside the point. Restrict command line arguments to the most basic settings like the network ports and packet rate.

Save statistics in a machine-readable format like CSV for further processing. This can be done through Lua’s default file IO facilities. Statistics should be saved on a per-task basis and aggregated during post-processing of the results as the inter-thread communication in MoonGen is currently limited to a bare minimum.

Always try to acquire timestamps and latency measurements if possible. The histograms of the latencies often offer interesting insights in the queuing behavior of the device under test.

Base your experiment scripts on one of our example scripts. It is often sufficient to modify a few lines of code to add the desired functionality as our examples try to be exhaustive.

### 5. PERFORMANCE

Writing the whole generation logic in a scripting language raises concerns about the performance. One of LuaJIT’s strengths is that it allows for easy integration with existing C libraries and structs: it can directly operate on C structs and arrays without incurring overhead for bound checks or validating pointers. Thus, crafting packets is very efficient in MoonGen.

The obvious disadvantage is that unchecked memory accesses can lead to memory corruption, a problem that is usually absent from scripting languages. However, the most critical low-level parts like the implementation of the NIC driver are handled by DPDK. The MoonGen core then wraps most of the potentially unsafe parts for the userscript if possible. Forgetting to allocate packet buffers or writing beyond buffer boundaries are the only operations in a userscript that can lead to memory corruption. This is an intentional design decision to aid the performance.

### 5.1 Test Methodology

Measuring the CPU load caused by a DPDK-based application is difficult because DPDK recommends a
1. Busy-wait loop \[12\], i.e. the CPU load is always 100% for a typical application. MoonGen and other DPDK-based generators like Pktgen-DPDK \[24\] are no exception to this. The bottleneck for packet transmission is usually not the CPU but the line rate of the network, so just measuring the achieved rate provides no insight. We therefore decrease the clock frequency of our CPU such that the processing power becomes the bottleneck. The performance can then be quantified as CPU cycles per packet. The same approach was used by Rizzo to evaluate the performance of netmap \[20\].

The tests in this section were executed on an Intel Xeon E5-2640 v2 CPU clocked at 2GHz, which can be clocked down to 1.2GHz. To ensure consistent measurement results, we disabled CPU features compromising reproducibility. These include Hyper-Threading, which may influence results if the load of two virtual cores is scheduled to the same physical core, as well as TurboBoost and SpeedStep, which adjust the clock speed according to the current CPU load and interfere with our manual adjustment of the frequency.

The performance of all tested configurations was very stable; we therefore omit error bars and confidence intervals for the throughput. This absence of a significant variance is typical for a framework like DPDK and was also observed for netmap by Rizzo \[20\].

5.2 Comparison with Pktgen-DPDK

Our scripting approach can even increase the performance compared to a static packet generator. We show this by comparing MoonGen to Pktgen-DPDK \[24\], a packet generator for DPDK written in C.

Figure 2 shows the packet rates of MoonGen and Pktgen-DPDK. Both were configured to generate minimum-sized UDP packets with 256 varying source IP addresses on a single CPU core. Pktgen-DPDK requires 1.7 GHz to hit the 10 GbE line rate (14.88 Mpps), MoonGen only 1.4 GHz. Therefore, MoonGen requires fewer cycles per packet: 89 vs. 103, i.e. MoonGen is 13% more efficient in this specific scenario.

![Figure 2: CPU frequency vs. generated packets per second](image)

This increased performance is an inherent advantage of MoonGen’s architecture. Pktgen-DPDK needs a complicated main loop that covers all possible configurations even though we are only interested in changing IP addresses in this test scenario. MoonGen, on the other hand, can use a script that consists of a tight inner loop that exclusively executes the required tasks: allocating pre-filled packet buffers, modifying the IP address, and sending the packets. So you only pay for the features you actually use with MoonGen.

5.3 Multi-core Scaling

The achieved performance depends on the script; the previous example was a very light workload solely for the comparison to Pktgen-DPDK, which is limited to such simple patterns. We therefore test a more involved script to put stress on MoonGen to show the scaling with multiple cores.

Figure 3 shows the performance under heavy load and the scaling with the number of CPU cores.

MoonGen was configured to generate minimum-sized packets with random payload as well as random source and destination addresses and ports. The code generates 8 random numbers per packet to achieve this. The packets were sent out on two different 10 GbE interfaces. As expected, linear scaling can be observed up to the line rate limit (dashed line).

The code was written in idiomatic Lua without specific optimizations for this use case: LuaJIT’s standard random number generator was used. It operates on floating point numbers, which were scaled to the appropriate 16 or 32-bit integer range and converted. A special-purpose integer random generator could speed up this code. Despite the lack of optimizations, the code was initially found to be too fast for meaningful scalability measurements (8.6 Mpps on a single core). We therefore reduced the CPU’s clock speed to 1.2 GHz and increased the number of NICs to 2 for this test.

5.4 Scaling Beyond 10 Gigabit

Sending traffic to multiple network cards is, from the
transmit task’s point of view, not different from using multiple queues on a single NIC. We tested MoonGen with up to 60 GBit/s on 6 different interfaces simultaneously without encountering notable issues.

40 GbE server adapters like the Intel XL710 family are currently being introduced to the market. The 40 GbE ports on this NIC are architecturally a quad 10 GbE port as the ports can be used as four independent 10 GbE ports [13]. We do not expect significant challenges when moving to 40 GbE due to this architecture and promising tests with multiple 10 GbE ports.

6. HARDWARE TIMESTAMPING

Another important performance characteristic beside throughput is the latency of a system. Modern NICs often offer hardware support for the IEEE 1588 Precision Time Protocol (PTP) for clock synchronization across networks. PTP can be used either directly on top of Ethernet as a layer 2 protocol with EtherType 0x88F7 or as an application-layer protocol on top of UDP [7].

We examined the PTP capabilities of the Intel 82580 GbE and the 82599 and X540 10 GbE chips: They support timestamping of PTP Ethernet and UDP packets on a configurable port. They can be configured to timestamp only certain types of PTP packets, identified by the first byte of their payload. The second byte must be set to the PTP version number. All other PTP fields in the packet are not required to enable timestamps and may contain arbitrary values. [9, 10, 11] This allows us to measure latencies of almost any type of packet.

Most Intel NICs, including all 10 GbE chips, save the timestamps for received and transmitted packets in a register on the NIC. This register must be read back before a new packet can be timestamped [10, 11], which limits the throughput of timestamped packets. Some Intel GbE chips like the 82580 support timestamping all received packets by prepending the timestamp to the packet buffer [9].

6.1 Precision and Accuracy

Timestamping mechanisms of the Intel 82599 and Intel X540 10 GbE chips operate at 156.25 MHz for 10 GbE speeds [10, 11]. The frequency is reduced to 15.625 MHz when a 1 GbE link is used. This results in a precision of 6.4 ns for 10 GbE and 64 ns for 1 GbE.

The datasheet of the Intel 82580 GbE [3] controller lacks information about the clock frequency. Testing shows that the acquired timestamps are always of the form \( t = n \cdot 64 \text{ ns} + k \cdot 8 \text{ ns} \) where \( k \) is a constant that varies between resets of the timestamping logic, so the precision is 64 ns.

All of these NICs timestamp packets late in the transmit path and early in the receive path to be as accurate as possible [9, 10, 11]. We tested the timestamping functionality by using loop-back multimode OM3 fiber cables on an 82599-based NIC with a 10GBASE-SR SFP+ module and Cat 7 cable between the two ports of a dual-port X540-based NIC. Table 1 shows measured latencies \( t_x \) for different cable lengths \( x \) for each NIC as well as the (de-)modulation time \( k \) and propagation speed \( v_p \), which can be calculated from these data points with the equation \( t = k + l/v_p \). The (de-)modulation on the copper-based NIC is significantly slower, this is likely due to the more complex line code required to transfer 10 Gbit/s over copper. This calculation does not take any errors in the cable length into account; we rely on the vendor’s specification.

Each experiment was repeated 100000 times. All measurements for each cable yielded the same result except for the 8.5 m fiber cable. This cable caused a latency of 345.6 ns in 50.2% of the measurements and 358.4 ns in the other 49.8% (Table 1 shows the average). This variance is due to the fact that the timer that is saved when the timestamp is taken is incremented only every two clock cycles on the 82599 chip [10], i.e. the granularity of the timer is 12.8 ns but the timestamping operates at 6.4 ns. The absence of a significant variance demonstrates a high precision, the plausible results for the modulation time [25] and the linear behavior of the propagation speed show a high accuracy.

6.2 Clock Synchronization

Test setups can involve multiple network ports that may even be on different NICs. For example, measuring the forwarding latency of a switch requires timestamping a packet on two different ports. MoonGen therefore needs to be able to synchronize the clocks between two network ports. This is even necessary between two ports of a dual-port NIC, which are completely independent from the user’s point of view.

MoonGen synchronizes the clocks of two ports by reading the current time from both clocks and calculating the difference. The clocks are then read again in the opposite order. The resulting differences are the same if and only if the clocks are currently synchronous (assuming that the time required for the PCIe access is constant). We observed randomly distributed outliers in about 5% of the reads. We therefore repeat the measurement 7 times to have a probability of > 99.999% of at least 3 correct measurements.

The median of the measured differences is then used to adjust one of the clocks to synchronize them. This adjust operation must be atomic as a read-modify-write cycle. Such an operation is also required by PTP, so the NICs support this.

Tests show that this technique synchronizes the clocks with an error of ±1 cycle. Therefore, the maximum accuracy for tests involving multiple network interfaces is 19.2 ns for the 10 GbE chips.
<table>
<thead>
<tr>
<th>NIC</th>
<th>$t_{2m}$ [ns]</th>
<th>$t_{8.5m}$ [ns]</th>
<th>$t_{10m}$ [ns]</th>
<th>$t_{20m}$ [ns]</th>
<th>$k$ [ns]</th>
<th>$v_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>82599 (fiber)</td>
<td>320</td>
<td>352</td>
<td>-</td>
<td>403.2</td>
<td>310.7 ± 3.9 0.72c ± 0.056c</td>
<td></td>
</tr>
<tr>
<td>X540 (copper)</td>
<td>-</td>
<td>-</td>
<td>2252.8</td>
<td>2310.4</td>
<td>2195.2 ± 9.6 0.59c ± 0.065c</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Timestamping accuracy measurements

Figure 4: Clock drift between multiple NICs

6.3 Clock Drift

Using two different clocks also entails the risk of clock drifts. Drift on X540-based NICs depends on the physical wiring as the timestamping clock is synchronized to the physical layer. Two ports on different X540-based NICs that are directly connected do not exhibit any clock drift while the link is established. However, the clocks of two ports on the same X540 NIC will drift if they are connected to two different NICs.

Figure 4 shows clock drifts in several configurations. All NICs were left unconnected during the test. MoonGen handles clock drift by resynchronizing the clocks before a timestamped packet is sent. The worst-case observed drift was 35 $\mu$s per second, i.e. a relative error of only 0.0035%. This error is too small to be significant for our purposes.

6.4 Limitations

Using PTP messages for latency measurements comes with limitations. The latency measurements are restricted to Ethernet frames with the PTP EtherType and UDP packets. MoonGen cannot measure latencies of other protocols.

The naïve handling of clock drift by resynchronizing the clocks for each packet allows for only one timestamped packet in flight, limiting the throughput to 1 Pkt/RTT. MoonGen scripts therefore usually use two transmission queues, one that sends timestamped packets and one that sends regular packets. The regular packets can be crafted such that the device under test cannot distinguish them from the timestamped packets, e.g. by setting the PTP type to a value that is not timestamped by the NIC. So MoonGen effectively samples the timestamps of random packets in the data stream. Note that the benchmarking standard RFC 2544 calls for only one timestamped packet in a 120 second interval [3]. MoonGen can timestamp several thousands of packets per second to calculate average latencies and histograms.

The investigated NICs refuse to timestamp UDP PTP packets that are smaller than the expected packet size of 80 bytes. Larger frames are timestamped properly. This restriction does not apply to packets with the PTP EtherType as the minimum PTP packet size is below 64 bytes in this configuration.

Measurements of inter-arrival times are restricted to GbE networks due to lack of hardware support for timestamping in line rate on 10 GbE NICs.

Based on the discussed measurement results and despite these limitations, we argue that special-purpose hardware is not necessary to conduct highly precise and accurate latency and inter-arrival time measurements.

7. RATE CONTROL

An important feature of a packet generator is controlling the packet rate and generating specific timing patterns to simulate real-world scenarios.

MoonGen utilizes hardware rate control features of Intel NICs to generate constant bit rate and bursty traffic. We also implement a novel software-based rate control for realistic traffic patterns, e.g. based on a poisson process. That is discussed further in Section 8; this section focuses on software rate control in other packet generators and hardware rate control.

7.1 Software Rate Control in Existing Packet Generators

Trying to control the timing between packets in software is known to be error-prone [2, 4].

The main problem with software-based rate control is that the packet generator needs to push individual packets to the NIC and then has to wait for the NIC to transmit it before pushing the next packet.

However, modern NICs do not work that way: they rely on an asynchronous push-pull model and not on a pure push model. The software writes the packets into a queue that resides in the main memory and informs the NIC that new packets are available. It is up to the NIC to fetch the packets asynchronously via DMA and store them in the internal transmit queue on the NIC before transmitting them. A good explanation of this packet flow can be found in the datasheet of the X540 chip [11] (Section 1.7), other NICs follow a similar process.
7.2 Hardware Rate Control

Intel 10GbE NICs feature hardware rate control: all transmit queues can be configured to a specified rate. The NIC then generates constant bit-rate (CBR) traffic. This solves the two problems identified in the previous section. The software can keep all available queues completely filled and the generated timing is up to the NIC. Figure 6 shows this architecture.

The disadvantage is that this approach is limited to CBR traffic and bursty traffic (by changing the rate parameter periodically).

7.3 Evaluation

We compare our hardware-assisted solution to the software-based rate control algorithms found in zsend 6.0.2 (an example application of the PF_RING framework [15]), and Pktgen-DPDK 2.5.1 [24] to quantify the adverse effects of software-based rate control.

We use an 82580 GbE controller, which is able to timestamp arbitrary received packets in line rate (cf. Section 6) to measure inter-arrival times. Figure 7 compares the inter-arrival times of packets generated by MoonGen. The packet generators use an X540 NIC, which supports operation at GbE speeds. The histograms have a bin size of 64 ns (precision of the 82580 chip) and were generated by observing 1,000,000 packets.

Traffic from a hardware rate-controlled NIC oscillates around the targeted inter-arrival time by up to 256 ns and it avoids generating bursts (inter-arrival time of 672 ns, marked with a black arrow in Figure 7) almost completely. Table 2 summarizes the precision of the tested packet generators. The best result in each column is highlighted.

We discussed these findings with the authors of zsend as we configured it explicitly to avoid bursts. We then tested several suggested configurations and versions. We concluded that these observations indicate a bug in the PF_RING ZC framework that is currently being investigated.

It stands to reason that the precision problems as well as the micro-bursts intensify further at rates beyond 1 Gbit/s with software-based rate control. Measuring inter-arrival times on 10 GbE is a challenging task: Reliable measurements require special-purpose hardware. Unfortunately, our testbed is not equipped with such hardware. We will address this measurement in future work.

We do not provide software-based measurements here because we believe they are too inaccurate and verifying their accuracy is impossible without special-purpose hardware.

We believe that the precision of our hardware-assisted approach even improves at 10 GbE speeds: The frequency of the internal clock on the NIC that controls the inter-departure times is scaled up by a factor of 10 when operating at 10 GbE compared to GbE [11].
### Table 2: Rate control measurements

<table>
<thead>
<tr>
<th>Rate</th>
<th>Packet Generator</th>
<th>Micro-Bursts</th>
<th>±64 ns</th>
<th>±128 ns</th>
<th>±256 ns</th>
<th>±512 ns</th>
</tr>
</thead>
<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>
</tr>
<tr>
<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>
</tr>
<tr>
<td></td>
<td>zsend</td>
<td>28.6%</td>
<td>3.9%</td>
<td>5.4%</td>
<td>6.4%</td>
<td>13.8%</td>
</tr>
<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>
</tr>
<tr>
<td></td>
<td>Pktgen-DPDK</td>
<td>14.2%</td>
<td>36.7%</td>
<td>58%</td>
<td>70.6%</td>
<td>95.9%</td>
</tr>
<tr>
<td></td>
<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>

#### 7.4 Effects of Micro-Bursts on Linux Systems

Figure 8 presents the interrupt rate on a Linux packet forwarder running Open vSwitch with respect to increasing load generated by MoonGen and zsend. The micro-bursts generate a low interrupt rate. The likely explanation for this is that the bursts trigger the interrupt rate moderation feature of the driver earlier than expected. This shows that bad rate control can have a measurable impact on the behavior of the tested system.

#### 7.5 Limitations of Hardware Rate Control

In our tests we encountered that the rate control feature of Intel NICs shows unpredictable behavior with packet rates above \( \sim 9 \text{Mpps} (\sim 6 \text{Gbit/s wire-rate with 64 byte packets}) \). A work-around is configuring two transmission queues and sending a CBR stream from both of them. Note that this is not equivalent to a single transmission queue with proper rate control as both queues control their transmission rate independently from each other. This means the inter-packet spacing is no longer constant.

The investigated NICs are also restricted to CBR traffic, so MoonGen still needs an implementation of software-based rate control for other traffic patterns.

#### 8. CONTROLLING INTER-PACKET GAPS IN SOFTWARE

To overcome the restriction to constant bit rate or bursty traffic, MoonGen implements a novel mechanism for software-based rate control. This allows MoonGen to create arbitrary traffic patterns.

##### 8.1 Sending Gaps on the Wire

We were not satisfied with the precision of existing software rate control mechanisms (cf. Section 7.3 and [2, 4]) so we present a new method here. All existing packet generators try to delay sending packets by not sending packets for a specified time, leading to the previously mentioned problems. MoonGen fills the gaps between packets with invalid packets instead. Varying the length of the invalid packet precisely determines the time between any two packets and subsequently allows the creation of arbitrary complex traffic patterns. With this technique, we can still make use of the NIC’s queues and do not have to rely on any timing related to DMA accesses by the NIC.

This approach requires some support by the device under test: it needs to detect and ignore invalid packets in hardware without affecting the packet processing logic. MoonGen uses packets with an incorrect CRC.
checksum and, if necessary, an illegal length for short gaps. All investigated NICs in our testbed drop such packets early in the receive flow: they are dropped even before they are assigned to a receive queue, the NIC only increments an error counter [9, 10, 11]. Subsequently, the packet processing software is not affected in any way by this software rate control mechanism.

Figure 9 illustrates this concept. Shaded packets $p_i$ have an incorrect CRC checksum, all other packets $p_k$ a correct one. Note that the wire and all transmission queues are completely filled, i.e. the generated rate has to be the line rate.

In theory, arbitrary inter-packet gaps should be possible. Unfortunately, the tested NICs pad packets to a minimum wire-length (including Ethernet preamble, start-of-frame delimiter, and inter-frame gap) of less than 76 bytes (8 bytes smaller than a minimal-sized Ethernet packet) even when padding is explicitly disabled. This means that gaps with a length of 1 to 75 bytes (0.8 ns to 60 ns on 10 GbE) cannot be generated.

8.2 Evaluation

We generate CBR traffic with our approach and compare it to CBR traffic generated by the hardware facilities of our NIC by comparing the response of a DuT.

Figure 10 shows the difference of the median forwarding latency of a server running Open vSwitch. The test is restricted to the range 0.1 Mpps to 1.9 Mpps as the DuT becomes overloaded at higher rates and the latency is a function of the buffer size of the DuT after this point. The maximum relative deviation of the median is below 2.5%, the 25th and 75th percentiles are below 4%, this shows that the system under test shows the same response and latency distribution to both traffic generation methods. The difference in the average latency is below 0.05 times its standard deviation at all measurement points.

Minor modifications to the DuT, e.g. an active SSH connection or rebooting the system, and re-running the test with hardware-based rate control have a larger impact than changing the method of traffic generation to our software approach. This shows that loading the DuT with a large number of invalid packets does not affect the software.

8.3 Example: Poisson Traffic

CBR traffic is often an unrealistic test scenario for measurements of latency. Adding bursts or a poisson process allows for more sophisticated tests that also stress buffers as the system becomes temporarily overloaded.

Figure 11 shows the measured latency of a server running Open vSwitch configured to forward packets with CBR (hardware rate control) and poisson (CRC-based software rate control) traffic patterns between two interfaces. The outlier at 0.4 Mpps for CBR traffic was
reproducible across multiple re-measurements on different servers. The sudden drop in latency before the system becomes overloaded was also reproducible. Both are likely artifacts of the interaction between the interrupt throttle algorithm and the dynamic interrupt adaption of Linux on the DuT. The artifacts are present regardless of how the CBR traffic is generated (cf. Figure 10), so this is not due to MoonGen but due to the DuT.

The system becomes overloaded at about 1.9 Mpps, resulting in packet drops and a very large latency (about 2 ms in this test setup) as all buffers are filled. The overall achieved throughput is the same regardless of the traffic pattern and method to generate it. This result shows that the traffic pattern can affect the DuT in an experiment measurably.

8.4 Limitations of our Approach

Shorter per-byte transmission times improve both the granularity and the minimum length that can be generated. This means our solution works best on 10 GbE where the granularity is 0.8 ns and only the range 0.8 to 60 ns cannot be generated.

Due to the minimum size of 76 bytes, gaps between 1 and 75 bytes cannot be precisely represented but only approximated. This is done by occasionally skipping an invalid packet and increasing the length of other gaps. The overall rate still reaches the expected average with this technique, i.e. the accuracy is high but the precision is low for these delays.

Our approach is optimized for experiments in which the device under test (or the first hop in a system under test) is a software-based packet processing system and not a hardware appliance. Hardware might be affected by an invalid packet. In such a scenario, we suggest to route the test traffic through a store-and-forward switch that drops packets with an invalid CRC checksum. This effectively replaces the invalid packets with real gaps on the wire. Note that the effects of the switch on the inter-arrival times need to be carefully evaluated first.

A possible work-around for gaps with a length between 1 and 75 bytes is using multiple NICs to generate traffic that is sent to a switch. The switch then drops the invalid frames and multiplexes the different streams before forwarding them to the DuT. This only works if the generated pattern can be split into multiple streams, e.g. by overlaying several poisson processes.

9. REPRODUCTION OF RESULTS

We encourage you to install MoonGen and reproduce the results from this paper to verify our work. All experiments conducted for this paper can be reproduced with the included example scripts and NICs based on Intel 82599, X540, and 82580 chips.

The performance evaluation in Section 5 was based on 13-multi-flows.lua and heavy-workload.lua on an Intel Xeon E5-2640 v2 CPU with a nominal clock rate of 2.0 GHz.

The timestamping accuracy in Section 6 was measured with the script timestamps.lua, the clock drift measurements with drift.lua.

All inter-arrival times in Section 7 were measured with inter-arrival-times.lua. The script 12-load-latency.lua with the timestamping task disabled was used to generate the tested traffic. The suggested workaround for the hardware rate control limitations at high rates is implemented in tx-multi-core.lua. Sending bursty traffic is implemented in 12-bursts.lua.

The example measurement of the interrupt rate in Section 7,4 was conducted with 12-load-latency.lua and zsend 6.0.2.

12-poison-load-latency.lua (with an additional option to send CBR traffic by replacing the poisson process with a constant) and 12-load-latency.lua were used for the comparison in Section 5.2. The latency measurements with poisson and CBR traffic in Section 5.3 were also based on these scripts.

The DuT for these tests was Open vSwitch 2.0.0 on Linux 3.7 with ixbge 3.14.5 running on a server with a 3.3 GHz Intel Xeon E3-1230 v2 CPU. Only a single CPU core was used by configuring the NIC with only one queue. Each test was run for at least 30 seconds with at least 30000 timestamped packets.

All measurements were conducted on Intel X540 NICs except for the inter-arrival times (Intel 82580) and fiber loopback measurements (Intel 82599). The tests were conducted with different versions of MoonGen. We confirmed that all described experiments are reproducible with commit TODD in our git repository.

10. CONCLUSIONS AND FUTURE WORK

We have presented a general-purpose packet generator that uses hardware features of commodity NICs to implement functionality that was previously only available on expensive special-purpose hardware. MoonGen represents a hybrid between a pure software-based solution and one based on hardware. It combines the advantages of both approaches while mitigating shortcomings by using both hardware-specific features and novel methods for rate control.

MoonGen supports measuring latencies with sub-microsecond accuracy and precision. The desired packet rate can be controlled precisely through both hardware-support and our rate control algorithm based on filling gaps with invalid packets.

We have shown that it is feasible to use modern imple-
mentations of scripting languages to craft packets without sacrificing speed. This makes MoonGen flexible and extensible. The flexibility goes beyond the capabilities provided by hardware load generators as each packet can be crafted in real-time by a script. Experiments that respond to incoming traffic in real-time are possible as MoonGen also features reception and analysis of packets.

We will continue to develop MoonGen and add support for more NICs. We are currently in the process of extending our testbed to include Intel XL710 40GbE NICs. We do not expect significant challenges due to promising tests with multiple 10GbE ports (cf. Section 5.4).

MoonGen’s flexible architecture allows for further applications like analyzing traffic in line rate on 10GbE networks or doing internet-wide scans from 10GbE uplinks. You can find the latest version of MoonGen in our git repository [5].

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11. REFERENCES


