VITO: VIrtual Testbed Orchestration for Automation of Networking Experiments

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ABSTRACT

In this paper we describe the VIrtual Testbed Orchestration platform VITO. It automates networking experiments in a virtualized environment on a single server. It serves for performance evaluation of networking protocols. Networking nodes are modelled by virtual machines and the Linux module TC is used to model link characteristics: netem applies link properties like packet delay, jitter, etc. and tbf enforces bandwidth limitations including buffer sizes. An experimental performance analysis gives recommendations for tbf configuration and provides an application example.

Keywords

Testbed; Networking; Virtual Machines; Simulation; Experimentation; Performance Evaluation

1. INTRODUCTION

In computer networking research, simulation, emulation, and hardware testbeds are used to implement new protocols and control mechanisms and evaluate their performance. With simulation, network control is easy and it is convenient to perform large experiments. However, a challenge is to correctly model complex protocols like various TCP variants with sufficient accuracy and to validate them. Some simulators allow the integration of real Linux network stacks, but this is bound to certain operating system versions that are currently not up to date which is a problem for testing latest protocol enhancements [15]. Highly complex communication technologies may take long simulation times if modelled on a low level. Network emulators interconnect real devices over a simulated network which can be easily configured. An example is NetSim [27]. Network emulators generally can support only low networking speeds so that only limited experiments can be conducted. Highspeed experiments are not possible.

Experimentation on hardware testbeds allows application of original protocol stacks and real protocol implementations. However, hardware testbeds are heavy-weight solutions. If an experiment is large in terms of nodes, it requires lots of physical hardware, administration overhead, experimentation is expensive, requires lots of space, energy, i.e., large overhead is involved, and it lacks configuration flexibility. In addition, separate management tools are needed to efficiently leverage different kinds of hardware.

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Another solution are networking experiments in a virtualized environment. The nodes of an experiment are modeled by virtual machines (VMs) which may run any operating system, therefore latest protocol stacks may be evaluated. Communication links between the VMs may be modelled with appropriate characteristics such as rate, delay, buffer sizes, packet loss, and possibly jitter.

There are a few frameworks for network experimentation in virtualized environments, e.g., Mininet [14]. They allow virtual interconnection of virtual nodes, but they do not provide detailed control over link characteristics which is essential for performance evaluation.

In this paper we describe a platform for VIrtual Testbed Orchestration (VITO) that supports automation of networking experiments on a single server for the purpose of performance evaluation. A major contribution is the automation framework and the configuration of virtual links using the Linux tool TC. We use netem to add delay and a token bucket filter (tbf) to model bandwidth and buffer size. We give recommendations for configuration and application examples.

The paper is structured as follows. In Section 2 we give an overview of related work. We describe VITO in Section 3. In Section 4 experimentally analyze various configuration options for TC and give recommendations for configuration. Finally, we provide an application example of VITO. Section 5 summarizes this work.

2. RELATED WORK

In this section, we briefly discuss other testbed orchestration tools. There are several commercial testbed orchestrators for both virtual and physical testbeds. We describe Mininet for its prevalence, Spirent Velocity [24] as an example for high-efficiency, the TRIANGLE project [10] as an example for technology-specific experimentation, and Virtual Wall [5] as an example for large scale testing.

2.1 Mininet

The most widely known testbed environment is Mininet. It was developed for SDN testing, especially in connection with OpenFlow [16]. Mininet emulates multiple nodes and links on a single, local machine. The nodes run in different name spaces, but share the same kernel. Their virtual interfaces are directly connected to a software switch. The Mininet approach is very lightweight with regard to memory and computing overhead. Configuration flexibility is limited because the configuration of the host applies to all virtual nodes. Due to their weak separation, the nodes can influence each other. Mininet is often used for testing of various SDN protocols and for demonstration purposes. This does not require accurate modelling of link behaviors. Network interfaces are all on the same host and transmission results in memory copies. Since version 2.0, Mininet also supports bandwidth and delay options. Nevertheless, it does not implement real separate networking stacks so that we cannot rely on Mininet to reveal the same quantitative behaviour as real hardware and software.

2.2 Spirent Velocity

Spirent Velocity is a testbed orchestrator aiming at high utilization of available resources. The concept comes with a virtualization environment and a software manager schedules tests on physical or virtual testbeds. As the experimentation platform is proprietary, validation of experimental results is difficult. Our aim is not high utilization of involved hardware, but separation of virtualized nodes to avoid performance impacts.

2.3 TRIANGLE Project

The TRIANGLE project is funded by the European Commission under the Fire+ initiative and runs over three years from 2016 until 2018. It offers a 5G testbed for app developers, mobile operators, and device makers. The testbed provides special hardware for the emulation of mobile links because it focuses on 5G operation. The resources can be leveraged from remote for experimental purposes. Our goal is to use the resources of a local server for testing protocols on layer 2 and higher.

2.4 Virtual Wall

Virtual Wall is a large scale testing environment consisting of 300 physical nodes which can be used with any operating system in any topology. The link characteristics are modeled in software using special FreeBSD [28] nodes. This approach offers the same flexibility as VITO but at a higher hardware cost since every node is a physical server. Since the links are also modeled in software this approach isn't more accurate than the one we propose.

3. VIRTUALIZED TESTBED ARCHITECTURE AND EXPERIMENTATION METHODOLOGY

We first give an introduction into VITO's virtualized testbed architecture and experimentation methodology. We report the virtualization environment and explain how experiments are orchestrated and executed with VITO. We explicate some optimizations for faster generation of virtualized testbeds. We describe the integration of physical network interfaces and their virtualization, which may be useful for some experiments. Finally, we show how link characteristics can be modelled using the Linux TC tool.

3.1 Introduction and Overview

Figure 1 gives an overview of the experimentation methodology. Physical nodes like end systems or routers are modelled by VMs and connected via one or more IEEE 802.1d [1] software bridges through virtual interfaces (vIFs). We call those VMs node VMs (NVMs) and the bridges experiment bridges (EBs). Possibly, additional auxiliary VMs (AVMs) may be used in the experiment to act as routers or switches. NVMs and AVMs are jointly denoted as experiment VMs (EVMs). A single managing VM (MVM) is connected to all EVMs in the testbed via a managing bridge (MB). The MVM orchestrates the virtual testbed consisting of EBs and EVMs, controls experiments, records the results and provides them for download, and finally removes the virtual testbed.

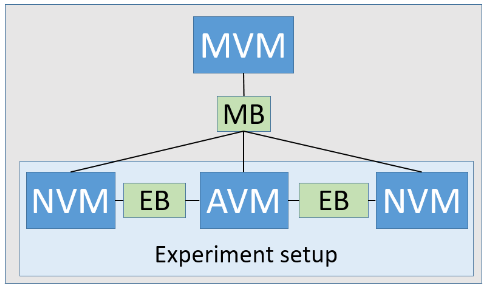


Figure 1: Experiments are executed with node and auxiliary VMs (NVMs, AVMs) that are interconnected by experiment bridges (EBs). NVMs and AVMs are denoted as experiment VMs (EVMs). A managing VM (MVM) is connected via a single managing bridge (MB) to EVMs.

3.2 VITO's Virtualization Platform

We use a server with an Intel Xeon processor as a physical machine and GNU/Linux as host system. We leverage the Intel VT-x [6] feature to enable hardware-accelerated virtualization of the x86 platform as the x86 by itself is not virtualizable. We use Linux Kernel-based Virtual Machine (KVM) [11] as a hypervisor which supports VT-x. VMs are created based on qemu [18] and are managed using the libvirt [20] framework. Software bridges are directly run on the host using the respective 802.1d Linux kernel module. Figure 2 visualizes this concept.

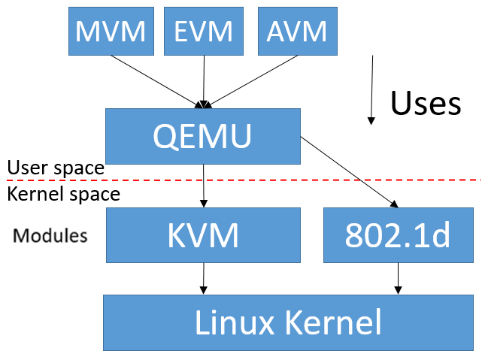


Figure 2: Virtualization experimentation platform.

3.3 Orchestration of Experiments

The experimentation platform itself has only the MVM and the MB running on top of a normal Linux as hypervisor system. The experimenter requires only access to the MVM but not to the host machine itself, i.e., he can create a virtualized testbed and perform experiments without root permissions on the host. Furthermore, he has a single point for the collection of experimental results.

An XML-based file is used for experiment description and control. The file comprises the configuration of all EVMs and EBs, the configuration of the network, and commands that need to be issued at specified times on the VMs. First, the MVM efficiently creates the testbed VMs using libvirt leveraging an XML-based template for VM creation. The CPU pinning option in the VM configuration may be activated to ensure that the VM is run on one CPU thread exclusively. This is helpful for EVMs running CPU-intense computations to ensure they have sufficient resources. Every EVM is equipped with a hard disk that is a snapshot of a template VM which will be described in Section 3.5.

The template foresees a single uplink interface per EVM which is assigned a random MAC address after creation. dnsmasq [22] assigns them IP addresses and makes them reachable via their host names which are configured in the description. As a result, the MVM can connect the EVMs via SSH and their host names and execute specified commands. The MVM creates required EBs, further interfaces on the EVMs with randomly generated MAC addresses, assigns them IP addresses, and connects them to the corresponding EBs. udev [12] rules are installed to rename interfaces according the description. Firewall rules are installed to prevent the usage of the uplink interface for other purposes than communication with the MVM.

For the purpose of a centralized data management, a Network File System (NFS [21]) server is installed on the MVM. This allows all EVMs to write data to a shared directory that is synchronized with the MVM.

3.4 Execution of Experiments

After creation and configuration of all EVMs and EBs, the experiment is started by executing experimentation commands specified in the experiment description. These may include comprehensive log operations, e.g., tcpflow [23] may log TCP state variables during experimentation and tcpdump [26] may log network activity on all non-uplink interfaces of EVMs. They need to be started prior to the actual experimentation and application log files may be moved to the NFS mount after completion. The actual experiment consists of a set of commands that are supposed to be executed at specified time instants after experiment start. For instance, a server process may be started on one EVM at the beginning of the experiment and clients are started slightly later on other EVMs. Commands may also change EVM configuration during the experiment, e.g., for modifying link bandwidths or simulating link failures. The virtual testbed is deleted after each experiment to avoid undesired side effects on future experiments. After deletion of the testbed, the MVN still has access to the entire data collection on the NFS mount, compresses the data, and provides it for download as a zipped tar-file.

3.5 Optimized Testbed Generation

Copying the hard disk consumes the major time fraction of EVM generation and deletion. To minimize this overhead, we use qcow2 [19] as an overlay disk image for VMs which is supported by qemu. With qcow2, all blocks initially refer to a read-only base image. If a block is written, a modified copy is stored in a qcow file. Reads are served from the qcow file if available, otherwise from the base image. During an experimentation, only little data on the disk image is modified, in particular as logs are stored on the NFS mount. Thereby, qcow2 is very efficient and saves lots of copying overhead. As a result, the whole process of creating and deleting a virtual testbed takes less than a minute.

3.6 Integration and Virtualization of Physical NICs

So far, we have only considered the use of virtual interfaces. However, physical network interface cards (NICs) may provide special optimizations like TCP segmentation offloading (TSO) [29]. With VT-d [8], PCI devices can be passed-through from the host to the VM. Therefore, it may be used to pass-through a physical NIC to a VM.

VT-c [7] comprises Virtual Machine Device Queues (VMDq) [9] which enables multiple queues per NIC, i.e., a single physical NIC (physical function, PF) is virtualized into multiple virtual NICs (virtual functions, VFs). VT-d in conjunction with Single Root I/O Virtualization (SR-IOV) [17], the virtual NICs can be passed-through to VMs. To that end, hardware-dependent kernel parameters need to be set to enable all required features. In addition, libvirt has to be configured to use a special pass-through method.

With physical or virtual NICs, a VM's interface is connected to the NIC device instead of the software switch.

3.7 Modelling Characteristics of Transmission Links

The Linux tool TC [13] offers access to netem (network emulator) [30] to modify the characteristics of a traffic stream. Constant or variable delay may be added or packets may be randomly dropped or duplicated. Another mechanism offered by TC is tbf [31]. It shapes a traffic stream according to a token bucket. The token bucket is configured with a rate, a burst size, and a latency. tbf generates tokens at the configured rate, saves them up to its configured burst size, and forwards packets as soon as sufficient tokens are available. To that end, packets need to be queued and the latency parameter determines the maximum queue size in time. As an alternative, the queue size can also be configured in bytes. If the number of tokens suffice, several packets can be forwarded at once. With tbf, rate control can be implemented for egress traffic on an interface.

The burst size is usually configured as a small multiple of a maximum transfer unit (MTU). We apply first netem and then tbf to all non-uplink interfaces of EVMs with parameters defined in the experiment description. For further details we refer to Section 4.

3.8 Scalability Considerations and General Applicability

The scalability of VITO depends on the host hardware. A typical server machine has up to 12 cores per CPU on which up to 24 CPU threads are supported. Thus, it suffices to equip one MVM and 23 EVMs with exclusive CPU threads. EVMs with only little CPU load do not need an own CPU thread so that the number of EVMs in the experiment may be even larger.

Any operating system may be used on EVMs if it supports SSH and NFS. Our release of VITO already provides a few Linux VM images for immediate use. However, own VM templates can be created by installing an operating system and provide an NFS mount and the ssh key for key login from the manager.

4. PERFORMANCE ANALYSIS WITH VITO

In this section, we investigate various uses of netem and tbf for link modeling and quantify appropriate rate-specific burst sizes for tbf configuration.

4.1 Modeling Link Characteristics

VITO uses the Linux tool TC to model link characteristics. With netem, constant or variable delay may be added to individual packets and random packet drops, reordering, or duplication can be realized. With tbf, a maximum data rate of the link can be enforced by delaying and dropping packets while respecting a configurable buffer size. Also active queue management (AQM) algorithms like random early detection (RED) [4] can be modelled with tbf. The two tools netem and tbf can be applied both to a single outgoing interface, but the properties of the resulting stream depend the application order.

In the following we use netem only for adding constant packet delay so that application order is expected to be irrelevant. We demonstrate plausible results for application order netem/tbf and show that application order tbf/netem does not work properly. As a workaround we propose the introduction of an auxiliary node so that netem/tbf and tbf/netem can be applied to a traffic stream on consecutive outgoing links which again yields plausible results. Finally, we experimentally show that the addition of an auxiliary node hardly impacts achievable throughput.

4.1.1 Combined Application of netem/tbf on a Single Link

We investigate the impact of the application order of netem and tbf on a single link. A web client (curl) [2] on one NVM communicates via a vIF and a software bridge with a web server (busybox httpd) [3] on another NVM with a vIF. The guest OS uses the Linux Kernel 4.8 with TCP Cubic. The client downloads via http/TCP a 100 MB file from the web server. TCP's state variables are logged with tcpflow and the packet stream is monitored with tcpdump for analysis.

In a first experiment, the following two commands are applied to interface `eth1` to configure it with external parameters that are passed via the `%s` placeholders:

```
tc qdisc add dev eth1 root handle 1:0 \
  netem delay %sms %s corruption %s loss \
  %s reordering %s
tc qdisc add dev eth1 parent 1:1 \
  handle 10: tbf rate %sMbit burst %s \
  latency %sms
```

The netem command effects that the packet stream is modified with delay (ms), jitter (%), corruption (%), loss (%), and reordering (%). In our experiments, only the delay is set to 100 ms and all other values are zero. The tbf command effects that the packet stream is spaced according to a token bucket with configured rate (Mb/s), burst size (bytes), and latency (ms). This roughly models a transmission link with the specified rate and a buffer size of $rate \cdot latency/1000$. In the following, we set $rate = 50$ Mb/s, $burst = 4542$ bytes, and $latency = 50$ ms. In a second experiment, the application order of netem and tbf is interchanged. We apply the same configuration for transmission from the client to the server and vice-versa.

Table 1 summarizes the results. While download time and goodput are rather similar for both application orders, packet loss, avg. TCP congestion window size (CWND), and avg. roundtrip time (RTT) differ significantly. For further analysis, we consider CWND and RTT over time which is illustrated in Figure 3. With netem/tbf, the RTT varies between 200 ms and 250 ms, and the CWND between 500 and 1050. In particular, CWND and RTT decrease after the occurrence of a lost packet. This is different with tbf/netem as no packet is lost. As a result, the CWND increases up to a maximum value of 2300 MSS and the RTT oscillates between 420 and 520 ms. RTTs in this order of magnitude are unexpected because the configured transmission and queueing delays can range only between 200 ms and 300 ms. Thus, the application order tbf/netem causes undesired behavior and should be avoided for experimentation.

Table 1: Performance metrics for a download of a 100 MB file with netem/tbf and tbf/netem configured on a single link with bandwidth of 50 Mb/s.

tool order	download time	goodput (Mb/s)	avg. CWND (MSS)	avg. RTT (ms)
netem/tbf	19.7s	40.6	821	231
tbf/netem	19.3s	41.5	2013	427

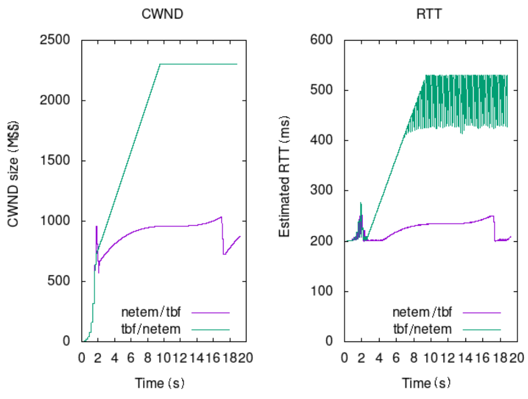


Figure 3: TCP's congestion window and roundtrip time for a single TCP flow on a link with 100 ms delay, a bandwidth of 50 Mb/s, and a buffer with a maximum latency of 50 ms; tbf's burst size is configured with 4500 bytes.

4.1.2 Application of netem/tbf on Consecutive Links

We now interconnect the client and the server NVM via another AVM and software bridge. The configuration is illustrated in Figure 4 for the application order tbf/netem. Thus, netem/tbf or tbf/netem are applied to consecutive links instead to a single one. The client and server NVM see only single links with combined properties.

Table 2 reports the experimentation results which hardly differ from the experiment with netem/tbf. The same holds for CWND and RTT over time for which figures are omitted. Thus, netem/tbf may be applied together on a single outgoing interface. If tbf/netem is the desired application order, an auxiliary node may be used to ensure correct behavior.

4.1.3 Impact of Auxiliary Nodes for Delay Addition

An additional AVM may add some delay. We show that this delay is so small that it hardly influences experimenta-

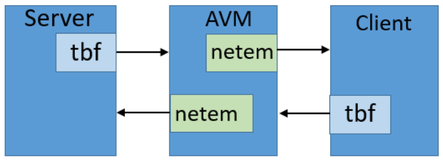


Figure 4: tbf/netem is configured individually on two consecutive links through introduction of an additional EB and AVM that just forwards traffic.

Table 2: Performance metrics for a download of a 100 MB file with netem/tbf and tbf/netem individually configured on two consecutive links.

application order	download time	goodput (Mb/s)	avg. CWND (MSS)	avg. RTT (ms)
netem/tbf	19.1s	41.8	834	224
tbf/netem	18.9s	42.3	845	229

tion results. To that end, we perform similar experiments like above but deactivate rate control and add a delay of 0 ms and 1 ms, respectively. We perform the experiments 20 times. Table 3 summarizes the utilization. Even without any base delay, the presence of the AVM is hardly visible by the increased download time and with a base delay of 1 ms, the download time is almost the same. Thus, AVMs add so little delay that it cannot even be perceived for small positive based delay.

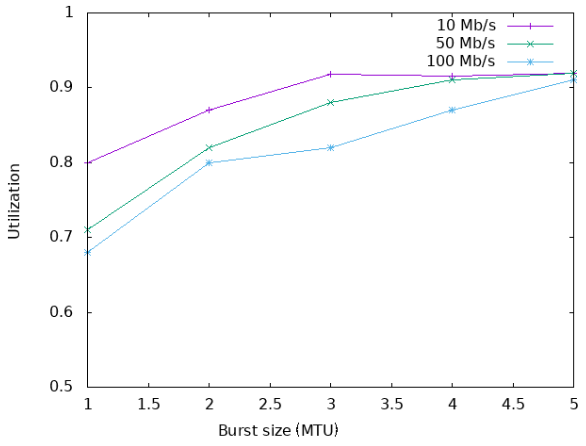
Table 3: Download time for various configurations depending on one-way delay with a configured bandwidth of 100 Mb/s and a 100 MB file size.

delay	w/o AVM	w/ single AVM	w/ jLISP
0 ms	8.68s	8.70s	9.21s
1 ms	8.72s	8.73s	9.22s

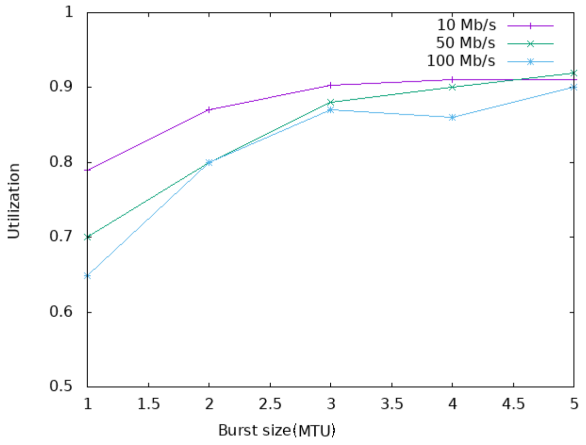
4.2 Configuration of Rate-Specific Burst Sizes

We first think of a simple rate controller that ensures a maximum bit rate of C. After transmission of a packet with size B, it transmits the next packet not earlier than after $\frac{B}{C}$ time. If the machine performs that task only slightly late, this reduces the maximum achievable data rate. To cope with the problem of late transmission, tbf uses a token bucket description for spacing. tbf continuously generates tokens and saves them in a bucket which is limited by its burst size. Packets are queued for transmission. A packet is sent if the number of tokens in the bucket is at least the packet size. If the number of tokens does not suffice, the machine retries again when enough additional tokens have arrived. On the one hand, this mechanism assures that transmission capacity is not lost if a packet is sent slightly later than possible, on the other hand it allows transmission of multiple packets so that packet bursts may be transmitted. Therefore, the burst size should be set only so large that the full transmission capacity can be leveraged, but also as little as possible to keep bursts small as the intention of a spacer is a smooth traffic stream.

In the following we evaluate the required burst size for various bandwidths. Figure 5(a) compiles the utilization for various burst sizes for a server NVM with little CPU load.



(a) Idle server with an avg. CPU load of 2%.



(b) Busy server with an avg. CPU load of 98%.

Figure 5: Impact of configured burst sizes on utilization depending on configured bandwidths.

The figure shows that large bandwidths require large burst sizes to minimize download times by fully leveraging the configured bandwidth. We perform the same experiment with a server NVM that performs other tasks in parallel so that its CPU load is close to 100%. The results in Figure 5(b) show that almost the same download time values are achieved because TC is granted high priority. Both experiments were repeated 100 times which resulted in a confidence interval of less than one percent in each direction for an alpha value of 0.95. We derive from Figure 5(b) recommendations about minimum burst sizes for specific values of configured bandwidths that are needed so that the full transmission speed can be achieved with tbf. We summarize these values in Table 4. The values may depend on software and hardware.

4.3 Application Example: jLISP

With VITO, the influence of protocol implementations on performance metrics can be assessed. As an example, we consider data transmission with tunneling. Tunneling requires encapsulation and decapsulation effort on the source and destination machine which reduces the maximum

Table 4: Recommended burst size for various values of configured bandwidth.

bandwidth (Mb/s)	burst size (MTU)
<= 10	3
<= 50	4
<= 100	5
> 100	7

throughput. This, however, cannot be quantified by simulations. We use jLISP [25], a user-space LISP implementation optimized for rapid prototyping purposes, for illustration. We perform the same experiment as in Section 4.1.3 w/o AVM but use jLISP for tunneling between client and server. Table 3 shows that the download time increases with jLISP and that its impact is larger than the one of an additional AVM. Nevertheless, the achievable throughput is still large enough for most applications so that jLISP does not represent a major performance bottleneck.

The experiment requires at least six nodes: two clients, two encapsulation routers, one Internet router, and a mapping system. A pure hardware testbed needs six nodes for this setup. For VITO, a single server with 4 CPU core is more than sufficient, one of them is used for management purposes. There is some intellectual overhead in using the management framework, but it is more than compensated by the fact that only a single VM image needs to be maintained for experiments, experiment setups can be easily archived, and experiments can be rerun which facilitates regression testing.

5. CONCLUSION

In this paper we proposed the VIrtual Testbed Orchestration (VITO) platform which allows automation of real-world networking experiments on a single server. Physical or virtual hardware components like NICs may be integrated for even more realistic experiments. Networking nodes are modelled by virtual machines (VMs) that are interconnected by software bridges and link characteristics are enforced by the Linux tool TC. The supportable experiment size in terms of networking nodes depends on the server machine, a lower bound is one networking node per CPU thread. VITO node VMs can accommodate any guest operating systems with SSH and NFS support. An experimental performance analysis showed how netem and tbf needs to be configured for modelling link characteristics demonstrated that the overhead of auxiliary VMs tends toward zeros, and gave recommendations for the configuration of burst sizes. Finally, the applicability of VITO was illustrated by assessing the impact of the jLISP implementation on forwarding performance.

6. REFERENCES

[1] IEEE 802.1D Standard. http://standards.ieee.org/getieee802/download/802.1D-1998.pdf.

[2] Daniel Stenberg . cURL. https://curl.haxx.se/, 2017.

[3] Denys Vlasenko et al. BusyBox. https://busybox.net/, 2017.

[4] S. Floyd and V. Jacobson. Random Early Detection Gateways for Congestion Avoidance. *IEEE/ACM Trans. Netw.*, Aug.

[5] iMinds. Virtual Wall – Generic Test Environment For Advanced Network, Distributed Software and Service Evaluation, and Scalability Research, 2014.

[6] Intel Corp. Intel Virtualization Technology (VT-x), 2006.

[7] Intel Corp. Intel Virtualization Technology for Connectivity (VT-c), 2012.

[8] Intel Corp. Intel Virtualization Technology for Directed I/O (VT-d) Architecture Specification, 2012.

[9] Intel LAN Access Division. Intel VMDq Technology. Whitepaper, Intel Corp, 2008.

[10] Keysight Technologies. Triangle Project. http://www.triangle-project.eu/project/, 2017.

[11] A. Kivity et al. KVM: The Linux Virtual Machine Monitor. In *Ottawa Linux Symposium*, 2007.

[12] G. Kroah-Hartman. udev – A Userspace Implementation of devfs. In *Ottawa Linux Symposium*, 2003.

[13] A. Kuznetsov and S. Hemminger. iproute2: Utilities for Controlling TCP/IP Networking and Traffic, 2012.

[14] Mininet Project. Mininet. http://mininet.org/, 2017.

[15] ns-3 project. ns3 Direct Code Execution. https://www.nsnam.org/overview/projects/direct-code-execution/.

[16] Open Networking Foundation members. OpenFlow Switch Specification.

[17] PCI SIG. Single Root I/O Virtualization and Sharing Specification 1.1, 2010.

[18] QEMU team. QEMU 2. http://wiki.qemu.org/ChangeLog/2.0, 2014.

[19] QEMU Team. qcow2. http://git.qemu-project.org, 2017.

[20] Red Hat. libvirt: The Virtualization API. http://libvirt.org, 2012.

[21] S. Shepler, B. Callaghan, D. Robinson, R. Thurlow, C. Beame, M. Eisler, and D. Noveck. Network File System (NFS) version 4 Protocol. RFC 3530, Apr. 2003.

[22] Simon Kelley. dnsmasq. http://www.thekelleys.org.uk/dnsmasq/doc.html, 2017.

[23] Simson L. Garfinkel. tcpflow. https://github.com/simsong/tcpflow, 2017.

[24] Spirent. Spirent Velocity. https://www.spirent.com/Products/velocity, 2017.

[25] A. Stockmayer, M. Schmidt, and M. Menth. jLISP: An Open, Modular, and Extensible Java-Based LISP Implementation. In *International Teletraffic Congress 28*, 2016.

[26] Tcpdump Team. Tcpdump. http://tcpdump.org, 2017.

[27] TETCOS. NetSim. http://tetcos.com/, 2017.

[28] The FreeBSD Project. FreeBSD. www.freebsd.org, 2017.

[29] The Linux foundation. tso. https://wiki.linuxfoundation.org/networking/gso.

[30] The Linux foundation. netem. https://wiki.linuxfoundation.org/networking/netem, 2017.

[31] The Linux foundation. tbf. https://linux.die.net/man/8/tc-tbf, 2017.