Performance Benchmarking of State-of-the-Art Software Switches for NFV

Tianzhu Zhang, Leonardo Linguaglossa, Member, IEEE, Paolo Giaccone, Senior Member, IEEE, Luigi Iannone, Senior Member, IEEE, and James Roberts, Senior Member, IEEE

Abstract—With the ultimate goal of replacing proprietary hardware appliances with Virtual Network Functions (VNFs) implemented in software, Network Function Virtualization (NFV) has been gaining popularity in the past few years. Software switches route traffic between VNFs and physical Network Interface Cards (NICs). It is of paramount importance to compare the performance of different switch designs and architectures. In this paper, we propose a methodology to compare fairly and comprehensively the performance of software switches. We first explore the design spaces of seven state-of-the-art software switches and then compare their performance under four representative test scenarios. Each scenario corresponds to a specific case of routing NFV traffic between NICs and/or VNFs. In our experiments, we evaluate the throughput and latency between VNFs in two of the most popular virtualization environments, namely virtual machines (VMs) and containers. Our experimental results show that no single software switch prevails in all scenarios. It is, therefore, crucial to choose the most suitable solution for the given use case. At the same time, the presented results and analysis provide a deeper insight into the design tradeoffs and identifies potential performance bottlenecks that could inspire new designs.

Index Terms—Network Function Virtualization (NFV), software virtual switch, performance benchmarking methodology

I. INTRODUCTION

For many years developers have used software packet processing for fast prototyping and functional testing but have relied on the superior performance of proprietary hardware for product deployment. The limitations of commodity off-the-shelf (COTS) servers, whose general-purpose kernels and chips were not optimized for packet processing, outweighed the flexibility advantage of software solutions. This situation has changed in recent years, thanks mainly to the impulsion of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) but also due to advances in the performance of COTS hardware. It is now widely accepted that significant savings in both CapEx and OpEx can be realized by replacing expensive, proprietary, and inflexible hardware appliances with Virtual Network Functions (VNFs) implemented in software. Additionally, the superior memory access efficiency. Software switches have largely benefited from the combined use of these acceleration techniques. As a result, such tools are widely employed by NFV platforms as dataplane to flexibly steer traffic. For example, the Snabb NFV project [4] proposes an NFV framework based on OpenStack and snabb switch [5]. Metron [6] extends FastClick [7] for traffic steering. Other NFV frameworks, such as E2 [8] and ParaBox [9], adopt BESS [10] as data plane, while ClickOS [11] and HyperNF [12] opt for netmap-based VALE switch [13].

While interest in software switches is soaring, the relative merits of different proposals are still not well-understood in the absence of comprehensive, comparative performance analysis. It is indeed a daunting task to perform such an evaluation [14], and most published comparisons relate to a small number of switch proposals [15], [16] or execute a limited number of test scenarios [5]. The objective of our work is to propose a methodology for comparing switch performance in terms of essential metrics like throughput and latency. Our methodology aims at a fair comparison of a broad range of state-of-the-art software switches in a set of representative yet straightforward test scenarios. It is critical for such a methodology to take into account the different design choices that guided the switch designs. For instance, Open vSwitch (OvS) [17] was tailored to support match/action semantics, VPP was constructed as a full-fledged software router, while other solutions such as Snabb, FastClick, and BESS embraced modular design to compose complex network services.

The contribution of our work is twofold: (i) we describe our proposed experimental methodology for a fair evaluation and comparison of software switch performance; (ii) we apply our methodology to evaluate the performance of seven state-of-the-art software switches, namely Open vSwitch DPK (OvS-DPDK) [18], FastClick [7], Berkeley Extensible Software Switch (BESS) [10], netmap suite [3], [13], [19], [20], Snabb [5], t4p4s [21], and FD.io VPP [22]. We start by analyzing the design space of these frameworks to build a basic understanding of their respective designs. We then define four test scenarios, introduced in [23], and intended to provide meaningful results for different segments of an NFV service chain. Finally, we provide experimental measurements of throughput, with unidirectional and bidirectional traffic, as well as latency. It is important to note that these experimental results depend significantly on the particular hardware and software versions used in our platform and are thus only

T. Zhang, L. Linguaglossa, L. Iannone, and J. Roberts are with Telecom ParisTech, Paris, France. P. Giaccone is with Politecnico di Torino, Italy.
indicative (for instance, VPP achieves higher performance under the FD.io Continuous System Integration and Testing (CSIT) tests [24] using a similar hardware configuration). Therefore, our aim is not to assess the performance in absolute terms for the adopted testing platform, but rather to define a proper comparison methodology and to identify possible performance impairments when the switches are used in the context of NFV.

Traditionally, VNFs are deployed in virtual machines (VMs) such as QEMU/KVM [25] and Xen [11] to achieve resource multiplexing. Recently, there has been an increasing trend to distribute VNFs into lightweight containers [26]–[28]. In our experiments, both virtualization techniques are considered to host VNFs. In particular, we chose QEMU/KVM hypervisor to instantiate VMs and Docker engine to manage containers. As explained in [29] and [30], Linux kernel stack imposes non-negligible overhead for both VM and container networking, we thus incorporate a collection of kernel-bypassing I/O techniques (e.g., vhost-user, ptnet, netmap veth) for different virtualized environments (the reader can refer to [31] for a more detailed analysis of different virtualization techniques). To facilitate reproducibility, all the scripts and instructions of our experiments have been released on GitHub [32]. We strongly encourage researchers and developers to use them to repeat the same set of experiments on their own servers and to build on this basis to gain further understanding.

The paper is organized as follows. In Sec. II we review related literature on software switches and their comparison. Then, in Sec. III we explore the design space of the considered software switches and highlight their specificities. In Sec. IV we describe the proposed test methodology. Experimental results are presented and discussed in Sec. V. We draw our conclusions and discuss future work in Sec. VI.

II. RELATED WORK

We first survey the panoply of open-source software switch proposals before discussing related work on performance comparison of different implementations.

A. Software switches

We first introduce the seven switches whose performance we have directly compared and then briefly describe alternative designs.

1) Evaluated Software Switches: The seven state-of-the-art software switches included in our comparison study have been chosen both for the availability of an up-to-date codebase and for their promised high performance.

**OvS-DPDK** [13] is a high-speed user-space variant of Open vSwitch [17]. It moves the data plane of Open vSwitch into user space. It adopts DPDK poll-mode drivers to deliver packets, completely avoiding the overhead imposed by kernel stack and interrupt handling.

**t4p4s** [21] is a platform-independent software switch specifically designed for P4 [33]. A compiler is implemented to generate switching code from P4 programs, and a hardware abstraction layer deals with platform-dependent details. For Intel NICs, t4p4s integrates DPDK to improve efficiency.

**FastClick** [7] extends the codebase of Click Modular Router [34] and integrates high-speed packet I/O techniques such as DPDK and netmap. Its data path is also optimized by leveraging acceleration techniques, including zero-copy, batching, and multi-queueing.

**Snabb** [5] is a high-speed modular software switch with a set of predefined modules enabling the composition of complex network functions. Like MoonRoute [35], it is based on Lua and LuaJIT [36]. Snabb is known for the introduction of the vhost-user protocol [37], featuring direct packet delivery between user-space processes and VMs, without kernel intervention.

**BESS** [10] is a modular software switch from UC Berkeley featuring a set of built-in modules used to compose network services. Modules can be glued together and fed to the daemon process, which deals with packet scheduling (enabling traffic prioritization) and processing.

**VPP** [22] is a software router that allows users to configure the forwarding graph and to process packets in batches. The VPP design incorporates a number of throughput optimization techniques while also supporting interrupt mode when using native drivers. In addition, VPP provides a CLI for experimentation and debugging while resorting to the binary API for production use (bindings to C, C++, Go, Python over a non-blocking, shared memory interface).

**VALE** [13] is an L2 software switch based on the popular netmap high-speed packet I/O framework. It adopts batch computing and memory prefetching to enhance processing efficiency. mSwitch [19] augments VALE with enhanced switching logic. A pass-through approach named ptnet is proposed to ensure high-speed packet delivery between virtual machines [20]. In contrast to most of the other switches that use the DPDK poll-mode driver and complete kernel bypass, VALE is built on top of netmap and relies on system calls and NIC interrupts for packets’ I/O. Therefore, it is interesting to compare VALE with other solutions.

2) Other Software Switches: We briefly reference some other software switches that we have not included in the present comparison.

**RouteBricks** [38] achieves multi-Gigabit/s packet processing speeds by exploiting parallelization both within and across commodity servers. **PacketShader** [39] boosts packet processing using graphics processing units (GPUs). **Hyper-Switch** [40] improves packet forwarding between virtual machines and the Xen hypervisor by adopting batch processing and computation offloading. **Cuckoo Switch** [41], a software Ethernet switch, adopts the cuckoo hashing algorithm for forwarding table lookup and DPDK for packet I/O operations, thus realizing both memory efficiency and high-speed processing. **MoonRoute** [35] is a software router based on MoonGen [42] and LuaJIT [36]. The use of the Lua scripting language improves programmability compared to other software switches that use C or C++. Despite their interesting features, we exclude these switches from the direct quantitative comparison because their codebase is quite outdated.

The Virtual Filtering Platform (VFP) [43] is designed to host SDN in cloud datacenters. **PVPP** extends VPP to support P4. Promising performance is reported in [44]. **ESwitch** [45]
employs template-based code generation to optimize OpenFlow optimization for Open vSwitch with extended Berkeley Packet Filter (eBPF). These solutions cannot be included for direct comparison as their code is not currently available.

**PISCES** [47] extends Open vSwitch with the support of the P4 language. **HyperV** [48] is a P4 dataplane hypervisor, and its DPDK target achieves comparable performance to PISCES. However, as detailed in [21], t4p4s outperforms it by two times running the baseline L2 forwarding application. We thus only consider t4p4s in our comparison. **Lagopus** [49] is a user-space OpenFlow switch based on DPDK. We do not consider this switch here due to its low performance. In [50], the **OfSoftSwitch** is enhanced by leveraging the PFQ framework [51]. However, like Lagopus, this switch has limited performance (≤ 4 Mpps with 64B packets) and is therefore not included in our comparison. Similar reason also applies for **BOFUSS** [52], another SDN software switch implementation that achieves performance close to standard Open vSwitch.

Finally, **ClickNF** [53], [54] extends Click with a set of modules enabling complex L2 to L7 network functions. Since ClickNF is similar to FastClick in terms of design and performance, we do not consider it to avoid duplicates. The same reason also applies for **REdge** [55], which extends VALE and netmap to build NFV backbone.

### B. Performance Comparison

The literature includes a number of works aiming to evaluate the performance of state-of-the-art software switches. The authors of [56] compare Open vSwitch throughput with Linux bridge and Linux kernel IP forwarding. According to their results, the standard Open vSwitch fails to achieve 2 Mpps with 64B packets. The same authors further analyze the throughput and latency of Open vSwitch in [13]. Paper [16] presents an evaluation of OvS-DPDK throughput using port/flow mirroring with 1 Gbps NICs. Our work differs in that we only focus on software switch implementations capable of achieving much better performance (e.g., more than two orders of magnitude higher throughput).

Several prior performance comparison works in the literature are particularly relevant to ours. The survey [57] presents a throughput and CPU utilization performance comparison of SR-IOV, netmap passthrough, OvS-DPDK, and Snabb under two test scenarios: inter-VM forwarding and 1-VNF loopback. In [27], the authors measure both throughput and latency for a containerized VNF chaining scenario using Bess switch. The throughput of VALE switch connecting LXC containers is studied, and compared to standard Linux bridges and veth interfaces. Our work differs in that we consider more software switches under a more diverse set of test scenarios. Moreover, since our work focuses solely on software switches, we attach physical NICs to the VALE switch, not directly to the VMs. We also omit hardware PCI passthrough techniques such as SR-IOV.

The authors of [5] compare the throughput of Snabb, Open vSwitch, OvS-DPDK, and Linux bridge while [14] evaluates the throughput of Bess, VPP, and OvS-DPDK using physical interfaces only. Our work focuses as well on NFV use cases and thus also considers VNFs hosted in a virtualized environment. In addition, all the aforementioned works do not compare performance in the important scenario of service chains with more than one VNF. This multi-VNF loopback scenario is considered in [58], [59], but the comparison is limited to VPP and OvS-DPDK.

None of the above-cited works consider latency, which is a critical performance metric. Both throughput and latency of Bess and ClickOS are compared in [60] under a loopback service chaining scenario. We preferred to consider VALE, rather than ClickOS, in our comparison as the latter is a full-fledged NFV framework rather than a software switch. Furthermore, in our comparison, all systems use the same QEMU hypervisor, avoiding the uncertainty arising when one system uses QEMU and the other Xen.

In contrast to the existing literature, in addition to providing measurement results, our work seeks to define a comparison methodology. This consists of a set of test scenarios and metrics designed to enable a deeper understanding of software switch performance and to help identify potential bottlenecks. There are two open-source projects, namely FD.io CSIT-1904 [61] and VSperf [62], that are very relevant to our work. CSIT-1994 aims at defining a comprehensive set of test scenarios for VPP and DPDK applications. VSperf, proposed by the Open Platform for NFV Project (OPNFV), focuses on the benchmarking methodology of virtual switches for the NFV infrastructure [63]. Currently, it has integrated vanilla OvS, OvS-DPDK, and VPP. Our work covers all the test scenarios defined by the two projects. Moreover, the reported experimental results relate to a set of representative, state-of-the-art software switches that is more extensive than any considered in prior work.

### III. Software Switches Design Space

We first discuss the importance of exploring the different design objectives of alternative software switches before considering how the seven representative state-of-the-art solutions fit into a design space taxonomy.

#### A. Design Objectives

Before performing a comparative evaluation, it is very important to understand the main design differences between the considered software switches. This may require identifying the adopted processing model, or ascertaining whether the switch has been designed for a particular application such as SDN or NFV. Such a task is time-consuming but appears an essential precondition to avoiding biased results or an incorrect interpretation of the impact of subtle, performance impacting details.

Rather than providing a detailed discussion of implementation and/or acceleration techniques, for which we refer to the survey in [64], we aim in this section to consider each switch design in relation to a number of technical aspects
TABLE I: Taxonomy of state-of-the-art high-performance software switches

| Architecture     | Programming Paradigm | Processing Model | Virtual Interface | Runtime Reprogrammability | Programming Language | Main Purpose     |
|------------------|----------------------|------------------|-------------------|--------------------------|----------------------|------------------|
| BESS             | ✓                    | Structured       | ✓                 | ✓                        | vhost-user           | High             |
|                  |                      |                  |                   |                          | C, Python            | Programmable NIC |
| Snabb            | ✓                    | Structured       | ✓                 | ✓                        | vhost-user           | High             |
|                  |                      |                  |                   |                          | Lua, C               | VM-to-VM         |
| OvS-DPDK         | ✓                    | Match/action     | ✓                 | ✓                        | vhost-user           | Medium           |
|                  |                      |                  |                   |                          | C                    | SDN switch       |
| FastClick        | ✓                    | Structured       | ✓                 | ✓                        | vhost-user           | Medium           |
|                  |                      |                  |                   |                          | C++                  | Modular router   |
| VPP              | ✓                    | Structured       | ✓                 | ✓                        | vhost-user           | Medium           |
|                  |                      |                  |                   |                          | C                    | Full router      |
| t4p4s            | ✓                    | Match/action     | ✓                 | ✓                        | vhost-user           | Low              |
|                  |                      |                  |                   |                          | C                    | Virtual L2 Ethernet |

affecting packet processing performance. The objective is to gain insight on how to devise meaningful experimental scenarios. A summary of this software switch taxonomy is shown in Table I whose details are now discussed.

B. Architecture

A significant difference between software switches derives from the way packet processing is configured and, more importantly, executed. A self-contained architecture is defined as a full-fledged software that can be deployed with minimal configuration effort. The switch data path is predefined, though modifications at compile time are allowed, and all processing functions are deployed in a single process. In contrast, a modular architecture targets a high degree of flexibility. This is usually achieved by providing a set of predefined, well-known network functions that can be arranged in a forwarding graph. The latter can even be re-configured at runtime, when each node is a different thread or process, or extended with custom network functions.

Our evaluation takes into account four switches designed with a self-contained architecture: VALE [13], VPP [65], t4p4s [21], and OvS-DPDK [18]. VALE is an L2 learning switch based on netmap, which can interconnect both physical NICs and virtual interfaces and forward packets at high speed. Though it is feasible to connect VALE with an external program, it is considered here as a self-contained architecture. VPP consists of a forwarding graph with hundreds of functions with support for additional plugins [66]. It exposes a command-line interface that can be used to configure the router with a syntax similar to the Cisco IOS operating system. OvS-DPDK is a software switch built for SDN in which packet processing is realized via a set of match/action tables (cf. Sec. II-C), which can be modified via the ovs-vsct1 API. Custom packet processing can be realized by adding new code that must be compiled into the original codebase. t4p4s is designed to support P4 [33] semantics, whose workflow is quite similar to OvS-DPDK. It consists of a parsing stage on packet entry and a de-parsing stage when packets exit. Match/action tables, described through P4, are deployed between these two stages to indicate the sequence of operations to perform on packets.

The other switch designs considered in our study, FastClick [7], BESS [10], and Snabb [5], belong to the modular category. FastClick, one of the latest versions of the original Click Modular Router, consists of a set of nodes that can be arranged using a Click-specific configuration language. BESS also has a modular architecture, although the modules are more general and less specialized than those of FastClick. Similarly, Snabb interconnects modules with links to compose network services.

C. Design Paradigm

Software switch implementations are heavily influenced by their target use cases. We classify the design paradigm into two categories. The first one adopts structured programming to route traffic across VNFs, as done by a majority of existing software switches. The second solution is to use the match/action programming paradigm exploited by OvS-DPDK and t4p4s. Packet processing is realized using built-in packet classification algorithms that match specific header fields and apply the corresponding actions.

D. Processing Model

When packets are delivered to a software switch, there are generally two ways to process them: run-to-completion (RTC) and pipeline. The former refers to a model in which a single thread performs full packet processing before being forwarded or discarded, while the latter refers to a model according to which packets go through several threads, each containing a portion of processing logic, to complete full processing.

Most frameworks (VPP, OvS-DPDK, t4p4s, and VALE) adopt the run-to-completion model to reduce the context switching overhead. Even FastClick, an extension of Click designed with a pipeline model in mind, has completely moved to a full run-to-completion approach. Snabb is the only considered switch that processes packets solely according to a pipeline model, while BESS can adopt either model depending on the implemented multicore approach.

E. Virtual Interfaces

Software switches mainly rely on virtual interfaces to interact with VNFs and steer traffic on NFV platforms. There are several techniques for VM and container networking. Most of the VMs under QEMU/KVM communicate with the outside world using the virtio [67] standard. It consists of the virtio_net paravirtualized frontend network driver and the vhost_net backend driver. Traditionally, vhost_net takes packets into the kernel and copies them back to the user-space software switch. However, this is not desirable from a performance point of view. To address this issue, Snabb implements vhost-user, a backend driver allowing direct packet exchange between software switches and VMs. Compared with vhost_net, vhost-user provides better performance as it eliminates the overhead imposed by the
kernel. DPDK also adopts this solution and hence all of the frameworks considered in this work, except VALE that is based on netmap, use vhost-user [37] as backend driver. VALE adopts ptnet for efficient VM networking. ptnet is a new paravirtualized device driver that grants the VMs direct access to packet buffers of netmap ports on the host using the netmap API. Compared with vhost-user, ptnet delivers packets in zero-copy manner without incurring the overhead of queuing (as for virtio) or packet descriptor format conversion, at the cost of a lower degree of host-VM isolation and more difficult live migration.

Compared to virtual machines that emulate resources at the hardware level, container is an alternative lightweight solution at OS level and achieves isolation through namespaces/c-groups. For high-speed container networking, DPDK community advocates using the virtio-user frontend driver [68]. Virtio-user is a shared memory mechanism based on virtio. It implements a vhost adapter to emulate virtio ports and bridge vhost backend drivers, without the involvement of any hypervisor. As demonstrated by [69], virtio-user manages to achieve more than 3.5× performance boost over the standard kernel-based approaches. We thus consider virtio-user as the virtual device driver for all the software switches using vhost-user backend. Netmap instead provides native support for the veth interface [70]. By specifying the kernel source path during compilation, the veth.ko module based on netmap optimization is automatically created. Container networking in netmap mode is made possible by moving veth pairs across different Linux namespaces. In our test, we attach one end of veth to a VALE switch and move the other end to the namespace of a Docker container, so as to implement peer-to-peer zero-copy packet delivery. To guarantee optimal performance, both sides of a veth pair must be attached to netmap applications.

### F. Runtime Reprogrammability

Although software switches are usually easy to program, it is also important to consider their degree of reprogrammability. As an example, programmable packet processors can be written as a simple C program. However, adding a new feature may require rewriting part of the code and, sometimes, to also rerun, recompile or replace binary executables. However, a highly reprogrammable software switch may offer the possibility to change behavior directly at runtime, without the need for recompilation. We categorize the switches into three degrees of reprogrammability: high, medium and low.

Snabb and BESS are the software switch implementations with the highest degree of reprogrammability. Thanks to the App engine and command-line tools of Snabb, standard modules can be loaded interactively, and the processing pipeline can be dynamically adjusted at runtime. Similarly, BESS provides a control utility (bessctl) capable of loading new configuration files and modules into its processing pipeline on the fly. Note that newly added modules do need to be compiled before being integrated into the processing pipeline. OVS-DPDK packet processing behavior can also be adjusted at runtime. In particular, external controllers can populate flow rules to the OvS match/action tables through southbound protocols such as OpenFlow. As a result, its runtime programmability really depends on that of the external control plane. Both VPP and FastClick allow to program some modules and execute custom packet processing applications. In particular, the VPP command-line interface allows existing modules to be configured and new plugins to be added at runtime. Nevertheless, changing the version of the same plugin requires restarting the software switch. Therefore, VPP has a medium degree of reprogrammability. Similarly, even though some modules can be interactively configured, FastClick instance has to be restarted when the processing graph is changed and therefore has a medium degree of reprogrammability. Finally, both t4p4s and VALE switch have a low degree of reprogrammability since they do not provide any means to dynamically adjust their packet processing at runtime.

### G. Programming Language

The choice of one particular programming language over another can be dictated by performance requirements, programmability, or time-to-market considerations. Most of the software frameworks for high-speed packet processing are written in C and/or C++. Since both languages are performant, feature-rich, and portable across different platforms, most of the software switches considered in our study implement their performance-critical components using them. Higher-level programming languages, such as Python and Lua, are also used by some software switches. For example, BESS additionally provides a Python API to facilitate the composition of configuration scripts. t4p4s implements its P4 compiler in Python. Snabb, on the other hand, is based on Lua. It also wraps snippets of C code using LuaJIT, which profiles and optimizes code execution at runtime [5]. With the relatively better programmability of Lua and dynamic optimization of LuaJIT, Snabb is expected to be an efficient solution.

### H. Switch Primary Purpose

Packet processing frameworks are able to sustain good performance, thanks to a large collection of acceleration techniques discussed in the survey [64]. The adoption of these techniques depends on the primary purpose for which the software switch has been designed. Considering this purpose is of interest for two main reasons: (i) it may provide hints on the performance of each design in some specific scenarios; (ii) it may be helpful in understanding which of the software switch implementations is more suitable for some particular user requirements.

BESS provides a native way to easily schedule packets without only using the simple FIFO approach, thus enabling custom policies, resource sharing, and traffic shaping. Resource sharing mechanisms may also be implemented on top of existing frameworks: e.g., the authors of [71] implemented fair sharing of both CPU and bandwidth using fair packet dropping on top of VPP. However, to the best of our knowledge, BESS is the only design that natively provides scheduling capabilities without the need to write a custom algorithm. Snabb targets a performant and straightforward packet processing framework. Its core optimizations leverage runtime profiling and rely on
LuaJIT to optimize the most frequently executed portion of code, rather than relying on the static compilation. Its app engine can dynamically register new apps, making it one of the most flexible solutions for high-speed packet processing. Unlike other switches, it implements its own compact kernel bypass mechanism without relying on DPDK or netmap. OvS-DPDK aims to provide the benefits of SDN (i.e., separation of data and control planes) with the flexibility of a software solution. Its data path is highly optimized thanks to the presence of internal flow caches. It can also be used as a static switch with predefined rules, or as a fully functional SDN switch in conjunction with an external control plane. t4p4s implements a high-speed, platform-independent P4 switch. Its compiler synthesizes P4 programs and generates core switch code, which is then converted to platform-specific instructions by its hardware abstraction layer. It is representative of several efforts to implement production-ready P4 switches. FastClick aims to provide a high-speed modular router that can process millions of packets per second by arranging custom functions in a graph-like fashion. The advantage of FastClick is the possibility to re-arrange its rich set of internal elements to realize different types of packet processing applications. P4V should be considered when a fully-featured software network function (e.g., switch, router, or security appliance) is required. Its code was part of Cisco high-end routers before being released as open-source and therefore contains a large set of software components that can be used for all kinds of possible L2-L4 applications. VALE fulfills the role of a high-speed L2 learning switch that interconnects multiple VMs. Its primary purpose is to provide a high-speed virtual local Ethernet switch.

IV. TEST METHODOLOGY

This section shows our methodology to compare the performance of generic software switches, in terms of throughput and latency, i.e., two crucial metrics to evaluate the performance and the scalability of NFV applications. When the traffic traverses a service chain of multiple VNFs, it follows a path through a sequence of interfaces which may be either physical (p) or virtual (v), as shown in the example of Fig. 1.

A. Test Scenarios

For a meaningful and comprehensive comparison in a NFV system, we propose to consider four reference test scenarios, p2p, p2v, v2v and loopback, as shown in logical view of Fig. 2. We assume a logical server with two dual-port NICs and denote the software switch as System Under Test (SUT). In practice, we will adopt a single server to implement all the scenarios, as described in Sec. IV-B.

p2p (physical-to-physical) scenario: Packets entering from one physical input interface are forwarded to the physical output interface by the software switch, as shown in Fig. 2a. Although this scenario does not deal with VNFs, it is still relevant since common network functions are increasingly hosted by software switches, either to augment the physical NIC or to reduce duplicated VNF processing. Evaluating the bare forwarding rate between physical interfaces thus provides a useful baseline reference. Furthermore, combined with other scenarios, p2p allows evaluating the overhead imposed by a virtualized environment, both qualitatively and quantitatively.

p2v (physical-to-virtual) scenario: The software switch forwards packets between a physical interface and a VNF hosted in a virtualized environment, as shown in Fig. 2b. This scenario can be mapped to the first and last hop of VNF chains inside a server. Combined with p2p, p2v reveals the software switch performance when connected to a virtualized environment.

v2v (virtual-to-virtual) scenario: The software switch transfers the traffic between two virtual interfaces, as shown in Fig. 2c. This scenario allows assessing the performance for the traffic exchanged by subsequent VNFs in a chain running in the same server. Since no physical interface is involved in this process, the forwarding rate in this scenario is not limited by the NIC's hardware, but by the underlying bus architecture (typically PCIe).

loopback scenario: The software switch transfers packets entering from one NIC through a chain of VNFs before exiting through the other NIC. An independent VM/container hosts each VNF. Fig. 2c shows the case of a 1-VNF service chain. We also take into account multi-VNF chains in our study. This scenario mimics a complete NFV service chain within the same server.

When comparing the four above scenarios, it is worth to notice that the memory bandwidth bounds the throughput for the v2v scenario, on the contrary, when the physical interface is involved (p2v, p2p scenarios), the throughput is bounded by the NIC capacity.
Fig. 3: Test scenarios mapped to our testbed with two NUMA nodes each associated with a dual port 10 Gbps NIC directly connected to the other NUMA node’s NIC. Blue arrows represent the data flow.

B. Measurement Testbed

This section describes the hardware and the software configuration that we used to implement our methodology. This description can be used as a reference to design a measurement platform based on the available state-of-the-art technologies.

Our testbed includes a commodity server equipped with two Intel Xeon E5-2690 v3 @ 2.60GHz CPUs (each with 24 virtual cores under hyper-threading and 32K/256K/3072K L1-3 caches), 198GB DDR4 memory @2.13GHz, and two Intel 82599ES dual-port 10Gbps NICs spread over two NUMA nodes. The server runs Ubuntu 16.04.1 operating system with Linux 4.15.0-65-generic kernel distribution. We deployed VNFs inside both VMs and containers to evaluate the efficiency of software switches interacting with different virtual environments. Containers are instantiated with Docker (version 18.09.7), while VMs are launched from a CentOS 7 image using QEMU virtualizer. In particular, we use QEMU 2.2.0 for BESS, as newer versions present various compatibility issues. For the other software switches, we use the newer QEMU 3.0.95 to exploit the up-to-date optimizations.

Furthermore, as recommended in [75] and [76], in the server, we set the CPU frequency scaling governor to “performance” and disable TurboBoost in order to reduce performance variance. We also reserve 1GB Hugepages to minimize Translation Lookaside Buffer (TLB) misses and assign 32 pages for each NUMA node. Finally, some cores are deliberately kept isolated from the kernel using isolcpus and reserved solely for the software switch under test.

The setup for each test scenario is illustrated in Fig. 3. Software switches are always deployed on a single core on NUMA node 0 to ensure a fair comparison. Single core is also arguably a reasonable assumption as network operators usually seek to limit resources devoted to networking. Each VM/container is allocated with four cores. We utilize a collection of high-speed software packet processing tools, including MoonGen, pktgen-DPDK (version 19.10.0), FloWatcher-DPDK, and netmap pkt-gen, for traffic generation and measurement. The DPDK version used for all the tests is always 18.11.3 (LTS) for both the host machine and the virtual environment.

It is important to note that the use of the same server for both traffic generation/reception and the system under test does not introduce spurious interference since the cores and memory are effectively isolated under the NUMA architecture of our server. In particular, we combine software switch utilities (e.g., handles or command line options to tune DPDK EAL parameters) with system tools (e.g., numacll, taskset) to guarantee core and memory affinities. For the v2v scenario, everything runs on NUMA node 0 without the involvement of physical NICs; thus, the traffic forwarding rate is only limited by the local memory speed. For the other scenarios, the TX/RX components run on NUMA node 1 while the software switch under test (and TX/RX for p2v scenario) is deployed on NUMA node 0. The cores only access memory in their local NUMA node and do not share remote memory. Note that since packets are transferred through physical NICs, their maximum bandwidth (10 Gbps) constitutes the theoretical bottleneck for these scenarios.

C. Software Switches Settings

For each tested software switch, we used the latest functional version/commit available at the time of writing, namely: FastClick (commit 9d5e9c6); BESS (“Haswell” archive, specifically built for Haswell CPU architecture); OvS-DPDK (version 2.11.90); snabb (commit 24c9a67); VALE (netmap commit 42270fc); t4p4s (commit 74055b3); and VPP (version 19.04). Moreover, we tune the default settings of some software switches in order to optimize their performance while imposing minimal configuration. The adopted tuning is described in Table II.

Here we report the settings required for each scenario, taking into account the specific software switches considered in the tests. Additional configuration details are reported in Appendix A.

**p2p scenario:** In this scenario, the software switch acts as a packet forwarder from one physical port to the other without the involvement of any virtualization layer. We configure MoonGen to transmit synthetic traffic at 10 Gbps from NUMA node 1 to the SUT, as illustrated in Fig. 3. We fix the packet size as 64B, 256B or 1024B. Packets are sent at maximum rate disregarding any drop.

Note that this is different from the usual Non-Drop-Rate (NDR) of RFC 2544 [50], a binary search for the NDR is not suited for evaluating software switches as it may converge to unreliable points due to even a single packet drop, caused at the driver level.
measure the corresponding throughput (in Gbps) on NUMA node 1, by collecting outbound traffic from NUMA node 0. We also consider bidirectional traffic, which doubles the packet processing rate that the switch has to sustain, measuring the bidirectional throughput by simultaneously transmitting packets towards both interfaces of NUMA node 0. We also run the baseline DPDK testpmd application \[81\] in the fastest forwarding mode and measure the bare-metal throughput as a performance reference.

**p2v scenario:** We run the SUT to allow the communication between the VNF and the physical NIC, as illustrated in Fig. 1(b). Since this is a hybrid test scenario (connecting the physical and virtual environments), we consider three possible combinations of the packets’ workflow. In particular, we consider a physical-to-virtual unidirectional flow (denoted as “unidirectional”), the reverse virtual-to-physical flow (called “unidirectional-reverse”) and the full-duplex combination of the above cases (named “bidirectional”). To obtain the highest throughput for each software switch under different virtualization techniques, we apply different configurations using specific software tools and virtual device drivers. The VALE switch requires a specific configuration, as it relies on netmap’s ptnet driver for high-speed VM networking. To enable ptnet inside VMs, we use a customized QEMU provided by netmap authors \[82\], as it supports ptnet virtual interfaces with VALE ports as their host backend \[20\]. Then we compile netmap with ptnet support in the guest VM and run netmap applications inside the VM to maximize throughput. Note that we are aware that ptnet also supports passthrough of physical interfaces directly, without connecting them using VALE. However, we decided not to use this feature because our work focuses on software switches instead of device passthrough. For high-speed networking testing between containers, netmap provides native support for veth interfaces. We built a Docker image with netmap applications (as VNFs), for experiments related to VALE. To bridge VALE switch with the containerized VNF, we put one end of the veth pair into the container namespace and attach the other end to a VALE instance.

For both VM and container tests in the p2v scenario, we use pkt-gen as VNF inside the container. In the unidirectional test, one instance of pkt-gen in RX mode is attached to the ptnet/veth virtual interface to measure the throughput, while for the reversed test, pkt-gen runs in TX mode. In the bidirectional test, two instances of pkt-gen in TX/RX modes are simultaneously attached to the virtual interface. To test the throughput of other switches with VMs, we use the standard QEMU and create a virtio-pci virtual interface with a vhost-user as backend. We further accelerate packet I/O inside VMs, we build a Docker image wrapping the DPDK suite and run VNF on top of a virtio-user interface with vhost-user backend supplied by SUT. We run FloWatcher-DPDK \[83\], a lightweight software traffic monitor, to measure the unidirectional throughput. To measure the bidirectional throughput, we use pktgen-DPDK, a high-speed traffic generator/monitor. For the unidirectional-reverse test, we use pktgen-DPDK only as traffic generation VNF. On NUMA node 1, MoonGen is used as a traffic generator for unidirectional tests, and it is used as a traffic generator/monitor for the bidirectional tests. FloWatcher-DPDK is used to measure the reversed unidirectional throughput. In the VM case, we configure snabb in client mode to flexibly reconfigure snabb without re-installing all the VMs. Instead, for the container case, we have to configure snabb in server mode since virtio-user cannot create the Unix socket in the absence of hypervisor.

To obtain bidirectional traffic, we initiate two pkt-gen instances (for VALE)/one pktgen-DPDK instance (for others) to TX/RX from inside the VM/container, and start another MoonGen instance to TX/RX simultaneously on NUMA node 1, as illustrated in Fig. 3(b). However, we experienced severe performance degradation when the two pkt-gen instances are attached to the same ptnet port inside the VM. To overcome this, we attach the pkt-gen instances to a netmap virtual interface, which is in turn attached to the ptnet port through a VALE instance inside the VM. Actually, this setting imposes an extra hop of packet forwarding, but this is the best option to achieve reasonable bidirectional p2v traffic with VALE. Without this bottleneck, the real bidirectional throughput of VALE is expected to be much higher. We do not observe the same issue in the container test with two pkt-gen instances attached to the same veth interface concurrently.

**v2v scenario:** In the v2v scenario, as illustrated in Fig. 3(c), we need to instantiate two VMs, each with a virtual interface attached to the software switch under test. The virtual interface configurations are similar to those in the p2v scenario. We deploy a traffic generator in the first VM/container and configure it to inject packets towards the software switch, which in turn forwards packets to the monitoring VNF. Similar to previous scenarios, different traffic generation/measurement tools are required to realize the intended data path for different switches.

For VALE unidirectional throughput, we deploy an instance of pkt-gen in each VM/container and configure them to perform traffic generation/measurement respectively. For other switches, we run pktgen-DPDK in the first VM/container as a traffic generator and FloWatcher-DPDK on the second VM/container to measure unidirectional throughput.

To generate bidirectional traffic, we deploy an instance of pktgen-DPDK in each VM/container to transmit packets at maximum rate and measure throughput simultaneously, for software switches other than VALE. Indeed, for the VALE switch, we need two pkt-gen instances in each VM/container to transmit and receive simultaneously. Similar to the p2v bidirectional test, for VM deployment, we attach both pkt-gen instances in each VM to a netmap virtual interface, which is attached to the ptnet virtual interface through a VALE instance. For the container deployment, we attach both pkt-gen instances to the veth interface directly.

**loopback scenario:** We instantiate a chain of VNFs, with four cores and a pair of virtual interfaces allocated to each VNF. Each software switch transfer traffic across the VNFs in sequence, forming a linear service chain. By default, a single instance of VNF is deployed in a VM or container. Fig. 3(d) illustrates the setup. For VALE, we configure two ptnet virtual interfaces for each VM in which we run a VALE
instance as a VNF. This VALE instance cross-connects the pair of ptnet ports. Each VM is linked to its successor through a VALE instance. The first and last VM also need to link the physical ports with two additional VALE instances. Similarly, for container configuration, two pairs of vhost interfaces are created, each of which has one end attached to VALE and the other end attached to a container hosting a new VALE instance as VNF. In all, we need \(N + 1\) VALE instances for an service chain of \(N\) VNFs. For the other software switches, we configure two virtio interfaces with vhost-user backend for each VM, in which we run an instance of the DPDK testpmd sample application that cross-connects interfaces and updates the destination MAC addresses. On NUMA node 1, we start MoonGen to generate 10 Gbps traffic through one port and measure throughput for different packet sizes from the other port. For bidirectional traffic, MoonGen is configured to generate 10 Gbps traffic from both its physical ports and measure the aggregated throughput. The software switch is configured to transfer packets between MoonGen and the service chain. We vary the number of VNFs from 1 to 5 to test the throughput of each switch with increasing service chain length.

Regarding the switch configurations, BESS exhibits compatibility issues with QEMU 3.3.10 and cannot instantiate more than 3 VMs simultaneously. As a result, we degrade to QEMU 2.2.0 specifically for BESS in this scenario. Furthermore, it was not possible to perform the loopback test for snabb with containerized VNFs due to a reported issue \[84\].

### D. Latency Test

We measure the round-trip time (RTT) latency, which in our case is defined as the time spent between packet emission by the traffic generator and the time the traffic monitor receives the packet.

In order to avoid saturation and perform meaningful latency measurements, it is necessary to identify the Maximal Forwarding Rate (\(R^+\)), defined as the maximum rate the software switch can forward packets without experiencing losses. Injecting packets at a speed higher than \(R^+\) causes congestion and leads to packet losses that would bias the measured latency. On the other hand, injecting packets at a very small rate may also impair latency as most solutions employ batch processing. It is well known that it is very hard to determine \(R^+\) since software traffic generators generally lack the stability of hardware and may induce non-deterministic packet losses. VNF chains in the loopback scenario tend to exacerbate this uncertainty. Rather than trying to identify the precise \(R^+\), we follow the methodology introduced in \[66\] and define \(R^+\) as the average throughput achieved under saturating input conditions. We measure latency at loads of 0.10, 0.50, and 0.99 times \(R^+\). Thus, 0.99\(R^+\) reflects the latency under heavy input load, 0.50\(R^+\) under intermediate load, while 0.10\(R^+\) shows the impact of batch processing on latency under low load.

We perform the described latency measurement specifically for p2p and loopback scenarios as, in these two scenarios, MoonGen can leverage the NIC to accurately and efficiently timestamp UDP packets \[42\]. We have not performed a latency test for p2v, as its RTT is expected to be similar to that of the loopback scenario with one VNF. For v2v, it is not possible to perform the same test as for p2p and loopback since virtual interfaces, unlike physical ones, do not support hardware timestamping. Fortunately, pktgen-DPDK implements a software timestamping feature that can still be utilized in both VMs and Docker containers. Although less accurate than hardware timestamping, it provides a means to compare different software switches under the same setup.

#### p2p scenario: To make RTT in the p2p scenario, MoonGen is configured with two threads. One thread generates synthetic traffic with 64B packets, as it was used for measuring throughput. The other TX thread periodically injects, as background traffic, Precise Time Protocol (PTP) packets with specific sequence numbers, collects these special PTP packets on their way back from the other port of the NIC in NUMA node 1, and calculates the round-trip time based on the difference between TX and RX timestamps. These timestamps are generated by the underlying Intel 82599 NIC, under the instruction of MoonGen.

#### v2v scenario: For the v2v latency test, we cannot leverage hardware timestamping feature of MoonGen inside virtualized environments. As a result, we have to adopt different methods for different tools to realize a relatively fair comparison. Thanks to the good compatibility with the operating system, standard tools can be used to measure the latency for VALE in this scenario. We simply configure routing using \(\text{ip}\) command for each VM. We then ping the second VM from the first and get the average RTT. Note that we cannot do the same inside Docker containers, as the veth interfaces are always in the down state and cannot be invoked with system tools. Other switches do not support system tools due to the complete kernel-bypassing architecture of DPDK. Instead, as mentioned before, we measure latency using the software timestamping feature of pktgen-DPDK to measure the RTT. The setup is exactly the same as the bidirectional v2v throughput test: we configure one virtio-pci/virtio-user interfaces for each VM/container. All the interfaces are attached to the SUT. In the first VM, we launch an instance of pktgen-DPDK with the latency test option enabled. Packets are timestamped and transmitted from one virtio interface towards the SUT, which forwards traffic to the second VM. The second VM, in turn, bounces the packets back to the SUT using the DPDK testpmd application. Then the SUT sends the packets to the first VM. The pktgen-DPDK instance in the first VM timestamps the received packets and calculates the RTT based on the difference between RX and TX timestamps. We set the packet size to 96B and transmit them at the maximal rate for all the tests. Although not as accurate as hardware timestamping, this approach reveals the main characteristics of the solutions.

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3 Precision is made more difficult by the coarse granularity of software traffic generators. MoonGen, for example, rounds up TX rates in the range \([9.88, 10]\) Gbps to 10 Gbps.

4 This is specifically required for pktgen-DPDK since smaller packet size always renders 0 \(\mu\)s RTT.
loopback scenario: The loopback latency test uses the same settings as the p2p test with $R^+$ set to the corresponding unidirectional loopback throughput. For all the switches except VALE, each VNF is essentially an instance of DPDK testpmd application running in “mac” forwarding mode. Similar to the throughput test, we deploy testpmd in both VMs and containers using the vhost-user backend. Again, we cannot show results for snabb with containers here due to the reported issue [84]. For VALE, we still run a VALE instance as 12 forwarding VNF inside the virtualized environment.

V. EXPERIMENTAL RESULTS

We now show the experimental results that have been obtained through our proposed methodology, presented in Sec. [IV] when evaluating the performance in terms of throughput (Sec. [V-A]) and of latency (Sec. [V-B]).

A. Throughput Tests

p2p scenario: Fig. 4 shows the throughput results for the p2p scenario. Considering unidirectional traffic, all the software switches saturate the 10 Gbps link with packets bigger than 256B, proving that they are all capable of handling realistic traffic (e.g., 850B average packet size in data centers [85]). For the most stressful input load with 64B packets, BESS, FastClick, and VPP still saturate the link at 10 Gbps (about 14.88 Mpps-million packets per second). Snabb achieves only 8.74 Gbps, as staging packets in internal buffers imposes extra overhead. OvS-DPDK achieves 8.07 Gbps due to the overhead imposed by its match/action pipeline. As the synthetic traffic consists of identical packets, corresponding to a single flow, OvS-DPDK’s flow cache does not help. VALE switch only achieves 3.36 Gbps since, by design, it prioritizes memory isolation and therefore performs expensive packet copying operations between its ports, in addition to source MAC learning and flow table lookup. t4p4s achieves 6.91 Gbps because it incurs the overhead of implementing multiple stages, including header parsing/de-parsing and flow table lookup.

Bidirectional traffic is more stressful and provides a more interesting comparison. As shown in Fig. 4, all the switches, except VALE, reach 20 Gbps with 256B and 1024B packets. Note that such limited performance could be explained with the same considerations on unidirectional traffic results. For small 64B packets, BESS, FastClick, and VPP manage to exceed 10 Gbps. BESS even reaches 16 Gbps and outperforms testpmd since it only performs very simple tasks like collecting statistics. FastClick additionally extracts and updates packet header fields while VPP performs a number of verifications. The other switches achieve similar results as with unidirectional traffic, as their bottleneck is the processing being less efficient and/or made of more complex operations.

p2v scenario: Results for the p2v scenario are shown in Fig. 5. Under unidirectional traffic, all the software switches considered in our evaluation sustain 10 Gbps under 256B and 1024B packets in both directions. For 64B packets, FastClick, VPP, snabb, and OvS-DPDK achieve less than their p2p results. Thus, these switches experience a bottleneck in dealing with the virtualized environments as vhost-user requires to enqueue/dequeue virtio rings by copying packets. Note that Snabb achieves quite distinct results for VMs (8.34 Gbps) and containers (4.33 Gbps), due to the different operation modes (i.e., client mode for VMs and server mode for containers, as discussed in Sec. [IV-C]). t4p4s achieves only 4.29 Gbps and 3.99 Gbps with VM and container, respectively, due to its less efficient processing pipeline and to the overhead imposed by vhost-user backend. On the other hand, VALE achieves a slightly higher throughput (3.91/4.98 Gbps for VM and container) than in p2p (3.36 Gbps) since netmap’s ptnet/veth supports zero-copy packet delivery and imposes less overhead than vhost-user. Note that BESS sustains 10 Gbps for both directions in both virtual environments regardless of the overhead from the vhost-user, as the tasks it performs are very basic and simple. The impact of vhost-user on BESS can only be understood with bidirectional traffic. It is also interesting to note that most switches achieve asymmetric throughput with p2v and v2p traffic: for example, Snabb presents a ratio of 2.2 for the container case. It is thus important to choose the software switch that best suits the specific application requirements.

Fig. 5(b) shows the performance for bidirectional traffic with 256B and 1024B packets. BESS still sustains line rate, i.e., 20 Gbps, but the impact of vhost-user is noticeable for the other switches. Indeed, VPP, OvS-DPDK, Snabb, and t4p4s fail to saturate 20 Gbps in all cases while FastClick fails in the container case, in contrast to their results in the bidirectional p2p test. VALE reaches only 10 Gbps due to the extra overhead imposed by the VALE instance inside the VM. The real throughput is expected to be much higher, and the results here only represent a lower bound, which can be verified in the container case (20 Gbps). For 64B traffic, BESS achieves 11.38 Gbps, much lower than it achieved in the bidirectional p2p test (16 Gbps), further illustrating the impact of vhost-user.

v2v scenario: Results of throughput for both VM and container are reported in Fig. 6. With 64B unidirectional traffic, VALE achieves 9.24/8.08 Gbps for VM/container. Compared with its corresponding p2v result (3.91/4.98 Gbps), it is clear that VALE is more efficient in both VM and container networking. This is mostly due to the efficiency of the ptnet/veth zero-copy packet delivery mechanism of the
As shown in Fig. 6, switches exhibit lower forwarding rate with bidirectional traffic, compared to the experiments with unidirectional traffic. For example, VALE achieves 35 Gbps with 1024B packets with the current VM deployment, which is only 64% of its unidirectional throughput. This occurs because bidirectional traffic doubles the number of packet copy operations between VALE ports and through virtio rings for the others.

**Loopback scenario:** Fig. 7 illustrates the throughput for the loopback scenario with VNFs deployed inside VMs. In particular, Fig. 7a, 7b, and 7c present the unidirectional throughput. For the 1-VNF case, BESS yields the highest throughput. However, as we increase the service chain length with more VMs, it is outperformed by VALE. This is mainly due to the fact that BESS needs to perform an increasing number of packet copies with an increasing number of VMs. Even though VALE still needs to copy packets between its VALE ports, this overhead is compensated by the efficient VM network I/O of ptnet. As shown in Fig. 7c, VALE manages to sustain 10 Gbps for unidirectional traffic with 1024B packets, regardless of the service chain length. Other switches achieve lower throughput due to the overhead (mainly packet copies) imposed by vhost-user. Note that when the service chain length reaches 4, Snabb becomes overloaded and its throughput plummets, as the workload is too much to handle with a single core. This is expected to be alleviated with multiple cores for Snabb. Results for bidirectional traffic are shown in Figs. 7d, 7e and 7f. In this case, VALE performance significantly degrades, especially for smaller packets. For 1024B packets, its performance begins to drop when the service chain length is greater than 2. This is due to the dominant impact of doubling the overhead of packet copying between VALE ports. Other software switches also present decreasing throughput as the service chain length grows, due to the increasing number of memory copies between the SUT and VMs.

Fig. 8 presents the results for loopback test scenario with VNFs deployed inside Docker containers. In general, all the switches follow the same trend as the VM case: their throughput decreases as the chain length grows long. VALE fails to achieve the same efficiency as in the VM case and is outperformed by other switches in most of the cases. This result demonstrates that veth, though works in zero-copy manner, is less efficient than ptnet. All the other switches
achieve comparable throughput with their corresponding VM scenario. We thus conclude that most of the software switches considered in our study can achieve similar throughput networking VNFs inside both QEMU-based VMs and Docker containers.
B. Latency Tests

**p2p scenario:** Fig. 9 shows the measured average RTT latency. Under 0.99R+ load, t4p4s presents a very high latency (174 µs), showing its instability under high loads. Since the other DPDK solutions do not face such problems, we believe this is due to the inefficiency of the t4p4s internal pipeline. The hardware abstraction layer of t4p4s presents a trade-off between performance and platform independence, and the level of abstraction can be re-factored to enhance performance. VALE also imposes high latency at high load as it uses interrupts for packet I/O, unlike BESS, FastClick, OvS-DPDK, and VPP that exploit DPDK busy-waiting for packet I/O. Snabb latency is also quite high (22 µs), mainly because its LuaTT compiler keeps evaluating its execution time in performing online code optimizations. Under 0.50R+ load, VALE presents the highest average latency of 34 µs, mainly because it uses interrupt instead of busy-waiting for packet I/O. t4p4s also presents a relatively high latency of 31 µs, due again to its inefficient internal pipeline. Among the other switches, snabb achieves 8.5 µs, because of the extra delay imposed by intermediate inter-module buffers. Under 0.10R+ load, we observe that t4p4s achieves higher latencies than in the 0.50R+ test. This is a consequence of the delay in constituting batches under low load.

**v2v scenario:** Fig. 10 shows that VALE outperforms other switches in terms of latency (only 100 µs), similarly to what observed for v2v throughput test. BESS, FastClick, VPP, t4p4s, and OvS-DPDK achieve very similar latencies for both VMs and containers, as they all use vhost-user to interconnect VNFS. BESS achieves the best RTT among them due to its simplicity; which is coherent with throughput tests. Snabb presents quite different RTT between VMs and containers; we believe this is due to the different server/client configuration orders, as explained in the throughput test section. While ptnet requires two packet copying operations between VALE ports, solutions based on vhost-user have to incur four copies on virtio rings.

**loopback scenario:** Fig. 11 shows the measured average RTTs in µs when varying the VNFS from 1 to 4. For all the switches we consider, latency for 0.99R+ load is always higher than for 0.50R+ load. This is as expected, since R+ is only the average throughput and the actual forwarding rate of each software switch fluctuates around it. Consequently, an unstable software switch might fail to sustain 0.99R+ in a specific time period, causing data path congestion and packet loss. Such a situation rarely happens under 0.50R+ load. Another significant result is the impact of batch processing of some software switches since, at a low input rate, time has to be spent to wait for new packets to complete a batch, thus impairs overall latency. As shown in Fig. 11 latency under 0.10R+ load is higher than under 0.50R+ for t4p4s, snabb, and FastClick, mainly due to their internal strict batch processing. We did not observe the same effect for FastClick and snabb in the p2p test because the batch effect could not accumulate as the loopback scenario with packets traversing FastClick multiple times. Other switches do not incur this issue since they dynamically adjust the batch size, and their RTTs do not increase so much as the service length grows longer. In all the cases, t4p4s presents the worst latency, reflecting the inefficiency of its processing pipeline. Snabb presents a huge latency leap from the 2-VNF VM test since it becomes overloaded at this point and fails to keep up with input traffic. The same phenomenon was observed in its throughput test. OvS-DPDK also experiences a relatively large leap at 4-VNF case, for both VMs and containers, due to similar reasons. In general, most of the switches achieve similar RTT between VM and container deployments, so that both virtualization techniques can be viable solutions in terms of latency.

C. Best Match Between Use-Cases and Switches

Based on the previous experimental results, we can make the following remarks on possible use cases for the considered switches. These remarks complement the taxonomy previously presented in Table I.

BESS achieves both high throughput and low latency in p2p, p2v, and 1-VNF loopback scenarios for VMs. It also achieves optimal performance for all the container-based loopback tests. It is a viable choice to switch traffic between physical NICs and one or multiple paralleled VMs, as well as to steer packets for containerized service chains.

Snabb performs well in most cases but suffers from overload in the loopback scenario with a chain of more than 3 VNFS. We also failed to find a solution to realize the loopback test with containers. It is easier to deploy than other solutions based on DPDK or netmap and is thus a good choice when the time-to-production of specific applications is critical.
TABLE III: Summary of use cases for each software switch

| Software Switch | Best use case                                      | Remarks                                      |
|-----------------|--------------------------------------------------|----------------------------------------------|
| BESS            | Forwarding between physical NICs and containers   | Chaining of containerized VNFs               |
| Snabb           | Fast deployment, runtime optimization             | Bottlenecked with multiple VNFs              |
| OvS-DPDK        | Stateless SDN deployments                        | Supports OpenFlow protocol                   |
| FastClick       | VNF chaining                                     | Supports live migration, high latency at low workload |
| VPP             | VNF chaining                                     | Supports live migration                      |
| VALE            | VNF chaining with high workload                   | Limited traffic classification and live migration capability |
| t4p4s           | Stateful SDN deployments                         | Supports P4 language                         |

OVS-DPDK and t4p4s have the advantage of supporting OpenFlow and P4, respectively, and are thus the only solutions that work with third-party SDN controllers and newly introduced protocols. OVS-DPDK appears the best option for a stateless SDN scenario, while t4p4s is preferable when some state is required (e.g., for a firewall).

FastClick and VPP have good performance in all scenarios and simplify VNF migration and redeployments thanks to the isolation provided by virtio. Moreover, unlike BESS, they are compatible with newer hypervisor versions and can, therefore, be used to build both linear and parallel NFV environments with reasonable trade-offs. Of these two solutions, VPP might be preferred when latency is the primary concern since it generally has lower RTT and avoids severe latency degradation at low input rates (e.g., $0.1R^+$).

Finally, VALE, augmented by ptnet passthrough, achieves relatively high throughput in v2v and the loopback scenarios. It is, therefore, well-suited to construct linear service chains in environments with high workloads. On the other hand, as ptnet is highly dependent on the host netmap module, it does not have the same level of memory isolation as the virtio paravirtualized driver. Thus, migrating its VNFs may require synchronization at host level. Another caveat is that VALE, as a simple Ethernet switch, has limited scope for classification compared to the other solutions and may require enhancement to support advanced traffic routing between VNFs.

VI. CONCLUSION

The emergence of high-speed packet I/O frameworks and the proliferation of NFV have given rise to intense research on the design of software switches running on COTS platforms. Many different designs have been proposed and implemented to route traffic between NICs and VNFs in NFV applications. In this paper, we have sought to improve understanding of the throughput and latency performance of these alternative designs by defining a performance measurement methodology and providing sample results for seven state-of-the-art proposals.

The methodology is based on four test scenarios, physical to physical (p2p), physical to virtual (p2v), virtual to virtual (v2v) and loopback (with multiple VNFs), designed to explore the performance of typical NFV configurations where traffic...
is forwarded between multiple physical and virtual interfaces. In the interest of reproducibility, the paper describes the experimental setup in detail, including specifications of tested software and hardware versions and the packet generation and monitoring tools used. In our evaluation, all the VNFs are hosted in two most popular virtualized environments, namely virtual machines and containers. The measurement results reveal that no one system prevails in all scenarios. This is as expected, given the different design objectives of the considered software switches, but is a useful reminder that the best switch choice depends significantly on the intended NFV context. The presented results and related discussion enable a more informed choice and should guide the design of potential enhancements to relieve identified bottle-necks.

It is worth noting that the present wide-ranging comparison has required considerable effort, both to understand the details of the considered switches and to setup and conduct the experiments. Therefore, we hope that other researchers will be able to profit from our experience in further exploring the performance dimensions of existing and emerging software switches and in further refining the evaluation methodology.

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To Tuning)
port “apps” using the PCI port addresses which are then interconnected through the “link” method:

```lua
local c = config.new()
config.app(c, "nic1", {pciaddr = pci1})
config.app(c, "nic2", {pciaddr = pci2})
config.link(c, "nic1.tx -> nic2.rx")
```

For OvS-DPDK, we configure a new bridge and attach the physical interfaces to it by specifying their PCI addresses using the `ovs-vsctl` command. Then we populate the flow table with direct forwarding rules between the interfaces using the `ovs-ofctl` command.

For netmap, we need to unload the `ixgbe` kernel module and load its netmap counterpart. The physical ports are then bound to the netmap device driver. Then we simply bind physical ports to a VALE instance (in this case `vale0`) using the `vale-ctl` command:

```bash
vale-ctl -a vale0:p1
da-ctl -a vale0:p2
```

B. p2v scenario

As for p2p, we need to follow switch specific approaches. The only difference is that we have to consider the virtual interface connecting software switches to VNFs. To interact with virtualized environments such as virtual machines or containers, each switch must create a virtual interface. Snabb, VPP, OvS-DPDK, FastClick and BESS achieve this using the vhost-user protocol. Netmap solutions, on the other hand, achieve this using `ptnet` [20]. Some configurations are required on the VNF side to realize p2v workflow. These are described in Sec. V. Here we specifically detail the minimal configuration required for each software switch. In particular, for BESS we configure a virtual interface “v1” using the `PMDPort` module by specifying the name and Unix domain socket path. Then physical interface “inport” is linked to “v1” to realize p2v workflow:

```lua
inport::PMDPort(port_id=0, ...)
in0::QueueInc(port=inport, qid=0)
v1::PMDPort(vdev="name,iface=path,...")
in0 -> PortOut(port=v1.name)
```

Similarly, for FastClick, t4p4s, and VPP, we create a virtual interface by specifying name and socket path through the DPDK “–vdev” option. Note that, by default, t4p4s does not work with virtual interfaces. We therefore disabled some offloading features and recompiled the source code to make it compatible with vhost-user. OvS-DPDK accomplishes the same by setting the type of virtual interface to dpdkvhostuser. The created interfaces behave just like physical ones and they can be linked to render the intended traffic steering behavior.

Unlike solutions based on DPDK, Snabb implements its own version of vhost-user backend. Consequently, we create a virtual interface “v1” leveraging its customized “vhostuser” module:

```lua
config.app(c, "v1", vhostuser.VhostUser,...)
```

As for netmap, we just create a virtual interface using `vale-ctl` and attach it to a VALE instance which relays traffic from the physical interface to the VNF:

```bash
vale-ctl -n v0
da-ctl -a vale0:v0
```

C. v2v scenario

To configure software switches realizing v2v workflow, we simply instantiate two virtual interfaces and interconnect them as described in the p2v scenario.

D. loopback scenario

For loopback, physical and virtual interfaces are created and interconnected as described for p2p/p2v scenarios. Note that in the loopback scenario, t4p4s relies on the VMs to modify the destination MAC address of each traversing packet according to the flow table.