Challenges and Solutions for hybrid SDN

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ABSTRACT

This Editorial summarizes the Special Issue entitled Challenges and Solutions for hybrid SDN (Chal. sol. HSDN) published in Elsevier's Computer Networks during 2021. We first provide the motivation and context for such a Special Issue, followed by a short explanation and classification of the articles accepted for publication, and concluded with some envisioned future research directions.

1. Introduction

During the last decade, the Software-Defined Networking (SDN) paradigm has thrived and fostered a whole new ecosystem [14], in which all users (from network providers to end users) profit from enriched network applications and use cases. Though the concept of programmable networks appeared for the very first time almost half a century ago [2], the emergence of OpenFlow [19], later on followed by the coining of the SDN term, finally fractured the network vendor lock-in, opening a wide range of new possibilities.

Nevertheless, following a *pure* SDN architecture, in which the control and data planes are clearly separated, is hard to achieve in practice. For instance, most popular SDN frameworks are hardly disengaged from the physical resources they control, hence being unable to provide *agnostic* Application Programming Interfaces (APIs), probably because manufacturers still find it hard to produce completely *white* network devices [25]. Furthermore, applying SDN in practical implementations might not be completely feasible or beneficial in some scenarios. In these situations, the architectural model follows what is usually entitled as a *hybrid* approach [1].

According to the SDN architecture, and based on a very simple classification, hybrid SDN encompasses two main types of *hybridization*, viz. horizontal and vertical. To better understand this idea, let us focus on a simple definition of non-SDN and SDN devices, as depicted in Fig. 1. Based on this idea, non-SDN devices have no clear separation of control and data planes (they are both merged by the manufacturer, both in hardware and software), and hence all control and data traffic is exchanged horizontally, in a distributed manner. On the other hand, SDN devices separate both planes, which indirectly causes that data traffic is still conveyed horizontally, but control plane is mainly exchanged vertically. Consequently, horizontal hybridization usually implies the coexistence of different architectural approaches (non-SDN- and SDN-based) in the horizontal axis of the architecture, i.e., affecting the exchange of data traffic. While, vertical hybridization usually affects the vertical axis, that is, the exchange of control traffic.

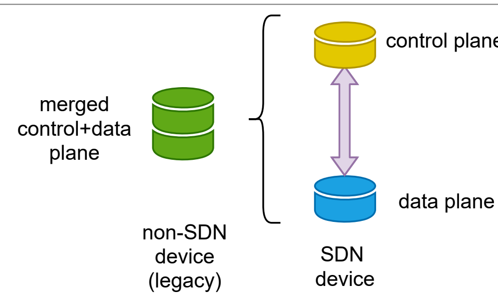

Figure 1: Types of devices based on the SDN definition: non-SDN (left) and SDN (right).

Fig. 2 summarizes some types of common hybrid SDN approaches. For instance, Figs. 2.a) and 2.b) exemplify two types of horizontal hybridization; the first one simply illustrates a network of three devices communicating (one SDN and two non-SDN), while the second is similar as we still have three network devices, but the one in the middle acts both as an SDN and non-SDN. These types of hybrid networks are often observed in deployments that are being migrated from a legacy-based to an SDN-based network, as directly applying the SDN architecture to a complete working network might be costly and risky. On the other hand, Figs. 2.c) and 2.d) depict a couple of examples of vertical hybridization; the former represents an SDN whose data plane is not completely dummy as it has not delegated all control to the control plane (above), while the latter shows a legacy device that has install a shim layer for compatibility with SDN-based control. More specifically, Fig. 2.c) is designed to lessen the control load of the SDN controller, as some part of the control is kept at the data plane to reduce the amount of exchanged control traffic; while an ex-

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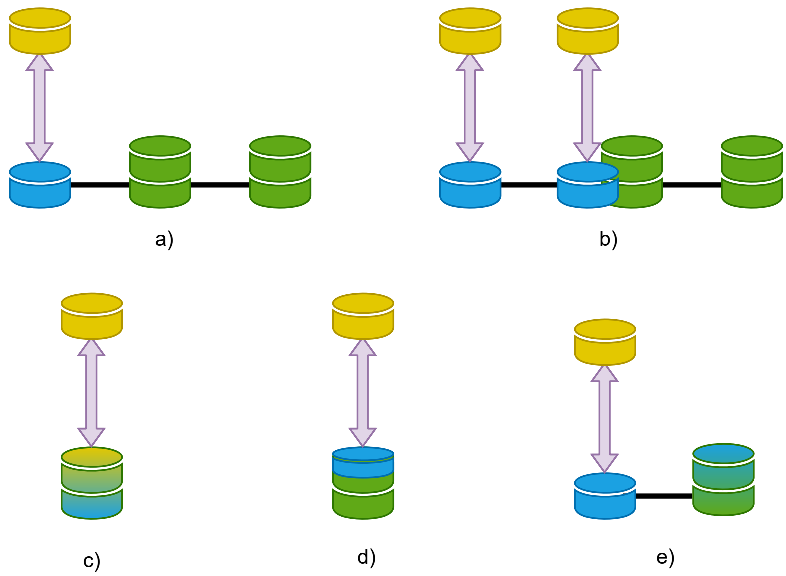

Figure 2: Some examples of horizontal and vertical hybridization (yellow = control plane; blue = data plane; green = merged control+data plane).

ample of Fig. 2.d) is Open Networking Foundation (ONF)'s Stratum [22]. Finally, Fig. 2.e) is another type of vertical hybridization, though it could be considered a mixed type, in which a non-SDN device (on the right) implements the data plane, but only partially (maybe due to computational constraints), and delegates the rest of the control to fully-fledged neighbor SDN devices. An example of it might be found in Low-Power and Lossy Networks (LLNs), in which network devices partially implement the SDN architecture due to memory and power limitations.

2. Overview of the Special Issue

This Special Issue has received a total of 38 submission, from which only 13 were finally accepted for publication. The average number of review rounds was two, and each manuscript was at least reviewed by four researchers to accomplish a high-quality standard.

From the whole set of accepted manuscripts, one of them is a comprehensive survey on hybrid SDN by Khorsandroo *et al.* [13], which revisits and analyzes more than 300 works. The survey presents architectural concepts, security and privacy aspects, network managment and traffic engineering aspects in hybrid SDN, while explaining the context of these technologies in currently emerging novel network scenarios and applications.

In the next sections, we summarize the published works based on the different use cases they cover, which we classified into the following five types: (1) network security, (2) intelligence-fostered networks based on Machine Learning (ML)/Artificial Intelligence (AI), (3) advanced data plane programmability, (4) wireless and heterogeneous networks, and (5) mobile and service provider networks.

2.1. Network security

Network security can benefit from hybrid SDN because, for example, it allows enhancing current network deployments, without modifying the whole architectural design, and it also provides a centralized view to monitor the network.

Yazdinejadna *et al.* [30] propose a kangaroo-based *Intrusion Detection System (IDS)* named KIDS for detecting security attacks and malicious behaviors for data planes in SDN. To achieve this goal, the proposed solution monitors packet parser and flow tables of an SDN switch to perform both flow-based and packet based intrusion detection. The proposed IDS is called a kangaroo-based approach because it uses consecutive jumps like a kangaroo after detecting each attach to announce the detected attacks efficiently to the SDN controller and other IDSs. To improve scalability, KIDS uses a zone based approach for detecting attacks in which each zone consists of several SDN switches. In this approach, a KIDS instance in each zone of the network performs intrusion detection activities without depending to other IDSs. The authors evaluate performance of the proposed solution by running six week data of 1998 DARPA intrusion detection evaluation and NSL-KDD datasets on KIDS architecture.

Dayal *et al.* [6] propose a trigger-based traceback mechanism called SD-WAN Flood Tracer to facilitate tracing attack sources in Software-Defined Wide Area Network (SD-WAN). The proposed solution can be used to monitor internal traces in the vicinity of a single controller and external traces in the vicinity of another controller. To reduce the unnecessary computation overhead, the internal traceback is used in the case of Distributed Denial of Service (DDoS) attacks and the tracer utilizes the available statistics at the controller. The proposed solution is designed for SDN networks, but it can be extended to facilitate tracebacking in non-SDN networks as well.

2.2. Machine learning and artificial intelligence

AI and, particularly, ML have drawn considerable interest in recent years thanks to their potential to take smart decisions and large-scale data processing. These benefits allow the current implement impasse between network maintenance and management to be resolved through an efficient tool [5]. For example, many researchers are trying to incorporate intelligent algorithms such as supervised learning, unsupervised learning, and deep learning, into SDN-based routing systems to escape the downsides of conventional routing approaches. Unfortunately, designing a routing mechanism that uses ML to achieve real-time and customizable optimization is a major challenge. In this regard, hybrid SDN facilitates this evolution towards intelligent networks.

Ibrar *et al.* [12] present PrePass-Flow, a ML-based technique to minimize Access Control List (ACL) policy violation due to links failure in hybrid SDN. In hybrid SDN, an SDN controller can directly poll the status of the SDN links via the OpenFlow protocol. However, the legacy links' status passes through SDN switches and reaches the controller, causing a delay. Due to this delay, the controller does not have the up-to-date status information of legacy links and ACL policies violation. To minimize the impact of a link failure in hybrid SDN, PrePass-Flow predicts link failures, recomputes ACL policies' locations, and installs the ACL policies (if applicable). The proposed model minimizes the ACL policy violation in case of link failures using ML algorithms. For simulation, PrePass-Flow has used the Mininet network emulator with a POX controller and it provides efficient communication in outages.

Sun *et al.* [27] propose a QoS-guaranteed intelligent routing mechanism in SDN. By using a novel data flow classification system, this paper investigates the issue of smart routing in SDN. The MACCA2-RF&RF data flow classification approach is proposed to classify the data flow type and achieve the QoS criteria by combining a number of ML algorithms (e.g. CART, KNN, Random Forest, CART-Naive Bayes- Random Forest voting classification algorithms). When a link is congested, the local routing algorithm is then advised to modify the links just before and after the congested link rather than the whole path. This paper finally proposes a QoS-guaranteed intelligent routing system named QI-RM in SDN to provide QoS guarantees for data flows. The results of the simulation indicate that the MACCA2-RF&RF can effectively identify data flows by an accuracy rate of 99,73%, and the QI-RM can guarantee QoS data flow specifications before and after link congestion.

2.3. Advanced data plane programmability

Data plane programmability can be an enabler for various hybrid SDN scenarios, as the ones shown in Fig. 2. Three papers of this Special Issue leverage programmable data planes to support enhanced hybrid SDN solutions, in which part of the needed functionalities is offloaded to the programmable hardware or kernel technology.

Cao *et al.* propose OVS-CAB [11], a novel solution aimed at improving performance of software Open vSwitch (OVS) [24] by offloading most of the OVS data plane functionalities to hardware Smart Network Interface Cards (Smart-NICs). OVS-CAB includes an enhanced rule-caching algorithm to optimize memory usage in the Smart-NICs, and a hardware prototype is built based on the P4 language [4]. Such a proposal can be very beneficial in hybrid SDNs, where P4 programmable Smart-NICs can be adopted to enhance capabilities of legacy software switches. The proposed hardware prototype is evaluated against the original OVS software implementation and is shown to achieve significantly less time memory usage and higher data plane hit rate, while also reducing the CPU usage of the host server.

H^2 [18], proposed by Mayer *et al.*, designs, implements and evaluates a programmable data plane solution for Linux routers that support Segment Routing [9] with IPv6 (SRv6) in hybrid IP/SDN networks. Additionally, the solution exploits extended Berkeley Packet Filter/eXtreme Data Path (eBPF/XDP) technologies [29] to speed up the performance of software-based SRv6 routers. H^2 is an important work towards a scalable adoption of SRv6 in hybrid SDNs. A proof-of-concept is implemented and evaluated in a performance monitoring use case: the results show that the proposed solution is around five times faster than conventional approaches.

Ollora Zaballa *et al.* [20] propose an In-band Network Telemetry (INT)-based [28] monitoring system that is able to work in hybrid SDNs consisting of P4 programmable switches and legacy devices that support Multiprotocol Label Switching (MPLS). The proposed system enables advanced traffic engineering features if P4 programmable switches are properly placed in the hybrid network, and moves a significant step towards the adoption of INT-like monitoring solutions in hybrid SDN solutions, especially as the ones depicted in Fig. 2.a). Different tests are performed in a mixed emulated-real testbed, and it is shown that the proposed monitoring system can be used to take traffic engineering decisions that are able to improve end-to-end flow latency.

2.4. Wireless and heterogeneous networks

The SDN paradigm is usually hard to apply in wireless and heterogeneous networks, and particularly in IoT-based networks, as they are usually constrained in memory or power, and hence cannot fully deploy the SDN architecture. This Special Issue encompasses three manuscripts in this area.

Liu *et al.* [16] present CluFlow, a cluster-based flow control in hybrid Software-Defined Wireless Sensor Networks (SDWSNs). CluFlow aims to reduce the control overhead by the definition of clusters. Their evaluation (rather comprehensive, including networks bigger than 100 nodes and performed with Cooja [23]) prove this reduction without degrading packet delay nor delivery rate.

Martinez-Yelmo *et al.* [17] describe eHDDP, an enhanced hybrid domain discovery protocol for network topologies with both wired/wireless and SDN/non-SDN devices. They evaluate eHDDP with ONOS [3] and Mininet-WiFi [10], using the BOFUSS switch [8] in networks comprising up to 80 nodes, with diverse percentage of SDN and non-SDN nodes. Although routing is not directly considered, they envision to use eHDDP as a way to generate in-band control channels as future work.

Finally, Kumar *et al.* [15] present Opt-ACM, an optimized load balancing based admission control mechanism for IoT-based SDWSNs. The authors compare Opt-ACM versus state-of-the-art and traditional protocols in diverse network scenarios, implemented in Mininet-WiFi, that follow common use cases. Their results in terms of packet delivery ratio, packet loss ratio, average delay and average jitter show a moderate-to-high improvement to other approaches. Opt-ACM needs to be configured accordingly for each network scenario to reach best results.

2.5. Mobile and service provider networks

Two papers of this Special Issue cover the adoption of hybrid SDN solutions in the landscape of mobile and service provider networks, addressing different challenges in the scenarios of federated multi-domain and mobile core networks.

Neto *et al.* [7] address the heterogeneity aspect of Management and Orchestration (MANO) in a federated multi-domain scenario, specially with regards to the need to deal with SDN controllers of multi-vendor characterized by the lacking a standard Northbound API. This work proposes a seamless and vendor-agnostic MANO abstraction running on top of federated SDN multi-domains: WAN Infrastructure Manager Agnostic (WIMA). WIMA abstraction provides a common Northbound API for external triggering, maintains a global-viewed topology of the federation as a whole, and deals with each SDN Controller directly harnessing an ontology-based scheme.

Silva *et al.* [26] adopt a transition solution for Mobile Core Networks from hybrid to fully-capable SDN networks. The paper presents a Hybrid SDN Mobile Core network (4G and Non-Standalone 5G) which integrates support for Wi-Fi access, traffic offloading capabilities and dynamic network slices instantiation. The results of the introduction of SDN and virtualization of the Mobile Core Network show non significant impact in terms of latency, attachment time and throughput in the hybrid mobile network when compared with the traditional deployment.

3. Future research directions

While hybrid SDN could be initially thought as a temporary solution to overcome current limitations of SDN or to be applied in legacy networks for a smooth migration, the truth is that hybrid SDN could be indeed seen as one of the latest evolutions in the SDN paradigm. In fact, one of the latest architectural references of SDN defined by the ONF [21] already describes the SDN architecture in a generalized way, in a client-server style, rather than control-data plane manner.

In our opinion, the future research directions of hybrid SDN are directly related with the five use cases in which we classified the published manuscripts: mobile and service provider networks are driving the network applications, and the focus is on wireless and heterogeneous networks, while advanced data plane programmability and AI/ML appear as enablers, and network security remains as a transversal requirement to meet at all times. In fact, 6G networks are already characterized by the growth in the amount of Internet of Things (IoT) devices, and the need for AI/ML in networking.

For example, one of the key missing points for a wide and effective exploitation of data plane programmability in hybrid SDN networks is the definition of a unified control plane able to configure the hybrid network's devices in a way that multiple technologies, such as P4 and eBPF/XDP, and applications, can coexist and provide the best end-to-end connectivity to the users. This is certainly a future research direction that needs to be further explored. Another research direction is the need for distributed AI/ML algorithms in constrained IoT environments, as currently most intelligent-based network still rely on centralized approaches, which might not be feasible in all cases.

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