

## Transport SDN at the dawn of the 5G era

## ARTICLE INFO

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## ABSTRACT

This editorial introduces the topic area of this special issue, namely the area of Software Defined Networking (SDN) controlled optical transport networks, i.e., so-called transport SDN (T-SDN) networks, that support emerging fifth generation (5G) wireless networks. We first outline the SDN concept and the main challenges and potential benefits of SDN control in optical transport networks. We then introduce the articles of this special issue, which we have categorized into articles addressing: (i) T-SDN control plane architectures, (ii) T-SDN provisioning and restoration, and (iii) control of specific transport technologies in T-SDNs. We conclude this editorial with a broad outline of future research directions related to T-SDNs supporting 5G networks.

## 1. Introduction

## 1.1. SDN overview

SDN is a breakthrough technology in networking that is revolutionizing the way data networks are designed, built, and operated—perhaps forever. The acronym stands for Software Defined Networks (or Networking) and the meaning is somewhat fuzzy, being variable according to the context and the background and point of view of who is speaking. However, there are some basic features common to all the interpretations. One of these is that the control plane is detached from the data plane, so as to make the control plane open and customizable. The motivation is, as oftentimes, cost reduction. Softwarization is the reaction of the operators to the high technology costs, that have been increasing over the years due to “vendor lock-in”. By opening up the control plane, many different players can start to participate in the network software development, including the operators themselves and low-cost start-ups with specialized network software expertise. The hope is to foster competition, which ultimately forces the big vendors to lower their prices.

Actually, this virtuous cycle did not prove to be equally applicable to all network segments, or at least not to all segments with the same rate of success. In particular, its application has proven difficult in the transport network segment. The transport segment is the part of the telecom infrastructure that transports very large aggregates of data, either in dense urban areas (metro networks) or over long distances (wide-area networks, including international, intercontinental, and *trans*-oceanic links). The main reason for a slow deployment of SDN in this transport network segment is that networks are real systems and, as such, they not only have a logical brain but also a physical body, which in the case of the transport segment has to be particularly “muscular”. In the transport segment, the trend towards softwarization hits against the complexity of long-distance and high-bandwidth transmission, coupled with huge

throughput switching. All these functions require specialized high-performance hardware, the design of which demands particular expertise. Moreover, the control of such specialized hardware is not easily separable from the equipment itself. Often, the control has to be provided by the same vendor that is constructing the specialized hardware. All these issues conspire against the concept of commoditization of the hardware, which underlays the success of SDN in the intra-datacenter and local-network contexts.

## 1.2. SDN for transport networks

The critical question is: Can SDN be applied to the transport network [1]?

To answer this question, we refer to the well-known SDN architectural scheme illustrated in Fig. 1. As Fig. 1 shows, the communication between the SDN controller and the network devices occurs across the so-called South-bound interface, while the North-bound interface is between the controller and the network applications (NetApps).

Equipment used in packet-switching networks is quite homogeneous in terms of functionality, as it conforms to well-established and consolidated standard protocols (both at layer 3 and at layer 2). This greatly simplifies the implementation of the controller and of the South-bound interface (see top part of Fig. 2).

A typical protocol that is very well suited for the implementation of the South-bound interface in case of packet switching is OpenFlow [2]. The OpenFlow protocol, which has been natively conceived for SDN, has represented a breakthrough, especially in the context of intra-datacenter networks and green-field installations. OpenFlow, developed and updated by the Open Networking Foundation [3], is indeed often confused with SDN itself. Most of the commercial networking products nowadays either exclusively implement or support OpenFlow.

In the context of transport networks, the situation appears to be quite different: networking equipment is heterogeneous, because devices have

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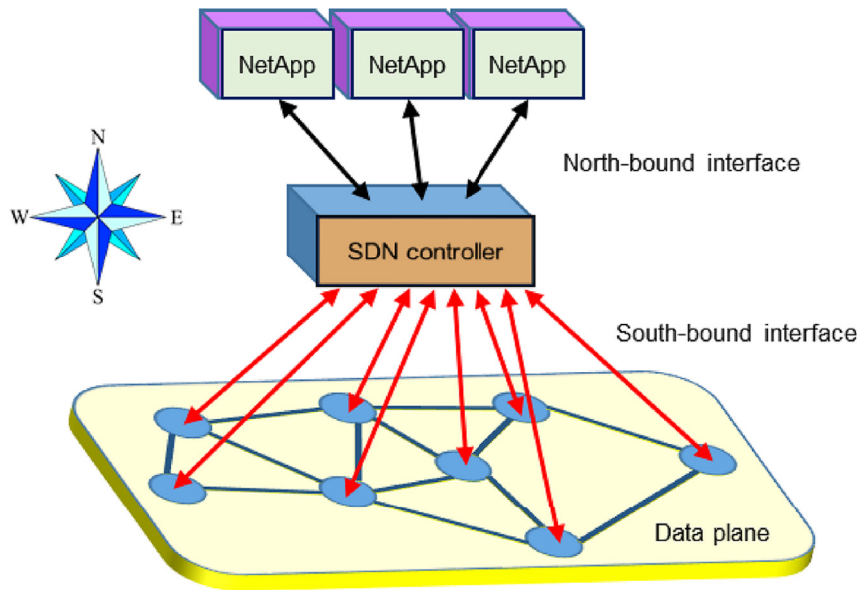


Fig. 1. General outline of the SDN architecture.

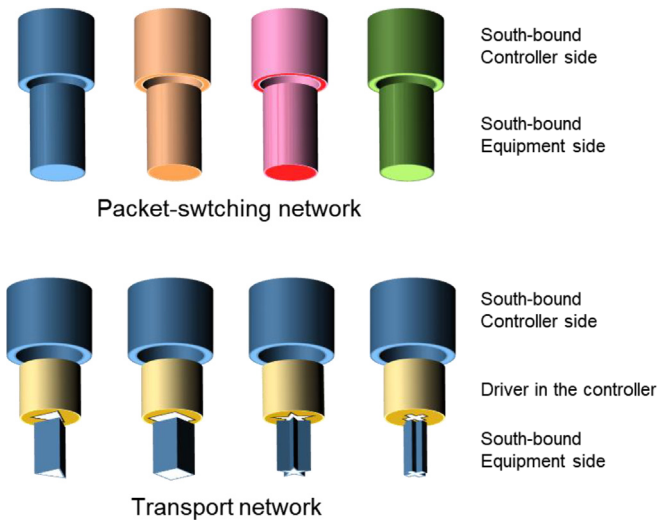


Fig. 2. Conceptual difference between South-bound interface in case of packet-switching and of transport network: the transport network requires a specific driver for each type of equipment.

to implement particular techniques to cope with the physical layer. This makes the usage of a single technology or protocol on the South-bound interface impractical, if not impossible. For instance, there have been several attempts to generalize and extend OpenFlow to adapt to several different use-cases [4], but to date they have not been a ground-breaking success.

1.3. Driver layer for South-bound interface

A better technique to address this problem may be to develop a “driver” layer (see bottom part of Fig. 2) within the controller to adapt the South-bound interface to the specific equipment types. The different specific drivers interface on the top of the driver layer with one common and generic standard controller. This allows then to use the most appropriate protocol to implement the controller-to-equipment communication. There is an extensive set of protocols that have been adopted in various cases. One of the most successful today is NETCONF [5] (or its close relative RESTCONF), in which, thanks to the YANG models [6], the

network equipment itself specifies to the controller how to build the driver suitable for that specific equipment.

The possibility of using various protocols for the South-bound interface is also beneficial for migration strategies of operators towards SDN. A lot of equipment deployed in current production networks does not support OpenFlow or other innovative protocols. Connecting the controller to switches and routers by already-supported “traditional” protocols, e.g., PCEP [7], BGP [8], SNMP, CLI, TL1, and TR-069, is of paramount importance to migrate the control plane to T-SDN, without losing data plane investments.

When the approach based on the drivers is not sufficient, T-SDN encompasses the possibility of structuring the control plane in a hierarchical architecture [9,10]. At the bottom of the hierarchy, each technology-homogeneous domain has its own low-level controller. A general parent controller coordinates all the low-level controllers. Several authors refer to this parent controller as a network orchestrator.

1.4. North-bound interface

Theoretically, issues related to the South-bound interface in T-SDN should have no impact on the North-bound interface. However, often the physical layer creates dependencies that emerge also in the logical functions needed to control the network. Typical examples are impairment-constrained routing and spectrum management in flexi-grid optical transport networks [11]. These functions can require the development of specific NetApps (e.g., for optimization and planning) operated over the North-bound interface of the network orchestrators. The diffuse need for implementing these functions in the transport network prompted standardization bodies to work on a possible standardization of the North-bound interface for transport, e.g., the so-called TAPI [12]. It should also be mentioned along this line, that recently a lot of interest and research is dedicated to the development of monitoring and data analytics subsystems: they add complexity in the T-SDN control plane, but allow to improve the performance of the system and to autonomously react to unexpected events. Most current open-source orchestrator projects integrate such subsystems, e.g., Refs. [13,14].

2. Overview of this special issue

At the time this special issue was conceived, the two guest editors had both just finished working independently on two surveys on SDN [15, 16], one of the two explicitly dedicated to T-SDN, the other one closely

related to this subject. These survey papers came after both editors and their respective research groups have been engaged in several technical projects on the topic. Collecting and studying the literature for the two surveys, we realized that the approaches proposed to deploy SDN on the transport network infrastructure were already plentiful and interesting. Thus, we thought it was the right time to launch a full special issue dedicated to T-SDN.

After the submission, review and selection process was completed, we were able to select seven high-quality contributions, providing outstanding samples of the research advances in this field. The affiliations of the contributing authors represent a good mix of academia, research centers, and industry, evenly covering the main regions of the world.

Let us introduce the papers included in the special issue. The contributions can be classified into three groups: papers focusing on T-SDN control-plane architectures, papers oriented towards provisioning and restoration, and a third group of papers dedicated to network applications to control specific transport technologies.

### 2.1. T-SDN control plane architectures

The first group, addressing T-SDN architectures comprises three papers.

Daniel King et al. (partners of the Metro-Haul EU project - invited paper) present T-SDN (together with Network Function Virtualization – NFV) as the key technology for new 5G networks. 5G is not just an enhanced mobile network: 5G is also envisioned to provide high-quality services for several “verticals” or “use-cases”, both business-to-business and business-to-consumers, and to integrate networking with processing capacity (multi-access edge computing (MEC) model). This large pool of services generates large amounts of traffic and thus requires a powerful network infrastructure to interconnect the points of presence (POPs) that only fiber-based optical links can provide. The METRO-HAUL project is a European Commission funded project that involves the design and development of a novel network solution using dynamic elastic optical networking [17–20], including both transparent and flexible optical switching. The METRO-HAUL architecture will need to integrate a wide range of transport SDN technologies. A new control plane with a hierarchical architecture will dynamically adapt to the needs of specific services and optimally exploit the data plane through relevant data monitoring and analysis schemes. The new control plane will also provision 5G and Internet of Everything (IoE) industry services and ensure the required end-to-end QoS.

Rafael B. R. Lourenço et al., (University of California, Davis, USA and Politecnico di Milano, Italy) propose another hierarchical control plane suitable to support 5G characteristics. Accordingly, the authors analyze how to design a robust hierarchical T-SDN control plane ensuring resilience against random failures through redundancy. Survivability against correlated failures (such as disasters [21]) can be achieved by optimally selecting the network nodes where control-plane elements are placed, and by deciding how to route control-plane traffic. The authors propose methods to design the control plane and heuristics for post-failure switch-controller reassignments. The proposed method can achieve high resiliency, at the cost of slightly increased network-resource utilization.

Sonali Chandna et al. (University of Ottawa, Ottawa, Ontario, Canada and University of Tripoli, Tripoli, Libya) extend the SDN concept from packet switching to the transport layers. They developed a Software Defined Survivable Optical Interconnect (SDSOI) architecture for the specific purpose of interconnecting Data Centers (DCs) [22]. The paper emphasizes the multi-layer feature of the proposed T-SDN architecture, encompassing layers 3 and 2 as well as circuit switching. Its multi-domain controller can provide automated controller-based restoration and protection, even for unprotected links in a multi-administrative domain, ultimately allowing guaranteed Service Level Agreement (SLA) maintenance. They minimize the time required

for interconnecting numerous DCs to meet high SLA demands. The architecture is built according to the overlay SDN concept, and categorizes the application layers into online, offline, and third-party applications. The study includes the creation of business applications and the development of the northbound interfaces used by the applications to interact with the controller.

### 2.2. T-SDN provisioning and restoration

Two papers can be ascribed to the second group, dealing with provisioning and restoration.

The paper by Marco Savi and Domenico Siracusa (FBK research center, Italy) is dedicated to T-SDN control functions to be deployed in a multi-layer transport network [23] comprising IP/MPLS and optical layers. In particular, the paper proposes algorithms for routing connections according to specific application constraints, while selecting the best restoration path and strategy. The proposed algorithms are implemented in a typical T-SDN network orchestrator, able to interface with both IP/MPLS and optical equipment.

Behzad Mirkhazadeh et al. (University of Texas Dallas, USA and Cisco Photonics, Italy) describe PRONet, an experimental network developed in the USA and entirely based on a hierarchical T-SDN control-plane architecture, and exploiting Ethernet-over-WDM data-plane technology. The network orchestrator automatically provisions optical circuits to efficiently meet the fault tolerance requirement of Ethernet flows as dictated by the applications. The orchestrator is thus able to implement multi-layer protection at the Ethernet layer and restoration at the optical layer.

### 2.3. T-SDN control of specific transport technologies

Finally, other two papers belong to the group dedicated to the control of specific transport technologies.

The paper by Bijoy Chand Chatterjee et al. (Indraprastha Institute of Information Technology, India and Kyoto University, Japan) exploits SDN to control a specific key technology for transport networks, namely management of the optical spectrum. The authors propose algorithms and techniques for a software-defined elastic optical network (SD-EON). Through bandwidth aggregation, segmentation, and elastic variation, the SD-EON control plane enables dynamic provisioning and releasing of optical lightpaths, accommodating 25% more admissible traffic than an EON without SDN.

Ahmed Triki et al. (Orange Labs and IMT Atlantique, France) deal with another particular technology, namely the Time-domain Wavelength Interleaved Network (TWIN) technology, to implement the data plane of a transport network in the metro area. The paper shows the Opex and Capex reductions that can be achieved by deploying the TWIN technology combined with a suitable T-SDN controller implementing the control algorithms for all transmitters, receivers, and transponders in the network. Simulations show cost advantages over classical circuit-switched network, even if the cost per TWIN equipment unit is higher than that of off-the-shelf technology.

## 3. Outlook

### 3.1. Scalability

Generally, SDN networks pose a wide range of scalability challenges [24]. Future SDN networks need to accommodate large numbers of data flows, large control domains, and frequent dynamic reconfigurations. The large physical capacities of the underlying fibers and the resulting enormous flow numbers and coverage distances of optical networks exacerbate these scalability issues and continue to call for innovative solutions. The principle of centralized control by an SDN controller or orchestrator poses particular scalability challenges for the control plane [25]. Several distributed SDN control strategies have been developed to

control large SDN networks in a scalable manner [26].

Future research needs to examine such scalable distributed control mechanisms in the specific contexts of optical transport networks with very high numbers of flows and long propagation distances covered by fibers. Moreover, 5G network services require nimble reconfigurations of SDN flows. The control of these reconfigurations poses significant challenges, see e.g., Refs. [27–29]. In particular, high mobility levels at the wireless frontend will require corresponding reconfigurations at the backhaul network segments and potentially, the transport network segment. Future research needs to address the scalability over the full life cycle of flows, from establishment, through reconfigurations, and to the termination.

### 3.2. Flexibility and adaptability through virtualization

The centralized SDN control with complete knowledge of the network status allows for flexible network adaptations [30,31]. Flexibility and adaptability through centralized SDN control is particularly attractive for optical networks, which have traditionally been statically provisioned, but have become more flexible through a variety of optical communications innovations, such as elastic optical networking (EON) with reconfigurable add-drop multiplexers (ROADMs) [32–35].

One particularly important aspect of adaptability for high-capacity optical transport networks is failure recovery. These networks carry large numbers of flows for a wide range of applications, including applications that require highly reliable data transport. The central knowledge of SDN control can enhance network adaptations to recover from failures, e.g., fiber link failures, through well-informed decision making about re-routing flows or re-allocating bandwidth: see e.g., Refs. [36–41].

SDN allows for an added dimension of flexibility through the combination with network virtualization by means of the so-called network hypervisors [42–46]. Virtualization allows one physical optical network infrastructure to be flexibly “sliced” into multiple isolated virtual optical networks. Future research needs to examine such virtualization mechanisms in the context of T-SDN support for 5G wireless networks. For instance, one important future research topic is to examine the efficient internetworking of virtualized optical transport networks with virtualized wireless networks. One possible approach may be to establish an end-to-end slice across the entire wireless and wired access network chain. An alternative approach may be to separately establish slices in the wireless frontend and various slices in the wired access network chain and then to interconnect these slices with some gateways.

### 3.3. Hybrid optical SDN networks

The acquisition and installation of SDN networking equipment can be very costly, especially for specialized optical networking equipment. As mentioned in Section 1.3, the transition from conventional networks to fully SDN controlled networks is a critical aspect of networking evolution. In order to ease such transition, so-called hybrid SDN networks mix conventional networking equipment and protocols with new SDN networking equipment and partial SDN control [47,48]. The detailed study of hybrid SDN networks in the context of T-SDN support for 5G networks is largely an open research area. Future research needs to examine how installed conventional networking equipment can efficiently interact with new SDN equipment in the highly heterogeneous setting of optical transport networks interfacing with 5G wireless networks. Hybrid SDN networks in the context of T-SDN support for 5G pose also the challenging problem of placing SDN equipment. Should SDN equipment first be deployed at or near the wireless frontend, or rather near or in the transport networks that backhaul the wireless traffic, or rather somewhere in between? Which SDN equipment deployment provides the most extensive level of SDN control for a given limited

equipment budget?

### 3.4. 5G system heterogeneity

The 5G system vision includes a wide range of heterogeneous wireless communications technologies as well as heterogeneous wired communications infrastructures and protocols for supporting the wireless frontend [49–52]. A particular challenge for SDN is to cohesively control the wide range of heterogeneous wireless and wired network segments in future 5G systems. For instance, the access network segment to the wireless communications frontend may need to carry specific signal formats [53], which have typically specific quality of service requirements for the transport network. On the other hand, the network segments that connect the wireless frontend to the backhaul gateways of the various network providers may employ an ample range of optical network technologies, such as passive optical networks [54–57], which require SDN control and possibly virtualization [58,59]. A key challenge is to form an overall integrated end-to-end network from these heterogeneous network segments [60].

Future research needs to examine in detail how these various heterogeneous network segments can efficiently cooperate to effectively provide an overall network service to increasing numbers of users and heterogeneous applications. Possibly, novel gateways and interface standards are required to smoothly internetwork and control the heterogeneous networking technologies [61,62]. The central SDN control may be able to extract synergies by exploiting the relative strengths of one technology while mitigating the weaknesses of the complementary network segments and their respective technologies. For instance, wireless mesh network transport may cost-effectively reach areas without fiber infrastructure, whereas fiber transport (in areas with fiber availability) may provide reliable transport.

Overall, the heterogeneous 5G technologies across the entire wireless and wired access network chain may require a driver layer, which we outlined in Section 1.3 for T-SDN. The driver layer could interface the different heterogeneous wireless and wired physical layer technologies with their specific physical characteristics and limitations with the central SDN controller.

### 3.5. Multi-access edge computing (MEC) and tactile internet

The ongoing trend to merge communication and computation as well as the need for low-latency service provisioning close to the users has led to the so-called concept of multi-access edge computing (MEC), which is also sometimes viewed as mobile edge computing or fog computing [63–71]. MEC brings computing resources within the vicinity of the users, such that there are only relatively short propagation delays between the users and the MEC location. This short distance, in conjunction with specialized low-latency communications protocols [72,73], enables low-delay services, which are required for a wide range of applications, e.g., industrial control, human-machine co-working [74] as well as a wide range of communications tasks in 5G systems [75].

More broadly, the emerging tactile Internet concept is based on the premise of a 1 ms roundtrip delay from a user via a communication network to some processing in the MEC and back to the user [76,77]. The increasing trend towards processing service requests “locally” in MEC systems poses interesting challenges for T-SDN. On the one hand, the short stretch on the order of ten or 20 km between users and MEC systems may emerge as the new critical transport segment. Novel optical networking mechanisms, e.g., low latency adaptations of PON technologies [78], may be needed to cost-effectively interconnect users and MEC systems. On the other hand, the local processing in MEC systems may fundamentally change the characteristics of the traffic that does need to be transported over longer distances, e.g., to and from remote data centers and cloud computing facilities. Future research needs to examine



how SDN control can aid to efficiently transport this “remote traffic”. Future research needs to thoroughly examine the characteristics of the “remote traffic” that needs to be transported over longer distances, as well as its quality of service requirements. Based on the traffic characteristics and service requirements, novel transport mechanisms may possibly be developed to efficiently transport this new “remote traffic.”

### 3.6. Artificial intelligence (AI)

The decision making in the central SDN controller can consider the complete knowledge of the network status. At the same time, the increased flexibility and adaptability of SDN networks provides a large decision space for a wide range of SDN tuning knobs. Accordingly, the decision making in the SDN controller becomes increasingly complex. Emerging AI techniques may aid in the controller decision making. A few studies have begun to examine this decision making for optical networks [79–85]. However, the study of AI based decision making in the context of optical transport networks, and in particular for T-SDN support for 5G services, is in its infancy. A key challenge is the efficient problem representation of the highly complex and heterogeneous 5G networks interacting with transport networks with their wide range of monitoring points [86]. Once a compact network status representation has been obtained, the decision making about optimally setting the wide range of SDN control “knobs” poses highly complex optimization problems [31]. Future research needs to develop efficient heuristics that exploit the AI mechanism for fast nearly optimal decision making.

### 3.7. Security and privacy

Optical transport networks and 5G networks carry communication flows that are critical for specific applications, e.g., for medical applications and for networked vehicle applications. Disruptions of the communication flows may endanger human lives or cause extensive property damage. The security and integrity of communication flows is therefore highly important. Generally, the photonics-based communication in optical networks is quite reliable. Nevertheless, optical networks can be targeted by malicious attacks and research on effective defense mechanisms has begun, see e.g., Refs. [87,88].

Transport network security research is still in its infancy, particularly in the context of SDN controlled transport networks that provide 5G services. The central SDN controller can aid in defense mechanisms as it has complete knowledge of the network. On the other hand, if a malicious attacker manages to compromise the controller, then the attacker can compromise the entire network, i.e., the central controller poses a critical vulnerability. Moreover, the heterogeneous communications technologies for the various network segments as well as their protocol interactions may offer attackers a multitude of possible points of attack. Future research needs to carefully examine these potential attack points and develop effective defenses.

Moreover, the reliability of the interactions of SDN optical transport networks with the various 5G network components needs to be examined in detail. Reliability mechanisms may try to exploit the various heterogeneous network segments for alternate transport routes that bypass failed network links or failed communication nodes.

A related and still largely open issue is privacy, which is highly important for communication flows that transport sensitive personal information, e.g., medical records. Recently, quantum key distribution has emerged as a promising privacy mechanism for optical transport networks [89–91]. Future research needs to further examine the privacy properties of quantum key distribution, particularly in the context of virtual network slices that should be isolated from each other, i.e., each network slice should provide a private network for its tenant. Moreover, in the context of 5G services, future research needs to examine how privacy characteristics of quantum key distribution in optical networks can be effectively extended to 5G wireless networks.

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