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Elastic Optical Networking for 5G Transport

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Abstract The 5th generation of mobile communication system (5G) is expected to change the communication landscape by 2020. 5G will provide a unified platform for connecting billions of devices and offering a wide range of networking services. The use-cases and the disruptive capabilities of 5G will bring forward a number of challenges for both the wireless radio and wired part of a 5G network. The wired transport network, typically consisting of access and core domains, has to adopt tailored networking solutions satisfying differentiated quality of service requirements as envisioned in 5G. While optical transport technology has been prevalent in core segments, it is also perceived as a key enabler for the 5G access networks due to its very high capacity and low transmission delay. However, existing optical transport technologies are hindered by inflexibility, poor resource utilization, and high costs, and cannot be stretched to 5G scale. On the other hand, optical technologies have been going through a paradigm shift towards an elastic optical network that is considered as the promising solution for future high-speed transport networks. This paper outlines key challenges for the design of a flexible, programmable, and dynamic 5G transport network, and discusses the enabling technologies and directions to address these challenges.

Keywords 5th Generation communication · Transport network · Flex-grid optical network · WDM/DWDM network · Network slicing

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1 Introduction

The 5th generation of mobile communication systems (5G) is on the horizon with the promise to revolutionize the communication landscape and user experience. 5G will support the massive growth in traffic volume, as well as in the number of connected devices (both fixed and mobile) and coverage, to provide unprecedented capabilities for accessing and sharing information [1]. It will enable a wide variety of services, new verticals, and a rich set of use cases, including massive broadband and machine to machine communications, tactile Internet, virtual/augmented reality, high definition media delivery, industrial applications, autonomous vehicles, real-time monitoring and control, and so on [2]. Many of these services have stringent quality of service (QoS) requirements in terms of latency, jitter, reliability, availability, and mobility. For instance, massive broadband communication has to deliver on demand high definition videos to thousands of users requiring tens of gigabytes of bandwidth, whereas ultra-reliable machine-type communication (uMTC) (e.g. factory automation, traffic safety control, and so on) demands high reliability and availability at a very low latency. In addition, the diverse QoS requirements have to be achieved without imposing significant capital expenditure (CapEx) in terms of infrastructure and without burdening network providers with high operational expenses (OpEx) for increasing infrastructure deployment, maintenance, management, and energy consumption.

While the standardization of 5G is still ongoing, the general consensus is that network operators will no longer follow "one-size-fits-all" architecture that treats all kinds of services similarly. They will deploy a networks-as-a-service model that provides multiple logical networks, each tailored to a particular service with specific QoS requirements, on top of a common physical infrastructure. These logical networks are commonly referred to as *virtual networks* or, in particular, *network slices* in the 5G literature [3, 4]. Another unified view of 5G projects is to leverage network function virtualization (NFV) that decouples network functions from dedicated proprietary hardware and deploys them on commodity servers, thus reducing CapEx [5, 6]. In addition, NFV will allow the deployment of virtualized network functions (VNFs) at different data centers (DCs), or even at remote clouds, to optimize CapEx, OpEx, and energy consumption, based on QoS requirements and user demands. Hence, 5G will require orchestration of heterogeneous resources from wide geographical regions to deploy and manage network slices.

A network slice can span multiple technological and administrative domains, i.e., wireless radio, access/metro/core transport networks, as well as edge/regional/core data centers (DCs) and evolved packet core (EPC), to provide the desired end-to-end connectivity as shown in Fig. 1. Although the wireless radio network between user equipments (UEs) and antennas will play a critical role in the 5G infrastructure, it only constitutes the last mile of the end-to-end path. In this article, we focus on the access/metro/core transport networks that will provide connectivity to the antennas. The access transport network will connect remote radio units (RRUs) to central offices located in edge DCs, while metro/core transport will provide connectivity to EPCs possibly located in regional/core DCs. Baseband units (BBUs) located at

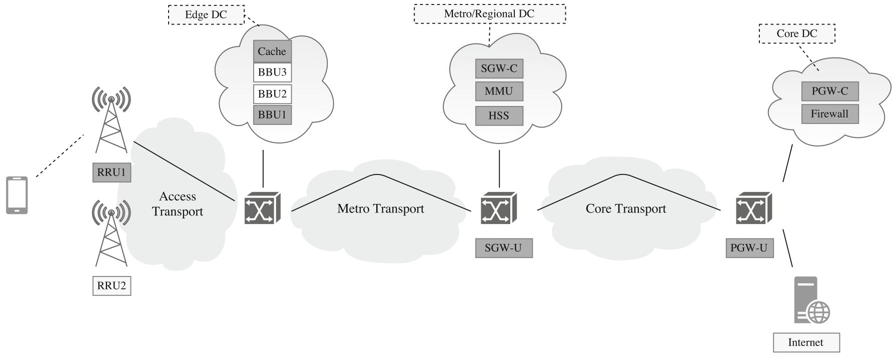

Fig. 1 5G mobile network architecture

central offices will perform baseband processing of the radio signal coming from the RRUs, and convert them to Internet Protocol (IP) traffic suitable for an EPC. The EPC will be the mobile core that provides functionalities such as mobility management entity (MME), serving gateway (SGW), packet data network gateway (PGW), and home subscriber server (HSS). These functions can be virtualized and deployed on commodity hardware as shown in Fig. 1. In this figure, shaded boxes such as RRU1, BBU1, Cache, MMU, HSS, SGW, PGW, firewall and the underlying connectivity among them construct a network slice. Last but not the least, the EPC will connect network slices to the Internet and cloud through its gateways.

Up until 4G long term evolution (LTE) networks as shown in Fig. 2, baseband processing is performed by the BBUs located at the antenna sites, and hence the IP traffic goes all the way to remote antenna sites. Furthermore, the EPC as well as other network functions are deployed as specialized and proprietary hardware as shown in Fig. 2. Both of these hinder the massive growth and dynamic scaling feature of 5G network slices. Current access transport networks have been using a variety of technologies, including Ethernet, IP/MPLS, WiMAX, satellite and so on [7]. In contrast, multi-layer architectures including IP-over-wavelength division multiplexing (WDM) and IP-over-dense wavelength division multiplexing (DWDM) networks have been predominantly used in the metro/core transport segments [8, 9]. These networks can take advantage of the best of both worlds', i.e.,

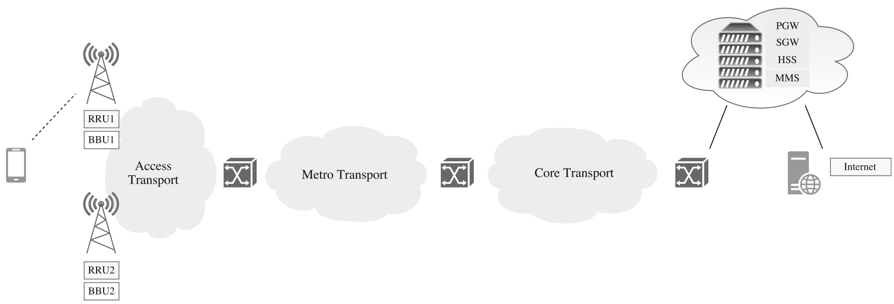

Fig. 2 Current mobile network architecture

IP network's flexibility and programmability, as well as optical network's high capacity and low latency [10]. However, they are being challenged by 5G disruptive capabilities and QoS requirements of 5G applications.

The QoS requirements of 5G applications and 5G disruptive capabilities will require a massive capacity increase, low latency communication, and highly dynamic scaling capability in both the access and core transport networks [11]. Furthermore, several emerging 5G radio access technologies, including millimeter-wave (mm-wave), massive multiple-input and multiple-output (M-MIMO), beam-forming, coordinated multipoint (CoMP), and enhanced inter-cell interference coordination (eICIC), and different deployment architectures (e.g., small cell, integrated radio base stations, centralized radio access network (C-RAN), and so on) will introduce new requirements on the access transport network that can not be achieved by existing technologies [12]. For further reading on the emerging 5G access technologies and deployment options, one can refer to [13, 14]. On the other hand, the core transport network will have to cater for the virtualization of EPC functions such as MME, SGW, PGW, and HSS among others and the deployment of EPC functions along geographically distributed DCs [15]. The multi-tenancy requirement imposed by network slicing will demand a highly scalable, reconfigurable, flexible core transport network that is hard to achieve by conventional *IP-over-WDM* or *IP-over-DWDM* networks [16].

The above challenges calls for a more sophisticated transport that can handle massive and dynamic traffic and satisfy the varying QoS requirements of network slices, while keeping CapEx, OpEx, and energy consumption at a reasonable level [17]. A number of research proposals, including [10, 11, 18–20] advocate for the adoption of optical networks as the way to go. However, we argue that current fixed-grid optical network technologies, such as WDM and DWDM networks, are not suitable for 5G communication networks for several reasons. First, although WDM and DWDM networks allow multiple wavelength channels to be multiplexed onto a single optical fiber to increase capacity; they allocate scarce spectrum resources in a fixed granularity of wavelengths. Each channel then adopts a fixed data rate leading to a fixed bandwidth per wavelength. This may result in poor resource utilization in 5G where bandwidth requirement of a network slice can range from very low (e.g., uMTC slice) to staggeringly high (e.g., ultra-high bandwidth slice). Second, due to the limited number of wavelengths in an optical fiber, the fixed-grid allocation puts an upper bound on the number of network slices that can be served. Third, the optical devices used in fixed-grid networks are rigid and cannot be easily reconfigured or virtualized, thus contributing to the increase in CapEx, OpEx, and energy consumption. In addition, these devices cannot dynamically adjust transmission properties (e.g., spectrum of wavelength, bit rate, modulation scheme, and so on) according to the rapid scaling need of a 5G network slice. Finally, they may not cope with the stringent requirements imposed by the access transport network or the network slice itself.

There has been a significant research body dedicated to making optical networks more resource efficient, flexible, and elastic, while keeping the benefits of WDM or DWDM based networks intact [21–23]. The combination of flexible grid spectrum allocation, innovations in transponders and optical switches, orthogonally modulated spectrum sub-carriers, and adaptive modulation have given rise to an elastic optical network (EON). The EON can be easily integrated with an IP layer to construct an *IP-over-EON* [24]. Fortunately, the same elastic optical technologies can offer massive bandwidth as well as flexibility and reconfigurability as outlined next. First, an EON allocates “just-enough” spectrum resources to a network slice with a particular bandwidth demand. Hence, an EON can make better use of the spectrum resources compared to its fixed-grid counterpart, thus resulting in more bandwidth available to users. For instance, depending on the bit rate and the modulation scheme, a gain in effective bandwidth between 33 and 100% could be achieved by using an EON instead of a fixed-grid network operating with the same spectral width [25]. Second, the spectral efficiency of an EON can further be improved by adopting different data rates for different spectral channels and by varying corresponding modulation formats and optical distances, thus offering a finer bandwidth granularity to network slices [26]. Third, bandwidth variable optical devices proposed for EONs have the ability to dynamically adjust the allocated spectral width, data rate, or modulation scheme in order to scale in or out based on the traffic disparity. These devices also offer the proper abstraction to virtualize an optical network into a number of network slices as demanded by the 5G architecture. Consequently, a higher number of network slices can be instantiated, while taking the QoS requirement of the network slices into account.

In this article, we examine the applicability of EON and IP-over-EON in the 5G access and core transport networks, respectively. The article begins by providing basic concepts of fixed-grid and elastic optical networks in Sect. 2. Section 3 presents key challenges to the access and core transports with respect to 5G networks and describes how fixed-grid and elastic optical networks attempt to address those challenges. In Sect. 4, we explore future research directions to facilitate a highly scalable, reconfigurable, flexible transport network. Table 1 alphabetically lists the acronyms used in this paper.

2 Fixed-Grid and Elastic Optical Networks

In this section, we provide fundamental concepts of both Fixed-grid and Elastic Optical Networks along with a brief comparative study as shown in Table 2.

2.1 Conventional Fixed-Grid Optical Networks

The traditional fixed-grid optical network (e.g., WDM or DWDM network) is a circuit switched network where a circuit (also known as a lightpath) is established between two optical nodes. Each lightpath is carried by an optical channel/carrier along the optical links in the path. The spectrum range in the C (190.9–196.1 THz) and L (184.4–190.8 THz) bands of each link is divided into separate channels. An optical channel is characterized by its central frequency and a spectral width [27]. Each central frequency corresponds to an approximate nominal central wavelength. For instance, the nominal central frequency of 195.90 THz corresponds to the approximate nominal central wavelength of 1530.3341 nm. As per the specification

Table 1 List of acronyms in alphabetical order

Acronym	Elaboration
5G	5th generation of mobile communication system
BBU	Baseband unit
BPSK	Binary phase shift keying
BVOXC	Bandwidth variable optical cross-connect
BVT	Bandwidth variable transponders
C-RAN	Centralized access network
CO	Central office
CoMP	Coordinated multipoint
D-RAN	Distributed access network
DC	Data center
DSP	Digital signal processing
DWDM	Dense wavelength division multiplexing
eICIC	Enhanced inter-cell interference coordination
EON	Elastic optical network
EPC	Evolved packet core
FEC	Forward error correction
HSS	Home subscriber server
IP	Internet protocol
LTE	Long term evolution
M-MIMO	Massive multiple-input and multiple-output
mm-wave	Millimeter-wave
MME	Mobility management entity
NFV	Network function virtualization
NWDM	Nyquist wavelength division multiplexing
OADM	Optical add/drop multiplexer
OFDM	Orthogonal frequency division multiplexing
PGW	Packet data network gateway
QoS	Quality of service
QPSK	Quadrature phase shift keying
RAN	Radio access network
ROADM	Re-configurable optical add/drop multiplexer
RoF	Radio-over-fiber
RRU	Remote radio unit
S-BVT	Sliceable bandwidth variable transponders
SDEON	Software defined elastic optical network
SDN	Software defined networking
SGW	Serving gateway
TFP	Time frequency packing
UE	User equipment
uMTC	Ultra-reliable machine-type communication
VNF	Virtualized network function

Table 1 continued

Acronym	Elaboration
WDM	Wavelength division multiplexing
WSS	Wavelength selective switch
x-QAM	x-quadrature amplitude modulation

Table 2 Comparison between fixed-grid and elastic optical technologies

	Fixed-grid	EON
Spectral width	Fixed per wavelength	Adjustable based on number of sub-carriers
Number of channels	Fixed based on spectral width selection	Variable
Transponder Technology	Rigid Transponder	Sliceable bandwidth variable Transponder
Optical Switch	Wavelength selective switch	Bandwidth variable optical cross-connect
Modulation Scheme/ bit rate	One type of transponder per modulation scheme	Configurable through software
Guardbands	Required between adjacent channels	No guardband between adjacent sub-carriers
Traffic grooming	Electronic layer grooming	Optical layer grooming
Reconfigurability	Hardware change needed	Can be done through software
Constraints	Wavelength continuity constraint	Spectrum contiguity and continuity constraints

ITU-T G.694.1 [27], the possible spectrum widths are 12.5, 25, 50 and 100 GHz. The equivalent approximate wavelength spacings are 0.1, 0.2, 0.4 and 0.8 nm. In a fixed-grid network, once a spectrum width is selected, all optical channels in a link are established with the same spectral width irrespective of the demands, as shown in Fig. 3 [28]. Depending on the selected spectral width, the number of channels/ wavelengths in an optical link becomes fixed, hence the name *fixed-grid* [21]. Since a wavelength carries only one lightpath, the number of lightpaths passing through an optical link becomes fixed.

A lightpath between a source s and destination d node in a fixed-grid network is established by assigning a free wavelength channel to a transponder attached to each of s and d. Transponders are required to transform electrical packets from the upper layer of the networking stack to optical signals and vice versa [29]. The transponder attached to node s is then connected to an optical add/drop multiplexer (OADM) that adds an optical signal to the corresponding wavelength of the optical link incident to s [30]. Another OADM, attached to the receiving transponder in node d, terminates the optical signal of the configured wavelength from the incoming fiber, and forwards them to the transponder that will convert the signal back to electrical packets. The intermediate nodes in the lightpath configure their OADMs in "expressed through a node" mode that allows a lightpath to transparently carry a

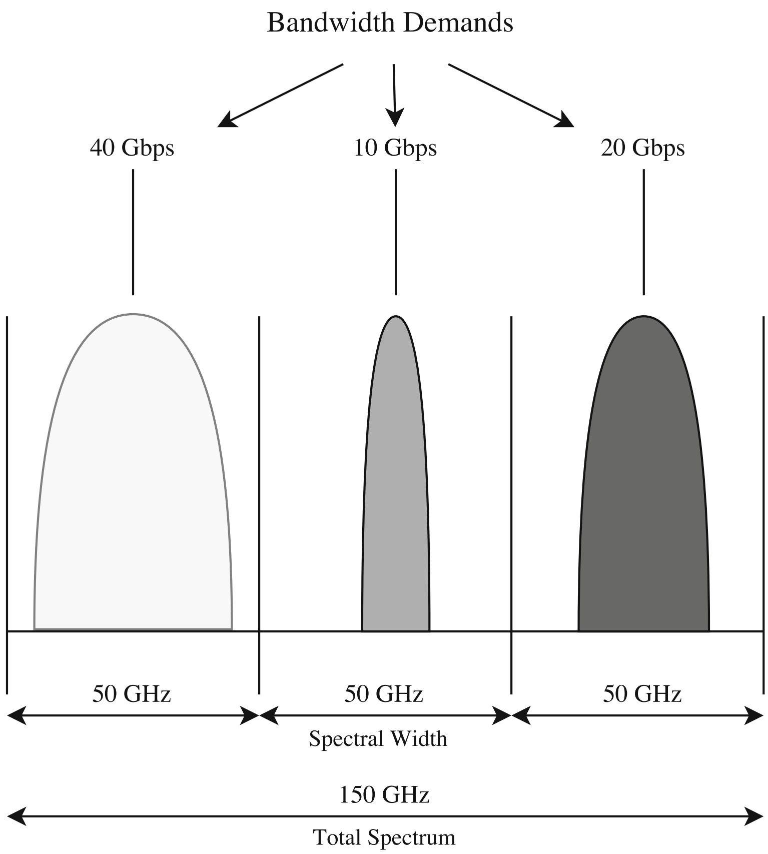

Fig. 3 Spectrum allocation in a fixed-grid network

signal through all the fiber links along the lightpath in the optical domain [31]. OADMs are manually controlled, thus requiring human involvement to configure them. To avoid human involvement, re-configurable optical add/drop multiplexers (ROADMs) have been proposed that can be remotely configured through software. ROADMs can be enhanced with wavelength selective switch (WSS) functionality that introduces additional degrees of switching to realize a mesh optical network [31]. In such a network, two lightpaths for two source-destination pairs can share a common fiber link. However, these two lightpaths must use different wavelength channels so that they do not interfere with one another. Each lightpath in a fixed-grid network (in the absence of wavelength conversion devices) has to satisfy a wavelength continuity constraint. This constraint enforces that a lightpath must use the same wavelength (i.e., same central frequency and spectral width) in the optical links along the lightpath. However, wavelength-convertible devices can convert an optical signal carried by an incoming wavelength to an optical signal for another wavelength [30].

Fixed-grid optical networks suffer from inefficient resource usage and inflexibility due to the fixed allocation of spectral width and tight coupling with hardware. We now discuss some of the major limitations of a fixed-grid optical network:

1. As an optical signal traverses multiple optical devices (transponders, WSSs, and so on) in a lightpath, the edge spectrum of the signal is affected by the finite slopes of the optical filters [32]. To reduce the effect of degradation of edge spectrum and to avoid cross-talk between adjacent lightpaths, appropriate spectrum separation, known as guardband, is required. A spectrum guardband is always needed between two adjacent channels in a fixed-grid network that is a mere waste of spectrum resources [21]. For instance, in a single bit per signal modulation scheme, a 10 Gbps signal requires a spectral width of more than 10 GHz.
2. Fixed allocation of spectral width not only limits the number of usable wavelengths (based on chosen spectral width) but also wastes a significant portion of spectrum resource or a number of transponders. If an optical link serves multiple lightpaths with different bandwidth demands, a fixed-grid network has to trade-off spectral resource with the number of transponders. To illustrate, consider two lightpaths that use the set of optical links; one of the lightpaths requires 40 Gbps bandwidth, while the other requires 10 Gbps. We discuss two possible spectral width choices: (i) Demultiplex 40 Gbps demand into four 10 Gbps demands using the technique known as inverse multiplexing and allocate guardband between them [33]. In this case, a network has to allocate 12.5 GHz spectral width to each of five 10 Gbps demands resulting in a total spectrum usage of 62.5 GHz. In addition, five pairs of source-destination transponders are needed to serve all the demands. (ii) Allocate 50 GHz spectral width to both the demands requiring only 2 pairs of transponders. In this case, total spectrum usage is 100 GHz, and 75% of the spectrum in 12.5 GHz lightpath is wasted. In addition, the capacity of the transponders for the 12.5 GHz lightpath are also unutilized.
3. Lightpath reconfiguration in a fixed-grid network is cumbersome and resource inefficient due to tight coupling with hardware and coarse granular spectrum width. For instance, setting up a new lightpath requires an additional pair of transponders at the source and destination of the lightpath. On the other hand, changing the channel spectral width of an optical link affects all the other lightpaths that use the optical link, and requires reconfiguration of their corresponding transponders. Although the modulation level (and the resultant bit rate) of each lightpath can vary among a small set of options, setting up different modulation formats requires the use of different pairs of transponders with different capabilities [34]. These limitations inhibit the adaptability of fixed-grid networks to respond to time-varying traffic. For example, if the traffic demand of the lightpath previously asking 40 Gbps suddenly increases in a way that it now requires 50 Gbps, a new lightpath of either 12.5 Ghz (choice (i)) or 50 Ghz (choice (ii)) has to be set up to serve the additional traffic. However, in choice (ii), 75% of the spectrum of new lightpath will remain unused. If there is not enough free spectrum left in the optical links of the current lightpath, a new

lightpath with a different set of optical links has to be set up. In the event that the traffic demand of the lightpath is now decreased to 30 Gbps, choice (i) may just free up one of the allocated channels, whereas choice (ii) has no option but to change the channel spectral width and central frequency.

4. Due to the cumbersome reconfiguration process and its impact on other lightpaths, a fixed-grid network remains mostly static [29]. Consequently, spectral width and source-destination pairs of transponders are usually provisioned for peak demand, and do not react to short- or mid-term traffic dynamics [21]. In addition, due to the coarse granular spectrum width of a wavelength, average traffic demand does not usually fit into the bandwidth granularity of a wavelength. As a result, a portion of the spectrum and part of the capacity of the transponder are unutilized during average traffic periods. To reduce such resource wastage, traffic grooming is usually used in the IP/MPLS layer before passing the traffic flows from different demands to the optical layer [35]. An electronic switch performs traffic grooming by combining multiple smaller traffic flows to fill in the bandwidth granularity of a wavelength and passes the groomed traffic to a transponder. Grooming performs similarly to a lightpath in the unlikely case when the source and destination of all the traffic flows groomed in a wavelength are the same. However, in reality, the traffic flows groomed in a source are directed towards different destinations. In this case, a lightpath is dropped at intermediate WSSs and the associated traffic flows are again groomed in separate wavelengths based on their destinations. This breaks the transparency of the lightpath and requires optical-electrical-optical (O-E-O) conversions at each intermediate electronic switch attached to a WSS. Furthermore, electronic layer traffic grooming introduces additional processing and buffering overhead to the electronic layer of the network.

2.2 Elastic Optical Networks (EONs)

To increase the efficiency, scalability, and flexibility of optical networks, there has been a paradigm shift towards EONs (also known as flexible or flex-grid optical networks). An EON can divide C and L spectrum bands into small frequency units (known as sub-carriers) and combine several adjacent sub-carriers into a channel to serve the bandwidth demand of a connection, as depicted in Fig. 4 [21]. Since channels are usually composed of variable number of sub-carriers, the basic unit of switching in EON is a sub-carrier instead of the wavelength in the fixed-grid case. The EON can adopt different transmission techniques to efficiently aggregate sub-carriers, including orthogonal frequency division multiplexing (OFDM), Nyquist wavelength division multiplexing (NWDM), and time frequency packing (TFP) [36]. Since the spectral efficiencies of these techniques are almost similar under ideal conditions, we focus on OFDM hereafter in this paper. OFDM signals can be generated either optically or electronically [23]. For the optical OFDM, ITU-T G.694.1 [27] has defined the sub-carrier spectral width as 12.5 GHz in order to be compatible with existing fixed-grid deployments. Standardization work is going on to define a narrower sub-carrier slot of 6.25 GHz [23]. When the signal is generated

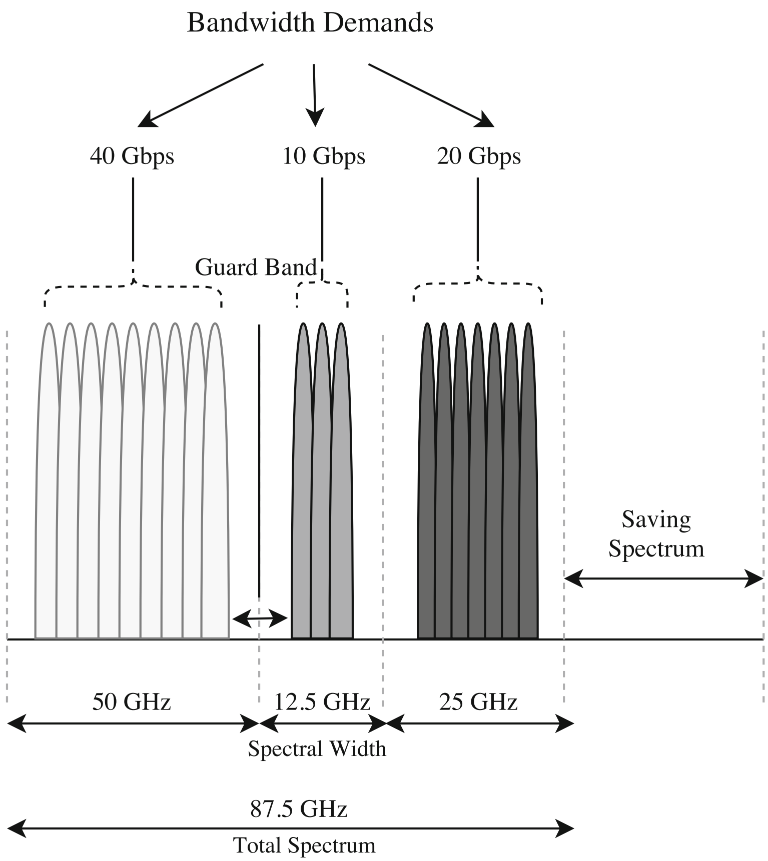

Fig. 4 Spectrum allocation in an EON

electronically, sub-carriers with lower spectral widths such as tens of MHz can be achieved [36]. In addition, OFDM allows for selecting separate modulation formats (with different bits per signal) for each sub-carrier in a channel, thus supporting a wide variety of bit rates from a few tens of Mbps to several Tbps [21, 36, 37]. Consequently, an EON can provide fine granularity of bandwidth to lightpaths using "just-enough" spectrum resources and the most appropriate modulation format [38]. Since the spectrum of adjacent sub-carriers are orthogonally modulated in OFDM, individual sub-carriers can overlap with each other, thus further increasing spectrum utilization [22].

An EON uses flexible transponders, also known as bandwidth variable transponders (BVTs), instead of the rigid transponders used in a fixed-grid network. A BVT can generate an optical signal using the "just-enough" number of sub-carriers with appropriate modulation level [38]. A more advanced version of a BVT is the sliceable BVT (S-BVT) that can simultaneously generate multiple optical signals with different spectral widths [36, 39]. The optical flows from an S-BVT are then routed to different destinations. In essence, an S-BVT can be considered as multiple virtual BVTs, each of which can serve different bandwidth demands. When an OFDM signal is generated electronically, an additional module (e.g., analog to digital converter/digital to analog converter) is needed before an S-BVT [23]. To establish a lightpath, BVTs (or S-BVTs) are then connected to ROADMs, whose roles remain the same as discussed in the fixed grid case. However, an EON replaces WSSs with bandwidth variable optical cross-connects (BVOXCs) that consist of a cross-connect block and one or more add/drop block(s) [40]. To establish a lightpath in an EON, every BVOXC on the lightpath has to allocate an appropriately sized cross-connection with sufficient spectral width. A BVOXC achieves this by configuring its spectral switching window in a contiguous and flexible manner, according to the spectral width allocated to the lightpath [38]. Therefore, a lightpath in an EON has to satisfy two sets of constraints (i.e., spectrum contiguity and continuity constraints) instead of the only wavelength continuity constraint in a fixed-grid network [22]. The spectrum contiguity constraint imposes that a selected number of sub-carriers must be contiguous in the spectrum, while the continuity constraint enforces that the same sequence of sub-carriers are used in every optical link present in the lightpath.

The use of digital signal processing (DSP) in both the sender and receiver BVTs (or S-BVTs) of an EON makes it convenient to configure transmission parameters, such as the number of sub-carriers, modulation formats, forward error corrections (FECs), bit rates, optical reaches, and so on, to achieve the most optimized spectral width [41]. Multi-level modulation formats (e.g., quadrature phase shift keying (QPSK), x-quadrature amplitude modulation (x-QAM)) can carry more bits per symbol than those carried by binary modulation formats (e.g., binary phase shift keying (BPSK)) [22]. Hence, multi-level modulation formats require fewer number of sub-carriers to provide the same bandwidth than those required by binary modulation formats. This spectral efficiency is achieved at the cost of a reduced tolerance to physical impairments for multi-level modulation, thus lowering its optical reach [23]. BVTs (or S-BVTs) can take advantage of this feature by trading-off between optical reach and spectral width for a particular bit rate while generating an optical signal. A BVT (or S-BVT) can increase (or decrease) the number of modulated bits per symbol to decrease (or increase) the spectral widths for shorter (or longer) lightpaths. For further reading on EONs, one can refer to [21–23, 33].

An EON can overcome the limitations of the fixed-grid network as discussed in Sect. 2.1 in the following ways:

1. In EON, no guardband is required between adjacent sub-carriers, thanks to the orthogonal modulation of OFDM. However, guardbands between adjacent channels are still needed to avoid cross-talk. The size of a guardband depends on the number of filters to be cascaded in a lightpath. The study in [42] shows that in a lightpath cascaded over 10 filtering stages, the optimum guardband for 12.5 GHz sub-carriers is 30 GHz. Hence, the spectrum wastage is much less in an EON than in a fixed-grid network that requires guardbands between all the adjacent channels [21].

2. Flexible allocation of sub-carriers increases spectrum utilization and reduces the number of transponders simultaneously. For instance, an EON can save up to 150% spectrum resources compared to a fixed-grid network to serve the same set of bandwidth demands [33]. Similarly, the study in [41] demonstrates a reduction of up to 44% in the number of transponders required by a variable bit-rate EON, compared to a fixed-grid network. We can also explain the savings in the example demands presented above: an EON can combine four adjacent sub-carriers of 12.5 GHz into a 50 GHz channel and assign it to the 40 Gbps demand. For the 10 Gbps demand, it can construct a channel with one sub-carrier and assign the channel to the demand. Since both demands have larger spectral width than their demands, no explicit guardband between them is necessary. In this way, the EON can serve both demands using the same 62.5 GHz spectrum as required in the fixed-grid option (i) and only two (or one) pair(s) of BVTs (or S-BVTs). In addition, it eliminates the need for inverse multiplexing 40 Gbps demand into smaller demands. The EON can further optimize spectral width by trading off between reach and modulation format. For instance, if the lightpath length of 40 Gbps demand falls below the optical reach of 16-QAM (4 bits per signal) modulation, the EON can assign one 12.5 GHz sub-carrier channel to 40 Gbps demand by using 16-QAM. However, if the lightpath length is longer than the optical reach of 16-QAM, the EON can switch to lower modulation level (e.g., 4-QAM with two bits per signal) and select a spectral width of 25 GHz for 40 Gbps demand. In contrast, for the 10 Gbps demand, the EON can select an even lower modulation level, such as BPSK (1 bit per signal), and provision a longer lightpath for the demand.
3. An EON simplifies dynamic lightpath reconfiguration, thanks to the advent of S-BVTS and finer granularity of sub-carrier aggregations. Unlike a fixed-grid network, multiple lightpaths can be simultaneously established using the same pair of S-BVTs. In addition, variable numbers of sub-carriers per channel are fundamental to an EON, and hence changing the spectral width of a lightpath does not affect other lightpaths. Finally, EON can configure signal properties through software without changing the corresponding hardware [43]. Hence, the EON has a number of tunable options to satisfy traffic dynamicity and to reduce power/energy consumption. For instance, when traffic demand increases beyond the capacity of a channel, the EON can expand the channel spectral width by switching on more contiguous sub-carriers. If a sufficient number of contiguous sub-carriers to fit the new demand cannot be found around the current central frequency of the channel, the EON has to relocate the channel to a new central frequency having an adequate number of free sub-carriers [43]. The EON can also increase the modulated bits per signal up to the limit of optical reach to meet the growing traffic demand. If none of the above reconfigurations are possible due to resource constraints, the EON has to tear down the current lightpath and setup a new one with different signal properties. When a traffic demand decreases, the EON can free up the unused sub-carriers or lower the modulation level.
4. The simplified lightpath reconfiguration process makes an EON perfectly suitable for time-varying traffic. In an EON, the optical spectrum of a lightpath

is tailored to the actual demand of a traffic at any time instance [21]. When the traffic demand fluctuates, the EON can either elastically expand (or shrink) the allocated spectrum or easily change the transmission rate. However, proper modeling of the time-varying traffic is needed to utilize the benefits of elastic expansion and efficient spectrum sharing. Due to such elasticity of fine granular of spectrum channels and flexibility of S-BVTs, the right amount of spectrum and transponder resources can be allocated to a small traffic demand, thus eliminating the need for electrical layer traffic grooming. Despite that guardbands are still needed between such narrow spectrum channels, resulting in spectrum wastages. To address this problem, optical grooming has recently been proposed that enables aggregation and distribution of traffic at the optical layer [44]. Optical grooming can group together multiple low demand traffic flows, without the need for guardbands between them.

3 EON in 5G Transport Networks

In this section, we first outline the challenges in 5G access and core transport networks. We then discuss how EONs can address these challenges.

3.1 Challenges in 5G Access Transport Networks

In a traditional radio access network (RAN) as shown in Fig. 2, baseband processing of radio signals is performed by BBUs collocated with radio units at an antenna site [13]. Due to the distributed nature of radio signal processing, this architecture is also known as distributed radio access network (D-RAN). In D-RAN, Ethernet/IP/MPLS functionality is extended all the way to remote antenna sites [45]. Hence, it incurs high CapEx investment and OpEx to install and maintain baseband processing units and Ethernet/IP/MPLS switches at remote cell sites. The D-RAN architecture conflicts with one of the enabling technologies in 5G: the dense deployment of low cost and low power small cells such as femtocell, picocell, and microcell aiming to increase capacity and coverage. These small cell deployments may not sustain the CapEx, OpEx, and the energy consumption incurred by on-site processing units. Furthermore, the densification of cells increases the number of users at cell-edge areas, thus requiring intelligent interference management and better coordination among cells. However, distributed processing of D-RAN leads to poor interference coordination and inefficient CoMP transmission and reception, especially at cell boundaries [46].

To overcome these barriers, 5G proposes a C-RAN architecture where BBUs can be decoupled from antenna sites as shown in Fig. 1. This incurs less CapEx, OpEx, and energy consumption, compared to the D-RAN architecture [13]. In C-RAN, basic radio functions remain at the cell sites as RRUs. An RRU in a C-RAN can be connected to a dedicated BBU unit, possibly located in a central office (CO) or an edge data center via an access transport network. The centralization of BBU processing results in a more efficient use of radio and computational resources, since radio signals from different antenna sites can be processed jointly [45]. Furthermore, it enables an intelligent inter-cell interference coordination and CoMP to optimize the utilization of wireless channels [46]. To achieve further optimization, the notion of dedicated BBU-RRU pairs can be replaced by a BBU pool (also called as BBU cloud or BBU hotel) located in geo-distributed DCs. A BBU pool dynamically pairs up a BBU with an RRU, based on traffic and coverage requirements to leverage statistical multiplexing gains [18]. A BBU pool also achieves better reliability in case of a BBU failure and better load balancing for highly dynamic traffic. The benefits of C-RAN come at the cost of imposing a significant overhead and stringent requirements on the access transport network, as discussed next.

The access transport network has to transfer large amounts of digital/analog sampling data generated from RRUs to BBUs. For instance, the capacity requirement of common public radio interface (CPRI), the most suitable protocol for digital radio-over-fiber (RoF) transmission, can quickly become overwhelming (in the range of tens of gigabits per second) [19, 45]. On the other hand, analog RoF signals such as mm-wave need a broader spectral width than a digital signal would take [12]. In addition, digital and analog RoF signals have to be transported to different BBUs, as they require different processing methods. Furthermore, M-MIMO along with beamforming could use tens to hundreds of antenna elements at each location to provide different data rates and capacity gains to network slices [11]. This requires flexible spectrum switch capability and fast reconfiguration of the bandwidth between RRUs and COs [12]. Besides the capacity requirements, the timing and synchronization of these technologies pose strict latency constraints, as summarized in [13]. Even tighter latency and synchronization constraints are introduced by advanced radio coordination solutions, such as CoMP and eICIC [11] since coordination is performed in a centralized fashion. To keep the capacity and latency constraints in the feasible range, different levels of centralization, by splitting radio functions to both RRU and BBU, are being explored [13, 45]. Hence, deploying a C-RAN with BBU pools and advanced radio technologies require that the access transport network supports massive data rates, high scalability and reliability, very low latency, and flexible switching capabilities.

3.2 How EON Can Help

A number of proposals, including [10, 11, 18, 19] advocate for the adoption of DWDM-based fixed-grid optical networks in access transport of 5G. We argue that although DWDM networks provide well known benefits, such as increased data rates, low latency, and high reliability, they have major drawbacks due to their coarse granularity in allocating spectrum resources and rigidity. Furthermore, they do not support different levels of centralization in C-RAN and the variety of radio access technologies due to their higher CapEx, OpEx, and energy consumption [47]. Additionally, a one-size-fits-all fixed-grid network cannot be simultaneously optimized for different kinds of enabling technologies, levels of centralization, and deployment options as expected in 5G radio access networks [45]. In contrast, EONs offer large degrees of flexibility, adaptability, and programmability that can be leveraged to optimize a network in different dimensions. Several works, including [12, 46, 48] already demonstrated the advantages of EONs in 5G access transport networks. In what follows, we will discuss the limitations of a fixed-grid network as the possible enabler for access transport network and elaborate on how an EON can support 5G disruptive capabilities, technologies, use cases, and deployment alternatives.

Enabling technologies and deployment alternatives in 5G access transport networks are numerous and each of these alternatives has its own set of constraints that may be conflicting with other alternatives [13]. Moreover, these technologies and deployment alternatives can co-exist side-by-side on the same access transport in support of different network slices. For example, one network slice can use digital RoF with narrow spectral widths, while another network slice can use analog RoF with a wider spectral demand. Similarly, multiple network slices using M-MIMO with a different number of antenna elements may require a variety of bit rates over the same fiber link. In addition, different levels of centralization in C-RAN can impose constraints in terms of bandwidth, data rate, and latency. As discussed in Sect. 2.1, a fixed-grid network cannot be efficiently configured for such spectrum, latency, and data rate variability, resulting in spectral and transponder resource wastages. In contrast, an EON can provide fine granular spectrum width consisting of variable numbers of sub-carriers according to the bandwidth demand and particular deployment technology. It allows both digital and analog signals to be transported and switched over the same optical fiber, thus facilitating technologies such as mm-wave [12]. In addition, the EON can tune signal properties (e.g., modulation format, bit rate, optical reach, and so on) to cope with the constraints of deployed technologies and different requirements of use cases. Hence, it can provide much larger bandwidth and more variety of bit rates on an optical fiber, compared to what a fixed-grid network could provide.

Deployment of a C-RAN with BBU pooling and improved CoMP requires establishing and tearing down of lightpaths dynamically [46]. In addition, to cope with traffic dynamicity and to increase energy efficiency, spectral width and bit rate of existing lightpaths need to be adjusted. However, a fixed-grid network, once configured, is restricted by a few hundred wavelengths, each configured with a coarse granular spectral width and a dedicated modulation format (e.g., bit rate). Hence, the number of possible lightpaths is limited, leaving less room for dynamically changing RRUs for a particular BBU. In addition, due to the tight coupling of a fixed-grid network with hardware (e.g., transponders), dynamic reconfiguration of spectral width and modulation format of a lightpath is very cumbersome and time consuming. As we discussed in Sect. 2.1, such reconfiguration may trigger hardware changes and impact other lightpaths in the network. Consequently, the fixed grid network is suitable for a fixed RRU-BBU connection that impedes the applicability of improved CoMP [46]. In contrast, an EON can utilize the full advantages of BBU pooling in a C-RAN and improved CoMP by dynamically reconfiguring lightpaths through S-BVTs. Due to finer spectrum granularity of channels, an EON can have arbitrary numbers of lightpaths on an optical fiber, thus favoring "any-to-any" RRU-BBU assignment of BBU pooling. Furthermore, lightpaths in an S-BVT can be flexibly teared down and set up through software to solve the inter-cell interference problem and to improve the cell-edge user throughput as required by the improved CoMP [46]. Finally, the EON can elastically adjust the assigned spectrum width, the modulation format, and the optical reach of an established lightpath to meet traffic scalability and to reduce energy consumption [43].

As described earlier, centralized radio and interference management in a C-RAN imposes tight latency constraints let alone the strict latency requirement of some 5G use causes (e.g., critical machine-type communications) [49]. However, such stringent latency requirements cannot be satisfied in a fixed-grid network that employs electrical layer traffic grooming as a resource optimization technique. This technique performs O-E-O conversions at each intermediate electronic switch attached to a WSS, each of which can require 13-15 microseconds [12]. The cumulative O-E-O delays could be detrimental to the overall end-to-end latency of which the essential contributors are the propagation delay due to the fiber length and processing time at a BBU. In addition, such traffic grooming augments the electronic switches with additional buffering overhead. Furthermore, power hungry electronic switches are required to be deployed in each optical node of a transport network that increases total energy consumption. In contrast, an EON performs traffic grooming directly at the optical layer, eliminating O-E-O conversions at intermediate WSSs. Therefore, a direct and transparent lightpath can be established between a RRU and a BBU, significantly reducing end-to-end latency and energy consumption [12].

3.3 Challenges in 5G Core Transport Networks

The combination of new radio access technologies, including small cells, mm-wave, M-MIMO, beam-forming, and others, will greatly enhance the capacity, density, and coverage of 5G radio access networks. This sets the stage for a number of 5G use cases, including on-demand video/content delivery, video surveillance, virtual/augmented reality, live high definition TV streaming, and many more. For the metro/core transport network, this translates to a massive aggregated bandwidth capacity increase. In fact, it is expected that the aggregate data rate will increase by roughly 1000 times from 4G to 5G [50]. Therefore, the core transport network will need to support several Tbps transmission rates in the 5G era [51]. Besides the capacity increase, 5G core transport networks will encounter traffic dynamicity due to high user mobility and tidal phenomenon in wireless communication and increased numbers of on-demand services. Such dynamicity includes not only temporal and spatial variability of traffic demands, but also sudden traffic surges in areas close to concerts, gaming events, flash crowds, or mass protests [52]. In addition, the heterogeneity of 5G use cases imposes diverse QoS requirements, ranging from ultra-low latency and high reliability to massive bandwidth and billions of devices enabled by Internet of Things (IoT) .

Several papers, including [15, 53–56] have identified that the current EPC architecture illustrated in Fig. 2 can no longer cope with the data traffic explosion and dynamicity requirements of 5G. This is due to the fact that current EPC architecture was not designed with elasticity in mind [57]. Hence, it relies heavily on the specialized and proprietary hardware for EPC entities (e.g., MME, HSS, SGW and PGW) that require static deployment, provisioning, and configuration [57]. Among EPC entities, MME and HSS provide only control plane functionalities, whereas S-GW and the P-GW are responsible for both control plane and user-/data-plane handling. The conventional hardware deployment of S-GW and P-GW are tightly coupled in control and date planes that have orthogonal scaling requirements. For instance, data plane processing is I/O bound, requiring high packet switching capacity, whereas control plane is CPU bound, asking for dedicated processing capability [57]. To meet the traffic explosion, current EPC architecture has to statically dimension both the control plane and data plane capacity simultaneously, resulting in poor resource utilization and a high CapEx and energy footprint. Therefore, the current EPC architecture is not scalable and flexible enough to satisfy 5G QoS requirements [58].

To improve EPC's scalability, the papers [15, 53–57] along with a 3GPP study propose to decouple power-hungry core gateways (SGW and PGW) into control plane (SGW-C and PGW-C, respectively) and user plane (SGW-U and PGW-U, respectively) components, as shown in Fig. 1. The benefit of such decoupling is that control plane functionalities such as MME, HSS, SGW-C, and PGW-C can be offloaded to DCs as VNFs. This provides rapid scale up and down capabilities without significant increases in CapEx and energy consumption. Such decoupling also allows offloading IP traffic into optical lightpaths at suitable bandwidth granularities [24]. Such a multi-layer network is called *IP-over-Optical* network where the physical communication is conducted at the optical layer with an IP overlay on top [59]. The lightpaths in a IP-over-Optical network for 5G need to be frequently (re)configured to facilitate the most optimized placement of control and user place functions, based on IP traffic dynamicity. In addition, the lightpaths have to respect diverse QoS requirements of the IP traffic as imposed by 5G use cases. This necessitates a more sophisticated optical network that can transport massive dynamic traffic by taking into account the QoS requirements of the IP traffic [17]. All these mandate efficient resource utilization, more flexibility, better programmability, and fast reconfigurability of the underlying core transport network.

3.4 How IP-Over-EON Can Help

To meet the growing traffic demand, network providers have been using IP-over-DWDM networks that adopt fixed-grid optical technologies in the metro or core transport segment. However, IP-over-DWDM networks are being challenged by the continuous growth in traffic and the increased uncertainty in predicting traffic patterns. As discussed before, they are not only deemed unsuitable for keeping pace with some of the 5G disruptive capabilities but also considered to raise the CapEx/OpEx and energy footprint required by 5G services. The recent advances in EONs pave the way for deploying IP-over-EON that promises to be the enabler for future transport networks. IP-over-EONs can leverage the benefits of elastic networking, discussed in Sect. 2.2, to address the challenges in 5G metro/core transport networks. In addition, EONs can be easily integrated with the software defined optical network (SDON) paradigm, thanks to EONs' increased degree of programmability and fast reconfigurability [60–62]. We will refer to such a network as a software defined elastic optical network (SDEON) in the remaining of this paper. An IP-over-EON adopting software defined principles in both the IP and EON layers is foreseen as the perfect match for the virtualized EPC core [63].

Although Tbps transmission rates are expected as a norm in 5G core transport networks, an IP-over-DWDM network does not directly support data rates beyond 400 Gbps at standard modulation formats [33]. Even the highest spectrum width of 100 GHz can provide 400 Gbps at the modulation of 16-QAM. Due to the fixed granularity of spectrum widths at the DWDM layer, setting the spectrum width of a wavelength to 100 GHz will force the smaller data rate demands to be electronically groomed into the wavelength capacity. Such electronic grooming is typically performed based on the destination, irrespective of the traffic’s QoS requirements. The DWDM network then transports the groomed traffic without differentiating between individual QoS requirements. Such equal treatment directly contradicts with the vision of 5G to simultaneously satisfy diverse QoS requirements of network slices. Although inverse multiplexing can provide higher data rates in a DWDM network, it will require unnecessary guardbands among the spectrum channels. Consequently, it will use up the spectrum resources very quickly if there are several demands with Tbps data rates. In contrast, an EON can leverage variable spectrum widths with narrow sub-carrier spacing and adaptive modulation rate to provide Tbps data rates, using lower spectrum resources than a fixed-grid network. For instance, an EON in the IP-over-EON can allocate a 250 GHz channel with the modulation of 16-QAM to provide 1 Tbps data rate. Apart from better spectrum utilization, the EON also allows to setup direct lightpaths with smaller spectrum widths that can serve lower data rate IP traffic demands. The direct lightpaths obviates O-E-O conversions for electronic traffic grooming at intermediate WSSs of the path and reduces end-to-end latency and energy consumption.

The ultra-high capacity and massive number of connections in a 5G network are propelling a network provider to dimension its network accordingly, potentially leading to huge CapEx and OpEx. However, the customers of a 5G network are not willing to pay proportionately. In order to be sustainable in such a competitive environment, a network operator should look for opportunities that minimize infrastructure cost and energy consumption as well as adopt affordable deployment, maintenance, management, and operation tools. Again, the IP-over-DWDM network, due to its technological barriers, does not facilitate the network provider to achieve this sustainability objective. As discussed in Sect. 2.1, an IP-over-DWDM network requires one dedicated transponder per wavelength [24]. As a result, both an IP router and an WSS in an IP-over-DWDM network need as many ports as the number of transponders (or the number of configured wavelengths). This results in a large number of IP routers and WSSs, since the number of ports in an IP router or a WSS is limited. Additionally, the IP-over-DWDM network needs electronic switches attached to each WSS for traffic grooming. All these burden a network operator with a significantly high CapEx, OpEx, and energy requirement of a large number of power-hungry and expensive devices including IP routers, electronic switches, and WSSs. An IP-over-EON can effectively reduce the number of transponders by virtualizing an S-BVT. The S-BVT connects to an IP router and a

BVOXC using separate single interfaces, thus significantly minimizing the number of routers and BVOXCs [24]. The IP-over-EON conducts traffic grooming fully in the optical domain; therefore, transit traffic processing at the electronic switches and IP routers is no longer required. Furthermore, it can support intelligent energy management techniques to put unnecessary devices to sleep, thanks to the fast reconfigurability of an EON.

To realize the decoupled architecture of EPC, data plane functions such as SGW-U and PGW-U can be deployed as high capacity optical switches (e.g., BVOXCs). Unlike specialized core gateways, BVOXCs are energy efficient and can scale in a cost effective manner. With the recent development of SDEONs, SGW-U and PGW-U BVOXCs can be integrated with an SDEON controller. Much like the software defined networking (SDN) controller for Ethernet [64], the SDEON controller has the whole network view, also known as the global knowledge view. The decoupled EPC architecture and the global knowledge of an SDN controller facilitate the optimized placement of control plane VNFs, as well as value added VNFs (e.g., web cache, video transcoder, firewall, and others). For example, VNFs for an ultra-low latency network slice can be placed at an edge DC to improve user experiences. Similarly, the SDEON controller can utilize extended OpenFlow protocol to establish lightpaths that provide the connectivity among the VNFs [61]. The sliceability of S-BVTs and BVOXCs and software control of modulation format make it easier to (re)configure lightpaths whenever VNFs are spawned, stopped, or migrated for IP traffic scaling and load balancing purposes. In addition, the SDEON controller can take into account the QoS requirements of the traffic or the network slice, while configuring the lightpaths. For instance, a low bandwidth, but latency-sensitive, network slice can be assigned the low bandwidth optical channel on the shortest lightpath, whereas a high bandwidth network slice can be assigned a longer optical path having enough spectral resources.

4 Research Directions

In this section, we first discuss existing research efforts pertaining to the use of optical technologies in 5G transport networks. We then highlight open research challenges that are yet to be addressed to realize the deployment of EONs in 5G transport networks.

4.1 What has been Done

Ponzini et al. [65] were the first to demonstrate the feasibility of WDM technology for carrying CPRI traffic over the access transport network in C-RAN. Through a practical implementation, they showed that a transparent WDM layer can meet strict latency and high capacity requirements of CPRI. Carapellese et al. [66] analyzed the delay requirements for transporting D-RoF baseband signals over WDM based Passive Optical Networks (WDM-PON). They addressed the joint optimization problem of BBU-placement and routing and wavelength assignment of traffic requests for C-RAN deployment to minimize the total number of BBUs. Later, in

[67], they extended the optimization framework to focus on the energy efficiency of the transport network. In this work, they took the power consumption due to O-E-O conversion of traffic grooming into account to minimize the aggregated infrastructure energy footprint. On the other hand, Musumeci et al. [20] explored three different BBU placement options for BBU pooling in C-RAN deployment. They addressed the optimization problem of BBU-placement and grooming, routing, and wavelength assignment of traffic requests to minimize either the total number of BBUs or the total number of fibers. Recently, Asensio et al. [47] studied the impact of the centralization level in WDM based C-RAN architectures in terms of CapEx and OpEx. They found that maximum centralization incurs more CapEx and OpEx than a lower level of centralization due to WDM network's tight coupling with hardware. All these works have adopted WDM based transport networks that suffer from the limitations we described in Sect. 2.1.

Raza et al. [48] analyzed the benefits of dynamic reconfiguration of 5G transport network slices in terms of rejection probability and network providers' revenue. They used WDM based transport network that may require re-mapping the network slice over existing lightpaths or over newly established lightpaths. Re-mapping the entire network slice due to traffic dynamicity in one part of the slice causes service disruption in the unaffected part of the slice. In addition, re-mapping over new lightpaths in a WDM network may increase network downtime due to complex lightpath setup process and expenses for additional hardware, as we explained Sect. 2.1. Recently, Zhang et al. [46] experimentally demonstrated lightpath reconfiguration on a DWDM network for an improved CoMP service. They observed latency in hundreds of milliseconds mainly due to software and algorithm processing time. However, they ignored lightpath setup time assuming that lightpaths are already established. Rostami et al. [68] developed a multi-technology orchestration architecture across DWDM optical transport, RAN and cloud, based on SDN. The orchestrator supports dynamic service creation across a heterogeneous set of resources in an efficient manner. Ohlen et al. [19] explored three different transport abstraction models for a C-RAN where transport traffic is carried over a hybrid DWDM network. Their proposed DWDM network is hybrid in the sense that each optical fiber is equipped with fixed number of wavelengths, whereas DWDM nodes use tunable transponders. Based on simulation, they concluded that the abstraction model that takes traffic variability into account and deploys several distributed BBUs exhibits the lowest rejection ratio. Despite using tunable transponders, their proposed hybrid DWDM network has the disadvantages due to coarse granular wavelength channels described in Sect. 2.1.

Zhang et al. [12] proposed to use EONs to provide elastic, transparent, and reconfigurable optical paths between RRUs and BBU pools. They conducted experiments on elastic lightpath provisioning between RRU and BBU pools in an SDN based testbed. Their SDN controller coordinates heterogeneous resources from three domains, i.e., BBU, radio, and optical domain to improve the intelligence of C-RAN. Using a small testbed, they were able to demonstrate that an EON can elastically adjust lightpaths in a time varying environment. Chen et al. [16] proposed a mobile core (i.e., EPC) network architecture based on SDEON. They proposed a scheme to optimize the selection of optical switches and assign optical resources in different granularities, based on mobile traffic load. Zhao et al. [63] built a testbed to evaluate the performance of the SDEON based EPC architecture proposed in [16]. They also proposed an optical resource load balancing algorithm for two different use cases in SDEON based EPC, i.e., users' handover and traffic overload. Through simulation they demonstrated the feasibility and performance of the SDEON based EPC architecture. The authors in [35] presented the application-centric IP/optical networking concept for 5G that has two main components: (i) a framework to establish application-aware elastic optical channels for IP connections, leveraging the advantages of EON; and (ii) a multi-layer orchestrator to allocate, schedule, and configure IP topologies over an EON.

4.2 What can be Done

As summarized in Table 3, the majority of existing research efforts have focused on fixed-grid optical technologies for 5G transport networks. However, it is evident

Table 3 Summary of research efforts that use optical technologies in 5G transport

Reference	Contribution	Technology	Transport	Methodology
Ponzini et al. [65]	Carry CPRI traffic	WDM	Access	Demonstration
Carapellese et al. [66]	BBU Placement and routing and wavelength assignment	WDM-PON	Access	Optimization
Carapellese et al. [67]	Energy-Efficient BBU Placement and routing ans wavelength assignment	WDM	Access	Optimization
Musumeci et al. [20]	BBU Placement and grooming, routing and wavelength assignment	WDM	Access	Optimization
Carapellese et al. [66]	BBU Placement and routing ans wavelength assignment	WDM	Access	Optimization
Asensio et al. [47]	Impact of centralization in C-RAN	WDM	Access	Optimization
Raza et al. [48]	Benefits of Programmability	Technology agnostic	Access and Core	Optimization
Zhang et al. [46]	Improved CoMP	DWDM	Access	Demonstration
Rostami et al. [68]	Resource Orchestration	DWDM	Access	Demonstration
Ohlen et al. [19]	Transport abstraction models	Hybrid DWDM	Access	Demonstration
Zhang et al. [12]	Elastic lightpath provisioning between RRU and BBU	EON	Access	Demonstration
Chen et al. [16]	Optical resource allocation	EON	Core	Demonstration
Zhao et al. [63]	Optical resource allocation and load balancing	EON	Core	Demonstration
Sköldström et al. [35]	Application-centric traffic grooming	EON	Core	Demonstration

from our discussion in Sect. 3 that fixed-grid optical technologies may not support many of the 5G RAN deployment alternatives and disruptive capabilities. Furthermore, in fixed-grid networks, costs scale proportionately to bandwidth, thus limiting the applicability of these networks for many bandwidth-hungry use cases expected to arise in the 5G era. Having observed these limitations and inspired by the recent development of optical technologies towards EON, researchers have started to explore the possibilities of deploying elastic optical technologies in 5G transport network [12, 16, 35, 63]. While initial results based on small scale testbed demonstrations indicate that there is significant potential in EON based transport networks, holistic solutions are yet to be developed. In addition, resource efficiency, programmability, and advanced functionalities brought by EONs will pose significant challenges to the networking layers [26]. Many of these challenges will be exacerbated by the envisioned capabilities and the use cases of 5G. Therefore, intelligent and adaptive control and management plane for an EON should be developed to fully support its emerging features. We now present some open research challenges that need to be addressed before the full realization of EON based 5G transport network is possible.

In a C-RAN deployment with BBU pools, dynamic lightpath configuration for traffic requests needs to optimize several factors including RRU-BBU pair assignment, as well as routing, spectrum, and modulation level selection, while satisfying strict latency and synchronization constraints and minimizing CapEx/OpEx and energy consumption. The latency and synchronization constraints, in turn, depend on the level of functional splits between RRU and BBU. On the other hand, spectrum assignment has to adhere to spectrum contiguity and continuity constraints, thus increasing the complexity of the problem. This complex and joint optimization problem demands intense investigation from both theoretical and implementation perspectives. Similar challenge arises in the core transport network where the problem is to jointly optimize the placement of control and value-added VNFs and the allocation of elastic optical resources to provide connectivity among the VNFs. Due to the presence of geo-distributed DCs, optical reach becomes another dimension to optimize in addition to the routing, spectrum, and modulation level selection present in the access domain. In this case, the resource allocation has to satisfy several QoS requirements (e.g., latency, jitter, throughput, and so on) imposed by end-user or operator use cases.

Another research challenge is how to efficiently predict traffic dynamicity. Such prediction models can allow an EON to allocate "just-enough" spectrum and transponder resources based on the predicted demand and to achieve statistical multiplexing gain, thus increasing resource utilization and reducing OpEx and energy consumption. Due to the complex and uncertain nature of mobile traffic pattern, machine learning techniques (deep learning techniques in particular) can be leveraged to capture the non-linear relationship between traffic pattern and a number of parameters such as location, time of day, day of the week, and so forth.

Since spectral widths in an EON varies based on demand, fragmentation in spectrum will occur over time that separates the available spectrum into small non-contiguous spectrum bands. In a highly dynamic 5G environment, where traffic demands range from very low to immensely high bandwidth with intermittent connectivity, the effect of fragmentation can be drastic. This is because incoming traffic demands may need to be rejected due to insufficient contiguous spectrum availability. To overcome the resource fragmentation problem, both proactive and reactive measures can be taken. Proactive measures aim to minimize fragmentation while configuring a lightpath. Due to churn in traffic demand, proactive approaches are not sufficient. Indeed, reactive spectrum defragmentation needs to be performed periodically to either re-allocate spectrum resources or re-compute the lightpath. However, spectrum defragmentation should be performed in a hitless manner so that it does not impact ongoing services. Although defragmentation strategies have been investigated extensively in the context of EONs [22, 23], more adaptive defragmentation strategies need to be developed for the highly dynamic 5G environment.

Failure in a large infrastructure network is a norm rather than an exception, and its impact can be costly [69, 70]. Since a transport network usually carries a tremendous amount of traffic, a failure (e.g., due to physical impairments, natural disasters, or system malfunctions) can dramatically affect millions of users, which can lead to immense loss of data and revenue. The advent of new technologies in 5G, such as multi-tenancy through network slicing and virtualization of BBUs, transponders, and network functions, magnify the complexity and dimensions of the fault management in a transport network. For instance, any failure in an optical fiber or an S-BVT can propagate to all the lightpaths passing through the fiber or the virtual BVTs configured on the S-BVT, respectively. However, not all the lightpaths/virtual BVTs require the same level of survivability as imposed by the QoS requirement of the corresponding use case. Existing protection and restoration schemes for ensuring the survivability in EONs do not take into account heterogeneous QoS requirements [22]. Therefore, differentiated survivability techniques should be investigated in the context of 5G. For instance, a traffic demand with higher reliability requirement can select a lightpath with highly reliable optical links and devices, whereas a traffic demand with low reliability requirement can select a best effort lightpath.

5G is expected to bring energy efficiency to a new level and deploy energy harvesting techniques throughout the infrastructure. As we discuss in Sect. 2.2, an EON has the ability to significantly reduce overall energy consumption by leveraging optical layer bypass, eliminating the O-E-O conversions at intermediate optical nodes, while using S-BVTs instead of a number of transponders. Therefore, new kinds of energy harvesting techniques for 5G transport networks should be developed that can harness the energy efficiency features of an EON. At the same time, 5G disruptive capabilities and dense deployment of enabling technologies will contribute to the increase in energy consumption. Therefore intelligent energy saving techniques should be developed to minimize energy consumption. This can be done, for instance, by taking energy consumption among other optimization objectives into account, when establishing a lightpath. Another approach is to put some EON devices or small cells/antennas into sleep mode when traffic is below a certain threshold.

New capabilities and flexibilities offered by EONs in 5G transport necessitate the design and development of advanced control and management planes. Therefore, new protocols should be developed or existing protocols such as generalized multi-protocol label switching (GMPLS), open shortest path first (OSPF), and resource reservation protocol-traffic engineering (RSVP-TE) should be extended to fully support the emerging features of both EON and 5G. It will be challenging to employ SDN principles to EONs. New scalability and synchronization issues need to be resolved to realize large scale SDEON deployments. In addition, the control and management plane need to orchestrate and manage multi-technology network segments comprising wireless radio, access/metro/core optical transport, and edge/regional/core data centers to provide end-to-end connectivity with the desired QoS. It is also important to consider the computational efficiency of the protocols and resource orchestration and management algorithms as well as signaling requirements, particularly critical to cope with the real-time requirements of some of the 5G use cases.

5 Conclusion

In this article, we have discussed the diverse requirements imposed on transport networks by 5G disruptive capabilities and use cases, as well as those required by different RAN and EPC deployment models and enabling technologies. These requirements along with virtualization of network elements (e.g., BBU pool, NFV, and so on) and softwarization of network control (e.g., SDEON) demand a transport network that is resource efficient, scalable, flexible, and programmable. To meet these challenges, we have explored the possibilities of applying state-of-the-art optical technologies in the 5G transport network. We have discussed how current WDM/DWDM based Fixed-grid optical technologies can impede the growth of future transport networks and inhibit many of the 5G RAN and EPC deployment models and features. We have also discussed how elastic optical technologies, with the advent of new optical devices, can help transport networks meet the diverse requirements of 5G services and applications. Finally, we have outlined some open research directions to realize the deployment of elastic optical technologies in 5G transport networks.

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