A Tutorial on the Flexible Optical Networking Paradigm: State-of-the-Art, Trends, and Research Challenges

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***Abstract*—Rigid fixed-grid WDM optical networks can no longer keep up with the emerging bandwidth-hungry and highly dynamic services in an efficient manner. As the available spectrum in optical fibers becomes occupied and is approaching fundamental limits, the research community has focused on seeking more advanced optical transmission and networking solutions that utilize the available bandwidth more effectively. To this end, the flexible/elastic optical networking paradigm has emerged as a way to offer efficient use of the available optical resources. In this work we provide a comprehensive view of the different pieces composing the "flexible networking puzzle" with special attention given to capturing the occurring interactions between different research fields. Only when these interrelations are clearly defined, an optimal network-wide solution can be offered. Physical layer technological aspects, network optimization for flexible networks, and control plane aspects are examined. Furthermore, future research directions and open issues are discussed.**

I. Introduction

The emergence of bandwidth-consuming and highly dynamic services dictates the evolution of conventional fixed optical networks that were based on wavelength division multiplexing (WDM). Traditional WDM-based networks offer the possibility to establish rigid connections (wavelengths) at a fixed bit rate, namely 10 Gb/s, 40 Gb/s, and recently 100 Gb/s, where the channels are modulated with a common (fixed) modulation format (e.g., OOK, DPSK or QPSK) and are spaced at a fixed channel-to-channel distance of 50 GHz. Flexibility in these networks is limited to that allowed by frequency-tunable lasers (i.e., each transponder can be assigned to a different wavelength) and to the limited reconfigurations allowed by optical switching nodes. As a result, the process of upgrading/modifying the network to adapt to changing traffic and network conditions becomes challenging [1]. Additionally, there is a growing awareness that the utilized bandwidth of deployed optical fibers is approaching its maximum limit [2], [3], [4], [5]. With this capacity crunch looming, it is of vital importance to make the most out of the scarce network resources—such as the fiber bandwidth—and allow accommodating the ever-increasing and dynamic traffic demands.

To this end, flexible optical networking concepts have been recently introduced [3], and [6]. The term "flexibility" refers to the ability of the network to dynamically adjust its resources—such as the optical bandwidth and the modulation format–according to the requirements of each connection. Note that the terms "flexible", "flexgrid or flexigrid", "elastic", "tunable", and "gridless" are often used interchangeably in the literature. Recent advances in coherent optical orthogonal frequency division multiplexing (OFDM), Nyquist WDM (N-WDM), and optical arbitrary waveform generation (OAWG) have set the stage for envisioning fully flexible optical networks [7], [8], [9]. These technologies enable the formation of spectrum-efficient "super channels", which consist of several densely packed sub-channels, offering tunable bit-rates from a few tens of Gb/s to the terabit per second range. Flexible transponders and switches are required for the transmission, switching, and reception of such super channels [10], [11], [12], and [13]. As conventional WDM network planning algorithms and operational tools cannot be applied to the flexible networks, novel resource allocation algorithms have been extensively explored [4], [14], [15]. Furthermore, advanced control plane solutions for flexible networks have been recently examined [16], [17], [18] as well as first experimental demonstrations proving their viability and effectiveness showcased [19], [20], [21].

In this work we aim to provide a comprehensive view of the different pieces composing the "flexible optical networking puzzle". Previous work from [22] is extended with special attention given to capturing the occurring interactions between the different research fields. Only when these interrelations are clear, a holistic "optimal" network-wide solution can be offered. Optimality in the overall network design with respect to the proper resources allocation can be defined when considering a set of potentially competing metrics, such as the minimization of the network-wide costs, the minimization of network outages, and the maximization of energy efficiency. In this contribution, we identify, classify, and analyze the three basic building blocks enabling flexible networking solutions: (i) physical layer technological aspects (Section II), (ii) network optimization (Section III), and (iii) control plane (Section IV). Section V focuses on presenting experimental setups where the functionalities of these three blocks are demonstrated. Future research directions and open issues are discussed in Section VI.

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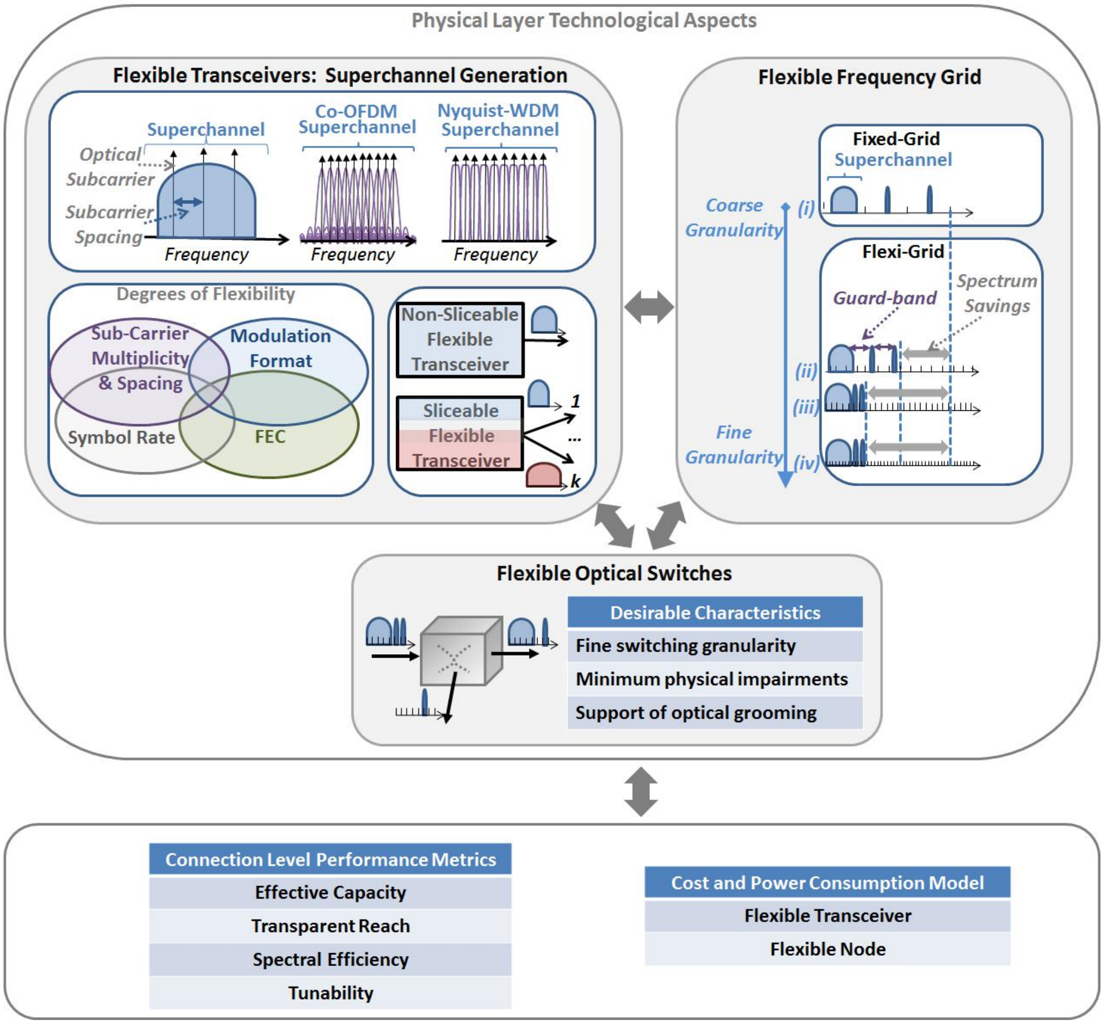


Fig. 1: Physical layer technological aspects are presented with respect to flexible transceivers, flexible optical switches and the flexible frequency grid.

II. Technological Aspects of Physical Layer

In this section we focus on the physical layer technological aspects of flexible optical networks. Fig. 1 presents the key enablers at the physical layer: flexible transceivers, flexible optical switches, and the flexible frequency grid. The characteristics and the combination of these elements determine the performance of the optical connections that can be setup as well as the cost and power consumption models of the respective network equipment. To evaluate the connection level performance, we define the following metrics:*effective capacity*, *transparent reach*, *spectral efficiency*, and *tunability*. We define the effective capacity as the bit rate that can be transported excluding overheads such as forward error correction (FEC). The transparent reach is the maximum distance that can be supported by the optical connection without requiring costly regeneration. The spectral efficiency is defined as the ratio of the effective capacity over the amount of spectrum that is required to be allocated for this connection. Finally, tunability refers to the ability to adapt the connection characteristics—namely the effective capacity, the transparent reach, and the spectral efficiency—to meet disparate connection requirements. Tunability can be characterized by the offered range and granularity of the performance metrics. For example examining the effective capacity, a transceiver may be able to operate between 100 Gb/s and 400 Gb/s at increments of 100 Gb/s. Network equipment with different capabilities in terms of offered connection level metrics incur different degrees of development and manufacturing complexity. This is reflected in the required costs for the network equipment (i.e., for the flexible transceivers and nodes). Furthermore, differences in equipment affect the power consumption profiles of the respective equipment. It is noted that cost, power consumption, and QoS are highly inter-related and tie into network architecture decisions. Thus, they are evaluated on the network level. As the key building blocks we provide more details on flexible transceivers, flexible frequency grid, and flexible optical switches.

A. Flexible transceivers

As traffic growth drives the demand for increasingly higher interface rates, research is conducted targeting channels in the terabit per second range. Due to technological limitations, such as the maximum sampling rate of analogue-to-digital and digital-to-analogue converters (ADCs/DACs), approaches that split up the targeted data rate into multiple parallel lower data rate streams have emerged. This leads us to the concept of super channels composed of multiple subcarriers. There are different approaches that enable the subcarriers to be efficiently aggregated: optical OFDM, N-WDM, and OAWG. Optical OFDM uses orthogonal subcarriers with spacing equal to multiples of the inverse of the symbol period [23]. N-WDM uses optical subcarriers with almost rectangular frequency spectrum close or equal to the Nyquist limit for inter-symbol-interference free transmission. These subcarriers are multiplexed with spacing close or equal to the symbol rate with limited inter-subcarrier crosstalk [7]. The ultimate spectral efficiency is almost identical for both methods under idealized conditions [24]. Finally, OAWG is capable of creating high-bandwidth data waveforms in any modulation format using the parallel synthesis of multiple coherent spectral slices [9].

As shown in Fig. 1, different degrees of flexibility can be offered by flexible transceivers with respect to the modulation format, the symbol rate, the ratio of the FEC over the payload, the number and the spacing of the subcarriers composing a super channel, as well as the inter-super channel spacing. Not all degrees of flexibility need to be simultaneously available. Depending on the available flexibility degrees, different variants of flexible networking architectures can be defined. For example, in [25] the notion of flexibility is in the number of subcarriers, while in [26] a data-rate elastic optical network architecture is proposed that only allows single-carrier transmission technology. Increasing the available degrees of flexibility, may improve the tunability supported by the transceiver at the expense of more complex and potentially cost-intensive transceiver design. In the following, we describe the effect of modifying each degree of flexibility on the connection level metrics. For simplicity, we first assume that all of the other degrees of flexibility remain constant. Detailed studies on the effect of different physical layer parameters on the connection performance can also be found in [7], and [23].

The deployment of higher order multi-level modulation formats leads to increased effective capacity and spectral efficiency—as a larger number of bits per symbol is transported. This improvement, however, results in reduced transparent reach. Similar tradeoffs are observed when increasing the symbol rate. The improvement in spectral efficiency is obtained because it is assumed that the spacing of the subcarriers and the inter-super channel spacing remain constant. Note that if these parameters are a function of the symbol rate (e.g., the minimum subcarrier spacing is set to be 110% of the symbol rate for N-WDM), then improvements in spectral efficiency are more modest.

Finally, in order to enable higher utilization of flexible transceivers, the concept of sliceable flexible transceivers has emerged [6], which promise to offer significant benefits over conventional transceivers. When conventional transceivers are deployed, the full capacity of the transceiver is allocated to only one source-destination demand-pair. Thus, the traffic demand between this source-destination pair has to fill the capacity of the transceiver—as it is very difficult to justify underutilizing equipment from a cost-perspective. This fuels the need to groom demands on the higher network layers (such as the IP/MPLS layer). Sliceable multi-carrier transceivers directly enable the sharing of capacity of a single transceiver between multiple source-destination pairs [6]. In essence, sliceable transceivers can be separated into multiple "virtual transceivers" each serving a different traffic demand. As a result, they reduce (or may even eliminate) the need for grooming in higher layers in a cost-effective way. Increased bypassing of the IP/MPLS layer translates into reduced power consumption (via the reduction of the power hungry IP/MPLS equipment) as well as to reduced latency (via the reduction of additional processing and buffering). Higher utilization offers easier economic justification for the deployment of flexible transceivers. For instance in [27], savings in the required IP router port count and spectral usage are shown by introducing multi-flow optical transponders. Therefore multi-layer network planning techniques are currently in development, taking into consideration the additional degrees of flexibility offered by emerging flexible optical networking capabilities, with special attention given to techniques that try to fully exploit the enhanced functionalities of sliceable flexible transceivers [28], [29].

By increasing the ratio of the FEC over the payload while keeping the overall transmitted bit-rate constant, the effective capacity and the spectral efficiency are reduced. In this way, gains can be achieved in terms of transparent reach [30]. Increasing the number of subcarriers, straightforwardly leads to linear increase in the effective capacity, but also to reductions in the maximum transparent reach - as the number of co-propagating channels increases. Additionally, the spectral efficiency is improved because the same inter-super channel guard band is assumed for a connection having greater effective capacity. Finally, increasing the spacing of the subcarriers within a super channel leads to increased transparent reach—as the effect of inter-carrier interference becomes less pronounced (however note that the effective capacity remains constant). Similar conclusions hold for the impact of the inter-super channel spacing. Table I summarizes these effects.

While multiple different options seem to be available from each of these potential degrees of freedom, this is not exactly the case in practical applications. We have to consider that it is not easy to have a complete freedom in the adaptability of each of these degrees of flexibility as the complexity in controlling all these degrees of flexibility and choosing the associated parameter values is quite difficult and optimizing each of them can be cost prohibitive and/or impractical. For example, the maximum transparent reach is obtained at the optimum launch power, which is a function of the symbol rate. Thus, it becomes challenging for transceivers to operate at different symbol rates within the same network. By setting a constant launch power for all cases, "penalties" are introduced in terms of the maximum transparent reach. On the other hand, by setting the optimum launch power for each case, the system design becomes impractical due to limitations at the amplification stages. This issue is addressed in [31], where trade-offs with respect to the utilized spectrum and the required transponders are identified. In summary, different combinations of these pa-

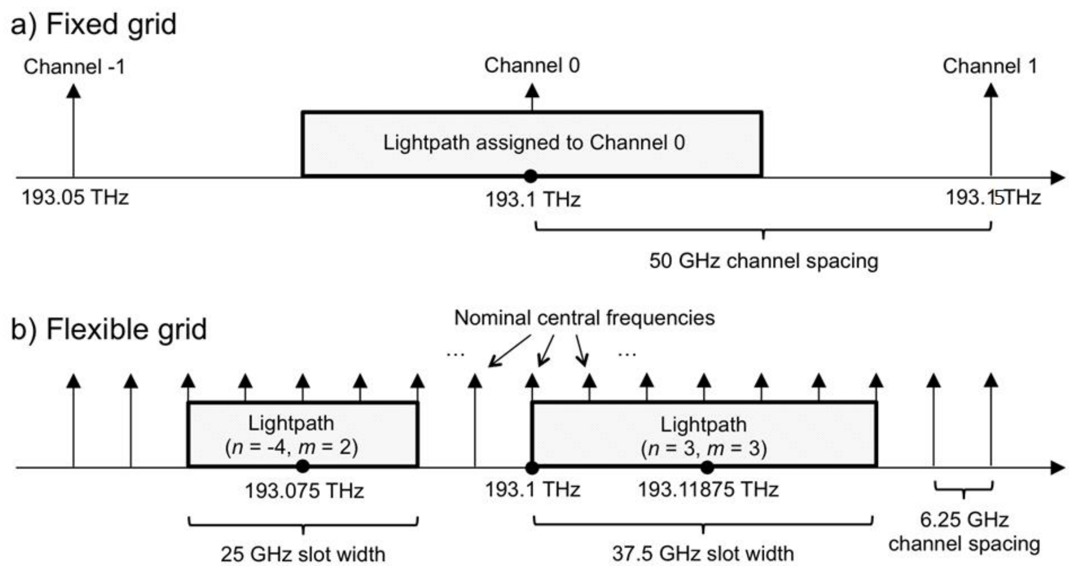


Fig. 2: Optical channel assignment under a) fixed and b) flexible grid.

TABLE I: The impact of the potential degrees of flexibility on the connection level metrics.

Potential Degrees of Flexibility	Connection Level Metrics		
	Effective Capacity	Transparent Reach	Spectral Efficiency
Modulation Format	⇑	⇓	⇑
Symbol Rate	⇑	⇓	⇑
Ratio of FEC and Payload	⇓	⇑	⇓
Number of Subcarriers	⇑	⇓	⇑
Inter-Subcarrier Spacing within a Superchannel	—	⇑	⇓
Inter-Superchannel Spacing (Guard-band)	—	⇑	⇓

rameters imply different transceiver designs and thus different cost and power consumption characteristics. Furthermore, the desired connection level performance metrics are a function of the considered network topology and traffic demand scenario. This issue is further discussed in Section IV.

B. Flexible frequency grid

In order to fully reap the benefits of flexible transceivers, it is necessary to migrate from the rigid standardization of the international telecommunication union telecommunication (ITU-T) frequency grid—operating typically at a granularity of 50 GHz—to a flexible configuration, which enables the occupation of multiple spectrum slots with finer granularity. The recent trend towards the adoption of flexible networking is reflected also in the industry and the standardization bodies, as a flexible DWDM grid definition has been introduced into Recommendation G.694.1 of ITU-T [32].

In Fig. 1, it is shown that by introducing a flexible frequency grid with a fine granularity may lead to significant spectrum savings. In the fixed-grid case, each connection is allowed to occupy only one spectrum slot, whereas multiple spectrum slots can be allocated to one connection in the flexible-grid case. Note that increases in the grid granularity are beneficial only to a certain degree (cases (ii) and (iii) on the top, right hand side in Fig. 1). Beyond this point complexity might increase, while the savings in terms of spectrum might saturate (case (iv) in Fig. 1). Thus, the selected supported granularity should provide a "good fit" to the bandwidth of the super channels generated by the flexible transceivers and vice versa—at the minimum complexity and cost. Note that the flexible grid with a finer granularity imposes more challenging requirements for the operation of the lasers at the transceivers and of the optical switches.

ITU-T has extended its recommendations ([32] and [33]) to include the concept of flexible grid. A new DWDM grid has been developed within the ITU-T Study Group 15 by defining a set of nominal central frequencies, channel spacing and the concept of frequency slot. The main difference with respect to the WDM network is the way the basic unit of switching is identified which is the frequency slot now rather than a wavelength. A frequency slot is defined by its nominal central frequency in the whole spectrum range and its slot width. The set of nominal central frequencies can be built using the following expression $f = 193.1 + n \times 0.00625$ THz, where 193.1 THz is ITU-T "anchor frequency" for transmission over the C band, n is a positive or negative integer including 0. It means that the central frequency can be moved in the C band at 6.25 GHz step. The slot width determines the "amount" of optical spectrum regardless of its actual position in the spectrum. A slot width is constrained to be $m \times 12.5$ GHz, where m is an integer greater than or equal to 1 and 12.5 GHz since a pair number of 6.25 GHz slots have to be allocated around the central frequency (see Fig. 2).

C. Flexible optical switches

Conventional optical switches perform switching of wavelength channels without requiring costly optical-electrical-optical (OEO) conversion capabilities. Flexible optical switches should be able to perform the switching of super channels with variable bandwidth characteristics (i.e., tunable optical bandwidth and center frequency per channel) at a fine granularity. The key to providing such variable bandwidth characteristics lies in wavelength selective switches (WSSs), which sit at the heart of the optical switch [34]. The very first proposal for a variable pass-band/flexigrid WSS is reported in [35].

It is possible to construct advanced WSSs using liquid crystal on silicon (LCoS) technologies [36] or micro-electro mechanical system (MEMS) [37].

As a signal traverses multiple optical switches, the edge subcarriers are affected by the imperfect shape of the WSS filter (as the filter edges have a finite slope). The introduced penalty is a function of the filter shape, the bandwidth of the optical filter, and the number of traversed WSSs. Furthermore, additional penalties may be introduced due to cross-talk between neighboring super channels. The penalties due to the filtering characteristics and cross-talk between super channels can, for example, be alleviated by increasing the bandwidth of the optical filter and introducing higher spectrum guard-bands between super channels [38]. This, however, comes at the expense of reduced spectral efficiency. Thus, there is an inherent trade-off occurring between the filtering characteristics of the flexible optical switch, the number of filtering stages that can be supported, and the spectral efficiency.

Moreover, such flexible switches could provide support for optical grooming. Optical grooming enables the aggregation and the distribution of the traffic directly at the optical layer and is further discussed in Section IV. The support of such functionality imposes further requirements on the architecture of the optical switches. For example, it leads to the adoption of broadcast-and-select structures [39].

Wavelength blockers (WB) and WSSs are important building blocks in re-configurable optical networks. For the "continuous spectrum" WB/WSS (CS-WB/WSS), the overall filtering passband of the WSS device can be adjusted in a quasi-continuous way by grouping two or more adjacent pixels offering enhanced switching flexibility at arbitrary channel spacing or multiline rates. However, loss and group delay ripples appear at each slot boundary causing degradation to the transmitted signal. Authors in [40] propose an analytical model and simulation studies to evaluate the relative impact of each imperfection on the overall cascadability performance of the WB/WSS is investigated.

In summary, the desirable characteristics of flexible optical switches include support for fine switching granularity and optical grooming, while keeping the introduction of physical impairments at a low level. There is a direct relationship between the minimum supported switching granularity and the granularity of the frequency grid. Note that different switch implementations incur different cost and power consumption models. For example, the physical size of the network equipment affects the rental cost, which is a significant portion of the operational expenditures (OPEX). When examining the total cost of ownership, not only capital expenditure (CAPEX) but also OPEX considerations are in order. This is further discussed in Section III-E.

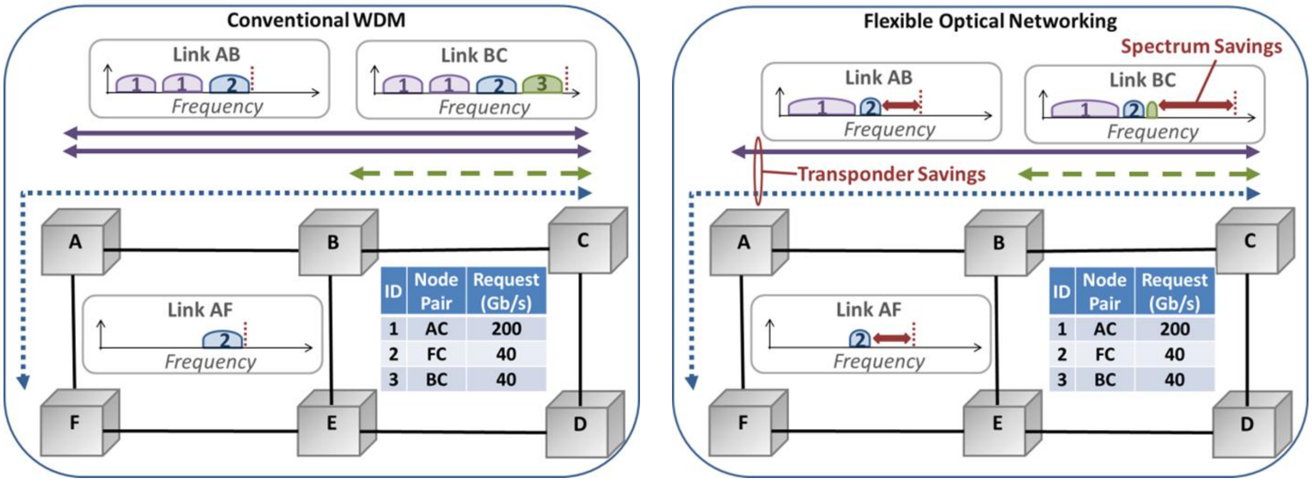
III. Flexible optical network design and optimization

Advances in physical layer technologies coupled with enhanced control plane solutions provide the basis to optimize the overall performance on the network level. Fig. 3 illustrates an example of how providing additional degrees of flexibility can prove beneficial—in terms of transponder and spectrum savings. The same set of traffic demands (200 Gb/s between node-pair AC and 40 Gb/s between node-pairs FC and BC) is accommodated (a) in a conventional WDM network and (b) in a flexible optical network. The conventional WDM network assumes a fixed-grid deployment that allows fixed bit-rate transponders operating at 100 Gb/s. Thus, a total of eight transponders are required—since the 200 Gb/s demand has to be split over multiple transponders—as opposed to the flexible optical networking case, where only six transponders are required. Additionally, spectrum savings are achieved due to two factors in this case. The first one is that guard-bands are not "wasted" on two separate channels for the connection between nodes A and C. The second reason is that the spectrum assigned to connections FC and BC is "tailored" to their respective reach requirements. Furthermore, as connection BC is shorter in length than AC, a higher order—and thus more spectral efficient—modulation format may be used for connection BC.

In the following we discuss issues involved in the optimization of flexible optical networks. Fig. 4 provides a categorization of the approaches for network optimization based on the design scope, the application scope, and the methodology. Additionally, an overview of the input parameters to the network optimization procedure as well as the network level performance metrics is presented. The input parameters to the optimization procedure include: the connection-level performance metrics, the control plane capabilities, the frequency grid granularity, the considered network topology, the traffic demand with the related service level agreement (SLA), the power consumption of the network equipment, and the cost model for CAPEX and OPEX. The considered network level performance metrics include: the required network equipment/resources, the required spectrum, the blocking probability, and the availability, the connection provisioning time, the energy efficiency, as well as the CAPEX and OPEX.

A. RWA vs. RSA problem

We first focus on the design scope aspects of network optimization. In order to efficiently utilize the capabilities



(a) Conventional fixed-grid WDM

(b) Flexible optical networking solution

Fig. 3: An example to show how providing additional degrees of flexibility can lead to reduced requirements in terms of transponders and spectrum is presented.

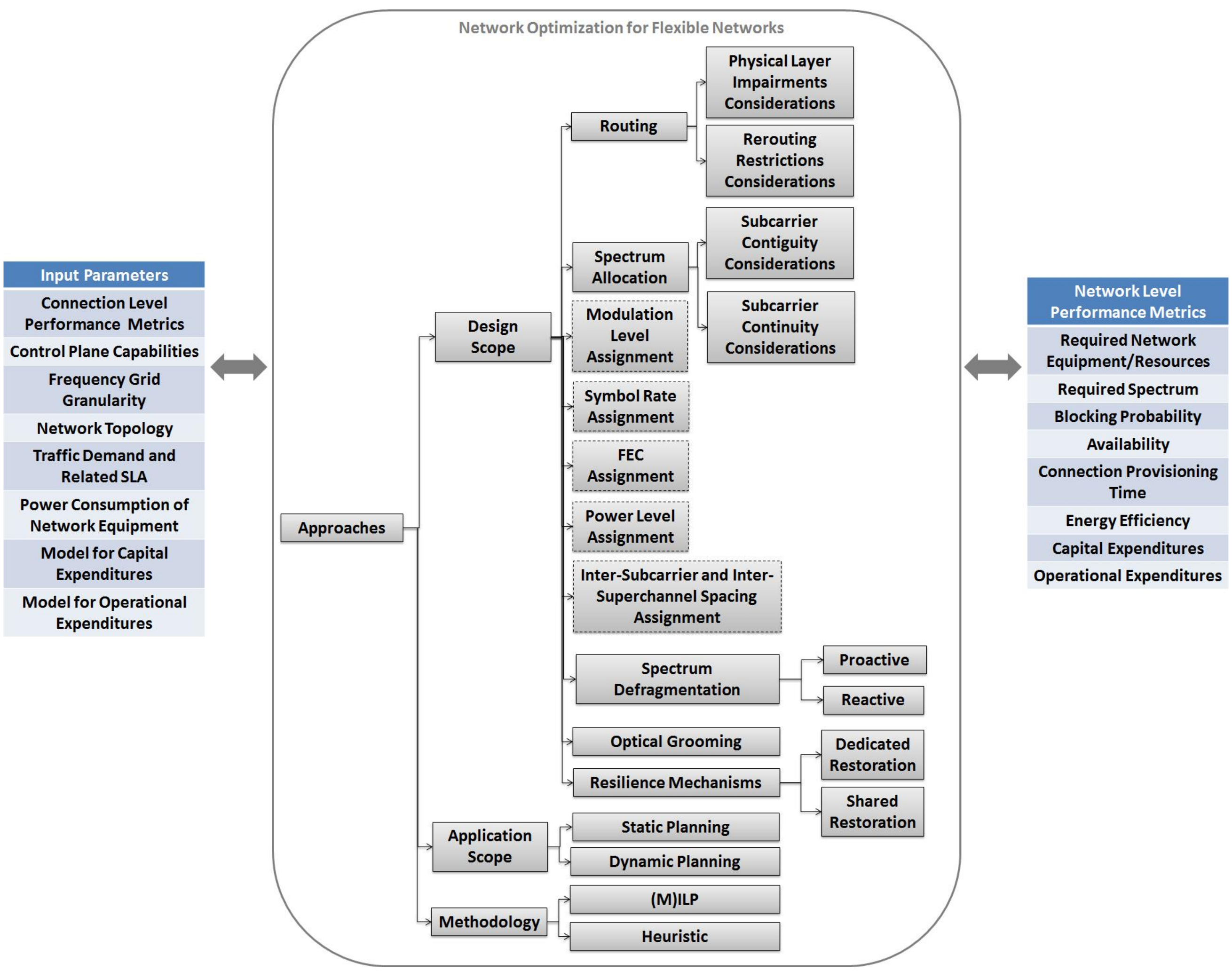


Fig. 4: Network optimization for flexible optical networks.

of the advanced physical layer on the network level, novel network planning techniques are required to be developed. In fixed-grid WDM networks, conventional routing and wavelength assignment (RWA) algorithms are applied. As flexible optical networks offer a multitude of degrees of flexibility, different routing and resource allocation schemes are applicable. For example, assuming that there is flexibility in the number of subcarriers that can be assigned - while all other options are fixed - then routing and spectrum assignment (RSA) techniques are applicable (as defined for the first time in [41]). If there is additional flexibility in the modulation format selection, then routing, modulation level, and spectrum allocation (RMLSA) techniques are in order [4], [42]. As a result, the introduction of extra degrees of flexibility dictates the enhancement of the network planning and optimization procedure to additionally consider the manner in which these extra parameters should be set. Furthermore, the tuning of the following parameters may be additionally considered per connection: symbol rate, FEC, power level, as well as the inter-subcarrier and inter-super channel spacing. Note that the actual resource allocation procedure can be transformed to be agnostic to the individual physical layer parameter settings. The input that is actually required is the effective bit-rate, the transparent reach, and spectrum requirements (in effect the connection level performance level metrics). By selecting the optimal combination of the connection level performance metrics, the setting of the physical layer parameters may be indirectly performed. Next, we examine the routing of connections in a flexible network. The consideration of physical layer impairments is required to determine the candidate paths to be considered in the optimization of routing procedure. The transmission distance—along with the number of traversed nodes—are commonly used metrics. Additional restrictions may be imposed on the manner in which connections are allowed to be re-routed. Re-routing of connections can be triggered in order to avoid blocking of new demands in the context of spectrum defragmentation procedures, which are discussed in the following. In multicarrier flexible networking solutions, a set of contiguous subcarrier slots have to be assigned to a connection instead of a certain wavelength—as would be required in fixed-grid WDM networks. Furthermore, the continuity of these subcarrier slots should be guaranteed in a similar manner as wavelength continuity constraints are imposed. In other words, it is imposed that the same subcarrier slots are allocated along all of the links of the path of the connection. At this point, it should be highlighted that sliceable flexible transceivers can be used in principle to "relax" the slot contiguity constraint. If enough contiguous slots are not available along the desired path, then the connection can be broken-up into multiple smaller demands. Each one of these smaller demands would then require a lower number of contiguous subcarrier slots.

B. *Spectrum defragmentation*

In a dynamic network scenario, where incoming connections are established and disconnected in a quite random fashion, spectral resources tend to be highly fragmented and "gaps" are unavoidably introduced in the spectrum leading to the so-called spectrum fragmentation problem. This problem is very similar to the memory fragmentation problem in computer architecture: over the time and with memory allocation and release, memory becomes fragmented into smaller contiguous areas and blocks of data cannot be allocated in memory even though enough overall free memory is available. As in the case of memory fragmentation, also spectrum fragmentation leads to inefficient resource utilization and performance degradation. In the specific case of spectrum, it finally leads to increased blocking probabilities as the unused frequency slots are "scattered" over the spectrum and not enough unused contiguous spectrum slots may be available for new connections to be established.

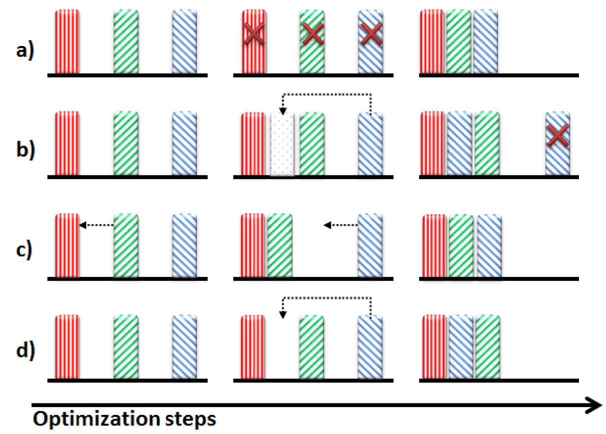
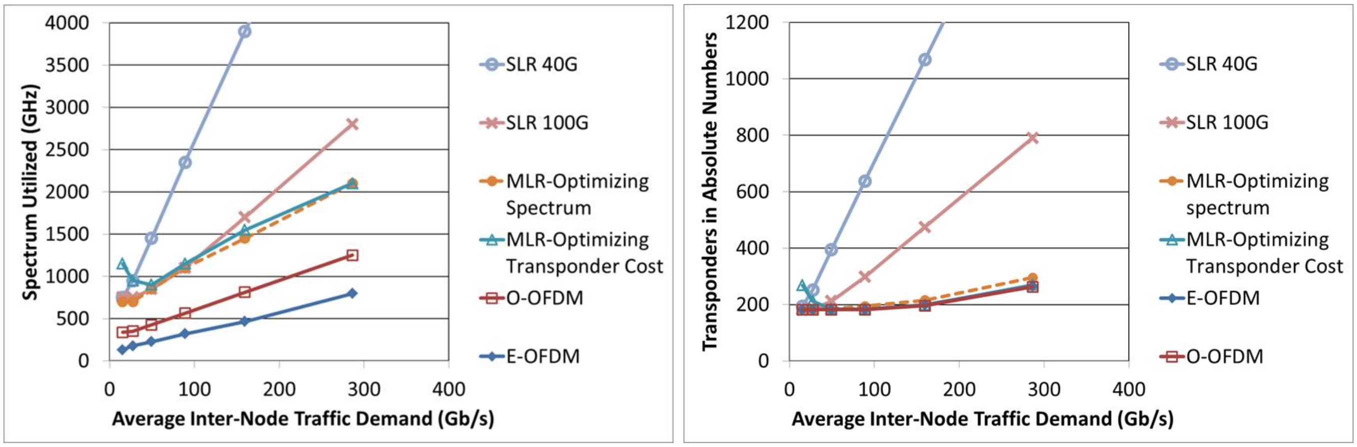


Fig. 5: Recent spectrum defragmentation techniques [43]: a) Re-optimization [44], b) Make-before-break [45], c) Push-and-Pull [46], and d) Hop tuning [47].

To this end dedicated spectrum defragmentation mechanisms have begun to be investigated. Their aim is to rearrange existing lightpaths to make room for the otherwise blocked demand(s). As rearrangement usually involves rerouting or spectral re-allocation of existing connections, defragmentation techniques may require large amount of time to converge. Hence, one of the key operational requirements is to not disrupt the service during the reconfiguration phase (or at least minimize its effects).

Fig. 5 shows the four main spectrum defragmentation techniques. *Re-optimization* technique is proposed in [44]: the process aims at compacting the assigned slots so to consolidates the available spectrum significantly and increase the possibility to allocate new connections. The authors in particular formulate the network defragmentation problem for flexible WDM networks, model it, and propose heuristics. *Make-before-break* approach is presented in [45]. For each blocked path connection demand, this technique finds an available alternative pair of route and slot set where the route is one that offers the same or better OSNR than the original route. If alternative pairs of route and slot sets are found for all existing conflicting paths, path relocation will be performed in the make-before-break manner, i.e. reserve the resources for the alternative route and slots set first, then activate the transmission using the new lightpath and release the old resources. Finally, both the *push-and-pull* technique [46] and the *hitless* (or hop tuning) technique [49], [50] consist of shifting the spectrum of conflicting connections over free and contiguous spectral bands in such a way that their route does



(a) Spectrum utilization (b) Absolute transponder usage

Fig. 6: (a) The spectrum utilizations obtained for the DT core network are presented for different optical networking approaches as a function of the average inter-node traffic demand [48]. (b) The required numbers of transponders obtained for the DT core network are presented for optical different networking solutions as a function of the average inter-node traffic demand (in absolute numbers) [48].

not change. From the technology perspective, such shifting can be realized by re-tuning the transmitter over the spectrum. The difference, as illustrated in examples of Fig. 5 is that, in push-and-pull, first the number of slots assigned to the lightpath to be moved is increased, then its central frequency is shifted towards the side of the adjacent lightpath, and finally the number of slots backs to the original value. In this way, the service is almost never interrupted. On the contrary, only the central frequency of the lightpath is shifted in hitless technique. Hence, transmission is interrupted during the re-configuration time. The duration of this interruption depends on the transponder tuning speed. Nonetheless, as shown in [47] by exploiting fast tunable lasers in the transponders and a rapid TX wavelength tracking scheme at the RX based on an athermal AWG and a PD-array, the proposed scheme can potentially achieve defragmentation operation with a service disruption time below 400ns.

Such mechanisms can be further classified into reactive and proactive mechanisms. Reactive mechanisms are invoked when a request cannot be accommodated given the network-wide spectrum allocation. In proactive mechanisms, the spectrum allocation is performed in a manner that unused spectrum slots are proactively preserved for future use, such as defragmenting periodically or according to some fragmentation degradation threshold. These mechanisms usually operate with the goal of confining the spectral usage to one side of the spectrum, and require the entire network to be considered for defragmentation simultaneously, as for instance in [44]. In [51] the defragmentation process is triggered when the proposed metric “spectrum-compactness” reaches a certain threshold value. In [49] an auto-defragmentation method to continuously ‘defrag’ flexible grid optical networks without service disruption is proposed. Whenever a signal departs, the network ‘retunes’ the signals occupying the neighboring slots to fill the gap.

In any case, defragmentation is a challenge (both in terms of complexity and service time), as many parallel operations may need to be launched and coordinated to rearrange the spectrum and make room for the incoming new request. Its technological and operational viability is discussed in Section V.

Table II summaries these four techniques and their main performance indicators.

C. *Offline and online approaches*

The discussed approaches can be further classified based on their application scope. Static network planning approaches address the offline network planning phase [4], [14], whereas dynamic network planning approaches are applied to dynamically provision connection requests [15]. A final classification involves the method used to conduct the network planning. Mathematical optimization methods, such as integer linear programming (ILP) and mixed ILP (MILP), can be applied. The advantage of these methods is that they offer a measure of the optimality of the solution they provide. However, they may lead to increased computational complexity. Heuristic approaches offer an alternative—especially if the computational complexity is a restricting factor—often making them the method of choice for dynamic planning. In general, optimality can be sacrificed in order to reduce the computation time. A well-known practice to drive-down the computation complexity is to decompose the problem in several smaller sub-problems (at the expense of optimality). It has been shown that decomposing the RMLSA problem into two sub-problems—namely, routing and modulation level assignment (RML) and spectrum allocation (SA) sub-problems—has only a minor impact [4].

As an example of offline network design problem, the authors in [48] evaluate extensively the performance of a typical all-optical core network based on various optical network technologies/approaches: 1) conventional single-line-rate (SLR) WDM networks operating at different channel-rates per case that deliver either 40 Gb/s or 100 Gb/s per

TABLE II: The qualitative comparison of spectrum defragmentation techniques [43].

Technique	Re-Optimization [44]	Make-before-break [45]	Push-and-pull [46]	Hop tuning [47]
Extra transmitter	No	Yes	No	No
Interrupt traffic	Yes	No	No	No
Reactive/proactive	Both	Reactive	Both	Both
Defragmentation spectral area	Any	Any	Limitation	Any
Defragmentation channels per time	Single channel	Single channel	Single channel	Multiple channel
Defragmentation speed	Long time	Slow	Slow	Fast ($<1\mu s$)
Complexity	Low	Moderate	Moderate	Quite high

channel; 2) multi-line-rate (MLR) WDM optical networks with supporting data rates on the same system of 10 Gb/s, 40 Gb/s, 100 Gb/s and 400 Gb/s; 3) two flexible/elastic optical network approaches based on multi-carrier solutions where subcarriers are either electrically generated/modulated/multiplexed (denoted as E-OFDM) or generated/multiplexed via an optical comb-line generator and individual optical modulators per subcarrier (denoted as O-OFDM). The performance evaluation/comparison is concerned with the overall utilized spectrum and optical transponders savings and is also extended to capital cost savings and energy efficiency improvements, for all cases/approaches. The authors considered the Deutsche Telekom (DT) core network (as in [4]), and a realistic traffic matrix for 2010 scaled in order to obtain different average internode traffic. In Fig. 6a and 6b (adopted from [48]) the utilized spectrum (a) and number of transponders (b) are presented as a function of the increasing traffic demands. The utilized spectrum shown in Fig. 6a, corresponds to the highest utilized spectrum slot over all network links. As expected, the SLR case deploying 40 Gb/s transponders has the worst performance in terms of spectrum utilization due to its limited spectral efficiency achieved, which is set at 0.8 b/s/Hz. Regarding the two variants of MLR case (i.e., minimization of utilized spectrum, and minimization of transponder cost), both achieve the similar performance in terms of spectrum utilization. On the contrary, the flexible multi-carrier solutions offer the most efficient spectrum allocation as expected from the optimized packing of the connections in the frequency domain. In particular, E-OFDM outperforms all of the examined cases; while the performance of O-OFDM is constrained by the fact that a rather large, but standardized, 12.5 GHz subcarrier spacing was assumed.

D. *Time-varying traffic*

Demands are not only dynamic in terms of arrival and duration but they are also (usually) dynamic in terms of bandwidth. For instance, a service provider may request more bandwidth from the network in some time periods to support the data backup service during night hours or to support video-on-demand services during evening hours. In conventional WDM networks, connections are over-provisioned in order to support changes in traffic demand. Whenever significant traffic changes are observed or expected, additional wavelengths are provisioned. On the contrary, in flexible optical networks, the allocated optical spectrum of a lightpath is tailored to the actual width of the transmitted signal. This new feature creates an additional problem, with respect to the adaptation of the number of slots allocated to each lightpath so as to follow the traffic bandwidth variations. In such a case, an offline RSA is not of course adequate to address this dynamicity. That is the reason that, recently, research has advanced from offline RSA to online or dynamic RSA, which additionally considers the time dimension of the problem. In particular, dynamic RSA focuses on the elastic spectrum allocation in response to bandwidth variations, in particular, expansion (or contraction) of the spectrum when the required bit rate of a demand increases (or decreases) [52].

To enable time-varying traffic service, additional contiguous slots need to be necessarily (pre-)allocated to the demands. In such a way, connections can accommodate increased bit rate by expanding their spectrum to such additional slots and return to the original state by contracting them. Different variants of spectrum expansion/contraction strategies exist. The easiest solution is to assign a fixed number of spectrum slots to each demand subject to time-traffic varying. Such additional slots can be used exclusively by certain connections or shared among any connections [53]. More complex approaches can not only expand/contract the spectrum but can also move its central frequency either within a short range, or along the whole spectrum range [54] [55]. Such cases are clearly more challenging as the algorithms must be robust enough to prevent conflicting resource allocation in case many connections require resource re-allocation at the same time.

Besides, it has been observed that traffic variation along a given period of time (typically days or weeks) tends to be periodic, making the expected traffic load in a network fairly predictable [56]. Hence, RSA schemes with expansion/contraction features can be better designed having some knowledge of the (expected) traffic fluctuations profile. For instance, in [55], the authors present the ILP formulation and biased random-key genetic algorithms to address the issue of multi-hour RSA problem, where traffic changes in a multi-hour basis. Results considering realistic national topologies and expected traffic profiles for the upcoming years show that the approach that allows the central frequency to be moved in a short spectrum range provides the better trade-off between performance and complexity.

Finally, the expansion/contraction feature can also operate coordinated with a defragmentation mechanism: if spectrum expansion is not possible, then an appropriate spectrum defragmentation policy can undertake the task of re-allocating connections in order to free up enough spectrum. Such solutions has been proposed in [5] with the notion of Dynamic Cooperative Spectrum Sharing (DCSS). The obtained results quantify the benefits that can be reaped in terms of blocking rate of the deployment of the proposed cooperative spectrum expansion and contraction policy. Furthermore, the employment of spectrum defragmentation techniques, based also on a cooperative rationale, further boosts the performance of the network. Contrary to previous works, where spectrum expansion/contraction and defragmentation are agnostic to the spectrum allocation of the neighboring connections, the notion of Dynamic Cooperative Spectrum Sharing (DCSS) is introduced in [5]. The schemes proposed therein encourage some form of ”cooperation” between connections. Cooperation in this respect is derived from the notion that each connection avoids consuming spectral resources from connections that have potentially less available resources. During the planning phase of the network, the RSA process decides the route and the initial location of the connections on spectrum. When the normal operation of the network commences, in order to support the dynamicity of traffic, a variety of spectrum expansion/contraction policies attempt to accommodate incoming requests. If spectrum expansion is not possible, then appropriate spectrum defragmentation policies undertake the task of re-allocating connections in order to free up spectrum. The results quantify the benefits that can be reaped in terms of blocking rate of the deployment of the proposed cooperative spectrum expansion and contraction policy. Furthermore, the employment of spectrum defragmentation techniques, based also on a cooperative rationale, further boosts the performance of the network. Tradeoffs with respect to the achieved reduction in blocking rate and the number of re-allocated connections during the spectrum defragmentation procedure have been examined and it has been found that higher order defragmentation policies do not necessarily lead to lower blocking probabilities.

E. CAPEX and OPEX analysis

It is noted that different optimization objectives can be selected for the network optimization procedure (corresponding to the presented network level performance metrics). While most studies concentrate on achieved spectrum savings, the ultimate selection criterion for the deployment of new technologies is cost in terms of both the CAPEX and the OPEX.

It has been shown that flexible optical networking can lead to significant cost savings [48], [57], [58], [59], [60], and [61]. These savings greatly depend on the granularity of frequency grid, the traffic load, and the assumed cost model. For instance, in [57] the authors report that, considering realistic national topologies and expected short and medium term traffic profiles, CAPEX investments in costly BV-WSS devices with 12.5 and 25 GHz slot widths are profitable in all scenarios. The methodology introduced in [59] is used to investigate the requirements in CAPEX of the flex-grid networks over the fixed-grid solutions in correlation with the gained spectrum optimization. It was shown that a transition to a flex-grid network can overcome the added cost of the equipment due to the minimized spectrum utilization. Other recent works have attempted a similar comparison between the proposed technologies that will support the future optical transport network and are focusing their studies on the spectrum utilization and cost efficiency [60], [61]. In any case, although considering that flexible technology may cost 2-3 times more than traditional WDM technology, the simplification of the IP/MPLS layer as well as the higher utilization of the installed fiber capacity, motivate the deployment of flexible optical networks.

Additionally, the energy efficiency of flexible optical networks has recently begun to be investigated—as it has gained increasing importance due to environmental awareness and the pressure to drive down the OPEX [48], [62], [58]. In general, solutions that offer finer bit-rate granularity and efficient spectrum allocation achieve low energy per bit as they use just the amount of network resources needed. For example, authors in [62] highlight the benefits offered by flexible optical networks in terms of energy efficiency. Indeed, the possibility of tightly configuring the flexible devices to the actual connectivity requirements (i.e., bandwidth usage, optical reach, modulation, etc.) reduces their power consumption.

F. Other issues

Optical grooming techniques, which are recently proposed, enable the aggregation and the distribution of the traffic directly at the optical layer [39], [63]. Thus, multiple low capacity demands can be grouped together in the same transceiver. In [39] an optical grooming approach is proposed that does not require the use of guard-bands or multiple light sources in flexible transceivers. It is demonstrated that significant savings can be achieved in terms of transceivers and spectrum. Assuming that a single type of flexible transceiver is deployed (e.g., offering rates between 40 and 400 Gb/s), optical grooming can lead to higher utilization of the transceivers. Note that this effect might be less pronounced when sliceable flexible transceivers are assumed—as a sliceable transceiver can carry multiple demands (at the additional cost of guard-bands and multiple light sources). In [64], the authors focus on the dynamic traffic-grooming problem and propose four variants of their spectrum reservation scheme, which basically consists on reserving spectrum for high-capacity transponders so that more connections can be groomed together and the capabilities of transponders can be utilized efficiently.

As services impose high availability requirements, it is of vital importance to design resilient networks. Resilience can be provided via dedicated and shared protection schemes. In contrast to dedicated protection, shared protection schemes allow sharing of the protection resources among connections with disjoint working resources. Recent works have examined the potential benefits that can be gained when deploying different protection schemes in flexible optical networks for both the offline [65], [60], [62] and the online approaches [66]. In [62] such benefits are examined, while conducting a comparison between conventional WDM networks and flexible optical networks. It is shown that the flexible network with shared protection has the best performance in terms of energy efficiency. In [66], in additional to the traditional backup sharing, the proposed scheme also exploits the new opportunity of spectrum sharing enabled by the elasticity of the transponders: 1) if the working paths of two connections are physically link disjoint, and 2) if their backup paths traverse two lightpaths which are adjacent on a fiber link, then the two backup lightpaths can share spectrum. Results show superior spectrum efficiency compared to other solutions.

IV. Control Plane for flexible optical networks

The elasticity and flexibility of emerging optical network lay some new challenges around efficient, bandwidth provisioning, and network automation. While the quest for achieving optimal cost/bit transmission economics is driving the need for 100 Gb wavelength technology, the business model of transport services necessitates a different approach than in the 10 Gb wavelength services. As optical technology takes its next step towards super channels, the divergence of service from optical wavelength speed will likely continue. The need for on-demand "elastic" bandwidth to cost-effectively and efficiently deliver bits whenever and wherever needed is the second challenge facing service providers.

Evolving traffic patterns motivated by the requirements of cloud computing networks [67] and data centers are driving providers to re-visit the architecture of their network. In particular the relationship between IP and optical transport layers should be re-engineered. The typical practice of over-provisioning the IP layer (i.e., running transport links at low utilization rates) and capping the optical layer to provide static fat pipes, "always on" 100 Gb point-to-point bandwidth is being outdated, as elastic/flexible transport solutions with integrated digital switching emerge. In order to provide on-demand bandwidth at Internet speeds, manual interventions should be eliminated from operational processes. This requires automation of processes across multiple network layers, from transport (and transmission) up through IP/MPLS. Besides, the orchestration of resources between separate domains, and vendors is required. In the optical transport layer, this means enabling rapid delivery of transport bandwidth in a cost and resource efficient manner and preferably without time-consuming process of wavelength engineering.

This dictates the deployment of advanced control plane solutions that fully support the emerging capabilities of the flexible optical networks. As outlined in [6], standards are needed to define a flexible client interface into a flexible transponder and control plane standards are required for signaling the setup, tear down, as well as the modification of a flexible connection.

The networking community is putting big efforts on establishing such standards to support flexible optical networks. Next, the two main approaches addressed are being considered, namely: 1) extending the existing Generalized Multiprotocol Label Switching (GMPLS) and Path Computation Element (PCE) control plane standards, and 2) adopting the new Software-Defined Network (SDN)/OpenFlow paradigm.

A. GMPLS and PCE extensions

GMPLS [68] offers a logical representation of multi-technology and layered networks and follows the definition of a control plane as the infrastructure and intelligence responsible for the establishment and maintenance of connections in a network, which is separated in three tasks consisting of: 1) routing protocol for the diffusion of information and the computation of the paths, usually the Open Shortest Path First with Traffic Engineering extensions (OSPF-TE), 2) signaling protocol for circuit provisioning, usually the Resource Reservation Protocol with Traffic Engineering extensions (RSVP-TE) and 3) link property correlation through the Link Management Protocol (LMP). Recently, the Path Computation Element (PCE) has been added to the equation. PCE is a centralized entity that executes the path computation task instead of GMPLS providing optimized resource utilization and performance. Due to its broad adoption and vast functionality many researchers consider GMPLS architecture a natural choice for implementing the control plane of flexible optical networks.

1) Standardization activities: During the last decade, the entire GMPLS protocol suite has been largely standardized, so as to not only be applicable to packet switching LSPs, but also time-division multiplexing, lambda and even fiber switching LSPs. However, its applicability to flexible optical networks is not straightforward. In fact, GMPLS for flexible grid must deal with frequency slots rather than wavelengths. In this transition, there might be scalability issues to be faced as it may require maintaining coherent global information representing up to 320 or 640 slots, whether they belong to the 12.5 GHz or the 6.25 GHz slot granularity, respectively [69]. If the granularity ever becomes finer reaching 3 GHz (some studies point to this possibility), there would be 1280 number of possible slot widths [70]. With this objective in mind, a significant amount of effort both inside and outside the IETF is being conducted to extend GMPLS to also encompass the new flexible optical switching capabilities [71], [72], [73], [74], [75], [76], [77], [78], and [79]. As commented in Section II, a new DWDM grid has been developed within the ITU-T Study Group 15 by defining a set of nominal central frequencies, channel spacing and the concept of frequency slot. In line with these definitions [78], defines a new GMPLS lambda label and its possible values format to support the flexible grid.

Amongst these efforts, those deserving to be pointed out are the, already mentioned in Section II, new DWDM grid developed within the ITU-T Study Group 15 by defining a set of nominal central frequencies, channel spacing and the concept of frequency slot, that has let to define a new GMPLS lambda label and its possible values format to support the flexible grid [80]; the OSPF-TE extension on collecting and flooding between nodes the available frequency ranges instead of the specific wavelengths [81]; the IETF draft defining the general framework for a GMPLS control plane of flexible optical network as well as a set of associated control plane requirements, i. e., describing the process of computing a RSA in GMPLS [27]; and the way that the PCE has to compute the routes according to the new constraints present in the flexible optical network such as the frequency slot and the width granularities, also discussed in [27].

2) Innovative GMPLS/PCE extensions: Beside the standardization initiatives, a number of other studies have addressed the issue of the design of GMPLS-based control plane for flexible optical networks, for instance [16], [17], [69], [81], [3], and [19]. The majority of the proposals concern methods to efficiently aggregate resource information and execute RSA algorithms in GMPLS/PCE suite. In [16], the authors show that advanced routing and distributed SA algorithms have marginal benefits with respect to simpler ones, which does not justify the implementation of complicated extensions in the RSVP-TE signaling protocol. In [17] an effective LSP provisioning scheme is proposed for PCE and the trade-offs between the frequency grid granularity and the blocking probability is evaluated. In order to establish a flexible LSP, [82] proposes to redefine RSVP-TE specifying new labels called start slot number and end slot number in the upstream label, explicit route, label, and record route objects, and introducing new parameters, such as the symbol rate, number of subcarriers, and modulation level, in the sender TSpec and flow spec objects. Finally, extensions to the PCE communication Protocol (PCEP) have been proposed in [81] to enable dynamic SA and format adaptation from DP-16QAM to DP-QPSK at 100 Gb/s.

B. SDN/OpenFlow initiatives

Software Defined Networking (SDN) [83], [84], [85], [86], and [87] is finding its way to the forefront of the networking industry, with the objective of addressing many of the current challenges of network providers. While there are many varying opinions on what SDN exactly means, there is one common term among them, which is “programmability”. The key question here is the relation of decoupled control and forwarding planes with the emerging converged optical transport layer with integrated switching. The optical transport layer, which plays an important role in optimizing network and underlines most of the Internet backbone, can also benefit from SDN/Open networking.

1) SDN/OpenFlow for transport networks: SDN concept appears as a quite much lower complex control plane architecture than GMPLS and it is winning momentum. Under the SDN approach, packets and circuits can be commonly thought of as flows, and the data-plane switches are abstracted and presented to external software-controllers running a network operating-system (netOS). All network control logic (such as for routing, TE, etc.) is implemented as applications on top of such a netOS [88]. In turn the netOS translates the map-manipulations into data-plane rules by programming the data-plane switch flow-tables via a switch-API (OpenFlow).

Requirements for SDN in multi-layer transport optical networks arise from the need for packet-optical integration. Packet-optical integration is about packet switches controlling the optical network switches [89]. It consists of the coupling between the packet network and transport layer equipment. This will allow the packet based switches and routers to operate jointly with the circuit based (i.e., optical) transport network elements. The need for packet-optical integration comes mainly from new traffic trends in wide area networks. Current transport networks, mainly based on time-division multiplex capable (TDM) technology, are operated completely as a separate entity with respect to the packet based networks. This causes the transport network to be too slow to react dynamically to traffic shifts in upper layers (e.g., IP routing). Interestingly, SDN/OpenFlow by design allows for packet-optical integration: the same controller that is in charge of the packet layers could also be in charge of the optical layers. SDN can not only act as an enabler for packet-optically integrated networks, but can even go beyond by offering customized and novel applications. Packet and circuit convergence (PAC.C) was the first proposal to offer clear extensions for the support of optical transport with OpenFlow. The proposal was first in the form of an addendum to the OpenFlow 1.0 specification [90]. The proposal and implementation have been presented in various occasions and most recently published in [90]. The advantage of this proposal is its simplicity of integrations to OpenFlows packet switch model. The main disadvantages of this proposal are the re-definition of technology specific encodings and the lack of support for multi-layer resource management (i.e., nesting, a concept at the foundation of GMPLS). Authors in [91] and [88] extend OpenFlow for lambda switching by defining OpenFlow agents for optical nodes, and more specifically reconfigurable optical add-drop multiplexers (ROADMs). This approach has the advantage of using existing optical switches equipped with a GMPLS control plane. The approach places an OpenFlow agent on top of the existing control plane to serve for communication between the optical switch and the OpenFlow controller. The multi-layer/multi-region (ML/MR) proposal enhances the PAC.C proposal by removing the burden of re-defining circuit and optical resource encodings, and by emulating GMPLS LSP nesting features. These enhancements are achieved by reusing the existing GMPLS encodings and the LSP logical concept using additional circuit flow table and extension of wire protocol for circuit provisioning [89]. In spite of distributed nature of GMPLS control plane and its protocols, many of the efforts and protocols can be re-used in SDN deployments for (optical) transport networks. For instance path computation element (PCE) is one of the southbound building blocks in OpenDaylight SDN controller.

2) Extensions for flexible optical networks: In [18] OpenSlice is presented as an OpenFlow-based control plane for flexible optical networks for dynamic end-to-end path provisioning and IP traffic offloading. Based on a quantitative evaluation done in terms of path provisioning, and conducted along with a comparison with a GMPLS-based control plane approach, the paper concludes that OpenSlice outperforms GMPLS when creating an elastic optical path with more than three hops.

An increasing number of network-based data center applications require the end-to-end guaranteed quality of service (QoS). Depending on the technological heterogeneity and resource diversity, the services delivery guaranteeing end-to-end QoS with cross stratum optimization (CSO) is practically impossible in independent operation scenario [92], and [93]. Recent works demonstrated a centralized software control architecture, which can provide maximum flexibility for the operators and make a unified control over various resources for the joint optimization of functions and services with a global view [94], [95], [96], [97], and [98]. Authors in [99] have recently demonstrated a novel eSDN architecture over eGrid optical networks for data center service migration. In summary, the SDN/OpenFlow approach, compared with ASON/GMPLS, reduces the control plane complexity, gives a full visibility across packets and circuits, and isolates the network-functions implementation from the state-distribution mechanism, provides a gradual adoption path via incremental deployment using a slicing-plane, and seems to be more cost-effective architecture.

Nonetheless, extensions and additional standardization are required to allow the SDN controllers to manage TDM circuit and wavelength-based architectures. With these extensions, LSPs, OTN circuits, and wavelength paths could be abstracted and managed by the SDN controller.

C. Network virtualization

Virtualization is a technology extensively adopted in cloud computing allowing sharing of servers and storage devices and increased its utilization. The evident advantage of such technology motivates its recent application to networking. According to the unifying definition provided in [50], network virtualization is any form of partitioning or combining a set of network resources, and presenting (abstracting) it to users such that each user, through its set of the partitioned or combined resources has a unique, isolated view of the network. In other words, any fundamental resource (router, switch, link, computing, storage, etc.) can be virtualized (even recursively) in such a way that a single physical substrate network can be shared among multiple virtual networks (usually referred as slice). Each slice is logically isolated from another and can customize its own characteristics to properly support its expected applications. Network virtualization allows the decoupling of the traditional roles of the Internet Service Providers (ISPs) into Infrastructure Providers who manage the physical substrate network and Service Providers who create the virtual networks and offer end-to-end services.

Network virtualization is a key enabler for the delivery of a wide variety of novel services for end users, for the exploration of new business models and a driver to down the costs. ITU-T already identified network virtualization as one of the most important issues and has standardized a basic framework recommendation ITU-T Y.3011 [100]. Detailed surveys on network virtualization can be found in [101] and an analysis on enabling technologies, perspectives, and frontiers in [50].

For the deployment of virtualization in optical networks, there is the need of two elements: 1) virtualizable and programmable devices and 2) coordinated and unified control operations.

Conventional WDM networks are tightly integrated with the underlying physical substrate (i.e., wavelengths), making it difficult to fully exploit the virtualization concept. On the contrary, flexible optical networking can be seen as network virtualization itself where spectrum resources in optical fiber links are segmented as shareable resources and seamlessly aggregated to create a slice [102]. In this direction, the recent development of sliceable flexible transceivers [6], elastic regenerators [103], and programmable routers and ROADMs [104] that employ BV WSS switches together with the flexible spectrum utilization, provides the hardware enabler for network virtualization.

In this new scenario where any resource can be abstracted and virtualized, a unified and coordinated management and service orchestration becomes a fundamental requirement. SDN provides the key functionalities for network virtualization through centralized control, data and control plane separation and software-based reconfiguration of network components. Indeed, SDN builds a unified resource view (abstraction) for a very diverse range of technologies -hiding thus its complexity and specifications-, creating, managing and operating multiple co-existing virtual networks and generic network functions (firewall, routing, discovery, etc.).

The combination of SDN/OpenFlow and elastic optical networks has recently achieved the widespread interest for its perfect matching between the software and the hardware sides in the network virtualization paradigm [96], [99], and [105]. One important point to mention is the level of abstraction when network virtualization is considered in transport optical networks. Providing a detailed abstraction of transport network will inevitably introduce the scalability issue. Furthermore, there are many parameters in the data plane of transport networks, which revealing all of them to the programmable forwarding and control plane brings the requirement for extra computational power and also scalability concerns.

V. Experimental demonstrations

With respect to the conventional WDM networks, flexible solutions present several technological challenges and the coordination actions to be taken between the three building blocks described above become a challenge per-se. In this section, we briefly describe the most innovative experimental demonstrations that have been setup to test the viability of the novel flexible optical networks functionalities.

The first experimentation demonstrating the feasibility of providing elastic optical path in a flexible optical network was published in 2008 [25]. The NTT laboratories presented the novel spectrum-sliced elastic optical path (SLICE) architecture and successfully established and transmitted elastic optical path with per-channel variable capacity of 40 Gbit/s to over 400 Gbit/s. The testbed used flexible rate optical transceiver based on OFDM and BV-WSS. This demonstration was the spark that finally started the era of flexible optical networks. After that, many other researchers moved from conventional WDM network to the novel spectrum flexible optical network architecture.

The viability of employing adaptive techniques to dynamically adjust the modulation formats in order to maximize the spectral efficiency has been proved in [19], [106]. In [19], the authors propose a performance monitoring method that dynamically reconfigures the modulation format in such a way that the optical signals maintain the required quality of service and bit error rate even for signals experiencing time-varying impairments.

Authors in [16], [21], [20] evaluate the performance of a GMPLS/PCE-controlled flexible optical network. In [20], the attention is put on the extensions required in the GMPLS control plane and PCE protocols to cover the new flexible functionalities. For the GMPLS case, the authors propose the new spectrum switching capability and encoding type as well as routing extensions to disseminate frequency slots availability and the aggregated unreserved bandwidth and signaling extensions to correctly describe the path parameters and reserve the adequate resources. In [21], the authors focus on the PCE architecture and propose protocol extensions to enable the dynamic configuration of both transmission parameters and frequency slots of optical paths. Finally, some dynamic RSA algorithms to establish flexible paths are experimentally evaluated in [16].

As commented previously, the recent advent of SDN and OpenFlow opens up a whole range of possibilities for flexible optical networks. Indeed, the application of SDN enables the customization of the heterogeneous network infrastructures by introducing virtualization, abstraction and programmability concepts in the network functions, protocols and elements. In this direction, the work in [18] presents the first implementation and experimental test of an OpenFlow-based SDN control plane for connectivity provisioning and network slicing (i.e., virtualization) in flexible optical network. In [107], similar experiments have been conducted but in a test-bed crossing multiple domains and different optical transport technologies including fixed and flexible grid and packet networks. The authors also evaluate a solution based on a hybrid GMPLS/OpenFlow architecture that, by taking advantage of the well-defined extensions for the control of optical networks, shows satisfactory performance compared to pure OpenFlow.

Particular mention deserves the experimentations conducted to evaluate the viability of employing defragmentation techniques [46]. As spectral fragmentation inevitably occurs in flexible optical networks due to the dynamic allocation of frequency slots, defragmentation becomes of great importance to limit the wasting of spectrum resources and, depending of the dynamicity of the connections, a computational and operational challenging task. In [46], authors propose and experimentally test the push-pull defragmentation method that, without causing service disruption, provides resource re-optimization. The technique consists of moving the lightpath only to contiguous and free spectrum frequencies along the same route of the original path. Experimental results show that, with current technology, a defragmentation of one lightpath requires around 7 seconds, including the equipment reconfigurations (tunable laser and BV-WSS) and control plane operations. In addition, authors in [47] demonstrate that a connection can be shifted to another conflict-free spectral band with no global synchronization between transmitter and receiver and a service disruption time below μs.

Finally, the work in [108] demonstrates, for the first time, an efficient restoration method. Once the real-time impairment performance monitoring module detects a QoT degradation, this technique triggers a combination of lightpath rerouting and modulation format switching to coordinate the simultaneously restoration of all affected connections.

VI. On-going Challenges and Future Research Directions

This contribution provided a comprehensive collection of technologies and concepts around the flexible optical networking. Starting from the physical layer technologies, possibilities to materialize flexible transceivers and flexible frequency grid and flexible optical switching were presented. The design, planning and optimization of flexible optical networks and related issues were covered and eventually the latest developments around the unified control plane, extensions and innovative approaches were presented.

Nonetheless, network traffic has consistently grown at an exponential rate, and there is no indication this relentless trend will cease. At present, industry is hard-pressed to identify how future networks will continue to scale in capacity, energy consumption, and economic viability as present day technologies are being stretched to their limits. Flexible optical networking solutions as those presented in this paper would be the first step in that direction.

However, from the physical layer technology point of view, even these approaches will reach their limits eventually and the research community will have to come up with new more advanced and more forward-looking solutions. In this direction, as a second step in the evolution, the nascent technology of space-domain multiplexing (SDM) for high capacity transmission [109], might be the only solution with the scaling potential/capability to meet the fast growing future traffic demands beyond 2020. However, there is still a large technological chasm between the transport point-to-point solutions and the overall requirements for SDM-based optical network implementation. In particular there is a need to extend the spectral flexibility concepts to the SDM domain while removing the current limitations related with the wavelength continuity and fragmentation issues [110]. The new spatial-spectral flexible optical networking concept (S2-FON) [111], should utilize the benefits of the high capacity, next generation, few-mode/multi-core fiber infrastructures or/and provide also a practical short term solution, since it is directly applicable over the currently installed multi-fibre cable links. The realization of the S2-FON approach should be enabled by the development of novel multi-dimensional spatial-spectral switching nodes, which may be fabricated by extending the designs of the existing flexible WSS nodes, incorporating advance mode/core adapting techniques [111]. The concept will be further supported by novel network planning algorithms and control plane extensions that will be enhanced appropriately with the additional space dimension.

From the control and operation point of view, extending the SDN vision towards transport networks including flexible optical networks is a key challenge that should be properly addressed. In [112] the concept of Optical Transport Switch is recently introduced. Authors of this paper claim that network virtualization through OTS enables building an overlay

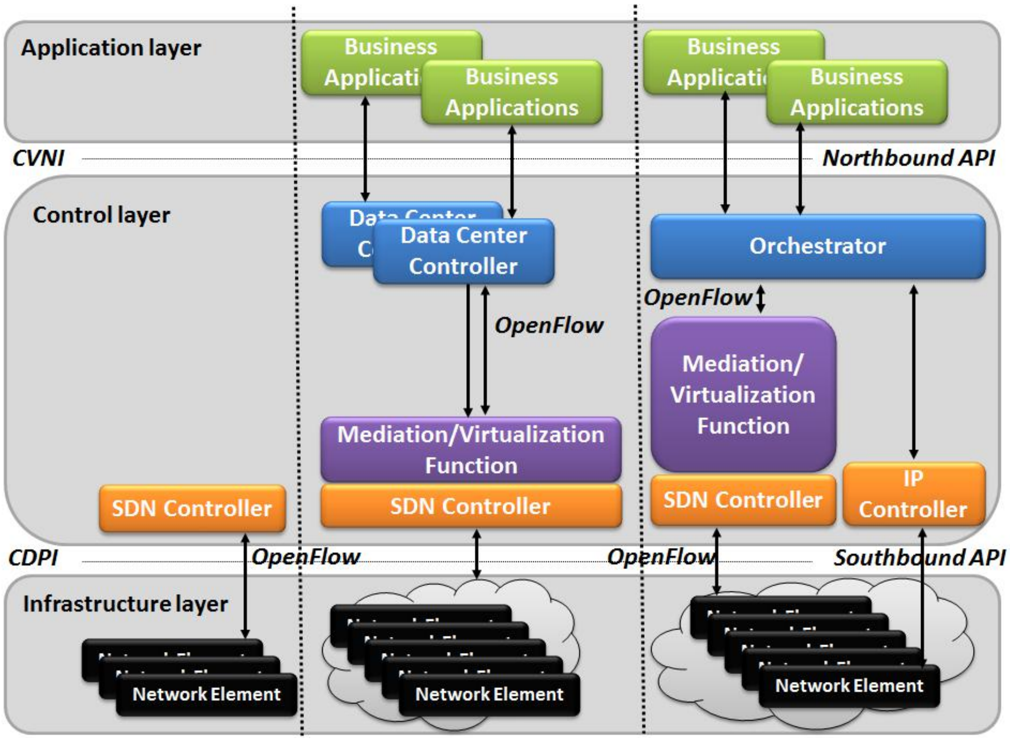


Fig. 7: The initial draft architecture of ONF Optical Transport working group.

network that applications can program to meet their specific service requirements irrespective of underlying protocol or encapsulation layers (L1/L2/L3 or OTN/MPLS/IP) used. Open Networking Foundation has shaped a special working group to address the SDN and OpenFlow based control capabilities for optical transport networks. The work will include identifying use cases, defining reference architecture for controlling optical transport networks incorporating the OpenFlow Standard, and identifying and creating OpenFlow protocol extensions. As a first step, this work group has defined three use-cases to address 1) private cloud computing by providing L0 network connectivity for data centers, 2) network virtualization and data center interconnection and 3) packet/optical interconnection to provide visibility and orchestration of IP and optical networks. The draft abstract model is depicted in Fig. 7. According to this draft model, the extended OpenFlow protocol, called OpenFlow control data plane interface (CDPI) is responsible to interface with network elements and the control virtual network interface (OpenFlow CVNI) is designed to provide the require bridge between the data center controller or orchestrator [113], [114].

Developing future extensions and additional standardization to allow the SDN controllers to manage TDM circuit and wavelength-based architectures (such as generic packet/TDM/fiber switching, CDC ROADM-based networks, sub-wavelength switched networks); and developing mechanisms that support a combination of centralized and distributed control over a multilayer network consisting of both electrical and optical switching are among key challenges and research area that should be further investigated [115]. With the former extensions, LSPs, OTN circuits, and wavelength paths can be abstracted and managed by the SDN controller. The later mechanisms are required to support and optimize network efficiency for evolving applications.

The utilization of distance-adaptive coherent optical transceivers in combination with a flexible finer-grained Wavelength Division Multiplexing (WDM) grid has been proposed in optical core networks to enable higher spectral efficiency and flexibility in the allocation of traffic flows. The application of distance-adaptive transceivers in metro networks, which are typically based on ring topologies and characterized by shorter distances and lower traffic volumes, is still an open research area both in terms of network resource savings and coherent technology requirements. Authors in [116] discuss and analyze an optical metro ring network architecture with distance-adaptive coherent transceivers and formalizes the routing, modulation level, and spectrum assignment. Comparisons with legacy WDM systems show significant savings in terms of spectrum occupation and transceiver utilization. The issue of flexible optical networking introduces benefits in metro and access networks. For instance authors in [117] propose a two-step procedure to design a flatten and flexigrid-based IP/MPLS national network. Authors in [118] extend the principles of SDN and OpenFlow for dynamic flex-grid wavelength circuit creation for OFDM access mobile backhaul overlays onto 10 Gb/s passive optical networks without ONU-side optical filtering, amplification, or coherent detection, over 20 km standard single mode fiber with a 1:64 passive split rate. Also authors in [119] propose a software-defined meta-MAC to exploit virtual OFDMA subcarriers as both finely granular and scalable bandwidth assignment units for future optical access networks.

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