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Challenges and Requirements of a Control Plane for Elastic Optical Networks

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Abstract

Elastic Optical Networks have emerged as a promising technology for the efficient use of optical network resources. Its adaptable characteristics and adjustable data rate enable operators to meet the diverse granularity of their clients needs. In order to automate an elastic optical network operation, a control plane is required. Wavelength Switched Optical Networks (WSON) may already rely on a robust control plane which enables dynamic network management, provides prompt demand reply optimizing spectrum use, and implements important network features as survivability strategies, differentiated service, and grooming procedures. Due to its specific characteristics, Elastic Optical Networks may not implement traditional WSON control plane solutions without further enhancement. Therefore, recent research efforts have been focusing on developing the control plane for this new technology, in most cases by proposing extensions to the currently available architectures. This paper describes a survey on the current ongoing research efforts to define Elastic Optical Network control plane architecture. It identifies and classifies the most relevant proposals currently found in literature, and discusses how these propositions address the main requirements to design a control plane which enables automating the specific functions of an Elastic Optical Network.

Keywords: Elastic Optical Networks, Spectrum Switched Optical Network, Control Plane, flexi-grid

1. Introduction

Recent studies show a continuous growth of data traffic demand as a trend in the Internet evolution. Core network data traffic has been doubling in value almost every two years and is likely to continue growing exponentially [1], [2]. Based on the current optical network development situation, it is hard to predict whether technology advances will be able to cope with the intense growth of resources requirements [3].

The fine granularity required by clients bandwidth is another demand upon the Internet, for it is not frequently met by the rigid Wavelength Switched Optical Networks (WSON) structure

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used by transport networks. In a WSON, a whole wavelength is usually assigned to a connection and the amount of resources it does not use is usually not shared between other connections [4]. Ad interim, network operators are now moving their long-haul connection services from 10 Gbps to 40/100 Gbps due to the proliferation of high bandwidth applications, while continuous traffic growth indicates 400 Gbps and 1 Tbps is expected to be a requirement in the long term.

Impelled by the foregoing facts, in the last half decade, research community and data transport providers have been demonstrating increasingly high interest in Elastic Optical Networks (EON) – also known as Spectrum Switched Optical Networks (SSON). Its adaptability to the clients requirements and the promising ability to enhance optical network performance promotes EONs as a potential provider for future Internet needs. EONs are based on the flexible use of the optical spectrum as is described in [5] and known as flexi-grid. Instead of traditional spectrum bands, spaced usually by 50 or 100 GHz, each one able to accommodate an individual wavelength with a flexi-grid, optical spectrum can be partitioned in narrower bandwidth slots. The resulting spectrum slots can be adaptively allocated in order to meet diverse clients connection requirements. Alternatively, when a large amount of spectrum slots are jointly allocated, the resulting channel may reach bit rate as high as 400Gbps, 1 Tbps [6], [7]. The so-called super-channels are able to meet core networks intense bandwidth requirement growth. Therefore, the new concept of SSON is defined as an extension of WSON with flexible capabilities, i.e., a data plane connection is switched based on an optical spectrum frequency slot with variable width, rather than based on a single wavelength within fixed grid and with fixed channel spacing such as it is for WSON. Fig. 1 depicts a WSON network, where different data rates are accommodated in its rigid frequency grid independently of their actual spectrum occupancy and an SSON network where each data rate occupies a variable slot width.

Generalized Multiprotocol Label Switching (GMPLS) is the *de facto* control plane for WSON; it enables automated connection provisioning, bandwidth adjustment and recovery operations.The introduced flexible grid implies some changes on GMPLS controlled optical networks. Mechanisms supporting dynamic resource assignment, bandwidth variation, as well as protocols extensions are still unresolved issues and under current research and standardization by the International Engineering Tasking Force (IETF) [7]. At the same time, alternative control plane architecture has been recently proposed based on Software Defined Networks (SDN), more specifically the OpenFlow protocol described in [9] and [10].

In this paper we present a survey on the current ongoing research efforts for defining an EON control plane architecture. We identify the most relevant proposals currently found in the literature, and classify the different control plane enhancement proposals into various categories according to the procedure they automate. In Section 2, we briefly introduce the EON environment. In Section 3 we explain the current developments and enhancements of path computation for EON and their impact on control plane requirements. Section 4 reports on the current extension standardization proposals for EONs control plane architecture. Finally, we present our concluding remarks in Section 5.

2. The SSON reference architecture

In an EON, the optical spectrum is divided into finer bandwidth portions called frequency slots (FS), where each FS consists of a fixed spectrum width of few GHz (e.g., 6.25 GHz or 12.5GHz). A slice is understood as a group of FSs. The central frequency in a group of FSs determines where the assigned spectrum is centered. A slot granularity refers to the amount of

FSs in a fiber, which relates to the FSs width. The portion of the spectrum assigned to a lightpath and characterized by its central frequency, number of slots and slot width is called a channel.

Recent advances in signal processing and modulation techniques which enable high-speed data stream using multiple lower-speed subcarriers with overlapped spectral positioning allow the effective optical spectrum use. Optical Orthogonal Frequency Division Multiplexing (OFDM) [11] and Nyquist WDM (N-WDM) [12], are the most common modulation techniques, both offering the same spectral efficiency and enabling flexible grid optical networks deployment [13]. In [11] and [14], authors explain the physical aspects of the OFDM as a class of multi-carrier modulation scheme transmitting high bit rate data stream by dividing it into a number of orthogonal channels. Authors in [12], [13], [15], [16] and [17] explain the physical aspects of the N-WDM , where subcarriers spectra are shaped in order to occupy a bandwidth close or equal to the Nyquist limit for inter-symbol-interference-free and cross-talk-free transmission.

The implementation of OFDM or N-WDM modulated signals enabling an EON requires the use of specific hardware. Bandwidth variable transponders (BVTs), bandwidth variable optical cross connects (BV-OXCs), and reconfigurable bandwidth variable optical add/drop multiplexers (ROADMs) are some of the fundamental network elements promoting, for instance, optical paths cross-connection with arbitrary bandwidth and nominal center frequency [18]. Information on hardware requirements can be found in [7], [18] and [19], whose implementation have been tested and experimented demonstrating EONs feasibility [20], [21], [22].

Similar to what happens in a WSON, a network control plane in SSON has to be introduced in order to automate the discovery of network resources, the computation of available routes from any source to any destination and the signalling of the corresponding Label Switched Paths (LSPs). The recent centralized constrained path computation solution of a Path Computation Element (PCE) can also be considered for SSON.

Fig.2 illustrates an SSON architecture with a centralized path computation performed by a PCE, a distributed control and signalling exploited, for instance, by GMPLS nodes, a data layer performing the label switching and finally the physical layer containing the hardware structure of the network comprising the optical fiber, optical transponders and bandwidth variable wavelength cross-connects containing wavelength selective switches.

3. The path computation in flexi-grid networks

The control plane of an EON allows the automatic provision of end-to-end paths as in a WSON. However, an EON presents additional constraints and capabilities which must be addressed as a control plane design requirement. In this section, we discuss the specific features of path computation in an EON as routing and spectrum assignment, modulation format selection, RSA with time varying traffic adaptability, defragmentation solutions, survivability, grooming and Quality of Service (QoS) proposals. We discuss the proposals currently available in the literature for the aforementioned functions, and we also focus on the impact of the proposals on the control plane requirements for an EON and resulting necessary enhancements.

3.1. Definition of the Routing and Spectrum Assignment problem

In an SSON the resources assignment refers to the allocation of spectrum resources; therefore, the WSON's routing and wavelength assignment (RWA) problem becomes, in an SSON, the routing and spectrum assignment (RSA) problem [23]. An RSA algorithm computes an end-to-end physical route and allocates a set of slots around a central frequency. In absence of wavelength converters, RSA is subject to the spectrum continuity constraint meaning that the same frequency slots in the optical signal must be assigned along the end-to-end path [24]. If the spectrum continuity is not observed, nodes must convert the central frequency along the path [6], an action that increases functionality cost and should ideally be avoided. The RSA problem must also regard the spectrum contiguity constraint which determines that if more than one FS is assigned to a connection the FSs must be contiguous to each other.

The RSA problem can be performed offline, during planning phase, or online in a dynamic scenario. It can be performed by a centralized entity such as the PCE or distributed throughout network elements as in the GMPLS architecture [25]. Numerous researches have been recently published proposing algorithms solving the RSA problem. Static RSA studies have been developed with both Integer Linear Programming (ILP) and heuristics. Algorithms proposals can be observed in [4], [23], [26], [27], [28], [29], [30] and [31]. For a dynamic RSA please refer to [18], [32], [33], [34], [35] and [36]. A brief review of these algorithms can be found in [7]. In this paper we limit our intention to detail the implication of the RSA problem to EON control plane.

Due to the specific characteristics of the RSA process, the control plane of an EON must be enhanced with SSON related information. To perform the RSA algorithm, either the network elements in the distributed scenario or the PCE in the centralized approach need information such as frequency slots availability, central frequency availability, slot granularity, switching capability, LSP label criteria, etc. These data must be distributed via a proper routing protocol. Label format must be redefined for EON. This new label must be able to represent the flexi-grid spectrum characteristics, such as slot granularity, channel width, and central frequency value. During signalling process, a resource reservation protocol should transmit, throughout the selected path, information on the assigned spectrum width and selected central frequency, instead of assigned wavelength [37].

The flexibility EONs offer also provides additional capabilities with respect to the traditional WSON networks. Such aspects are detailed in the following sub-sections.

3.2. Modulation format as a new variable of RSA

Aggregated to the RSA problem, the set of physical layer parameters such as modulation level, bits per symbol and number of sub-carriers may also be considered in the computation of the path. In some articles, such problem is known as the Routing, Modulation and Spectrum Assignment (RMSA) [25] or distance adaptive RSA. The selected modulation level relates to the length of the resulting path. For instance, a short length elastic optical path is bound to undergo reduced signal impairment and, therefore, its signal may be modulated using a format occupying less optical spectrum. Nevertheless, it might still reach destination with acceptable signal quality level [38]. For instance, a modulation format such as 16-QAM can be selected for short paths (usually less than 500 km) and a more robust one, such as QPSK, can be selected for longer paths, resulting in more efficient spectrum resources use [36]. Such approach can even be extended as proposed in [39] where an impairment-aware routing algorithm can change the modulation format on regenerator nodes to better match the optical spectrum with the remaining length of the path. For the sake of simplicity, we use in this paper the general term RSA when referring to both RSA and RSMA problems.

An SSON control plane needs to be enhanced to select the most adequate modulation format for a given connection. Protocol related to the RSA should be able to exchange information regarding available modulation format options [40] and the computed path length. Furthermore, the resulting selected modulation format must be properly codified into a path computation reply message [41].

3.3. Adaptation to time-varying traffic

The elasticity provided by SSON networks supports time-varying traffic, by increasing or decreasing the spectrum assigned to a lightpath as demand rate requires [42]. Adaptive spectrum assignment with a known a priori 24-hour traffic pattern have been addressed in [43]. Concurrently, an online dynamic adaptation of sub-carriers is studied in [44]. In [45], the authors identify three alternative solutions for spectrum assignment with time-varying demands:

- Both the assigned central frequency (CF) and spectrum width do not change in time; therefore, a demand may use either the whole or a fraction of the spectrum as convenient;
- The assigned CF is fixed but the width of the allocated spectrum may vary according to the demand;
- Both the CF and the spectrum width can change in time.

It is clear that the higher the elasticity of spectrum assignment, the higher the complexity of the network control. For instance, important issues which need dedicated mechanisms are possible traffic disruptions, likely to occur when changing the amount of the assigned spectrum and specially the CF. The control plane protocols must be extended to accommodate specific information requirement so responding to adaptive spectrum allocation is viable. If both CF and spectrum width do not vary, the control plane must be able to allocate a fixed channel and a maximum bandwidth usage.

Regarding the scenario where the spectrum width may vary according to connections bandwidth usage fluctuation, the control plane signalling protocol must be enabled to perform dynamic increment or decrement of a connection's assigned spectrum. The current spectrum usage per link information must be properly updated by a routing protocol [45].

For the fully adaptive option, the control plane must be enhanced in order to be able to perform dynamic modification of CF and allocated spectrum. A path and resource assignment request must promptly trigger a computation process whose algorithm must be robust enough to prevent conflicting resource re-allocation in case many connections requirements occur at the same time [45]. Therefore, the information concerning released and reserved spectrum fragments should be updated within optimum intervals. In case the adaptation of traffic follows a previously known hourly pattern [46], the information must be stored in a database. The resource assignment algorithms in this respect must regard this information to frequently re-allocate resources to active connections.

3.4. The fragmentation problem

The constant channel sets-up and releases leads to the fragmentation of spectral resources, resulting in non-contiguous spectral bands in an SSON dynamic operation scenario. This spectral fragmentation decreases the probability of future assignment of contiguous frequency slots to a channel, jeopardizing the network's spectral efficiency [40] and increasing blocking probability. Defragmentation techniques have been investigated and proposed in [40], [47] , [48] and [49]. In [48] a defragmentation technique is proposed as a distributed procedure of spectrum reallocation, improving network performance without traffic disruption. In [49] a non-disruptive defragmentation technique relies on lightpath retuning and reconfiguration of allocated spectrum.

RSA algorithms to prevent or solve the fragmentation issue are known as fragmentation-aware RSA and are proposed in [44], [50], [51], [52], [53] and [54]. Some fragmentation-aware RSA strategies are based on the analysis of the individual links belonging to the candidate path and/or their adjoined links [52]. Other strategies focus on the analysis of the candidate paths and their gaps of available FSs [53]. In a different approach, spectrum positions are reserved to connection requests according to their bandwidth requirement. Accordingly, connections with higher bandwidth requirements would be allocated to one end of the spectrum while connections with lower bandwidth requirements would be allocated to the other end [54]. A similar alternative is to reserve FSs groups to connections with different source-destination pair [44]. Fig. 3 depicts an illustration of spectrum before fragmentation, after fragmentation and after a defragmentation technique.

To perform a defragmentation, the control plane must be extended to convey the network elements required information to execute rerouting and/or spectrum re-assignment. A request procedure has to be defined to trigger the defragmentation process minimizing clients' perception of active connection disruptions for spectrum re-allocation.

3.5. Survivability

In a high capacity EON, failures may result in large amount of traffic loss if no survivability strategy is implemented [55]. The RSA problem may also allow survivability strategies as proposed in [56]. As in conventional WDM systems, survivability strategies may focus on either protection or restoration schemes. Backup resources are provisioned in advance for working connections in a protection scheme, which is usually preferred due to its rapid recovery response [24]. Protection schemes may implement shared or dedicated protection [57]. The elected survivability strategy usually relates to the differentiated service policy of the network, where priority classes determine which protection scheme would be applied to which priority service level. This approach is addressed in Section 3.6.

In a shared protection scheme, active connections allot the same path and resources as backup path. In a traditional fixed grid WDM network, all ligthpaths have the same bandwidth promoting simply managed resource sharing. For an SSON network, however, optical paths have different bandwidths and, therefore, spectral resources backup are shared among sub channels with different data rate [58]. It means that protection in SSON is more challenging than in WSON networks not only due to the varied data rate of optical channels but also due to the additional spectral continuity and contiguity constraints [24]. Shared path protection for elastic optical network is proved to be a NP-complete problem in [58] where authors propose heuristics based on working path first, fixed routing for working and backup paths and first-fit subcarrier allocation to solve the problem.

In a restoration scheme a backup path with required available resources is calculated on demand once a failure occurs. When it happens, the resulting calculated alternative route length may exceed the optical reach of the original optical signal. Authors in [59] propose a solution where the control plane computes a modulation format which achieves the highest possible bit rate for the detour route considering the available spectrum resources.

In order to effectively implement a survivability scheme, an SSON needs to rely on a control plane able to provide and access information on pre-calculated back-up paths. The control plane and the resource reservation protocol in particular must have knowledge of which connections have a dedicated protection scheme and which share a backup path with other connections. Pre-reserved resources would be represented in terms of reserved spectrum widths and nominal central frequencies.

In summary, an EON control plane must be able to promptly respond to a triggering mechanism when failure is detected. The required resource for the restoration must be computed in terms of frequency slot widths, modulation format, and nominal central frequencies.

3.6. Quality of Service

QoS can be provided regarding diverse connection characteristics such as, availability, survivability or quality of transmission.

Connections optical signal are prone to impairments, as any optical communication system. One of the possibilities to guarantee a desired level of service is to monitor the acceptable level of impairments as Bit Error Rate (BER) or Optical Signal to Noise Ratio (OSNR). In [60], a real time performance monitoring method is proposed to enable the network to dynamically adjust the modulation format to maximize the spectral efficiency and maintain the required level of QoS. In case a link in a given optical path experience QoS detriment, the monitoring mechanism placed at the end nodes will detect and inform the impairment issue to the control plane. The control plane will, then, instruct source nodes to either lower the spectral efficiency or modify the central frequency of the affected paths. In case OSNR on the problematic link eventually returns to an acceptable level, node monitors would inform the control plane of the possibility of restoring the system.

The aforementioned strategy aims to guarantee a minimum level of service quality to all connections in general; however, it is possible to serve clients' demands with different service quality levels. For instance, service providers may grant diverse priority levels, following different policies, in accordance with Service Level Agreements (SLA). In [61] different priority levels demands are served following bandwidth constraints and higher priority demands may preempt part of the resources used by lower priority connections. To be able to offer such differentiated levels of service, an SSON should rely on RSA related protocols which, in turn, are able to respect priority level values of demands. The information describing traffic priorities must be formatted aiming at universal understanding by diverse protocols and, ideally, by different autonomous systems. On a differentiated service aware network, priority levels must be regarded not only for arriving demands but also for all active LSPs.

QoS strategies may also rely on availability and survivability mechanisms. Authors in [62] and [63] propose connections with different priority levels may be granted lightpaths with different levels of link availability and/or survivability strategies (fast protection, restoration or unprotection). They classify traffic into mission critic and best-effort traffic. In case of failure, the control plane reduces the rate of best-effort traffic keeping just a committed rate for this service and assigns released resources to the mission critic traffic. Thus the network manages to attend a higher number of requests than traditional restoration policies. To be properly implemented, this strategy would require control protocol extensions to identify the committed and excess streams, as well as bandwidth allocated to best effort traffic.

3.7. Grooming

Multiple low speed connections may be aggregated and switched in a single high capacity channel to decrease the number of multiplexed flexible channels while transporting the same amount of traffic. This procedure, consubstantial to the one applied in WDM systems, is also known as traffic grooming [64].

Traditionally traffic grooming is performed electronically in a Time Division Multiplexing (TDM) or packet switching capable layer. The groomed electrical signal is then converted back to optical signal, and the whole operation is known as electronic grooming (e-grooming) [64]. E-grooming, however, is not cost-effective nor is power-efficient as it requires additional optical-electrical-optical (O-E-O) conversion and electrical subcarrier switching at intermediate nodes [65]. In order to avoid the drawbacks of e-grooming, solutions for optical grooming (o-grooming) have been proposed where traffic is distributed and aggregated directly at the optical layer and O-E-O conversions are not required.

In the o-grooming scheme proposed for an EON in [66], optical paths with same source initiated by the same bandwidth variable transmitter are groomed together in an optical channel. Connections with same source and destination nodes are switched as a single optical channel. Connections with same source but different destination nodes can be either dropped or switched optically at any intermediate node along the path [66]. Fig.4 illustrates the procedure: When an optical path needs to be separated from the optical channel at a given node, the optical channel is then split into multiple optical channels containing one or more optical paths, each resulting optical channel can be subsequently switched by BV-OXCs [66].

Authors in [64] and [67] propose the routing, wavelength assignment, subcarrier assignment and spectrum allocation problem (RWSSA) to perform o-grooming. In their proposal data are switched between channels in a modulated radio frequency (RF) subcarrier level without the need for any electronic client level operation. With the o-grooming technique, connections may be aggregated (Fig. 5a), separated (Fig. 5b), crossed (subcarrier switching without subcarrier conversion) (Fig. 5c), and switched (subcarrier switching with subcarrier conversion) (Fig. 5d) at the optical level.

In case grooming is implemented in an SSON, even though they do not have a guard band between them the nodes must be able to distinguish the signals belonging to different connections and properly adjust the filtering when switching a connection. Therefore the label hierarchy for the spectrum channels must be organised adequately guaranteeing connections will be correctly dropped when reaching their destination.

3.8. Summary

Table 1 summarizes and classifies the features related to the path computation problem in SSON networks.

Table 1: Summary of RSA algorithms in the literature

Feature	Main references	Implications to the control plane
Static RSA	[23], [26], [27], [28], [29], [30]	Control plane protocols must be able to understand and comprise information as: network's slot width granularity value, nominal central frequency value granularity.
Dynamic RSA	[32], [33], [34], [35], [68]	Control plane protocols must be able to understand and comprise information as: network's slot width granularity value, nominal central frequency value granularity. Current state of active connections' frequency slot use and their nominal central frequency.

Distance-Adaptive RSA (RMSA)	[4], [18], [31], [36], [39], [69]	Control plane protocols must be aware of all modulation formats adopted by all connections in the network, the available modulation formats in the network, and their physical characteristics such as modulation level, bits per symbol, number of sub-carriers, and maximum path distance.
Time-Varying RSA	[23], [42], [43], [44], [45], [46], [70]	Control plane must be aware of connections variation pattern. Resource reservation protocols should be able to differentiate reserved FSs and re-allocated FSs. In general the control plane should be robust enough to rapidly apply new resource allocations. Active connections may be disrupted and reallocated, therefore optimum update of network state database is required.
Survivable RSA	[24], [56], [58]	Control plane should contain information on pre-calculated back-up paths, connection's with dedicated or shared protection scheme. Reserved resource information would be described in terms of frequency slots and nominal central frequencies.
Defragmentation and fragmentation-aware RSA	[40], [47] , [48], [49], [44], [50], [51], [52], [53], [54]	Defragmentation mechanism should be triggered in the control plane once a fragmentation threshold is reached. A resource reservation protocol must follow the selected defragmentation mechanism. Active connections may be disrupted and reallocated, therefore optimum network state database update is crucial.
QoS RSA	[62], [63]	RSA algorithm should consider differentiated priority values when calculating a route and assigning spectrum to a connection. Preemption mechanisms can be considered to release entirely or partially the spectrum resources reserved by lower priority connections to make room for higher priority ones. The priority values of arriving demands and active connections must follow same format codification that must be universal throughout different control protocols.

Grooming	[64], [66], [67]	SSON switching nodes must be able to distinguish the signals belonging to different connections and filter them adequately. Switching nodes must be able to rely on hierarchical LSP label set.

4. Control plane extensions for flexi-grid networks

A control plane comprises a set of protocols responsible for dynamic provisioning of connections [41] and other specific features, such as traffic grooming, QoS, and survivability strategies. Although well designed and standardized for WSONs, evolution to encompass the flexi-grid optical technology is still in an early stage. Presented as a framework to this end, [71] proposes a set of requirements for the control plane of SSON networks, where high-capacity super channels are enabled. These requirements can be considered requisites in general, as they also apply to low-data rate connections. In more detail, an EON control plane should:

- Allow optical channels to be flexible in size or width;
- Enable optical channels to support various modulation formats, either with single or dual polarization modes;
- Allow channel resizing;
- Comply with allocated frequency definitions stated in [5];
- Enable super-channels to be either allocated on a contiguous spectrum portion or place in separated positions on the spectrum grid;
- Support the co-routing of the composing waveband members of a split spectrum super-channel;
- Be able to seamlessly manage nodes that have flexi-grid or fixed-grid functionality, allowing deployment of flexi-grid segments in a legacy fixed-grid network;
- Allow fast restoration upon failures, with or without pre-computed path and/or resource reservation;
- Enable restoration to be reversible, reinstating the network to original state once failure has been corrected.

GMPLS is the current control plane solution for WSON networks. Its architecture and protocols are currently being extended to meet the aforementioned requirements for EON networks. On the other hand, research community recently proposed a control plane based on SDN architecture, more specifically relying on the OpenFlow protocol [72]. OpenFlow is an open protocol that allows separation of data and control plane. Such protocol is based on flow switching with the capability to execute software/user defined routing, control and management applications in a centralised OpenFlow controller.

In this Section we revise the current GMPLS extensions proposed to adapt the control plane architecture and its respective protocols to EONs. Then, we review SDN as an alternative control plane architecture. We end the Section discussing extensions proposed for the PCE architecture as an independent solution for path and resource computation.

4.1. GMPLS enhancements for EONs

GMPLS protocol suite described in [73] is the most commonly adopted control plane architecture for optical networks. Due to its broad adoption and vast functionality, many consider the GMPLS architecture a natural choice for implementing EON control plane [41]. The GMPLS architecture standardizes a suite of protocols for link management, resource discovery, topology dissemination, path computation, as well as connection signalling, protection and restoration [41]. The GMPLS protocol suite is typically composed by Link Management Protocol (LMP) [74], Open Shortest Path First with Traffic Engineering extensions (OSPF-TE) [75] and Resource Reservation Protocol with Traffic Engineering extensions (RSVP-TE) [76]. Although not as common as OSPF-TE and RSVP-TE, Intermediate System to Intermediate System (IS-IS) [77] is an alternative routing protocol whilst Constraint-based Routing Label Distribution Protocol (CR-LDP) [78] is an alternative resources reservation protocol.

During the last decade, the entire GMPLS protocol suite has been broadly standardized, so as to not only be applicable to packet switching LSPs, but also to time-division multiplexing, lambda, and fiber switching LSPs. However, its applicability for EONs is not completely described yet. GMPLS for EON must regard frequency slots rather than wavelengths. Scalability issues may arise from the fact that, in EON, the control plane protocols are required to maintain coherent global information representing up to 320 or 640 slots, in the 12.5 GHz or the 6.25GHz slot granularity respectively [79]. Some studies indicate that spectrum granularity may become even finer reaching 3GHz resulting in 1280 number of possible slots [80]. Next subsections review the most significant efforts on extending each of the protocols comprised by the GMPLS architecture.

4.1.1. Link Management Protocol (LMP)

The LMP protocol is introduced in GMPLS to perform several tasks related specifically to network links. LMP's responsibilities are:

- Maintaining the connectivity of the control channels between neighbouring nodes;
- Correlating and validating the properties of transport plane resources between neighbouring nodes;
- Verifying neighbouring nodes connectivity;
- Providing fault isolation capabilities upon failures in transparent optical networks, where failure alarms can propagate downstream from the failure point;

Initiatives within the IETF are devoted to extend LMP link property correlation procedures to EON environments [81]. The rationale behind these initiatives is that, in the evolution towards SSON networks, fixed-grid DWDM nodes will be gradually replaced by flexi-grid EON nodes. Interworking issues can potentially exist between EON nodes and legacy fixed-grid nodes and between two EON nodes with inconsistent characteristics (e.g., inconsistent grid granularity or slot width tuning range).

Authors in [81] provide new protocol encodings extending LMP for dynamic negotiation of parameters, thus avoiding negotiation conflict. For example, a link between two flexi-grid optical nodes, each of them supporting different grid granularity, must be configured to align with the larger granularity. However, in case of tuning range conflict, the slot width tuning range should be selected as the tuning range intersection. Consider a node supporting a slot width tuning range from 12.5 to 100 GHz, and its neighbour a tuning range from 25 GHz to 200 GHz. In this scenario, the slot width tuning range in the link between these nodes would be set from 25 GHz to 100 GHz. As for an interworking conflict between fixed-grid and flexi-grid capable interconnected nodes, consider three nodes in a row, where the endpoints are flexi-grid capable and the one in the middle fixed-grid capable. In this situation, flexi-grid properties must be negotiated so as to be aligned with the fixed-grid values, and LSPs between the endpoints must respect the fixed-grid slot width and central frequencies, so as to be fully backwards compatible.

In a traditional GMPLS controlled network, neighbouring nodes exchange LinkSummary messages containing common link properties. When receiving a LinkSummary message from a neighbour, a node compares the properties in the message with those stored in its local database. If all properties match and there is complete agreement, the response is a LinkSummaryAck. Conversely, if node properties differ, the message is a LinkSummaryNack including the inconsistencies and suggested values. Upon receiving the LinkSummaryNack message, the node must send another LinkSummary message including new values of those conflicting properties in order to reach an agreement. To extend this operation to EONs, [81] introduces a new DATALINK sub-object named grid property, which is responsible for correlating the grid property between two neighbouring nodes. Fig. 6 exemplifies the encoding format of this new sub-object.

The grid value represents the type of grid supported by the node interface. In [82], authors define DWDM and CWDM values, while [83] defines flexi-grid values. The Channel Spacing (C.S.) value represents the channel spacing for a fixed-grid, whereas for a flexible grid interface, it represents the central frequency granularity. The Min & Max value informs the slot width tuning range the interface supports and should be set to zero (i.e., not applicable) in fixed-grid nodes [81].

Fault management seems to be applicable as it is for EONs, provided that optical nodes have fault detection capabilities per optical channel. Link connectivity verification should be performed per frequency slot in EONs, instead of being per wavelength as it is in WSONs. However, it is still an open issue how control information can be sent in-band to verify each frequency slot connectivity.

4.1.2. Open Shortest Path First with Traffic Engineering Extensions (OSPF-TE)

The OSPF-TE protocol is responsible for advertising link/node connectivity and resource availability and reservation. This network state information is transmitted via Link State Advertisement (LSA) messages to all GMPLS network nodes, thus guaranteeing synchronized populated and updated traffic engineering database (TED). In an EON, the routing protocol must be extended to properly describe network elements, such as BVT and ROADMs. Furthermore, extended it efficiently conveys detailed TE links statuses including nominal central frequency status and frequency slots availability [41]. In [84], authors mention two different OSPF-TE extensions for flexi-grid channel statuses advertisement. The first option adds a free/occupied state field to LSA Available Label Set sub-TLV. This enhancement would enable the status advertisement of a set of contiguous slots by using the start slot, the end slot, and the current state of the slot.

The second option also relies on the Available Label Set sub-TLV; however, every single slot status is informed by a *bitmap*, whose size varies according to the existing total number of frequency slots in the fiber [84].

In [41], authors mention that either aggregated or detailed TE link information can attain topology and resource advertisement. By aggregating TE link information, only the total amount of free optical spectrum in the TE links (in GHz) is advertised, enhancing the scalability of LSA operation at the expense of obliterating important link state information as current spectrum fragmentation. In contrast, detailed individual slots link state information is advertised via a new link attribute object [41], which extends the original OSPF-TE LSA message.

A new switching capability describing a Super Channel Switch Capable (SCSC) interface is introduced in link state advertisement, as proposed in [85]. Optical nodes with SCSC interface advertise frequency slots state information considered for super channels allocation.

In EON, the optical spectrum flexi-grid enables diverse bit rates and modulation format channels. Channels with diverse characteristics placed with proximity to each other are prone to suffer a higher intensity of cross-phase modulation (XPM) impairment effect. Aiming at reducing XPM effect, authors in [86] propose extensions to OSPF-TE. Such extensions advertise a partitioning of the fiber spectrum in sub-bands, where a sub-band is intended to allocate signals with similar bit-rate and modulation format. This new information would be regarded when allocating resources to incoming connections in an impairment aware dynamic RSA.

4.1.3. Signaling and Resource Reservation

When the RSA problem is divided into two phases, the route and the spectrum assignment operations are separated and the spectrum assignment is performed in a distributed fashion by the signalling process. In a GMPLS network, the signalling process is performed by RSVP-TE and the spectrum assignment is triggered in each GMPLS node by the arrival of the RSVP-TE path message, which contains the requested information to setup a lightpath from a source to a destination node at a given bit rate [20].

During the signalling process, the RSVP-TE mechanism searches for the contiguous required number of slots in every link comprised by the signalled route. The spectrum assignment is performed at the destination node, relying on the RSVP-TE LabelSet object, properly extended to collect frequency slot availability information hop-by-hop as the message travels through all links in the path [25]. If the message reaches the next intermediate node and there are frequency slots unavailable at the outgoing link in the LabelSet object, removing the unavailable identifiers [87] updates the LabelSet object. As the message arrives at the destination node, LSP set-up is blocked if the LabelSet object is empty. Otherwise, the destination node selects n adjacent slots, according to the bit-rate and modulation format the LSP being established requires.

The selection of slots can follow different strategies. For instance, authors in [79] describe First-fit and Multiple of n strategies, n being the required number of slots. In the First-fit strategy, if any slot l has n adjacent available slots, it is selected and slot l to slot l + (n-1) are reserved, as in Fig. 7a. In the Multiple of n strategy, the lowest indexed slot is selected if it is multiple of the required number of slots (n) and its n adjacent slots are available [79]. In Fig. 7a by applying multiple of n strategy, n being equal to 3, the lowest indexed slot selected would be slot 3 and slot 2 would be discarded from the label set of available slots.

In [79], authors propose an aggregated signalling promoting a better scalability for the RSVP-TE protocol in EONs. In such proposal, frequency slots are grouped in sets of n adjacent selected slots to establish the LSP, n being the required number of slots. Each group with n adjacent slots will be given a group identifier (id) to be carried in the LabelSet object. Since LabelSet object carries the group ids, instead of the slots ids, the number of possible available combinations is minimized. When the message carrying the LabelSet object reaches an intermediate node, it checks for unavailable slots in the outgoing link. With at least one in the group, the whole group is considered unavailable and the corresponded group id is removed from the LabelSet object. Once the LabelSet object reaches the destination node, it assigns the slots in a first fit basis by selecting the lowest indexed group. The mechanism is illustrated in Fig. 7b.

Similar approaches are presented in [25], where frequency slots selection policies are classified into two main types: slot based and range based. In the slot based policy, all slots are checked iteratively, defining a preliminary slot i and searching the following consecutive slots for n available slots, n being the required number of slots. If n available slots are found, they are reserved. In range based policies, n being the required number of slots, a feasible range has m consecutive available slots, so that m is greater than or equal to n. Once all ranges are explored, one is finally selected, following two possible strategies: Either the smallest feasible range is chosen, or one is randomly chosen among all feasible ranges.

In an EON, the signalling process regards:

- Label format and semantics;
- Controlled resource identification;
- Frequency slot status;
- Client signal characteristics;
- Explicit Route Object (ERO).

The RSVP-TE extension requirements are listed in [20] as:

- The switching type field in the generalized label request carried by the RSVP-TE path message would have to be extended to describe spectrum switching capable LSPs.
- The Upstream Label object, the ERO, the Label Object, and Record Route Object would contain start slot and end slot.
- The Sender TSpec Object and the Flow Spec Object would have information on modulation format conveying symbol rate, number of sub-carriers, and modulation level.

In [41], the distributed spectrum allocation reuses procedures from WSON in order to collect nominal central frequencies. The central frequency and its status are collected by RSVP-TE path message during signalling. Each nominal central frequency is indexed with a 16 bit identifier, starting with 1, for the purpose of classification. The generalized label encodes the first or lowest central frequency, known as the base frequency slot and the number of contiguous frequency slots assigned to the request [41]. In detail, once a path computation process is concluded, a resulting ERO object containing optical parameters is included in the RSVP-TE path message with the necessary information provided by path computation procedure. Knowing the requested resources, the set of available frequency slots and slot width, the egress node may perform slot allocation [41].

Authors in [87] propose a new label object format as depicted in Fig. 8. A new grid value 3 refers to a flexible grid scenario. The label object also contains a Channel Spacing (C.S.) sub-object, as defined in [82] and extended in [83], representing the nominal central frequency granularity (e.g., value 5 represents 6.25GHz). An Identifier field is introduced containing a local integer used to distinguish different lasers in one node, when they can transmit the same frequency lambda [83]. The value n can be either positive, negative or zero, and is used to calculate the frequency which the connection calculated by equation 1 [82] would use.

$$\text{Frequency (THz)} = 193.1THz + n * \text{channel spacing (THz)} \tag{1}$$

4.2. Software Defined Networks

The GMPLS architecture is not the only architecture being proposed as an EON control plane. An alternative control plane architecture is Software Defined Network (SDN) from which OpenFlow is a protocol described in [9] and [10]. Authors in [9] mention that the OpenFlow protocol [72] provides higher flexibility and that its centralized and simple architecture meets operator preferences better than the suite of protocols in GMPLS architecture do.

In OpenFlow for packet-based network, each switch contains a flow-table. Each flow-table entry header specifies a flow and an associated action to be taken towards an incoming packet matching the respective entry. Whilst each packet is switched individually, all packets in a flow are switched the same way, being the flow the fundamental unit [88].

In a DWDM circuit switched network, a flow is identified by a port, a wavelength, and a signal type. In an EON, a flow would be identified by a port, a nominal center frequency, a slot width, number of slots, and the type of signal fields associated with the switch [10]. The OpenFlow protocol is managed by a network control platform called NOX and utilizes inter-domain and intra-domain flow tables. The inter-domain flow tables contain the flow identifier and associated actions for network elements interconnecting different neighbouring domains [10]. If two domain support different technologies, the action associated to that interconnection must comply with specific mapping rules. If the interconnection happens between a flexi-grid and a fixed-grid network, each center frequency and bandwidth must be compatible with the DWDM fixed-grid. Conversely, if the interconnection happens between a packet and an EON domain, packet flows must be mapped to each center frequency and bandwidth [10].

EON characteristics allow it to be software-programmable, enabling software-defined optics (SDO) which refers to programmable optical signals with variable capacity and spectral allocation [89], [90]. The implementation of software-programmable transceivers able to adapt data rate, modulation format, forward error correction and electronic signal equalization to specific application requirements [90] enable software-defined optical networks (SDON). With intent to enhance the OpenFlow protocol ability to meet particular optical layer constraints, an intermediate approach where OpenFlow may use an embedded GMPLS control library is proposed in [91].

4.3. Path Computation Element

As introduced in Section 2, the PCE has been developed by the IETF in order to perform highly CPU-intensive path computation in a centralized fashion by a specialized entity. Initially proposed for MPLS and GMPLS [92], [93], the PCE can also be implemented in tandem with other control plane architectures such as OpenFlow [94]. The PCE became a popular solution because it enables multi-domain end-to-end path computation, among other reasons.

Different schemas are proposed in the literature to deal with the complexity of the RSA process, as well as its additional features described in Section 3. When a PCE is enabled in an EON it may centrally perform the complete RSA process or, given its complexity, the task may be divided into routing, modulation and FEC computation being performed centrally by the PCE and spectrum assignment in a distributed manner by the resource reservation protocol [41].

Authors in [41] and [95] explain an important difference between the PCE architecture for WSON's RWA and SSON's RSA problem. As introduced in Section 3, in RWA the modulation format and the forward error correction (FEC) work as a constraint in the path computation. On the other hand, in RSA they are part of output alternatives of the path computation process. The PCE in an SSON must be able to regard these new constraints in the RSA algorithm and output the computed solution in a reply message.

In EON, the PCE protocol (PCEP) needs to be extended to support information regarding flexible network features. The PCEP reply (PCRep) message, for instance, must include extended objects defining the modulation format and number of slots to be assigned [25]. Authors in [41] propose an ERO sub-object named RSA as an extension to the PCRep message. The RSA sub-object contains the optical parameters, expressed as type-length-value (TLV) tuples, elected by the PCE. Such parameters can be a list of possible modulation formats, a list of FECs or the necessary spectrum amount for the selected modulation and FEC. In [95] and [96], a PCE architecture named impairment validation (IV) & RSA PCE is proposed as an enhancement of the IV & RWA PCE architecture previously introduced by [97]. the suggested architecture performs both impairment validation and RSA.

Regarding survivability capability, the PCE architecture can be enhanced with dynamic re-routing [96]. The re-routing relies on a dynamic switching over a secondary path computed by the PCE, implying a reconfiguration of the BV-OXCs and of the BVTs that select most adequate modulation format for the transmitted bit-rate.

Regarding the fragmentation problem in [40] the PCEP is extended in order to optimize the use of the network spectrum through defragmentation. To trigger the reroute or spectrum reallocation, the PCEP is extended with two new types of messages: the Spectrum Defragmentation Request Message and the Spectrum Defragmentation Reply Message. Both messages are enhanced with the Spectrum Defragmentation Target Object (SDTO), as in Fig. 9. The SDTO contains the following sub-objects: the ”Target Clutter Value” refers to the defragmentation threshold, or the level of fragmentation that should trigger the defragmenation mechanism while the ”R” field refers to whether triggering the defragmentation mechanism is obligatory or not in the network. The field ”Id 1” refers to the available defragmentation methods, ”Id 2” represents the number of methods to trigger defragmentation, and ”L” field informs the limit of interrupting rate or defragmentation time [40].

In addition, [40] also proposes extensions to the PCEP in order to request to the PCE the execution of a specifically selected RSA algorithm. The PCReq message is, therefore, upgraded with a RAEO-list object which include the algorithms identifier (id) and a priority (Pri) field as illustrated in Fig. 10.

4.4. Summary

Table 2 summarizes and classifies references regarding control plane extensions for EONs.

Table 2: Summary of control plane extension proposals

Control Plane	Protocol	Article
GMPLS	LMP extensions	[81], [85]
	OSPF-TE extensions	[85], [86]
	OSPF-TE adaptations	[79]
	RSVP-TE extensions	[87]
	LSP label extensions	[87], [83]
SDN	OpenFlow	[9], [10]
	PCE extensions	[40], [41], [95], [96]

5. Conclusions

The fast and continuous growth of internet bandwidth consumption promote the need for high-capacity and cost effective optical data communication. Furthermore, it requires data-rate-flexible and reconfigurable systems, providing resource and energy efficient networks. The evolution of researches on modulation techniques has resulted in the development of an optical spectrum grid alternative design where resources are optimally allocated in a flexible manner. The so called flexible grid may be implemented relying on Nyquist WDM technology; however, the use of OFDM as modulation format is further developed.

A flexible optical network has different channel and subcarriers structure if compared to regular fixed grid WDM networks. Wherefore, in order to implement dynamic functions in this type of network, new control plane structures or adaptations to the current control plane architectures must be developed. Recently, many efforts have been done proposing a new design for a suitable control plane for EONs. An IETF study group called CCAMP are currently publishing articles about the developments on this field, most of which are based on the enhancement of current GMPLS architecture. Concurrently, other researches are proposing alternative methodologies for the control plane as, for instance, the OpenFlow protocol which is part of SDN architecture. Each approach has its own benefits or disadvantages. The GMPLS architecture has the advantage of being a well structured current industry adopted solution, and; therefore, enhancements on this architecture may promote a straightforward implementation on an EON. The SDN solution, however, has the benefit of being a flexible control plane solution that seems to be promising and gathering many industry enthusiasts.

Concerning specific mechanisms, such as grooming and survivability, studies have been presenting new methodologies and ideas for new strategies that require controlling and management protocol enhancements.This survey presented the state-of-the-art and on going research efforts in the context of extensions and standardization proposals for EON control plane. The subject covered included extension proposals for GMPLS protocol suite comprising enhancements for the LMP, OSPF-TE and Signalling and Resource Reservation protocols and enhancements for the OpenFlow as an alternative control protocol. We have also explained the routing and resource assignment problem and enumerated RSA off line and dynamic algorithms currently found in the literature. For centralized dynamic RSA fashion we presented the current extension proposals for the PCE architecture.

With this survey, we intended to draw an organised and classified view of the state of the art on control plane enhancements for EONs. We believe this work is a helpful tool for the scientific community regarding the next steps of a novel EON control plane architecture development.

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Appendix A.

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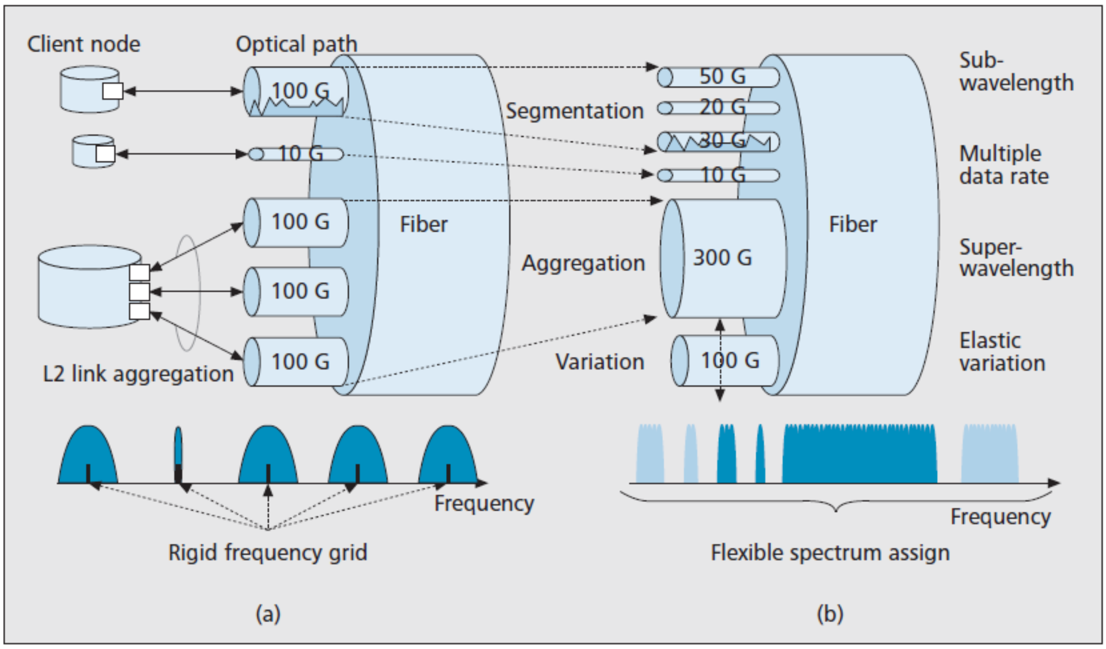

Figure 1: Spectrum assignment: a) in traditional WDM network; b) flexi-grid optical network [8]

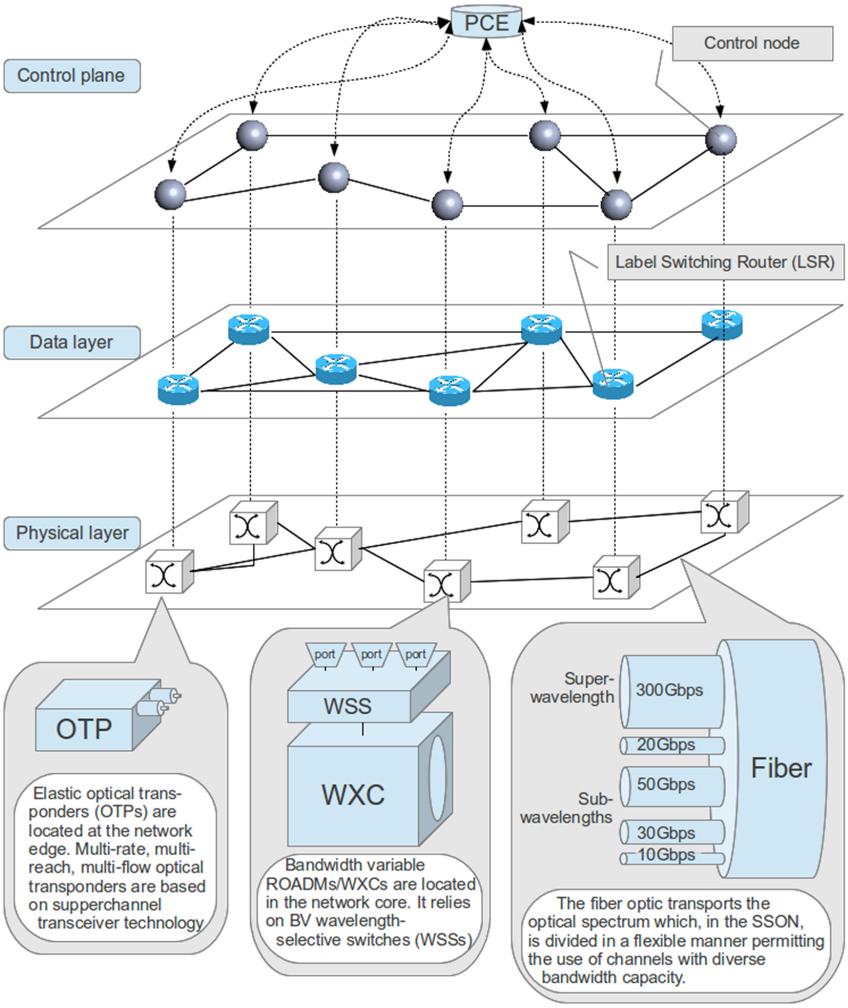

Figure 2: SSON layered architecture with centralized path computation, distributed control and signalling, label based switching and a physical layer based on recent technology advances

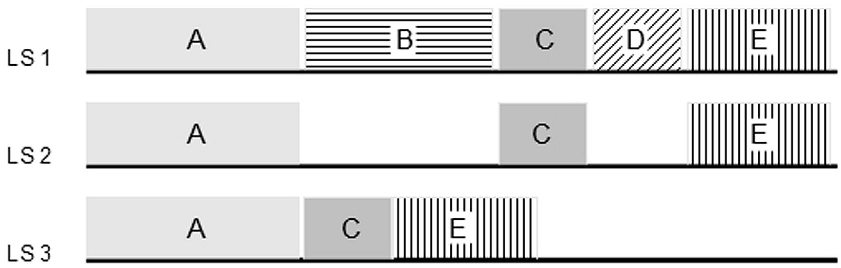

Figure 3: A,B,C, D and E are client paths on a given link, LS 1 is the original link state before channels tear down, LS 2 is the link state after channels tear down, LS 3 the link state after defragmentation.

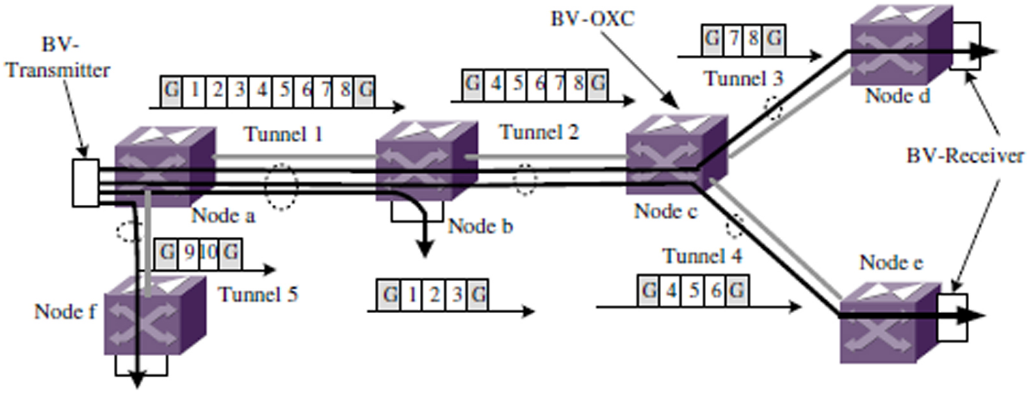

Figure 4: Optical grooming in an elastic optical network [66]

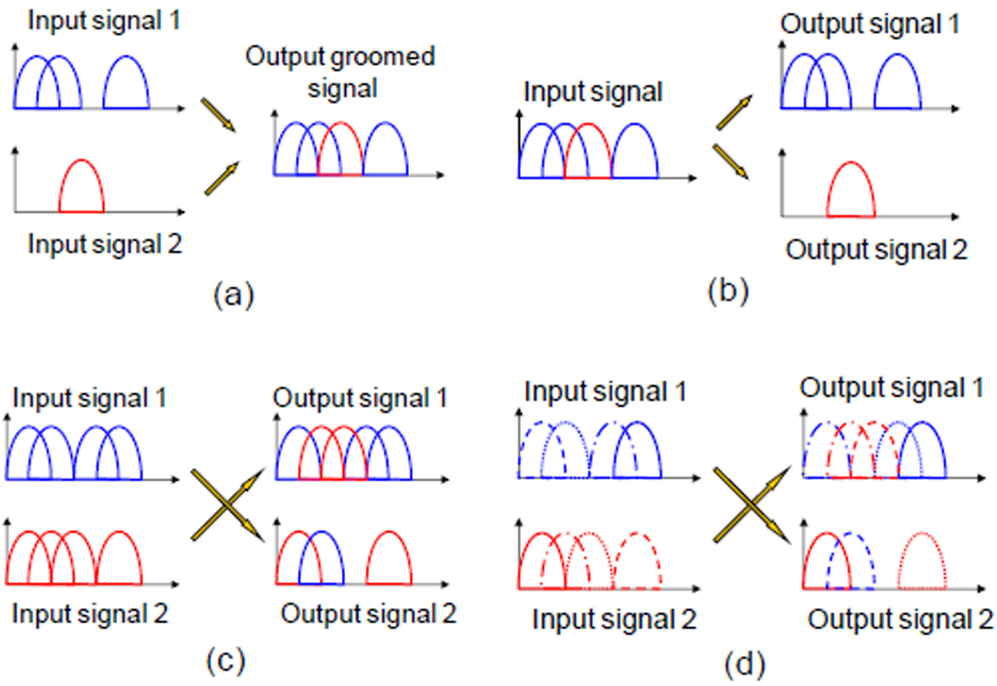

Figure 5: O-grooming, a) aggregation, b) separation, c) crossing, d) switching at the optical level[67]

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |    Length     |           Reserved            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Grid |  C.S  |    Reserved     |      Min      |      Max      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 6: LMP Extension grid property sub-object [81]

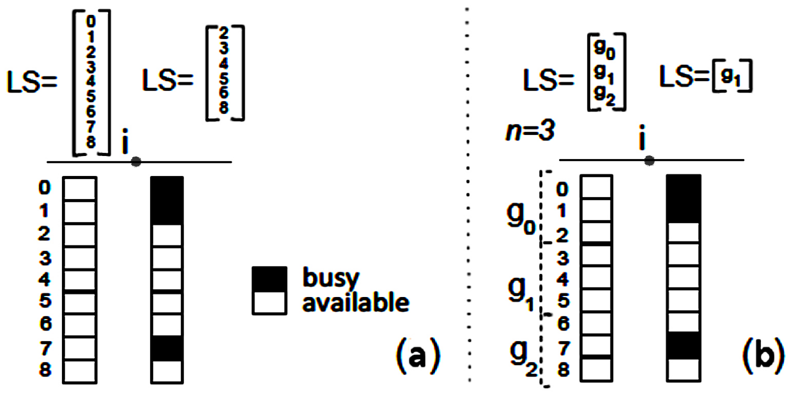

Figure 7: (a) LabelSet update; (b) aggregated LabelSet update [79]

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Grid | C.S. |   Identifier     |               n               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          m                    |   Reserved                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 8: Label object TLV [87]

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Object-Class  |  O.T. |Res|P|I|   Object Length (bytes)       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Flags                | L |Id1|Id2|R| Pri |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Target Clutter Value                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
//                        Optional TLVs                        //
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 9: PCEP extended with SDTO object [40]

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Object-Class  |  O.T. |Res|P|I|   Object Length (bytes)       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Flags           |    Algorithm Id       | Pri   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
//                        Optional TLVs                        //
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 10: PCReq extended with the RAEO-list object [40]

Figure A.11: Joana Sócrates Dantas

Figure A.12: Davide Careglio

Figure A.13: Jordi Perellò

Figure A.14: Regina Melo Silveira

Figure A.15: Wilson Vicente Ruggiero

Figure A.16: Professor Josep Solè-Pareta