Adaptation and Monitoring for Elastic Alien Wavelengths [Invited]

F. Cugini
CNIT
Pisa, Italy
Email: filippo.cugini@cnit.it

N. Sambo, F. Paolucci, F. Fresi, P. Castoldi
Scuola Superiore Sant'Anna
Pisa, Italy

***Abstract*—In this paper, we provide a comprehensive view of the most advanced techniques and solutions we contributed to design and validate for adaptation operations in Elastic Optical Networks (EONs). Data, control and monitoring aspects are discussed, identifying potentials and open issues, also in the context of challenging multi-vendor/domain scenarios as the case of elastic alien wavelength.**

I. INTRODUCTION

Flexible grid technologies and advanced transmission techniques based on coherent detection strategies have enabled the introduction of a new generation of transport networks, named Elastic Optical Networks (EONs) [1], [2], [3], [4], [5], [6].

In EONs, data plane is based on reconfigurable optical add-drop multiplexers (ROADMs) employing Bandwidth Variable Wavelength Selective Switches (BV-WSSs) and multi-flow Bandwidth Variable Transponders (BVTs) [7], [8]. BV-WSSs enable the reservation of the minimum required portion of spectrum resources. Multi-flow BVTs enable the transmission of independent super-channels composed of multiple subcarriers, each one operating at either 100 or 200Gb/s, thus guaranteeing an overall bit rate of 1Tb/s and beyond.

BVTs are designed to support multiple modulation formats, typically including Polarization-Multiplexed Quadrature Phase Shift Keying (PM-QPSK) or 8/16 PM Quadrature Amplitude Modulation (PM-8/16QAM) [9]. In addition, Forward Error Correction (FEC) and/or Low Density Parity Check Coding (LDPC) redundancy can be configured to provide error free performance over the selected path [10], [11]. That is, according to the required optical reach and traversed BV-WSSs (i.e., filters), effective configuration of BVT parameters and flexi-grid ROADMs can be potentially performed, thus optimizing transmission conditions while minimizing the utilized amount of spectrum resources.

More recently, such EON capabilities have been evolving to support procedures and techniques for automatic and hitless adaptation of transmission parameters. For example, a number of effective techniques have been successfully demonstrated, including hitless shifting of carrier central frequency (i.e., push-pull [12]), hitless LDPC code rate adaptation [13], and hitless channel spacing reconfiguration [14].

These techniques, besides guaranteeing effective resource utilization, also enable self-adaptation configurations that significantly simplify the network commissioning procedures, moving towards the deployment of plug-and-play BVTs [14].

To adequately support the aforementioned procedures, specifically designed control plane solutions have been proposed and demonstrated, both in the traditional distributed architecture enabled by the Generalized Multi-protocol Label Switching (GMPLS) and in the centralized paradigm of Software Defined Networking (SDN) [15], [16], [17].

So far, EONs have been been mainly applied in the context of a network environment provided by a single Vendor. A first multi-Vendor BVT inter-operability experiment has been successfully described in [18], [19], focusing on a provisioning scenario where a single Operator controls both BVTs at TX and RX sides.

However, further progresses are needed to enable the dynamic adaptation and self-configuration of the lightpath transmission parameters in a multi-Vendor environment, also possibly controlled by different administrative domains. Such multi-domain scenarios, especially elastic alien wavelength, is attracting significant interest for the deployment of data center (DC) interconnections. Indeed, two remote DCs may require direct interconnection passing through, in a transparent way, a network domain provided by a different network Operator.

Supporting transmission adaptation in such multi-domain scenario, as discussed in this paper, may provide a number of relevant benefits to both DC and network operators.

In this invited paper, we first summarize the most relevant control plane-driven transmission adaptation techniques that we have proposed and demonstrated for EONs. Then we report on the monitoring techniques and architectures that we have proposed to adequately support the aforementioned techniques. Finally, we discuss the next expected steps and open issues, targeting the effective deployment of elastic alien wavelengths for DC to DC interconnection.

II. Adaptation techniques

In this section, the most relevant control plane-driven transmission adaptation techniques that we have proposed and validated are summarized.

A. Modulation format

Modulation format adaptation represents the most considered scenario to show the benefits of elastic operations. In [17], we focused on the Path Computation Element (PCE) architecture for modulation format adaptation, implementing novel PCE Protocol (PCEP) extensions to enable the configuration of both transmission parameters and required frequency slots. In addition, the work considered the presence of Optical Signal to Noise Ratio (OSNR) margin to possibly apply narrow filtering, thus achieving a further reduction in the overall amount of occupied bandwidth. The architecture was deployed and validated on a flexible optical network testbed. In particular, the PCE successfully triggered dynamic frequency slot assignment and format adaptation at 100Gb/s from PM-16QAM to PM-QPSK. The PCE architecture performed extremely fast, requiring just few milliseconds to complete the message exchange and path computation. Moreover, despite the proprietary BV-WSS software took 0.5s to pass the commands, the actual BV-WSS switching and filter configuration were performed at the data plane level in less than 30ms, showing that effective implementations of dynamic control plane driven adaptation strategies were feasible and effective.

B. Push-pull shifting

In [12], we defined a novel control-plane driven defragmentation technique called push-pull, discussed and experimentally validated over flexi-grid optical networks. The technique allows the hitless shifting of a lightpath. It operates by tuning the central frequency at the transmitter side, then by leveraging on the frequency tracking capability implemented in the digital signal processing (DSP) of the receiver. This technique requires specifically designed control plane operations. Lightpath shifting can be implemented without additional hardware components and without introducing traffic disruption, subject that no other lightpaths are overlapped.

The push-pull technique operates in three steps. First, dynamic reconfiguration of the allocated spectrum resources (i.e., the traversed flexible BV-WSSs) is performed, including additional contiguous and free spectrum resources among those allocated to the original lightpath. The second step consists in the re-tuning of the original lightpath, pushing the tuning of the TX laser towards the target final frequency. The RX is seamlessly pulled to follow the same central frequency. The third step, consists in the further dynamic reconfiguration of the allocated spectrum resources such that only the original amount of spectrum resources is reserved around the final target central frequency.

The study reported on the technological and impairment-related issues that have to be considered to implement the technique. With current external cavity laser (ECL) technology, flexi-grid nodes and automatic frequency control capabilities of the coherent receiver, no limitations are typically introduced in terms of retuning speed. The push-pull technique was then experimentally demonstrated, successfully providing no traffic disruption with 100Gb/s PM-QPSK transmission with coherent detection. Control plane operations in support of the push-pull technique were also proposed and validated. The overall re-optimization of one lightpath required about 7s, mainly related just to proprietary BV-WSS configuration latencies. Indeed, the actual lightpath frequency re-tuning required just few tens of milliseconds.

C. Code adaptation

In [13], a novel PCE-driven code adaptation solution was proposed and experimentally validated over flexi-grid optical networks.

The PCE first computed and applied the most adequate Low Density Parity Check (LDPC) code rate value, expressed as i/j, i.e. i bit of information out of j transmitted. For example, for the optical reach in the considered experiment, a code rate of 8/9 was set over a PM-QPSK 100Gb/s transmission system. Then, upon a soft failure (i.e., degradation of the quality of transmission) occurrence, a more robust code rate of 4/5 was computed and communicated to the ingress node through PCEP protocol. The new coding was activated in the transmitted data via software configuration of the configurable electrical data generation block of the transmitter (e.g., 64k bits per data block). Within the preamble of each data block, a 3-bit field within the overhead was configured to communicate to the receiver the coding to be used for the detection of the subsequent data block. This way, the receiver became aware of the code rate to apply (e.g., 4/5). It processed the next incoming data through the new coding, successfully supporting the more robust transmission. Such adaptation was successfully performed without experiencing traffic interruption or disruption due to the code adaptation procedure.

D. Channel spacing

In [14], we focused on the adaptation of the subcarrier channel spacing in a super-channel. In particular, an experimental validation was applied on the central

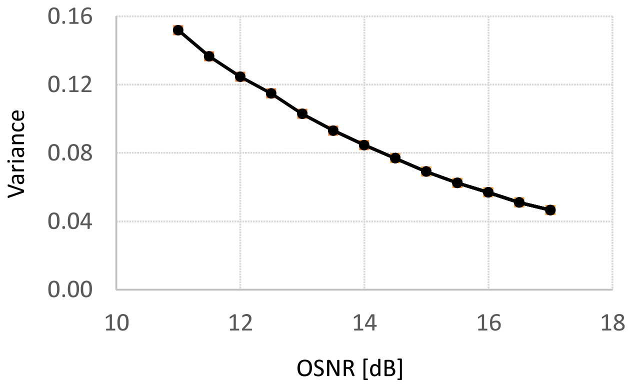

Fig. 1. Variance of the acquired samples as function of the OSNR.

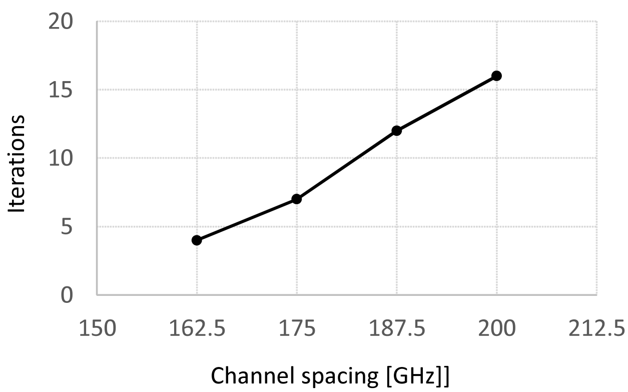

Fig. 2. Maximum number of iterations of the BCJR detector with iterative LDPC decoding.

frequency of each subcarrier accounting for the experienced impairments. The procedure, exploiting accurate monitoring information, operated sequentially on each subcarrier, shifting the transmitter laser to the new frequency value by applying the aforementioned push-pull technique [12]. The new value for the central frequency of each subcarrier was computed such that the overall frequency slot of the whole super-channel was safely reduced of one spectrum slice of 12.5GHz. Once all the subcarriers have completed the shifting, the retrieved monitored performance is again compared to predefined target range. If below, the procedure is iteratively repeated, until limit conditions are experienced targeting an effective tradeoff between margin and spectral efficiency.

III. Monitoring techniques and architecture

To fully exploit the previously detailed transmission adaptation capabilities, advanced monitoring techniques and solutions are needed. In this section, the monitoring techniques that we have recently proposed and preliminarily demonstrated are summarized, together with the reference NETCONF-based hierarchical management architecture that we have introduced in the framework of the ORCHESTRA Project.

A. DSP-enabled monitoring techniques

The introduction of coherent detection has not only enabled ultra-high rate optical transmissions, but also new effective monitoring techniques. In particular, by evaluating the parameters and performance of the LDPC digital signal processing, it is possible to derive relevant information also on minor degradations, and even before unacceptable bit error rate (BER) increase takes place.

1) Symbol variance: in [13], the observation of the uncorrected BER (pre-FEC) and the variance of the acquired samples is specifically considered. Indeed, samples variance is deeply related to OSNR and can be efficiently exploited for monitoring OSNR variations.

Fig. 1 shows the measured variance of the acquired samples as function of OSNR. Moreover, the figure shows the OSNR range of use where the applied code (i.e., 8/9 in this case) can successfully operate. It is important to highlight that the variance does not depend on the applied LDPC code. Monitoring of variances can be used to reveal OSNR degradation, also indicating if working-limit condition is approaching for the code in use. Such monitoring system is able to predict degradation in advance, before reaching the working limit condition. For example, if the OSNR degradation exceeds a threshold and remains within the margin (e.g., 0.07 for 8/9 coding), no post-FEC bit error rate (BER) degradation is experienced, and a warning alarm can be triggered to adapt to a more robust code.

2) Equalization parameters: in [14], the maximum number of iterations of the Bahl, Cocke, Jelinek, and Raviv (BCJR) detector with iterative LDPC decoding is considered. Indeed, the number of iterations is strictly related to the quality of the received signal. Thresholds on the number of experienced iterations, averaged within a reasonable monitoring time interval (e.g., few minutes), can be defined to identify safe working conditions, warning conditions and critical performance.

Fig. 2 shows the maximum number of iterations of the BCJR detector with iterative LDPC decoding, experienced by a subcarrier of a super-channel for different values of channel spacing to the adjacent subcarriers. In particular, results show that the lower the channel spacing, the higher the experienced impairments, and in turn, the higher the number of required iterations performed by the detector to successfully recover the received data.

B. Monitoring architecture

A hierarchical monitoring architecture is presented in Fig. 3 [20]. Each monitoring entity is responsible for a specific set of lightpaths (LPs). Each monitoring entity (e.g., $LP_{1,level0}$) provides operation, administration, and maintenance (OAM) functions: collecting and correlating alarms and triggering actions to maintain services. Each layer correlates and filters the received information efficiently sending less amount of monitoring information to an upper layer toward the OAM Handler of the Controller (e.g., in-line with the Application-Based Network Operations - ABNO - architecture [21]). The *level 0* is responsible for OAM of single LPs, thus, each entity is associated to an LP. Upper layers are responsible for a set of LPs (e.g., LPs starting from the same ingress node). While the level in the hierarchy increases, the monitoring entities are responsible for a larger set of LPs, up to being able to correlate information of all LPs in the network. In case of multi-Vendor network, a generic level *level i* groups all lightpaths terminating in the domain of an associated Vendor, and finally, the upper level, as the OAM Handler, groups information related to all the domains. Such hierarchical architecture, as demonstrated in [20], provides high scalability reducing the number of alarms to be processed per entity.

Moreover, the hierarchical monitoring architecture suitably abstracts the entities involved during the adaptive operations aforementioned in the previous sections. Several adaptations can be taken at *level 0*. First, monitoring of a single LP is performed at the *level 0*. Then, based on the monitoring into the DSP, proper decision algorithms identify the type of degradation and the proper action to be taken. Thus, *level 0* can trigger the adaptive reaction. In particular, if the operation does not involve a change in the passband of traversed filters, other control components such as the PCE and Traffic Engineering Database (TED) or Label Switch Path Database (LSP-DB) are not involved. Thus, if code, modulation format, and channel spacing adaptation do not imply an increase of the ITU-T frequency slot width [22] (i.e., the passband of traversed filters), adaptation is triggered by the monitoring layer identifying the affected service and is locally executed (at *level 0* in this case). Instead, if adaptation implies a slot width increase or in case push-pull is required, the OAM Handler has to be notified and the TED has to be consulted to check spectrum resource availability and, eventually, re-routing has to be ordered to preserve the service (thus, involving PCE). In case adaptation implies a reduction of the frequency slot, the OAM Handler will be notified and the reconfiguration of traversed filters will be triggered to save bandwidth.

IV. Control plane

Extended control is required to handle dynamic adaptation of physical parameters of EON-based optical connections. The most considered control frameworks include GMPLS in combination with PCE (GMPLS-PCE) and SDN, OpenFlow and NETCONF/YANG (Fig. 4). The former GMPLS-PCE control includes a centralized PCE, responsible of path computation and adaptation, and distributed GMPLS controllers located at each network node, responsible of distributed resource reservation (e.g., by means of RSVP-TE signaling protocol). PCEP session is established between the source node and the PCE. PCEP stateful extensions are particularly suitable for adaptation procedures, since providing dedicated messages (i.e., Path computation `Update` and `Report` message) with the explicit request of modification of specific path attributes. In this context, PCEP and RSVP-TE extensions have been proposed and implemented to trigger modulation format, code rate and hitless shifting. In particular, modulation format and code rate adaptation parameters are handled in the extended Explicit Routing Object (ERO) referred to source and destination nodes (i.e., those hosting the BVTs requiring transmitter/receiver adaptation) of both PCEP and RSVP-TE. Hitless shifting is handled through ERO Label subobject (i.e., by specifying the same channel width and a different central frequency) and with a dedicated `PUSHPULL` object in the Path message with the specification of the hitless tuning range in order to relax frequency drift threshold alarms raised by BVTs monitoring systems. In the SDN control plane approach, a centralized controller communicates with all the SDN agents co-located with the physical nodes of the optical network directly configuring the node hardware (e.g., BVT physical parameters, SSS filter shape). In this case, adaptation procedures are completely handled by the controller by sending extended OpenFlow `FLOW_MOD` messages or extended NETCONF edit-config operation with specific *create* or *replace* attributes. In the OpenFlow option, `FLOW_MOD` messages have been extended to support the full description of the selected signal in terms of number

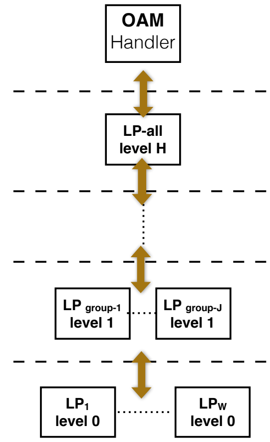

Fig. 3. Hierarchical monitoring architecture.

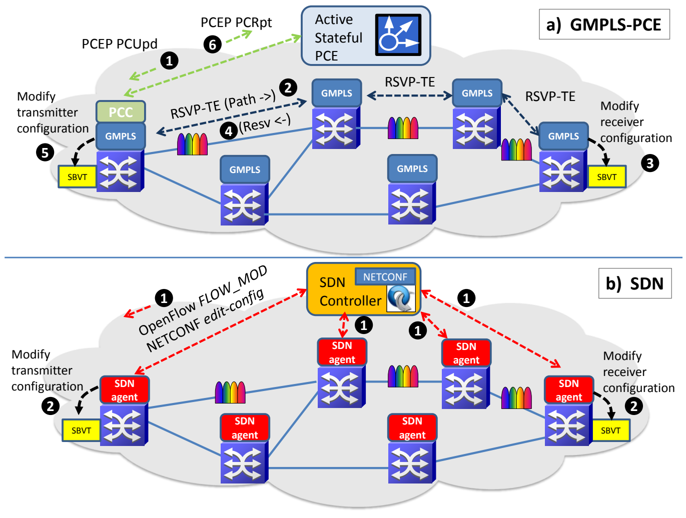

Fig. 4. Control plane architectures.

of carriers, modulation format, baud rate, code type and rate, thus enabling adaptation procedures in a fast fashion with a limited number of messages sent in parallel to involved nodes only. Moreover, automatic channel spacing adaptation and optimization procedure have been demonstrated through a novel OpenFlow message, called `REQ_FLOW_MOD`, sent by the source BVT SDN agent, explicitly requiring the optimized filter configuration to the Controller using the superchannel width values automatically adjusted by the BVT SDN agent itself. This way, the Controller configures the optimized superchannel channel width along the entire connection route.

V. Open issues and future goals

The joint availability of effective adaptation techniques and monitoring infrastructures poses the basis for additional challenging objectives and use cases. Indeed, so far, all the benefits provided by adaptation techniques have been mainly considered for applications within a single Vendor island, controlled by a single Operator. However, two main use cases are pushing for inter-operability in EON.

First, as preliminary investigated in [18], equipments provided by different Vendors may be jointly utilized within the same Operator network, enabling relevant CAPEX savings.

Second, equipments provided by the same or different Vendors may be used under different administrative control, as the case of DCs transparently interconnected through a network domain provided by a different network Operator, i.e. elastic alien wavelengths (Fig. 5).

Several benefits are expected from the implementation of such use cases. For, example, the overall interconnection availability may be improved by exploiting additional alternative routes. Moreover, benefits in Capital Expenditures (CAPEX) may be achieved by efficiently exploiting the whole network resources and enabling the setup of connections with limited margins (i.e., not designed for end-of-life scenarios of fully loaded systems). Benefits are also expected in terms of Operational Expenditures (OPEX), by significantly simplifying installation and commissioning procedures thanks to the plug-and-play capability. Finally, advantages can be obtained in terms of management and recovery procedures, enabling efficient handling of more complex scenarios like soft failures.

To achieve these goals, the following open issues have to be addressed:

1) Data plane interoperability: data plane interoperability can be achieved by standardizing a basic set of transmission parameters that need to be supported with adequate performance by different Vendors. Although top performance (e.g., ultra long haul distances) and additional configuration options will be enabled only by proprietary solutions, agreement on a subset of elastic operations may be achieved in the future. Indeed, modulation formats like PM-QPSK and PM-16QAM are good candidates to cover core and metro optical reaches and they are going to be both supported by the main flexi-grid equipments. Some of the 100Gb/s transponders already support multiple FEC types (typically a standard one and several proprietaries). In the future, different standard FEC types may be supported to enable the optimization of the robustness level according to the required optical reach. More in the long term, transponders may also support shifting operations (e.g., for channel spacing optimization in super-channels) or hitless adaptations in case of soft-failure events.

2) Control and Monitoring plane interoperability: the availability of common data plane definitions will require proper standard ways to control and monitor the installed equipments. YANG is gaining significant consensus as a common data modeling language that can be used to define the ways parameters and devices are controlled. Differently with respect to flow-based OpenFlow extensions for optical networks, YANG and NETCONF can exploit the structures based on eXtensible Markup Language (XML) to efficiently control any type of technology and parameter. For example, a BVT [23] can be modeled as a list of sub-carrier modules, detailed with configuration and state data. The configuration data includes the actual parameters, selected among the list of supported ones (listed in the state data). The basic set of commonly agreed information should include bit rate, baud rate, modulation, FEC, central frequency, and bandwidth. In the case of multi-Operator scenario, agreement on common control and data plane operations has to be further complement with advanced monitoring infrastructures, en-

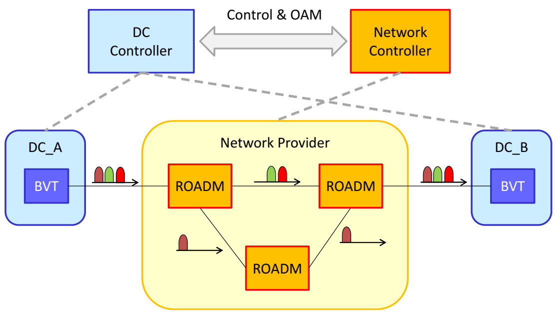

Fig. 5. Elastic alien wavelength scenario for DC interconnection.

abling efficient failure localization schemes as well as common exchange of in operation parameters, such that both Operators can take advantage from the data plane information retrieved by each monitoring system and collaborate towards a more efficient exploitation of available resources. For example, a DC Operator may allow pre-FEC information to be retrieved by the network Operator, such that, in case of degradation, effective adaptation could be applied in a coordinated way. Such joint monitoring and control infrastructure seems to be the most difficult goal to be achieved in the near term and represents a relevant topic for future innovation and standardization.

VI. Conclusions

In this paper, we first reviewed the most effective adaptation techniques we proposed for elastic optical networks (EON) based on flexi-grid technology. Second, we presented our recent advances in terms of EON monitoring, both from a data and management plane perspective. Then we reported on the state of the art of control plane solutions for EON. Finally, we discuss the application of all these solutions and technologies in the context of more challenging use cases, such as the elastic alien wavelength for DC-to-DC interconnection transparently traversing a different administrative domain.

VII. Acknowledgement

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