Push-Pull Defragmentation without Traffic Disruption in Flexible Grid Optical Networks

F. Cugini Member, IEEE, F. Paolucci, G. Meloni, G. Berrettini
M. Secondini, F. Fresi, N. Sambo, L. Poti Member, IEEE, and P. Castoldi Member, IEEE

Abstract—In flexi-grid optical networks, fragmentation of spectrum resources may significantly affect the overall network efficiency. Effective techniques for defragmentation (i.e., re-optimization) are then required to limit the wasting of spectrum resources. However, current defragmentation techniques can only be implemented thanks to the presence of additional resources, such as spare expensive transponders.

In this study, we propose, discuss and evaluate a novel defragmentation technique called push-pull. The technique is based on dynamic lightpath frequency retuning upon proper reconfiguration of allocated spectrum resources. It does not require additional transponders and does not determine traffic disruption. All the relevant technological limitations that may affect the push-pull applicability are discussed in the context of both optically-amplified direct and coherent detection systems.

The technique is then successfully demonstrated in two different flexi-grid network testbeds, reproducing the two aforementioned scenarios. In particular, the re-optimization of a 10Gb/s OOK lightpath is safely completed in few seconds (mainly due just to node configuration latencies) without experiencing any traffic disruption. Similarly, the push-pull is successfully performed on a 100Gb/s PM-QPSK lightpath, providing no traffic disruption.

Index Terms—defragmentation, reoptimization, flexi-grid, flexgrid, elastic, BV-WSS, ROADM, spectrum, reallocation

I. INTRODUCTION

RECENT technology advances enable the reservation of a configurable portion of the frequency spectrum, such that the number of assigned frequency slices (e.g. 12.5GHz) is tailored to the required minimum channel width, called slot width in the context of GMPLS [3], [4]. This flexi-grid (or elastic) technology, based on bandwidth-variable wavelength selected switches (BV-WSSs), by removing the constraints due to a fixed grid spacing, has the potential to significantly improve the network resource utilization [5]–[9]. However, the well known wavelength continuity constraint may still affect the overall network efficiency, causing fragmentation of spectrum resources. In addition, unexpected network evolutions, channel tear-down operations and network recovery and maintenance procedures typically worsen such fragmentation.

To improve network efficiency, defragmentation (i.e., re-optimization) techniques can be applied by re-routing selected connections along different available resources, thus compacting the utilized spectrum frequencies and guaranteeing larger contiguous resources to future lightpath requests [10], [11]. Thus, a number of defragmentation solutions have been recently proposed for flexible optical networks [7]–[9], [12]–[14]. However, they are not free from limitations. In particular, to minimize traffic disruption, they require additional resources, such as spare expensive transponders or wavelength converters. In addition, they may perturbate the optical layer stability by requiring complex channel re-equalization procedures, potentially affecting also the stability of other active lightpaths.

In this paper, expanding upon [1], a novel technique is introduced to perform defragmentation while avoiding the aforementioned limitations. The technique, called push-pull, is specifically designed for flexible optical networks. It operates at the physical layer by re-tuning the transmitting laser source of selected working lightpaths, such that fragmentation is minimized.

In this paper, the applicability of the push-pull technique is first considered in the context of flexible optical networks operated with lightpaths based on on-off keying (OOK) modulation and direct detection. Limitations to push-pull applicability due to laser technologies and impairment accumulations are discussed. In particular, a closed-form expression is proposed to estimate the maximum range of re-tuning, in a single operation, for impairment-controlled defragmentation. Such expression is validated and applied in a flexible network testbed.

The applicability of the push-pull technique is also considered and discussed for lightpaths based on advanced modulation formats (e.g., polarization multiplexed quadrature phase shift keying - PM-QPSK) and coherent detection. In this case, no limitations practically affect the push-pull operation, which can be applied as a single operation with any range and speed of frequency shifting enabled by current technologies.

Then, the push-pull technique is experimentally demonstrated for both direct and coherent detection.

The demonstration includes control plane procedures and extensions specifically proposed and implemented to drive lightpath reconfiguration.

Results successfully demonstrate the capability of the push-pull technique to perform effective spectrum defragmentation without requiring additional resources at the physical layer, without affecting the physical layer stability, and, most important, without inducing detrimental effects on traffic delivery, i.e., guaranteeing no traffic disruption.

Manuscript received August 20, 2012
F. Cugini (email: filippo.cugini@cn.it) and L. Poti are with CNIT, Via Moruzzi 1, Pisa, Italy. F. Paolucci, G. Meloni, G. Berrettini, M. Secondini, F. Fresi, N. Sambo, and P. Castoldi are with Scuola Superiore Sant'Anna, Via Moruzzi 1, Pisa, Italy.

This paper is an extended version of the work presented in [1] and [2]. This work was partially supported by the COTONE project and by ERICS-SON Italy. Special acknowledgment to Giulio Bottari and Antonio D’Errico.
II. DEFRAGMENTATION TECHNIQUES

A. Previous works

Several studies have recently addressed defragmentation in flexible optical networks. Most of them (e.g., [9], [12]–[14]) propose valuable heuristics and ILP-based solutions without focusing on the actual technique adopted at the physical layer to perform lightpath reconfiguration. Other studies (e.g., [15], [16]) propose the utilization of additional devices such as all-optical wavelength converters to dynamically perform lightpath reconfiguration. However, these devices are still quite expensive and technologically not mature.

Studies including discussions on implementation aspects (e.g., [7], [8]) typically consider a solution called make-before-break (MbB) [17]. In MbB, for any connection identified for reconfiguration, an additional connection is first established between the same source and destination pair. Then, the client traffic is switched between these two active connections. Finally, the original one is torn-down. MbB guarantees minimal or null traffic disruption. Indeed, only minor issues due to traffic switching inside the source node or delay variations caused by different latencies (e.g., if different routes are considered) may introduce some minimal packet duplication or loss. However, when applied at the optical layer, MbB suffers from a relevant drawback: it requires the availability of additional spare and expensive transponders at both the source and the destination node (it is important to note that re-optimization is typically considered specifically to limit and/or post-pone investments in the network). A further issue affecting MbB refers to the additional operations possibly needed at the optical layer in the whole network. Indeed, both setup and tear-down operations vary the number of active lightpaths along the traversed links, i.e. along the traversed optical amplifiers, with possible implications on the re-equalization of other active lightpaths.

B. Push-pull technique

A network management system (NMS) or a network node, possibly relying on a path computation element (PCE), is considered to identify the sequence of lightpaths to be re-configured [1], [11]. Fig. 1a shows a portion of a network composed of four nodes and three links. A lightpath from A to B has a slot width equal to \( m \) (i.e., it occupies \( m \) frequency slices) with \( f_0 \) as the nominal central frequency. A second lightpath from B to D occupies \( m \) slices on links B-C and C-D (\( f_1 \) the nominal central frequency). This scenario prevents the setup of a new lightpath from A to D even if \( m \) slices are globally available along the considered route. In this case, with the purpose of defragmenting the network resources, the NMS identifies lightpath B-D for reconfiguration, with \( f_0 \) as its new nominal central frequency instead of \( f_1 \). This way, as shown in Fig. 1b, occupied spectrum resources are compacted, enabling the potential setup of an A-D lightpath.

The push-pull defragmentation technique, for each lightpath identified for reconfiguration, operates in three steps.

The first step consists in the dynamic reconfiguration of the allocated spectrum resources (i.e., the traversed flexible BV-WSSs). With reference to Fig. 1c, the reservation of contiguous and free spectrum frequencies along B-D is performed such that the \( m \) slices having \( f_0 \) as nominal central frequency get included within the frequencies allocated to the original lightpath. As a result, a number \( M \) of slices is allocated to lightpath B-D at the end of the first step \( (M = 2m, M > m) \). In principle, i.e., without accounting for technological and Quality of Transmission (QoT) limitations, any value of \( M \) could be considered.

The second step consists in the re-tuning of the original lightpath from the nominal central frequency \( f_1 \) to \( f_0 \). Given \( f_0 \) the actual central frequency of the transmitter laser at source B, we have \( f_0 \approx f_1 \) at the beginning of the second step. Then, frequency \( f_B \) is pushed from \( f_1 \) to \( f_0 \) by tuning the TX laser. This way, the receiver is seamlessly forced to operate at \( f_B \), slowly pulled from \( f_1 \) to \( f_0 \). Therefore, at the end of the second step, \( f_B \approx f_0 \).

The third step, consists in the further dynamic reconfiguration of the allocated spectrum resources. The release of spectrum frequencies along B-D is performed such that only the \( m \) slices having \( f_0 \) as nominal central frequency remain included within the frequencies allocated to the B-D lightpath.

The push-pull defragmentation technique is suitable for flexible optical networks thanks to the presence of BV-WSSs (and the absence of fixed-grid WSSs and array waveguide gratings (AWGs)). The technique does not require the availability of additional spare and expensive transponders. In addition, no lightpath setup/tear-down processes or switching operations on traffic tributaries are performed. Thus, the number of active lightpaths per link (i.e., per traversed optical amplifier) remains constant and no optical power re-equalization is required subject that the usual flat gain erbium-doped fiber amplifiers (EDFAs) are employed. As shown in this paper, the technique can be applied in systems based on direct or coherent detection, with no traffic disruption.

The technique performs defragmentation by moving lightpaths only to contiguous and free spectrum frequencies along the same route of the original path. Such constraint limits the efficiency of the overall re-optimization, particularly when the
optical network is heavily loaded. However, as preliminarily shown in [1], when the network load is still limited, good optimization performance is achieved. Further studies are ongoing, aiming at evaluating the actual performance under various network topologies and traffic conditions, in combination or not with different re-optimization techniques (e.g., with MbB if a global optimum is targeted and/or some limited disruption is accepted), or when it is utilized very frequently (i.e., upon any connection tear-down or regular time interval).

In this paper, instead, we focus on the feasibility demonstration and performance evaluation of such technique at the physical and control layer. In particular, we aim at demonstrating the push-pull capability to avoid any unacceptable QoT degradation, i.e. the capability to perform seamless defragmentation with no traffic disruption.

III. PUSH-PULL APPLICABILITY

A. Technological constraints

Two main technological aspects need to be considered for the applicability of the push-pull technique.

The first aspect refers to the tunable laser technology and related performance in terms of tuning range and tuning speed. Recent advances on integrate continuous wave tunable laser sources allow volume production of small footprint, high optical power, narrow linewidth and low power consumption tunable lasers compliant with Optical Internetworking Forum (OIF) Implementation Agreements on Integrable Tunable Laser Assembly (iTLA) [18] and micro-iTLA [19]. Two main technologies are typically exploited to this purpose. The first one employs indium phosphide (InP) based digital supermode distributed-bragg-reflector laser encompassing a semiconductor optical amplifier integrated within the same chip (DSDBR-SOA). DSDBR-SOA sources are not suitable for push-pull application since they guarantee only a quasi-continuous wavelength selection over the full range spanned by the rear reflection comb. On the other hand, laser sources based on miniaturized cooled external cavity laser (ECL) technology are highly appropriate for push-pull. Indeed, such solution provides smaller form-factor, narrow linewidth, low noise, excellent frequency accuracy, and, most important, it ensures fully continuous tunability at constant power over the whole C-band. This way, no constraints are introduced by laser sources in terms of tuning range. In terms of tuning speed, both technologies guarantee the shifting of the carrier wavelength across the whole C-band (35 nm) with a typical tuning time of hundreds/tens of milliseconds.

The second technological aspect that need to be considered for the applicability of the push-pull technique refers to the adopted BV-WSS technology. A typical solution exploits liquid crystal on silicon, providing the capability to dynamically control the spectrum allocation in steps of either 1 or 12.5GHz within the whole C-band. Thus, no constraints in the push-pull applicability are typically imposed by current BV-WSSs. In terms of configuration time, in [20] are reported experimental measurements proving that such technology enables an actual filter configuration time in the order of tens of milliseconds (e.g., 30ms). However, in some cases, the proprietary software module in charge of the actual node and filter configuration may add significant latencies, even in the order of 1-2 seconds. Such delay, if present (it is expected to be significantly reduced in commercially available BV-WSSs), may however increase the overall time required to successfully complete the defragmentation technique, since filter reconfigurations need to be performed at both step 1 and 3.

To summarize, current BV-WSS and some ECL-based lasers enable the implementation of the push-pull technique.

B. Constraints on QoT in direct detection systems

To guarantee defragmentation with no service disruption through push-pull, it is important to evaluate its possible impact on QoT. In particular, in transmission systems based on direct detection, two main causes of QoT degradation can be expected and are addressed in this section: (i) the increase of the noise-noise beating component of the detected signal due to the increase of the allocated optical bandwidth (steps 1, 2); (ii) the time drift of the detected signal induced by wavelength retuning in the presence of a residual chromatic dispersion (step 2).

In optically-amplified direct detection systems, the noise-noise beating component of the photodetected signal has a relevant impact on system performance [21] and should be kept low by limiting the bandwidth of ASE noise before photodetection through optical filtering. In the fixed-grid scenario, the optical bandwidth is typically limited by fixed-grid WSSs or AWGs to 50 or 100GHz values, depending on grid spacing, while narrower optical filtering can be performed in the flex-grid scenario. On the other hand, the application of the push-pull technique requires a temporary increase of the optical bandwidth from the starting value $B_m$ imposed by the signal spectrum (i.e., $m$ slices at step 0) to the higher value $B_M$ required during the retuning operation (i.e., $M$ slices at step 1 and 2).

To estimate the OSNR penalty induced by the increase of the optical bandwidth, the following closed-form expression is proposed, based on the Gaussian approximation presented in [5], [21]:

$$\Delta_{\text{OSNR}} = 10 \log_{10} \left( \frac{Q + \sqrt{2B_M}T + 1}{Q + \sqrt{2B_m}T + 1} \right)$$

where $T$ is the bit time and $Q$ the reference Q-factor, related to the reference BER as BER=$10^{-Q/\sqrt{2}}$. Such a simple approximation is reasonably accurate only when the optical filter has no impact on the signal component, i.e. when filter bandwidths are significantly larger than the bit rate $1/T$.

The impact of such penalty due to ASE noise in steps 1 and 2 could be rather relevant and, as shown in Section V, may impose constraints in the value $M$ of frequency slices included during push-pull operations. However, if larger ranges are required, multiple push-pull operations on the same lightpath can be safely performed.

The second cause of QoT degradation may be induced by the presence of residual uncompensated chromatic dispersion. In this scenario, a retuning of the optical carrier wavelength induces a variation of the signal propagation time, i.e., a time
drift of the received data stream. Such a drift can be seen as originated by a deviation of the signal baud rate for the duration of the tuning time and can be tolerated by the receiver provided that the observed deviation is within the pull-out range of the clock-and-data recovery circuit. Given the residual dispersion $d$ of the path and the wavelength tuning speed $\lambda'$, the receiver observes a relative deviation of the incoming rate with respect to the actual rate $r = \lambda' d$. Therefore, the relative pull-out range $r_{PO}$ of the clock recovery circuit imposes a constraint on the maximum tuning speed

$$\lambda' \leq r_{PO}/d$$

(2)

As an example, for a path with a residual chromatic dispersion $d = 500 \text{ps/\text{nm}}$ (approximately equal to the maximum value tolerated by a 10Gbs OOK system) and a pull-out range $r_{PO} = 20 \cdot 10^{-6}$ (as required by [22]), the maximum tuning speed tolerated by the receiver is $\lambda' = 4 \cdot 10^3 \text{nm/s}$, meaning that arbitrary retuning over the whole C band can be performed in about 1ms. This value is lower than the typical tuning time of the laser sources, i.e. it does not typically impose constraints during the push-pull tuning operations at step 2.

To summarize, in optically-amplified direct detection systems, only filter broadening operations during push-pull need to be considered for preserving adequate lightpath QoT. However, this is not an issue since multiple consecutive push-pull operations may be simply applied to cover the entire frequency shifting instead of just a single operation.

C. Constraints on QoT in coherent detection systems

In transmission systems based on coherent detection, QoT needs to be carefully considered during the re-tuning of the optical carrier wavelength from the nominal central frequency $f_1$ to $f_0$ (step 2 of the push-pull technique). Given $f_B$ and $f_D$ the actual central frequencies of the transmitter laser at source $B$ and of the local oscillator at the receiver in $D$, respectively, before re-tuning it will be $f_B \approx f_D \approx f_1$. Then, frequency $f_B$ is pushed from $f_1$ to $f_0$ by tuning the TX laser at a frequency sweep rate $f' = df_B/dt$ that, in commercial devices, can cover the entire C-band in even 10ms. Thanks to its automatic frequency control (AFC) capabilities (see [23], for instance), the coherent RX digitally estimates and automatically compensates for the increasing frequency offset $\Delta f = [f_D - f_B]$. To avoid that $\Delta f$ exceed the maximum offset tolerance $\Delta f_{MAX}$ of the AFC, the digital estimate of $\Delta f$ is used as a feedback error signal to control $f_D$. This way, $f_D$ is forced to follow $f_B$, slowly pulled from $f_1$ to $f_0$. Depending on the adopted AFC strategy (e.g., data-aided or non-data aided, open-loop or closed-loop, ...), different offset tolerance $\Delta f_{MAX}$ and maximum tracking speed can be achieved [24]. Typically, for a symbol rate of $R_s$, the maximum tolerated offset is at least $\Delta f_{MAX} = 0.1 R_s$ (even limited by the optoelectronic front-end bandwidth) and a residual (after AFC) offset $\Delta f < 10^{-3} R_s$ should be obtained to avoid performance degradation. Therefore, the AFC can be easily designed (by setting its equivalent bandwidth) to track $f'$ without performance degradation [23], [24]. Moreover, the local oscillator frequency $f_D$ only needs a rough (more accurate than $\Delta f_{MAX}$) and slow (at same rate as $f_B$ and with a loop delay shorter than $\Delta f_{MAX}/f'$) control. The robustness of a practical AFC algorithm for coherent detection to frequency re-tuning operations is investigated in Section V by experiments and numerical simulations.

To summarize, in coherent detection systems, push-pull can be applied (also as a single operation) without expecting limitations or constraints due to filter broadening or frequency shifting.

IV. CONTROL PLANE OPERATIONS AND EXTENSIONS

The data plane operations of the push-pull technique require to be properly supported by adequate control plane procedures. In this study, GMPLS control plane for flexible optical networks is assumed [3]. In the re-optimization signaling phase, the distributed resource reservation carried out by the Reservation protocol with Traffic Engineering Extensions (RSVP-TE) follows the three steps explained in Sect. II-B. In the first step, the Suggested Label object in the Path message and the Label object in the Resv messages trigger filter broadening of traversed BV-WSS by including the novel spectrum indications (e.g., $M$ slices as slot width). Then, no protocol operations are required to perform step 2, i.e. when the source node tunable laser is shifted from $f_1$ to $f_0$. In step 3, additional RSVP-TE messages trigger filters tightening centered to $f_0$ with the initial slot width indication of $m$ slices. In agreement with other re-optimization techniques (e.g., make-before-break), the procedure also follows some additional RSVP-TE specifications. In particular, a unique Tunnel id and different LSP id values are assigned to each signaling step with Shared Explicit reservation style, in order to avoid double concurrent reservation and preventing admission control errors. The procedure at the control plane level terminates by tearing down (at the logical level only) the LSPs with the LSP id used at step 0 and 1. Note that the procedure is performed only if no errors occur (e.g., spectrum not available between $f_0$ and $f_1$).

However, laser re-tuning operation may impact control and monitoring/alarm functions of involved node transceivers. For example, [18] defines status report messages between the laser module and the transmitter management and monitoring system including warning and fatal alarms due to maximum frequency thresholds (referred to as $WFreqTh$ and $FFreqTh$, respectively [18]) deviation occurrence. Since re-optimization may trigger wide frequency shift, such alarms need to be inhibited or re-configured during push-pull, for instance by temporarily setting appropriate threshold values (e.g. $WFreqTh = B_M$). In addition, the destination node and possible intermediate nodes need to be informed about the frequency shift range and possibly activate specific Operations, Administration, and Maintenance (OAM) procedures. For example, the receiver node may need to apply additional monitoring procedures to verify the received QoT or it may need to monitor the actual central frequency value $f_0$ at the end of the procedure.

To this extent, a novel RSVP-TE object, namely push-pull Object, is proposed to be carried within the Path message at step 1. The object is specifically introduced...
to notify that a push-pull re-optimization procedure is starting. The object encloses the utilized grid parameters (e.g., grid type and channel spacing), $f_1$ (i.e., $f_{init}$) and $f_0$ (i.e., $f_{target}$) values, expressed as integer offset from reference 193.1THz [3]. The object triggers the push-pull procedure start and informs involved nodes to re-configure monitor alarms. Finally, by providing $f_1$ and target $f_0$, it indicates the frequency shift and forces to interpret the central frequency value at step 1 enclosed in the Suggested Label object of the Path message (i.e., $\frac{193.1+f_0}{2}$) as the central frequency of BV-WSS filters, with no reference to the current central frequency of the TX laser.

V. EXPERIMENTAL DEMONSTRATION

A. Direct detection systems

The first testbed used for the experimental demonstration of the push-pull technique is depicted in Fig. 2. This testbed aims at demonstrating the proposed technique in the context of OOK transmission and direct detection. Two lightpath channels are generated by means of an ECL and a distributed feedback laser (DFB) laser, respectively. The ECL TX laser has a tuning range covering the whole C-band with a maximum tuning speed of 100nm/s (i.e., the entire C-band is covered in around 300ms). Both signals are modulated independently by means of two intensity Mach-Zehnder modulators driven by a 10Gb/s NRZ-OOK (2$^{31}$-1)-long electrical pseudo random bit sequence (PRBS) generated by a bit pattern generator (BPG). A 50:50 optical coupler is employed to couple together the modulated signals, which are launched into the fiber with a per-channel mean optical power of −1dBm. The optical path consists of two identical links, each one composed by an 80km-long standard single mode fiber (SMF) span followed by a -1.360ps/nm dispersion compensating fiber (DCF) spool and an erbium-doped fiber amplifier (EDFA) to compensate for the link losses. After each link, a BV-WSS is used to dynamically configure the allocated spectrum resources. Each BV-WSS has the capability to dynamically control the spectrum allocation in steps of 1GHz within the whole C-band. The receiver consists of a photoreceiver followed by a bit error rate tester (BERT) with a clock recovery module. The ECL nominal central frequency and the BV-WSS filters shaping are dynamically reconfigured by the GMPLS controllers running over Linux boxes.

Figure 2. Setup for the push-pull validation in the case of 10Gb/s OOK transmission with direct detection

First, the validity of the theoretical formula in (1) is verified in a back-to-back (BtB) configuration by measuring the BER of the OOK signal, generated by the ECL, for different values of the slot width $B_M$ set by the WSS. In particular, Fig. 3 shows the BER as a function of the OSNR for $B_M$ ranging from 25GHz ($M=2$) to 750GHz ($M=60$), while Fig. 4 reports the corresponding OSNR penalties at a BER of $10^{-9}$ with respect to the case $B_m=25GHz$ ($m=2$). The theoretical values obtained by (1) are also reported for comparison, showing a reasonable agreement with the experimental results, the actual penalty being slightly lower than the theoretical value. This is due to the fact that (1) does not account for signal degradation induced by narrow filtering, therefore overestimating its beneficial effects (i.e., overestimating the penalty for a large bandwidth $B_M$ with respect to the narrow reference bandwidth $B_m$ considered here). As a result, (1) represents a safe and fast solution to estimate the maximum slot width $B_M$ for a single push-pull operation.

To experimentally demonstrate the push-pull technique, a fragmented scenario is considered. Fig. 5 reports the optical spectrum of the signals in every procedure steps. At step 0, the two lightpath channels operate at $f_j=192.850THz$ and $f_1=192.275THz$, respectively. The two lightpaths have a slot width of $B_m=25GHz$ ($m=2$). The lightpath operating at $f_1$ is then identified for re-optimization, targeting $f_m=192.300THz$ as its final central frequency (i.e., at 25GHz from the central frequency of $f_j$). At step 1, the filter broadening to a value

Figure 3. BER vs OSNR for different frequency slot width values

Figure 4. OSNR penalty as a function of the frequency slot width for both the direct detection and the coherent detection system
of $B_M=550\text{GHz}$ is then considered. Such value is allowed by the QoT constraint on the ASE noise accumulation. Indeed, by (1), a penalty of up to 3dB will be introduced (see Figs. 3 and 4), which is largely acceptable in this case. No additional constraints are also introduced by the traversed BV-WSSs which are able to successfully configure such slot width value. Thus, with the considered lightpath QoT and $B_M$ value, the push-pull technique can be performed in a single operation.

At step 2, the tuning of the original lightpath from the nominal central frequency $f_1$ to $f_0$ is obtained by moving the ECL central frequency through a proper command from the GMPLS controller. The maximum tuning speed of the ECL laser can be successfully considered since it is significantly larger than any critical speed related to residual uncompensated chromatic dispersion (see Sect. II-B). At the final step 3, the reconfiguration of the allocated spectrum resources is obtained by tightening the filters bandwidth to the original $B_m=25\text{GHz}$.

The bit error rate (BER) measurements as a function of the received OSNR are reported in Fig. 6 for all the steps above mentioned. A power penalty value at BER=10^{-9} in agreement with the limits expected with (1) is obtained in the case of $B_M=550\text{GHz}$ (Step 1 and Step 2) with respect to the case of $B_m=25\text{GHz}$ (Step 0 and Step 3). The slight deviation between the curves in the cases of Step 0 and Step 3 can be imputed to the uncompensated residual chromatic dispersion, that is more appreciable when the filter is narrower and less noise affects the measure (i.e., with respect to the cases of step 1 and 2).

Fig. 7 shows the control plane messages (i.e., RSVP-TE packets) exchanged by the GMPLS controllers during the overall push-pull re-optimization procedure. Shown packets are captured by the GMPLS controller located at the source node. RSVP-TE packets 1 and 3 are reported just to show the setup of the LSP (with Tunnel id=1, LSP id=1) to be reconfigured. That is, after these messages the LSP is active and the operating condition on the step 0 (i.e., these messages are not part of the push-pull technique). Step 1 is triggered by Path message (packet 5, Tunnel id=1, LSP id=2), which is detailed in the capture. The packet, carries the BV-WSS filter broadening indication within the Suggested Label object and the initial and target central frequencies within the push-pull object, as described in Sect. II-B. Step 1 terminates upon the reception of the relative Resv message (packet 9), which triggers step 2. The actual source node central frequency retuning is performed, with the considered ECL laser source, in around 50 ms. Step 3 triggers BV-WSS filter tightening indication (packets 11 and 13, Tunnel id=1, LSP id=3). Finally, logical LSPs established at step 0 and 1 are torn down (packets 15 for LSP id=1 and 17 for LSP id=2), thus terminating the control plane procedure.

The amount of time required to perform re-optimization mainly depends on the utilized BV-WSS proprietary software configuration tool, requiring about 1.6s to load and actuate filter shape operation (with Linux drivers). The overall re-optimization requires about 7s, 6.4 of which needed for BV-WSS shaping and the remaining 0.6s mainly introduced by other software elaborations (e.g., on RSVP packets).

### B. Coherent detection systems

A second testbed is used for the experimental demonstration of the push-pull technique for PM-QPSK transmission and coherent detection (see Fig. 8).

This testbed includes the transmitter and receiver derived from the work in [20]. In particular, a PM-QPSK transmitter at 112Gb/s (100Gb/s plus overhead) is employed. For the
In this case, due to the higher insertion loss (polarization decorrelation), and a polarization beam combiner (PBC). Finally, in this case, no DCF spools are required, being the transmission considered (the static channel at \( f_1 \) is not included). The signal generation is performed through the tunable ECL (line-width of about 100kHz), modulated using an integrated double nested LiNbO\(_3\) Mach Zehnder modulator (IQ-MZM). A bit pattern generator (BPG) is used to generate the driving binary electrical signal for the in-phase (I) and the quadrature (Q) branches of the modulator (a 28Gb/s PRBS of length \( 2^{17} - 1 \)). This way, a 56Gb/s QPSK signal is generated. The bit rate is then doubled by emulating polarization multiplexing through a 50/50 beam splitter, an optical delay line (for polarization decorrelation), and a polarization beam combiner (PBC). Finally, in this case, due to the higher insertion loss of the IQ-MZM modulator, an EDFA is introduced to provide an optical launch power of 1dBm.

At the receiver, intradyne coherent detection is employed by using an additional ECL as a local oscillator. Signal and local oscillator are mixed by means of a 90° hybrid optical coupler. Balanced photoreceivers perform the conversion of the mixed optical signal to the electrical domain, and a real-time oscilloscope (50GS/s, 16GHz bandwidth, 8 bit resolution) is used as analog to digital converter. Digital samples are then resampled at two samples per symbol and processed by an adaptive two-dimensional fractionally-spaced feed-forward equalizer, followed by an asynchronous detection strategy. Both the asynchronous detection and asynchronous adjustment of the equalizer taps are performed, off-line, as in [23], adopting the recursive computation of the phase reference symbol \( g_{i,k} \) given in [25], with a modification to include the AFC into the asynchronous detection strategy. In particular, the phase reference symbol \( g_{i,k} \) for the \( k \)-th symbol of the \( i \)-th polarization is recursively computed as

\[
\tilde{a}_{i,k} = \alpha h_{i,k-1} + y_{i,k-1} y_{i,k-1}^* \hat{a}_{i,k-1}
\]

\[
g_{i,k} = h_{i,k}(y_{i,k} g_{i,k-1} \hat{a}_{i,k-1} + y_{i,k-1})
\]

where \( \{y_{i,k}\} \) are the received samples, \( \{\hat{a}_{i,k}\} \) the (differentially-decoded) detected symbols, \( h_{i,k} \) accounts for the estimated phase rotation over a symbol time due to carrier frequency offset, and \( 0 < \alpha \leq 1 \), \( 0 < \beta \leq 1 \) are two forgetting factors (set to 0.999 and 0.9, respectively, in the following experiments), whose amplitude is chosen as a trade off between tracking speed and accuracy—the slower the variations of frequency or phase, the higher the value of \( \alpha \) and \( \beta \), respectively.

Transmitter and receiver are connected through the flexible optical network shown in Fig. 8, including, besides BV-WSS, two 80km-long SMF links. Differently from the one considered in the previous validation on direct detection systems, in this case, no DCF spools are required, being the transmission linear impairments compensated by the off-line processing.

In the case of coherent detection, no penalty is expected by changing the allocated spectrum resources (step 1 and step 3 of the push-pull technique). Fig. 4 reports (circle points) also the results of the BER measurements experienced when frequency slot is equal to 50GHz and 750GHz (reference BER at \( 10^{-3} \)).
since forward error correction (FEC) is expected). Results confirm the absence of penalty. Moreover, BER measurements for the step 0 and the step 1 are reported in Fig. 9, confirming the performance independence from the allocated BV-WSSs bandwidth. Thus, to evaluate the performance of the push-pull technique in coherent systems, only step 2 needs to be specifically considered. During step 2, as previously described, the re-tuning of the original lightpath from the nominal central frequency \( f_0 \) may introduce a frequency offset \( \Delta f \) between the signal and the local oscillator at the receiver. Therefore, the signal processing at the receiver, and in particular the AFC algorithm, needs to be able to follow the variation of the frequency offset \( \Delta f \) without performance degradation. Due to the off-line processing of the utilized coherent receiver, two additional experiments are then performed to evaluate such capability. In both experiments, the frequency \( f_B \) of the TX laser is moved at a tuning speed of \( f_T = 80 \text{nm/s} \) (maximum speed enabled by the ECL laser utilized for the local oscillator at the receiver).

In the first experiment, while the TX laser moves, the local oscillator is kept fixed at the original frequency \( f_1 \). Fig. 10 shows the frequency offset estimated by the AFC algorithm \( \Delta f_1 \), during a single acquisition of \( 40 \mu s \) (about 400MHz in 40\( \mu s \) corresponding to a tuning speed of \( 80 \text{nm/s} \)). A value of BER equal to \( 10^{-3} \) is verified for the whole acquisition, successfully demonstrating the AFC capability to follow the variation of the frequency offset at the considered speed without performance degradation (the recovered constellation of the signal is also reported in the Fig. 10 inset).

In the second experiment, the loop back control at the receiver is activated, enabling the compensation of the frequency offset induced by the tuning of TX laser. An overall \( \Delta f = 50 \text{GHz} \) is applied. In particular, 40 iterations are performed, each imposing a frequency shift of \( \delta f = 1.25 \text{GHz} \) at the transmitter side. For each iteration, the receiver first performs a data acquisition of \( 40 \mu s \). Then, it elaborates off-line the received data obtaining an estimation of \( \delta f = f_B - f_{LO} \). Finally, it triggers the tuning of the local oscillator to nullify the estimated offset.

Fig. 11 shows the estimated frequency offset values \( \delta f \) at the receiver, for each acquisition. At the beginning, \( \delta f = 0 \). When the step 2 of the push-pull technique starts, i.e. the signal frequency begins to move, a different value of \( \delta f \) is estimated and subsequently compensated. This process is repeated for each iteration. An almost constant estimation of \( \delta f \) around \( 1.25 \text{GHz} \) is experienced during the overall pushpull operation at the receiver (Fig. 11). When the pushpull is terminated and the overall \( \Delta f = 50 \text{GHz} \) is achieved, the loop back control successfully estimates \( \delta f \approx 0 \). The BER value for each pushing step are reported in the inset of Fig. 11, demonstrating no performance degradation during the push-pull operation.

C. Numerical simulations

A further performance analysis of the AFC algorithm implemented in the DSP coherent receiver has been carried out through simulations, to evaluate the impact of re-tuning on QoT in specific conditions that could not be realized experimentally. In the considered scenario, a PM-QPSK signal at 100Gb/s is generated with an OSNR=14dB, corresponding to a mean square error (MSE) of 0.095 and a BER of \( 1.6 \times 10^{-3} \), with \( f_B = f_D = f_1 \), corresponding to \( \Delta f = 0 \). The AFC forgetting factor in 3 is set to \( \alpha = 0.999 \).

First, the impact of a static frequency offset on the BER is measured: starting from the zero-offset condition, \( f_B \) is pushed away from \( f_1 \), and BER is measured on the signal after \( f_B \) is stabilized on its new value. This way, the AFC is able to track and compensate for the frequency offset even for values comparable with the Baud rate. However, for values higher than 2GHz, the signal spectrum is more and more distorted by the bandwidth limitations of the ADC (16GHz have been considered) and BER increases, as depicted in Fig. 12.

Then, the robustness of the AFC with respect to the TX laser

![Figure 12. Impact of Frequency offset on the BER for PM-QPSK signal at 100Gb/s with OSNR=14dB and coherent detection](image)

![Figure 13. Frequency offset estimation performed by AFC (a) and MSE calculation (b-e) over 20us time interval for different values of tuning speed: 1500 nm/s (b), 3500 nm/s (c), 6500 nm/s (d), 15000 nm/s (e).](image)
frequency sweep speed has been assessed, also considering tuning speed significantly higher than commercially available devices. Starting from the zero-offset condition, $f_B$ is pushed 2GHz away from $f_1$. Four different values are considered for the tuning sweep speed. As state-of-the-art commercially available tunable lasers can cover the entire C-band in around 10ms, corresponding to 3500mm/s, the following values have been considered: 1500mm/s (b), 3500mm/s (c), 6500mm/s (d), and 15000mm/s (e). The effect of the frequency sweep is measured as the impact on the MSE during the transient time. As shown in Fig. 13, for an AFC forgetting factor $\alpha=0.999$, no impact is observed in case (b), (c) and (d), while for the highest speed (e) the MSE increases up to 0.12 (Fig. 13(e)-black line) during the laser re-tuning transient, corresponding to a BER of $5\times10^{-3}$. However, Fig. 13(e) also shows that the MSE degradation during retuning can be practically avoided (thus increasing the maximum tolerated sweep speed) by reducing the AFC forgetting factor to $\alpha=0.996$, with a negligible impact on the steady-state performance. This means that, if needed, the AFC can be easily designed to operate at a tuning speed much higher than that of commercially available tunable lasers.

VI. CONCLUSIONS

In this study, a novel defragmentation technique called push-pull is proposed, discussed and experimentally validated over flexi-grid optical networks. The technique is investigated and successfully experimented considering two different transmission and detection strategies: OOK transmission with direct detection and PM-QPSK transmission with coherent detection.

Control plane operations in support of the push-pull technique are proposed and successfully validated.

Technological and impairment-related issues are carefully considered. With current laser and BV-WSS technologies no limitations are typically introduced in terms of tuning speed. When OOK transmission and direct detection is considered, effects due to filter broadening operations need to be specifically considered to avoid unacceptable QoT degradation during defragmentation. To this extent, a closed-form expression is proposed and validated to assess the maximum range of defragmentation to be performed in a single push-pull operation. However, if larger tuning ranges are required, multiple push-pull operations on the same lightpath can be safely performed. Whit coherent detection, no degradation is introduced during filter broadening operations. Moreover, the automatic frequency control (AFC) capabilities of the coherent receiver are discussed, showing also in this case that no limitations are typically introduced in terms of retuning speed. The push-pull technique is then experimentally demonstrated, successfully providing no traffic disruption with either 10Gb/s OOK transmission and direct detection or 100Gb/s PM-QPSK transmission with coherent detection.

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. Thus, this technique can be considered even for very high frequent utilizations, since it does not require additional transponders and guarantees seamless spectrum reallocation.

REFERENCES