Self-Autonomous Multi-Carrier Optical Transmissions

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***Abstract*— In order to activate high-data-rate connectivity, super-channel transmission strategy is becoming a suitable solution. Optical Software Defined Networking (OSDN) architecture leverages NETCONF protocol for the configuration and management of optical devices. To support a vendor-neutral approach, OpenConfig YANG models are adopted in the NETCONF communication. In OpenConfig, all the proprietary parameters (i.e., Forward Error Correction (FEC), bit rate, modulation format) are mapped to operational modes, maintaining a basic compatibility between vendors. In this work, the experimental analysis of an automatic super-channel optimization is shown. In particular, for each established super-channel, the sub-carriers are partially overlapped and tightly filtered, achieving spectrum saving with margins reduction, while guaranteeing a level of Quality of Transmission (QoT). The procedure has been demonstrated using an SDN Controller with an SDN-based Optical Network, including OpenConfig 600 Gbit/s transponders and emulated ROADMs. After the setup of a lightpath, the optimization procedure is activated by the transponder agents, without involving the SDN controller, to find the optimal super-channel configuration, according to the reach and the desired modulation formats. A spectrum saving of 25% is achieved with respect to the nominal conditions, still guaranteeing the minimum QoT level for the channels involved, in terms of pre-FEC Bit Error Rate (BER).**

Keywords*— *Super-channels, Optical Networks

I. INTRODUCTION AND RELATED WORKS

Elastic Optical Networks (EONs) [1] were developed due to the need for high spectral efficiency to optimize fiber usage. Coherent technology and the use of various modulation formats allow for a balanced approach between spectral efficiency and optical reach. The traffic demands of source-destination pairs can vary, leading to differing bandwidth needs. The ITU-T flex grid [2] offers flexibility in modulation format, bandwidth, bit rate, and channel spacing. Super-channel transmission, supported by EONs, is a promising solution for meeting the increasing traffic demands [3]. However, optimizing super-channels is difficult due to sub-carrier cross-talk and filtering effects that impact the quality of transmission [4]. The transponders of new generation, enhanced with digital signal processing (DSP) and coherent receivers, offer more versatility, precision, and efficiency, allowing for dynamic network reconfiguration. However, large physical layer margins are often used to deal with changes in physical conditions [5]. This leads to over-allocated optical connections in terms of physical conditions and capacity. Reducing margins and improving network efficiency could significantly reduce network costs, leading to various research studies on margin reduction [6]. By minimizing margins and approaching the minimum performance threshold, Elastic Optical Networks (EONs) can be even more flexible, supporting higher bit-rates, and conserving spectrum costs by adapting connections to changing traffic. Monitoring physical-layer parameters is essential for efficiently operating EONs with reduced margins and effectively addressing critical performance issues. Additionally, further automation of the network is required to strike a balance between reliability and efficiency.

The adoption of Software Defined Networking (SDN) paradigm in the control of optical networks has conveyed flexibility and automation, dividing the devices into two logical portions: the control plane, to communicate with the controller, and the data plane, which represents the physical resources. The control plane is implemented in the form of agents connected to the SDN controller. NETCONF [7] is a standard protocol and has been selected to realize the control plane in optical networks. It uses a model-based approach, where the models are written in YANG [8], through Remote Procedure Call (RPC) methods for communication between the SDN controller and the SDN agents. The OpenConfig working group [9] has proposed a set of YANG models to control the network devices, including optical transponders. The goal of the initiative is to design vendor-neutral models, where the proprietary transmission parameters are hidden within operational (OP) modes [10]. In [11] the authors propose a process that dynamically retunes the subchannel transmitter (TX) lasers to compensate for soft failures and optimize the capacity or the minimum subchannel QoT performance.

In normal conditions, the configuration of the optical connections is performed by the SDN controller, that runs the Routing and Wavelength Allocation (RWA) and configures, accordingly, the selected transponders (i.e., by setting their frequency, OP mode and TX power), and the traversed filters, reserving the proper bandwidth. Unfortunately, the scenario becomes more complicated regarding the super-channels optimization, with the SDN controller becoming too involved in the long iterations needed to configure the sub-carrier spacing. This paper extends the procedure proposed in [12], by introducing a strategy for the adaptation of a super channel to the conditions of the transmission, optimizing the spectrum

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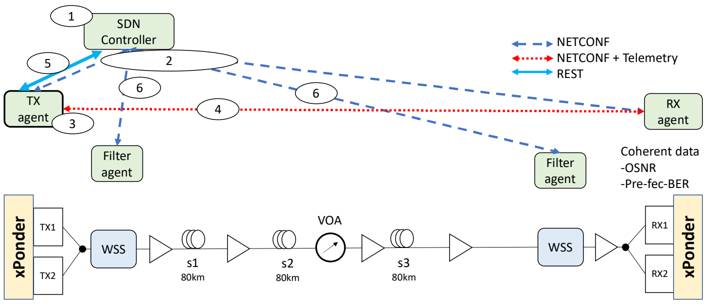

Fig. 1. Reference scenario with experimental testbed and control plane workflow.

occupancy (i.e., reducing the spectrum occupancy of the super channel), while maintaining/guaranteeing the QoT of the subcarriers, using peer-to-peer telemetry [13]. All the super channel optimization operations are performed by the TX agent, involving the SDN controllers only when the optical filters are to be reconfigured.

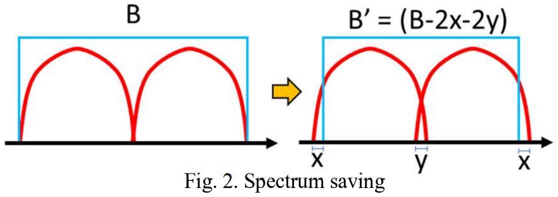

Fig. 2. Spectrum saving

II. AUTOMATIC SUPER-CHANNEL PROCEDURES

As presented in [12], the general idea of the proposed solution is to deploy a super-channel connection, while trying to reduce the spectrum occupancy as much as possible, yet still guaranteeing the minimum QoT. In particular, super-channels composed of two sub-carriers are considered (i.e., SC1 and SC2). Each SC provides the possibility to (re)configure their central frequency with the granularity of 6.25 GHz, according to the Flex Grid paradigm. As shown in Fig. 2, the two SCs are moved closer to one another, exploiting cross-talk due to a partial overlap of the two SCs. Moreover, the filters are configured to cut the margins at the edge of the super-channels, thus introducing tight filtering. This causes the degradation of the QoT of the two SCs, resulting in the increase of the pre-FEC Bit Error Rate (BER) at the receivers. In this paper we refer to homogeneous super-channels, where the two SCs (SC1 to the left and SC2 to the right) are configured with the same operational mode, according to OpenConfig model, using NETCONF edit-config messages. As shown in Fig. 2, the super-channel bandwidth saving is the sum of the 6.25 GHz slots saved both at the filter edges (x, at left and at right) and at the overlap of the two SCs (y, which is same for each channel due to the overlap symmetry). The increase of y is obtained by shifting both of the SCs in steps of 6.25 GHz towards one another. For example, if the SCs are moved one step closer to each other (i.e., y=1 per single SC), their frequencies are then 12.5 GHz closer. The value x results from the filtering effects caused by the reclosure of filter, at the end of the procedure, by the SDN controller. Following, the spectrum optimization and the super-channel adaptation procedures are described.

A. Super Channel for Spectrum Optimization

In the initial phase, the SDN controller runs the Routing and Wavelength Assignment (RWA) computation (step 1) and configures, via NETCONF edit-config messages, the two TX transceivers, and the two receivers, by setting frequency of the two sub-carriers (i.e., guaranteeing the nominal spacing among them). Moreover, it configures all the traversed filters, reserving the bandwidth for the super-channel (step 2 in the figure). In addition, a telemetry stream conveying the coherent data collected at the receivers (i.e., the pre-FEC-BER and the OSNR) is activated, setting the TX agent as collector (step 3). With respect to the previous studies [12], in this case the optimization procedure is activated at the TX agent (step 4) to explore all the possible spectrum saving configurations. The optimization phase focuses only on one SC (i.e., SC1, the left sub-carrier), considering that similar behaviour will be presented by the SC2 under the same conditions. It is important to notice that during this phase the filter is not modified, but it remains in the nominal condition (i.e., no spectrum saving) for the entire procedure execution. Considering that the maximum spectrum saving for a sub-carrier is 3 slots of 6.25 GHz (i.e., 6 slots for the super-channel), the procedure explores all the saving combinations, distributing the amount of bandwidth slot to x and y starting from 3 slots to below. The nominal condition QoT is registered, recording the data received for SC1 and SC2 on the telemetry channel. Considering the 3 slots saving (18.75 GHz of band saving per SC), the procedure considers the steps: s1=(x=3, y=0), s2=(x=2, y=1), and s3=(x=1, y=2). The step s1 is obtained by moving the left SC1 3 slots (i.e., 18.75 GHz) to the left margin of the filter, with no cross-talk experienced from SC2. After the configuration change, the QoT of SC1 is recorded (reading the telemetry data). In s2, SC1 presents 12.5 GHz saving due to the edge cut and 6.25 GHz saving due to the overlap with SC2. After s2 recording, the routine moves to s3, where SC1 presents 6.25 GHz saving due to the filter cut and 12.5 GHz saving due to the crosstalk with SC2. The case with (x=0, y=3) is not considered during the execution, because the cross-talk effects cause the super-channel to become unfeasible. Then the procedure starts exploring the case with 2 slots saving (12.5 GHz of band saving per SC). Similarly to the previous case, the steps considered cover all the possible combinations of x and y: s4=(x=2, y=0), s5=(x=1, y=1), s6=(x=0, y=2). For each configuration, the QoT of SC1 is recorded. Finally, the case with 1 slot saving (6,25 GHz of band saving per SC) is considered with s7=(x=1, y=0) and s8=(x=0, y=1). The step with the highest spectrum saving that guarantees the minimal QoT (pre-FEC-BER > 1E-3) is selected. The selected configuration of SC1 is also applied to SC2, sending a REST request to the SDN controller for the reclosure of the filter (step 5). If the nominal bandwidth of the super-channel is 150 GHz and 2 slots saving is selected, the spectrum saving is 25 GHz (4 × 6.25 GHz) and the TX agent will request a bandwidth of 125 GHz for the super-channel. Then, the SDN controller recloses the filters (step 6).

B. Super Channel Adaptation

This novel procedure has been defined to maintain the optimized super-channel alive during its lifecycle. In fact, an optimized super-channel is less robust with respect to its nominal version. In particular, the reduction of the margin can dramatically impact the super-channel, causing failures of the transmission. In case of performance degradation, above the considered threshold, or when a failure occurs, the data collected during the optimization phase can be reused in order to reconfigure the super-channel to a more robust configuration (with less spectrum saving and higher QoT).

TABLE 1

Saving	*Band (GHz)*	*OP5 (75GHz, 300Gbps)*	*OP6 (75GHz, 200Gbps)*
(0,0)	150	1.0E-4	1.2E-6
(1,0)	137.5	1.4E-4	1.4E-6
(0,1)	137.5	2.2E-4	2.7E-6
(2,0)	125	3.5E-4	9.6E-6
(1,1)	125	2.4E-4	1.9E-6
(0,2)	125	9.7E-3	7.4E-4
(3,0)	112.5	7.0E-3	8.3E-4
(2,1)	112.5	2.4E-3	2.1E-5
(1,2)	112.5	2.2E-2	1.9E-3

In case of failure (hard or soft), detected on the telemetry data of the super-channel, the TX agent notifies the SDN controller of the failure and requests the bandwidth availability side to the super-channel. If there is no additional bandwidth to be assigned to the super-channel, the normal rerouting procedure is applied selecting a new path and/or new portion of the spectrum. In alternative, the SDN controller reconfigures the filters to a larger portion of the spectrum, communicating the new central frequency and new bandwidth free to be used to the TX agent. Then, using the performance data recorded during the optimization of the super-channel and according to the adjacent available slots, the TX agent finds new SC1 and SC2 configuration, compensating the observed QoT degradation.

III. REFERENCE SCENARIO AND RESULTS

The proposed solution has been validated considering the experimental scenario shown in Fig. 1. In the bottom, the data plane is shown, considering a link composed of 3 spans, with 80km length each, to interconnect two NETCONF OpenConfig-based Fujitsu 1Finity T600 transponders. Two line ports are coupled in order to form the super-channel. Two WSSs have been used to filter the optical super-channel at TX and RX sides. Each device is controlled by a dedicated SDN agent, using a custom built SDN controller (in the top of the figure). The optimization procedure has been repeated two times, considering a super-channel composed of two SCs configured with op mode=5 (i.e., 300Gbps, with 75GHz of nominal bandwidth and 8PSK-2 modulation format) and op mode=6 (i.e., 200Gbps, with 75GHz of nominal bandwidth and 8psk modulation format). Table 1 summarizes the data collected during the optimization procedure. The final configuration selects the spectrum saving (2,1), that produces a 37.5 GHz of overall bandwidth saving. It is important to notice that the optimization procedure is performed right after the lightpath deployment, as a training phase. In fact, after each reconfiguration of the carriers of the super-channel, the connection becomes unavailable for the end user.

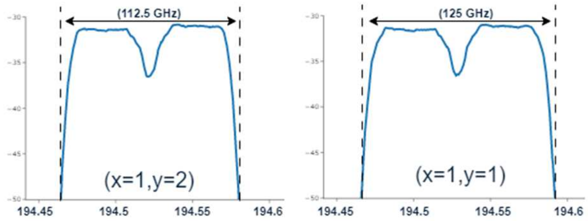

Fig. 3. Spectrum view during optimization and adaptation.

Then, the VOA along the link is used to perform a degradation of the QoT of the SCs, with the pre-FEC-BER that goes above the threshold. This event is detected from the telemetry data streamed by the receivers. Then, the adaptation procedure is activated, where TX agent requests the spectrum availability to the SDN controller and reconfigures the system to a spectrum saving configuration (1,1), that produces a spectrum occupation reduction of 25 GHz. Fig.3 shows the super-channel spectrum view collected with an Optical Spectrum Analyzer, after the setup of the super-channel (at the left side of the figure). reconfiguration due to QoT degradation (right side), with a clear impact on the bandwidth occupied by the super-channel.

IV. CONSLUSION

This paper presents a solution for the automatic super-channel optimization and adaptation. The spectrum occupancy of a super-channel is reduced exploiting sub-carriers overlap and tight filtering. The optimization procedure is carried out by TX agent without involving the SDN controller. During the lifecycle of the super-channel the QoT is maintained, by adapting (i.e., reducing) the saving effects on the involved sub-carriers.

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