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Experimental Optimization of Power-Aware Super-Channels in Elastic Optical Networks

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***Abstract*—Power-aware super-channel optimization is experimentally demonstrated using a 600Gbit/s transponder in the SDN-controlled Elastic Optical Network. The trade-off between power consumption and spectrum efficiency is investigated by operating super-channels at nominal and low-margin conditions. Results show that physical layer and operational modes impact power consumption regardless of the spectrum efficiency. Experiments on 800 Gbit/s super-channels show 7% power saving when super-channels are operated at nominal spectrum usage.**

Keywords—Super-channels, Elastic optical networks, Power consumption.

I. INTRODUCTION

The energy expenditure of telecommunication equipment has been recognized as a relevant contributor to the global energy consumption. Currently, the ICT sector accounts for 5-9% of electricity use [1], and roughly 3% of global CO_2 emission [2]. The European Commission estimates that ICT carbon footprint might increase to 14% of global greenhouse emissions by 2040 if no action is taken [1]. Furthermore, the rising cost of energy should encourage solutions for achieving high energy efficiency and better use of available resources. Therefore, it is necessary to address energy saving while supporting high-speed traffic demands.

Coherent technology has enabled dynamic network re-optimization by providing flexibility, higher granularity and efficiency. In current commercial transponders, which use coherent receivers and digital signal processing (DSP) for modulation/demodulation and mitigation of several physical impairments [3-5], electronic application specific integrated circuits (ASICs) are identified to be relevant modules impacting power consumption. In fact, DSP algorithms of such transponders are mainly operated to fulfill transmission requirements. For example, advanced DSP techniques have been exploited to manage Elastic Optical Networks (EONs) with reduced margins, thus identifying operational modes and transmission conditions (e.g., narrow filtering) that enable significant saving of spectrum resources while increasing efficiency [6]. However, such algorithms mainly operate with limited attention to power consumption.

Super-channel transmission, supported by the EONs, is a suitable method for accommodating high data rates to satisfy continuous Internet traffic growth. Nevertheless, the optimization of super-channel parameters for spectrum-efficient transmission might be challenging due to the linear cross-talk, reduced spacing among sub-carrier central frequencies, and narrow optical filtering resulting in the quality of transmission (QoT) degradation [6]. So far, power consumption has never been deeply considered in the optimization of super-channel transmission, such as trading off between energy and spectral efficiency and margin reduction.

Software Defined Networking (SDN) paradigm has been recognized in the control of optical networks to satisfy automation and flexibility requirements [7]. NETCONF is a standard protocol exploiting the model-based approach for device configuration and performance monitoring [8]. YANG represents a key language for describing data models. The OpenConfig YANG model enables vendor-neutral configuration and monitoring of the main transponder parameters by exploiting NETCONF protocol. The OpenConfig `terminal-device` model supports the key OTN state parameters monitoring (e.g., pre-FEC-BER). It is augmented with OpenConfig `components` YANG model enabling (re-)configuration of the optical channel parameters. However, advanced vendor-specific transmission parameters such as Forward Error Correction (FEC), bit rates and modulation formats are mapped to operational (OP) modes [9]. The OpenConfig `platform` YANG model also includes information on power consumption [10].

In this work, we propose and experimentally demonstrate an automatic procedure for power-aware super-channels optimization, with the aim of investigating the trade-off between super-channels power consumption and transmission performance (e.g., spectrum saving). Power consumption is monitored and reported relying on NETCONF <get> message considering two cases: one that involves spectrum saving techniques (i.e., super-channels operating at reduced margins) and nominal spectrum usage operation. The procedure considers homogeneous super-channels, i.e., super-channels composed of sub-carriers with the same OP mode, and hybrid super-channels that are composed of sub-carriers with different OP modes. The latter allows for higher flexibility in meeting the actual traffic requirements (i.e., requested line rate) while satisfying proper Quality of Transmission (QoT). Optimization is experimentally demonstrated by utilizing an OpenConfig-enabled transponder capable of different bit rates (i.e., 200-600 Gbit/s) and OP modes in an SDN-controlled EON testbed. Then, experiments are conducted considering two scenarios with optical reach of 40 km and 320 km, respectively.

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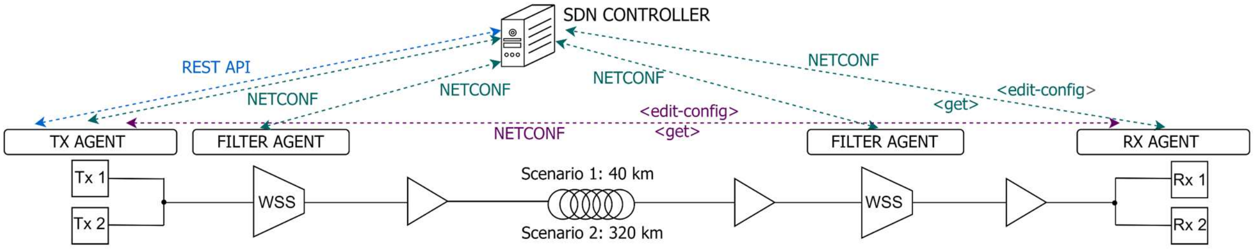

Fig. 1. Network Reference Scenario and Experimental Testbed

II. Power-Aware Super-Channel Optimization

The proposed procedure designed for the identification of the most power-efficient super-channel configuration during provisioning or inventory validation is described in this section. The procedure utilizes traditional OpenConfig YANG models for both the re-configuration of the sub-carriers (e.g., by setting the specific OP modes) and the monitoring of the QoT (i.e., pre-FEC-BER). Power monitoring has been performed exploiting the platform YANG model, including the chassis instantaneous power consumption (“`used-power`”).

Initially, the super-channel bit rate and the required optical reach over the computed path are taken into account. Furthermore, nominal spectrum resources (e.g., 150 GHz for two 75 GHz sub-carriers) are reserved along the selected path. The procedure then provides the suitable homogeneous and/or hybrid super-channels that satisfy the traffic requirements and the physical characteristics of a path (i.e., modulation format and its correlation to the optical reach). Next, super-channel sub-carriers are configured one at the time by exploiting <edit-config> NETCONF message and OpenConfig `components` YANG model. Configuration of the sub-carriers’ OP modes, Tx and Rx frequencies are carried out directly by the transceivers’ agents instructed by the procedure, thus limiting the involvement of the SDN controller. Each super-channel is first considered in the condition where no spectrum saving techniques have been applied (i.e., nominal spectrum usage). Then, super-channels are re-configured operating under low margins and are then observed. Low-margin operation is achieved by narrow optical filtering and packing sub-carriers closer in the frequency domain. Regardless of the super-channels’ spectrum-efficiency, after each re-configuration the procedure utilizes <get> NETCONF message and OpenConfig YANG models (i.e., `terminal-device` and `platform`) to obtain pre-FEC-BER values and power consumption.

Finally, once all suitable super-channels have been configured and their pre-FEC-BER values and power consumption recorded, the procedure provides the SDN controller with two optimal solutions, one optimizing power savings and the other optimizing spectrum efficiency. The SDN controller then decides on the appropriate super-channel configuration based on the network requirements or operational policy.

III. Experimental Validation and Results

The experiments of the automated procedure have been conducted in the context of the testbed reported in Fig. 1. Two optical channels of a Fujitsu 1Finity T600 transponder are aggregated at the Tx side to build a super-channel of desired capacity. Then, a link of 40 km or 320 km of optical fibers is traversed to determine the effect of the optical reach on power consumption. Finally, the super-channel reaches Rx side, where coherent detection is performed. The testbed also employed an electrical power analyzer. Besides the OpenConfig agent for transponder configuration, a dedicated NETCONF agent was implemented to report measured electrical power consumption.

The results of power-aware optimization procedure for an 800 Gbit/s super-channel operating in C-band are presented in Table 1. 800 Gbit/s super-channel can be obtained in four different configurations encompassing two sub-carriers: (i) by combining OP1 (600 Gbit/s, 75 GHz, DP-QAM64) and OP6 (200 Gbit/s, 75 GHz, 8PSK), (ii) OP1 and OP7 (200 Gbit/s, 50 GHz, DP-QAM16), (iii) OP2 (500 Gbit/s, 75 GHz, DP-QAM32)

TABLE I. Power consumption and pre-fec-ber values according to the optical reach for 800 Gbit/s super-channels

		Power Saving				Spectrum Saving			
	Super-channels	BW [GHz]	pre-FEC-BER	Power Level [W]		BW [GHz]	pre-FEC-BER	Power Level [W]	
				Node	Line			Node	Line
40 km	OP1 (600Gb/s, 75GHz, DP-QAM64) OP6 (200Gb/s, 75GHz, 8PSK)	150	2.25E-02 1.81E-08	311	191	131.25	2.24E-02 1.56E-07	314	194
	OP1 (600Gb/s, 75GHz, DP-QAM64) OP7 (200Gb/s, 50GHz, DP-QAM16)	125	2.30E-02 5.95E-06	303	183	**106.25**	2.40E-02 1.15E-04	**306**	**186**
	OP2 (500Gb/s, 75GHz, DP-QAM32) OP5 (300Gb/s, 75GHz, 8PSK-2)	150	4.68E-03 5.32E-06	**293**	**173**	118.75	1.14E-02 1.92E-05	299	179
	OP3 (400Gb/s, 75GHz, DP-QAM16) OP3 (400Gb/s, 75GHz, DP-QAM16)	150	2.04E-04 5.15E-04	297	177	125	2.79E-03 4.56E-03	313	193
320 km	OP2 (500Gb/s, 75GHz, DP-QAM32) OP5 (300Gb/s, 75GHz, 8PSK-2)	150	1.83E-02 3.05E-04	**306**	**186**	131.25	1.87E-02 2.00E-02	318	198
	OP3 (400Gb/s, 75GHz, DP-QAM16) OP3 (400Gb/s, 75GHz, DP-QAM16)	150	2.53E-03 3.05E-03	307	187	**125**	2.27E-02 2.22E-02	**319**	**199**

```
<components xmlns="http://openconfig.net/yang/platform">
  <component>
        <name>shelf-1</name>
        <config>
          <name>shelf-1</name>
        </config>
        <state>
          <name>shelf-1</name>
          <type xmlns:opt="http://openconfig.net/yang/platform-types">opt:CHASSIS</type>
          <used-power>306</used-power>
        </state>
  </component>
</components>
```

Fig. 2. <get> message reporting `used-power`

and OP5 (300 Gbit/s, 75 GHz, 8PSK-2), and (iv) OP3(400 Gbit/s, 75 GHz, DP-QAM16) and OP3 sub-carriers. It is important to note that the choice of OP mode may depend on the physical-layer conditions. For example, OP1 sub-carriers cannot be utilized for longer optical reach due to their high-order and less robust modulation format (i.e., DP-QAM64).

The <get> message reporting power consumption values is shown in Fig. 2. Total power consumption of the transponder (referred to as node power level in Table 1) consists of a fixed power component (around 120 W), representing a state when transponder is not operating (i.e., idle mode) and a dynamic component, i.e., the transmission power, that depends on the OP modes used (referred to as “line” power level in Table 1). Super-channels operating under low margins are enabled by the spectrum saving optimization procedure described in [6], which allows slight sub-carriers overlap and narrow optical filtering. Spectrum and power saving optimization results are highlighted in Table 1 according to the optical reach.

Power consumption depends on the OP modes combination used to build a requested super-channel. Results show 9.42% variation in transmission power consumption levels (i.e., 5.79% variation in total power consumption) considering 40 km optical reach and super-channels operating under designed margins (i.e., when the spectrum saving approach is not applied). Furthermore, for 40 km optical reach the power-aware optimization procedure reveals that the most power-efficient super-channel is OP2 OP5 super-channel, while the most spectrum-efficient one is composed of OP1 and OP7 sub-carriers. However, the most spectrum-efficient super-channel contributes to 7% higher transmission power consumption (i.e., 4.25% higher total power consumption). On the other hand, OP1 sub-carrier becomes unavailable considering 320 km optical reach due to its high-order modulation format (i.e., DP-QAM64). Therefore, OP2 OP5 super-channel has been identified as the most power-efficient, while OP3 OP3 super-channel represents the most spectrum-efficient one. Similar to the 40 km reach, OP3 OP3 super-channel contributes to 6.5% higher line power consumption and 4% higher total power consumption. In fact, operating all considered super-channels under low margins leads to higher power consumption given more errors to be compensated at the receiver. Additionally, for similar reasons, physical-layer conditions impact power consumption. There is an increase of power consumption when comparing OP2 OP5 (7% of transmission power consumption and 4.25% of total power consumption), and OP3 OP3 (5.35% of transmission power and 3.26% of total power consumption) super-channels for nominal spectrum usage and 40 km and 320 km, respectively. Moreover, the comparison of spectrum-efficient OP2 OP5 super-channels for 40 km and 320 km shows that not only less spectrum can be saved as we increase the optical reach (40 km: 118.75 GHz, 320 km: 131.25 GHz), but power consumption increases as well (9.6% higher transmission power, and 5.97% higher total power consumption).

IV. CONSLUSION

Power-aware super-channel optimization procedure has been successfully demonstrated through experiments in an EON testbed. We have experienced that spectrum-efficient super-channels and longer optical reach lead to higher power consumption. Results identified a trade-off between spectrum-efficiency and power consumption. In particular, a power saving of 7% per line card can be achieved if spectrum resources are kept at nominal values. This might be relevant if additional spectrum resources are made available through multi-band or SDM.

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