Non-Disruptive Lightpath Passband Characterization Using Optical Frequency Combs

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***Abstract*: Optical frequency comb-based probes are investigated for rapid, online measurement of lightpath transmission passbands in elastic optical networks and shown to provide accurate measurement without disrupting existing optical connections.**

Keywords—nondisruptive probe, optical frequency comb

I. Introduction

Optical network monitoring in active communication systems is gaining interest as a tool for enabling lower margin operation, higher reliability, and data driven AI methods. While many methods focus on metrics such as optical signal to noise ratio (OSNR) or quality of transmission (QoT) metrics, these techniques generally monitor the performance of active signals and do not provide information about unoccupied spectrum. Provisioning and general system reliability would benefit from telemetry on the system both inside and outside the active channel bands. Such data might better enable the use of digital twin methods to run what-if scenarios including different channel configurations without disrupting the ongoing system operation [1]. Typical approaches to evaluate the wavelength dependent performance of DWDM optical components consist in using transceivers and optical channel monitors (OCMs) in the nodes. In addition, optical time domain reflectometry (OTDRs) that interrogates the open spectrum in line systems is used to detect fibre faults and loss anomalies without any wavelength discrimination. OTDR approaches — unless they are applied out of band and bypass amplifiers and other components — disrupt the current network state by introducing probing signals that interfere with data bearing channels. At the same time OCMs only monitor occupied spectrum and established channels. Probing with transceivers has been studied but not used in practice as it too would disrupt the current state of the system in-band. On the other hand, nondisruptive probing methods enable online in-band probing of spectrum, without interfering with other [2]. A critical aspect in elastic optical networks (EON) is the narrowing of the transmission passband due to cascading wavelength selective switches (WSS) [3]. Accurate, real-time and rapid characterization of lightpath passbands, prior to provisioning, is essential in reconfigurable optical networks, in which spectral shaping directly impacts signal routing and system performance. In this regard, several models to estimate the filtering penalties were proposed [1,4]. However, a common limitation of all these approaches is the difficulty in accurately estimating the input physical parameters required by the models. In this work, we propose a novel non-disruptive probing technique to characterize the filter passband of an optical channel. Specifically, we present proof-of-concept experiments showing that an optical frequency comb (OFC)-based probe signal enables single-shot, online, and non-disruptive measurement of the lightpath passband.

II. Non-Disruptive Passband Characterization

Fig. 1 (a) illustrates a reference mesh network architecture, namely an EON composed of multiple nodes interconnected through reconfigurable optical add-drop multiplexers (ROADM). ROADMs are commonly exploited in metro and core scenarios to configure lightpaths. In this work, we consider ROADMs with route-and-select architecture, comprising booster- (BA) and pre-amplifiers (PA) as well as WSSs for multiplexing and demultiplexing wavelength division multiplexed (WDM) channels. In such networks, filtering penalties are critical due to the significant variation in the transmission passbands, depending on the lightpath (i.e., on the number of cascaded WSSs, the specific devices encountered and the channel index). Another critical aspect in EONs is the occurrence of power excursions caused by the automatic gain control (AGC) algorithms implemented in Erbium doped fibre amplifiers (EDFAs). Namely, a change in input wavelength configuration into an EDFA can affect the channel gains through wavelength dependent gain and hole burning effects [5]. We propose a probing subsystem to monitor the lightpath transmission passband during network operation, featuring the following capabilities. *i)* Rapid *one-shot* measurements: we employ an OFC as a multi-wavelength probe source, enabling the simultaneous amplitude and phase characterization of the entire WSS passband in a single acquisition. This approach contrasts with a wavelength-tunable single-tone sources, which are inherently sequential, susceptible to temporal drift, and unsuitable for monitoring dynamic or thermally sensitive components. *ii)* Online *non-disruptive* operations: the use

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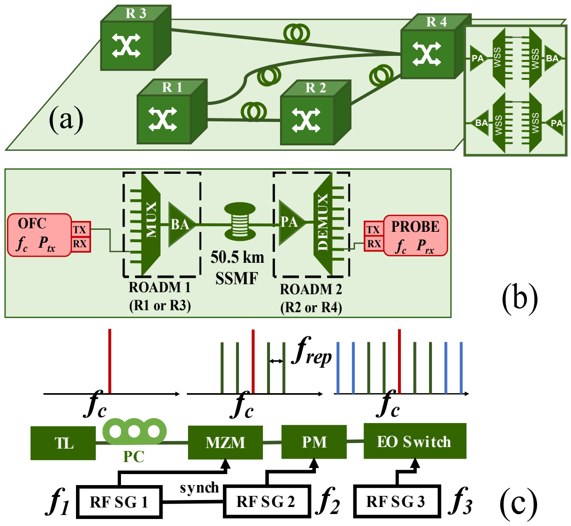

Fig. 1 (a) Reference network architecture and ROADM, (b) experimental setup to characterize the passband and (c) block-diagram of the EO configuration to generate the OFC-based probe.

of a pulsed probe, with the duration much shorter than an EDFA AGC's response time (on order of tens of microseconds [2]), ensures the probing does not cause power excursions.

The proposed probing scheme relies on an OFC to enable rapid, single-shot measurements. It is important to note that various configurations can be used to generate OFCs, but we employ an electro-optic (EO) modulator-based comb approach due to its simplicity and cost effectiveness [6]. Fig. 1 (b) shows the experimental setup used in this work to generate the OFC. A tunable laser (TL) is used to produce a continuous-wave (CW) output with a central frequency *fc*. A cascaded configuration, comprising a single-drive Mach–Zehnder modulator (MZM) followed by a phase modulator (PM), is used to generate a broadband OFC [6]. The MZM is biased at its null transmission point and driven by a sinusoidal radio frequency (RF) signal with a frequency f_1, effectively generating a periodic train of optical pulses through intensity modulation. The PM, driven at f_2 generated by a second RF source, introduces a strong sinusoidal phase modulation that broadens the optical spectrum via sideband generation and interleaving, as shown pictorially in Fig 1 (b). By carefully optimizing the modulation indices, RF drive powers, and relative phase between the RF signals, a relatively flat, broadband, and phase-coherent comb is generated. Finally, to avoid the undesired power excursion effects, an EO switch driven by a third RF source is used to generate short-duration pulses. While this configuration employs bulk optical components, the setup may be readily implemented using integrated photonic devices. Furthermore, this approach opens the door to other comb-based techniques, such as dual- comb methods, which enable heterodyne detection of the comb spectrum via the RF domain, offering a low-cost and scalable alternative [7].

The method followed in this work to estimate the passband consists of capturing the spectrum at the transmitter (i.e., before any ROADMs) and the spectrum after the ROADMs. Then, the peaks of the two spectra (i.e. comb lines' peaks) are measured and subtracted from each other to obtain an estimation of the transmission passband.

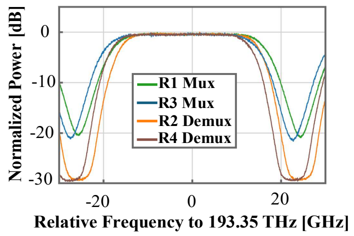

Fig. 2 Transmission passband after different ROADMs.

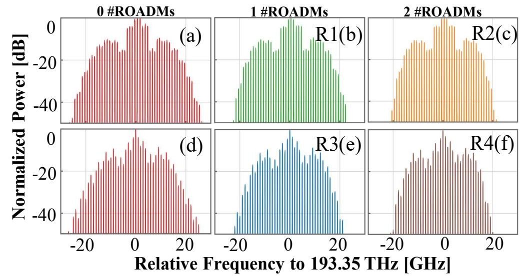

Fig. 3 Optical spectra of two OFC-based probing signals in back-to-back (a, d), after 1 ROADM (b, e) and after 2 ROADMs (c, f).

III. Experimental Setup and Results

The experiments were carried out at the OpenIreland optical testbed exploiting multi-vendor commercial optical equipment [8].

A first experiment was carried out to evaluate the suitability of the method to characterize the passband. We evaluate the optical transmission over a lightpath composed of two ROADMs and one link consisting of a spool of standard single mode fiber (SSMF) with length of 50.5 km (Fig. 1 (b)). The tunable frequency f_c of the OFC-based probe signal was set to 193.35 THz and its average optical power at the ROADM's input was approximately -7 dBm in CW mode and -19 dBm when pulsed mode. In this work, we set f_1 and f_2 equal to 1 GHz and 3 GHz, respectively so that the OFC repetition rate f_{rep} is fixed at 1 GHz to match the WSS spectral sampling requirement.

An OSA with a 16 pm resolution was employed to collect the spectra at different locations depicted in Fig. 1 (b): *1)* after one ROADM; and *2)* after 2 ROADMs and one 50 km SSMF transmission span. Different ROADMs were considered as WDM signal multiplexer and demultiplexer, fixing the WSS's bandwidths to 37.5 GHz. Fig. 2 shows filter shapes measured with ASE noise broadband source after mux and demux WSSs i.e., ROADMs labelled as R1 and R3 and as R2 and R4, respectively). Interestingly, different devices exhibit similar bandwidths but different central frequency shifts with values detailed in Table 1.

Moreover, Fig. 3 shows example of captured optical spectra of two independent OFC probe signals measured without crossing any ROADMs (a, d) and after one (b, e), and two (c, f) ROADMs, respectively. Fig. 4 compares the broadband ASE measured transmission passbands (line) with the average ones (markers) obtained with the proposed method considering a total of 43 comb lines. Specifically, the passband average powers and the standard deviations computed over 5 samples for ROADMs R1 and R2 (a) and over 10 samples for ROADMs R3 and R4 (b) are shown. Furthermore, Fig. 5 shows the average absolute errors and the standard deviations obtained in estimating the spectrum powers plotted versus the normalized optical power. Note,

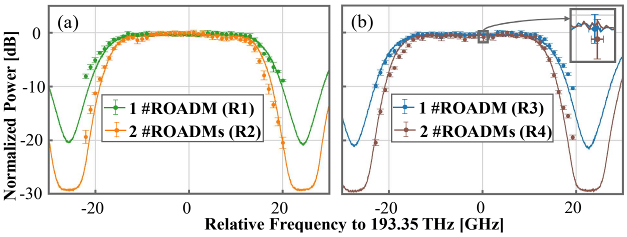

Fig. 4 Lightpath passbands measured with ASE broadband source and with the OFC-based probe after ROADMs R1-R2 (a) and R3-R4 (b).

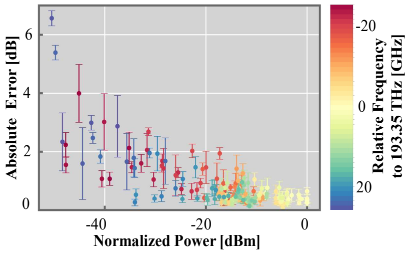

Fig. 5 Absolute errors in estimating the transmission passband powers.

Table 1 Passband central frequency shift | Passband bandwidth [GHz]

		Actual	Estimated	Absolute Error
ROADM	R1	0.75 | 33.67	0.95 | 34.12	0.41±0.25 | 0.55±0.47
	R2	0.65 | 30.78	0.85 | 29.87	0.26±0.21 | 0.90±0.61
	R3	2.42 | 33.73	1.83 | 34.10	0.59±0.12 | 0.50±0.30
	R4	2.45 | 30.84	1.84 | 31.20	0.62±0.11 | 0.41 ±0.25

that the errors are higher at the edges where the filter shapes are steeper and thus a slight tilt of the probing signal leads to increased errors. In addition, Table 1 provides two metrics retrieved from the actual (ASE source-measured) and estimated (probe-measured) passband powers: the central frequency shifts and the bandwidth both measured at -3 dBm. Specifically, for each ROADM the actual average values the estimated ones are detailed as well as the means and standard deviations of their absolute errors.

Moreover, an additional experiment was conducted to verify the non-disruptive nature of the proposed OFC-based probe signal. We consider a lightpath composed of three ROADMs and two links based on SSMF spools with lengths of 50.5 and 50.4 km, respectively (Fig. 6). Three input signals were injected: two data channels generated by commercial TRXs labelled as TRX1 and TRX2 (in Fig. 6) and frequencies f_{ch1} and f_{ch2} equal to 192.25 and 192.30 THz, respectively; and the OFC-based probe signal with tunable frequency f_c set to 195.25 THz. The channels were spaced by 50 GHz following the ITU grid and the EDFAs used AGC with a 15 dB target gain. The data channels and the OFC probe (in CW) were set to the same channel average optical power P_{trx} equal to -10 dBm at the input of ROADM 1. The WSS's bandwidth was set to 43.75 GHz and the data channels were modulated with DP-16QAM and operating with a baud rate of ~30 GBaud. Fig. 7 (a-d) show the interquartile range calculated over 50 samples of the optical powers of data channels 1 (b) and 2 (a) measured at the output of the demux WSSs (see Fig. 1(a)) as well as ΔQ-factor values retrieved from TRX1 (c) and TRX2 (d), respectively. ΔQ-factor was obtained by subtracting the average Q-factor values with the average Q-factor measured in absence of the probe. The QoT metrics were obtained in three different cases: *i)* with a CW probe; *ii)* with a pulsed probe; and *iii)* in absence of the probe. As shown, the presence of a pulsed OFC probe has a negligible

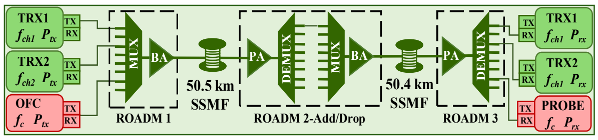

Fig. 6 Experimental setup to assess non-disruptive OFC-probing.

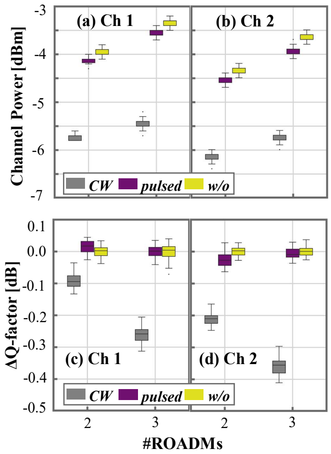

Fig. 7 Channel powers (a-b) and ΔQ-Factors (c-d) obtained in three cases: with a CW probe, a with pulsed probe and without any probe.

impact on the power of the data channels and does not degrade their Q-factor.

IV. Conclusions

To conclude, we demonstrate the feasibility of using OFC-based probe signals to perform single-shot characterization of the lightpath transmission passband in EONs.

Experimental results show that accurate passband measurements across multiple ROADMs can be carried out on a live network without impacting the performance of the data channels. Moreover, we show that useful metrics such as the passband bandwidths and the shifts of the passband central frequency can be retrieved from the estimated passband measurements. Other comb-based techniques, such as dual frequency combs shall be tested to improve accuracy and to enable scalable and cost-effective RF based signal retrieval.

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