All-Optical In-Band OSNR Estimation in Coherent Optical OFDM Systems

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ABSTRACT
In-band OSNR measurement for CO-OFDM systems using high-resolution spectral analysis is experimentally demonstrated. It is shown that signal and noise levels can be monitored by direct optical spectrum analysis, avoiding the need for data demodulation.

Keywords: Optical performance monitoring, optical modulation, coherent optical OFDM.

1. INTRODUCTION

Automation of optical networks without human intervention is one of the most significant challenges that need to be addressed in the near future. This high degree of autonomy can be achieved thanks to the active processing of real-time network monitoring information in a software defined networking (SDN) environment. This monitoring information enables learning from the effects of the decisions taken for providing an optimal set of network resources to satisfy new service demands and dynamically re-optimize the services already deployed [1][2]. Thus, a significant increment of the network efficiency and cost-effectiveness is expected when including these aspects in optical networks.

An important subsystem to provide the aforementioned network automation is the optical performance monitor, which is in charge of providing the feedback needed to guarantee end-to-end quality of transmission (QoT) and quality of service (QoS). For the specific case of optical circuit switching networks, a non-intrusive optical performance monitoring system can be deployed at the network nodes to automatically extract the different performance parameters [1][2]. However, common optical performance monitoring techniques are either valid for specific transmission technologies (e.g. those techniques based on polarization nulling are not suitable for polarization multiplexed signals) or exhibit a limited range of functions for extracting the figures of merit that will be employed to configure the different network resources. Thus, a key aspect to address is the advancement in optical performance monitoring techniques in order to create a common subsystem that is agnostic to the optical signal waveforms (which may feature different multiplexing schemes and modulation formats) and capable to provide the suitable figures of merit to the control, orchestration and management planes. Among all the available performance indicators, the optical signal to noise ratio (OSNR) is the most common parameter used to measure the degradation of the signal quality, because it is transparent to bit rate and modulation format, and can be easily related to the bit error ratio (BER), which is the main performance indicator [3].

Along a different line, the advent of new and advanced optical modulation formats is attractive for improving the transmission performance; even they pose new challenges and/or opportunities from the optical performance monitoring point of view. Precisely, optical orthogonal frequency division multiplexing (O-OFDM) has gained attention in optical communications as it represents a promising candidate for implementing programmable bandwidth/bitrate variable transceivers, since it enables software-defined optical transmission [4][5]. In fact, O-OFDM also provides advanced spectrum manipulation capabilities, including arbitrary sub-carrier suppression and bit/power loading (BL/PL) [6]. Thanks to these features, O-OFDM-based transceivers can be ad hoc configured for achieving a certain reach and/or coping with a targeted data rate adopting optoelectronic subsystems featuring different degrees of complexity [5][6].

Additionally to the robustness against transmission impairments, O-OFDM can provide electronic monitoring and equalization. The overhead of information (e.g. pilot tones, training symbols, cyclic prefix), which must be allocated for correctly recovering the signal, allows monitoring system parameters for channel estimation and performance optimization [5][6]. However, this self-performance monitoring technique is performed in the electrical domain, requiring an optical receiver front-end. For an appropriate network management, a more simple and non-intrusive signal quality monitoring per subcarrier is desirable at the nodes of the network [1][2][7][8]. Thus, the control and management planes can dynamically reconfigure the parameters of each O-OFDM transceiver in order to overcome the signal degradation for specific subcarriers without the need for optical to electrical conversion [8]. This can be achieved by balancing the modulation format per subcarrier and/or adding/suppressing subcarriers, when transmitting along a specific lightpath [8].

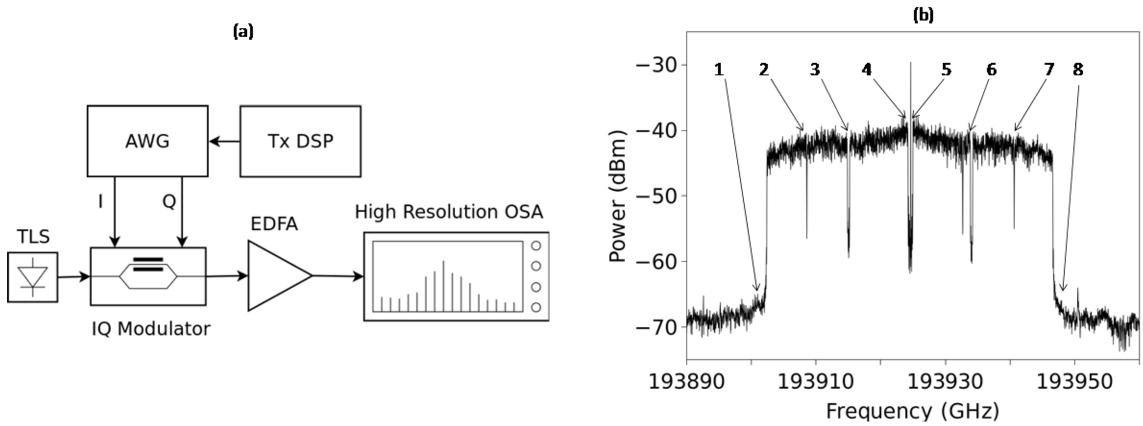

Figure 1. (a) Experimental setup scheme.(b) Sample of the detected spectrum at 35.7 dB OSNR, indicating the position of the spectral gaps

Table 1: Spectral gaps considered for the analysis

Gap no.	Number of subcarriers	Bandwidth
1	20	1968.75 MHz
2	1	93.75 MHz
3	3	281.25 MHz
4	2	187.5 MHz
5	3	281.25 MHz
6	3	281.25 MHz
7	2	187.5 MHz
8	18	1687.5 MHz

Among the DSP-based O-OFDM options, those based on complex modulation and coherent detection constitute a reliable solution for the implementation of BVTs. In fact, they enable the full characterization of the optical channel (including magnitude and phase) in order to properly equalize the signals at the receiver side. Furthermore, spectral efficiency is ensured with no need for electrical guard bands nor tight optical filtering at the transmitter side [5].

In this paper, in-band OSNR measurements for coherent optical OFDM (CO-OFDM) systems are demonstrated using high-resolution spectral analysis. We show that amplified spontaneous emission (ASE) noise level can be monitored in-band by direct spectrum analysis, using no polarization analysis or coherence properties and avoiding the need for data demodulation.

2. EXPERIMENTAL SETUP

The experimental set-up is described in Fig. 1a. First, the OFDM signal is generated with off-line DSP using Matlab software. A stream of bits running at 240 Gb/s is mapped into 32-QAM symbols and modulated using a 512-points inverse fast Fourier transform (IFFT). The digital OFDM signal is loaded onto an arbitrary waveform generator (AWG), to provide a 48 Gbaud/s complex signal. The signal at the output of the AWG then drives an IQ modulator, which modulates the output signal of an external cavity tunable laser source (TLS) running at λ_0=1550 nm with measured linewidth of 100 kHz.

The spectral analysis is performed with BOSA spectrum analyzer. The equipment's performance is based on the stimulated Brillouin scattering (SBS) that couples two counter-propagating waves in a spool of fiber, i.e. pump and signal under test, to achieve a narrow gain filter that can be used to scan the signal spectrum by changing the pump's wavelength. Spectral width achieved with SBS filter when sweeping at a constant speed can be of 10 MHz at its full width halfs maximum (FWHM), and 60 MHz width at 40 dB below maximum response [9]. Noise filtering techniques ensure sensitivity below -70 dBm and dynamic range above 80 dB.

Since each OFDM subcarrier has a bandwidth of 93.75 MHz, there is the possibility of creating the suitable spectral gaps in order to easily performing the measurement of the ASE noise level. In order to analyze de best strategy for ASE noise estimation, 8 different spectral gaps covering different portions of the optical spectrum have been created and analyzed. Fig. 1b shows a sample spectrum where the main spectral gaps created are

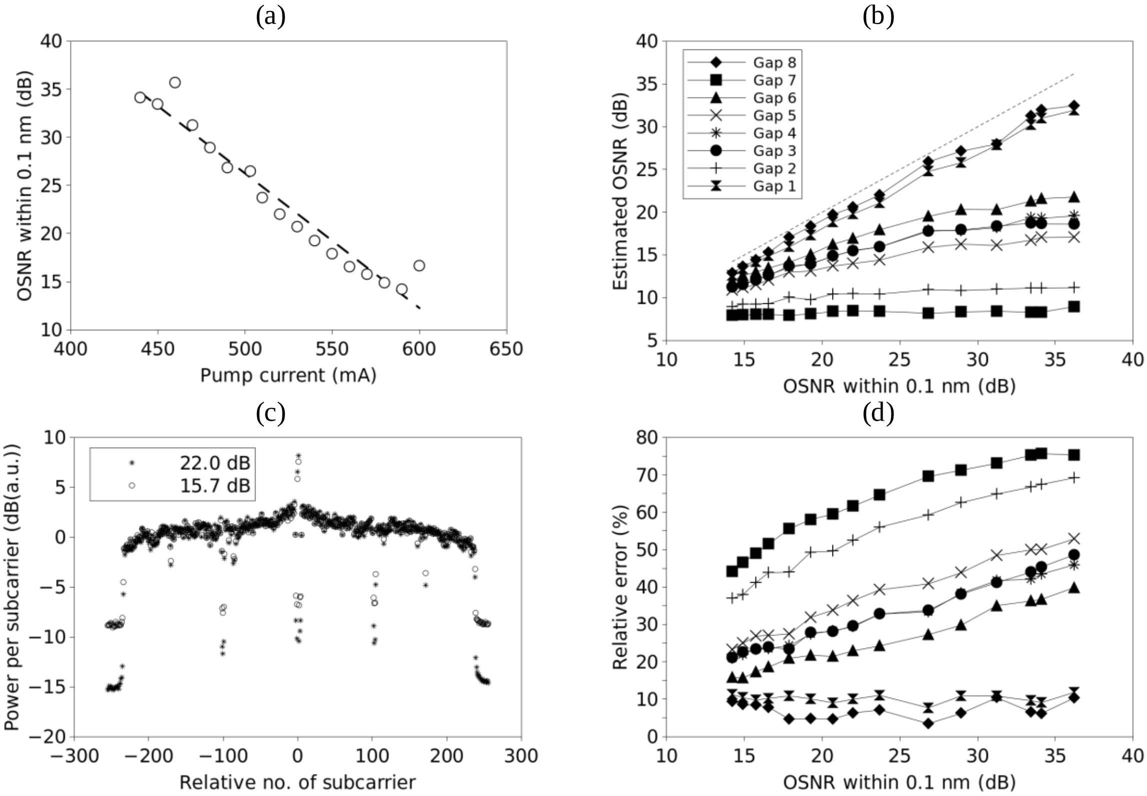

Figure 2: Optimization of OSNR variation by changing the EDFA pump current (a). OSNR estimated through the different gaps in the signal spectrum (b) and the corresponding relative error (d). Sample of the power levels per subcarrier acquired for OSNR values of 22.0 dB and 15.7 dB (c).

numbered and highlighted. Table 1 summarizes the characteristics of each gap, including the number of suppressed subcarriers and the corresponding bandwidth. There we can observe that different portions of the signal spectrum are arranged for noise estimation, featuring widths from 93.75 MHz up to about 2 GHz.

In order to experimentally analyze the ASE noise and perform an in-band measurement of the OSNR of CO-OFDM signals in the optical domain, an additive white noise generated by an Erbium Doped Fiber Amplifier (EDFA) is introduced in the system. In order to effectively vary the OSNR of the transmitted signal, the bias current of the pump laser of the EDFA is adjusted. Results are shown in Fig. 2a, where it can be observed that the OSNR, defined in 0.1 nm, can be varied within the range between 14.21 dB and 35.7 dB.

3. OSNR ESTIMATION: RESULTS AND DISCUSSION

Since the resolution of the BOSA provides values of the power in a 0.08 pm bandwidth, we first precisely estimate the position of the signal central wavelength. Based on this, the position of each OFDM subcarrier and the corresponding power are computed. Samples of these calculations are shown in Fig. 2c for OSNR values of 22.0 dB and 15.7 dB referenced to 0.1 nm. In order to obtain the OSNR level referenced to 0.1 nm, the signal level is found by calculating the equivalent power spectrum density and integrating its value across the entire signal spectrum. The noise level is estimated at the selected frequency ranges (signal gaps), corresponding to the selectively suppressed OFDM subcarriers. Assuming a flat noise spectrum, the equivalent noise power inside the bandwidth used for evaluating the OSNR can be estimated. In the following discussions the OSNR levels are all referenced to 0.1 nm.

Results for the OSNR estimation are shown in Fig. 2b and c. There we can see the estimated OSNR when estimating the noise in the spectral gaps highlighted in Fig. 1b and the corresponding relative error. The dashed line of Fig. 2b represents the theoretical behavior (i.e. one-to-one correspondence between measured and estimated OSNRs). When estimating the noise in the gaps located at the edges of the OFDM signal (gaps 1 and 8), the noise level can be estimated with high accuracy, featuring the lower possible error. In fact, the relative error between OSNR measured and the one estimated using the spectral gaps ranges from 3.5 %, for low values of OSNR, up to 11.8 %, for high OSNR values. In theory, the SBS gives more than 40 dB extinction for the 93.75 MHz subcarrier spacing approached in the experiments. However several other factors, such as laser phase noise, jitter, etc.., reduce the sensitivity and, consequently, the OSNR estimation.

Gaps 3 and 6 have an intermediate behavior, with a relative error of OSNR estimation ranging from 15.7 % up to 48.6 %. The main reason is that no specific filtering or waveform is considered for each OFDM subcarrier.

So, each OFDM subcarrier features a sinc-shaped spectrum, with certain sidelobe overlap between neighboring subcarriers, that limits the performance of the noise estimation. Since only 3 subcarriers are used for noise estimation the mentioned overlap of sidelobes is certainly high, reducing the dynamic range for noise estimation. Also it should be noted that we are shaping the OFDM signal (including gaps) in the discrete frequency domain, which may not correspond at all to the measurements taken in the continuous frequency domain [10].

Even gaps 4 and 5 are similar to gaps 3 and 6, the relative error of OSNR estimation is quite high, within the range between 21.0 % and 50.1 %. The reason is that these gaps are created in the vicinity of the optical carrier. Therefore, a large portion of them is lost because of the behavior of the optical carrier, which has a Lorentzian shape, masking the noise level.

Therefore, in case of O-OFDM-based bandwidth variable transponders, in which carriers can be adaptively suppressed, several frequency gaps can be conveniently created in order to be used for noise measurements.

4. CONCLUSIONS

This paper demonstrates the potential that high-resolution spectral analysis can bring to multicarrier modulation formats in order to monitor optical performance parameters such as OSNR. Typically, O-OFDM monitoring is performed at the edges of the network, when decoding/demodulating data in the electrical domain. This implies the use of high speed optoelectronic devices.

Here, a more affordable OSNR measurement employing high resolution OSA has been demonstrated for CO-OFDM, avoiding the need for data demodulation and, thus, relaxing the component requirements. Depending on the range of frequencies considered for the measurement, OSNR level in 0.1 nm bandwidth could be estimated with less than 4 % error.

This enables live monitoring of quality parameters, which can be performed at the nodes of the optical networks with no need for data demodulation. Thus, it becomes a key point towards better management of OFDM-based systems in SDN flexible and elastic optical networks.

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