European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Optical Performance Monitoring of Digital Subcarrier Multiplexed Signals using Amplitude Modulation Pilot Tone

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Abstract *We propose a performance monitoring method for digital subcarrier multiplexed signals using amplitude modulation pilot tones in spectral valleys. The estimation of OSNR and nonlinear interference noise is experimentally demonstrated with an enhanced robustness. ©2022 The Author(s)*

Introduction

Digital subcarrier multiplexing (DSCM) based on advanced digital signal processing (DSP) has attracted extensive attention as it has emerged as a promising solution for future optical networks [1-2]. The multiple subcarriers with a reduced baud rate provide various benefits including the increased network flexibility using adaptive control of individual subcarrier's parameters (e.g., data rate, probabilistic constellation shaping (PCS) rate) and the robustness against impairments such as equalizer-enhanced phase noise (EEPN) and fibre nonlinearity [1]. In order to fully exploit such advantageous features of DSCM signals, an effective system supervision for cognitive network management is imperative. In particular, a simple and practical way to monitor amplified spontaneous emission (ASE) and nonlinear interference (NLI) noises, which are known as major performance-limiting factors in long-haul transmission systems, is highly desired. Recently, various techniques to jointly estimate optical signal to noise ratio (OSNR) and NLI power have been proposed for conventional single-carrier signals, based on spectral correlation [3], link parameters [4], zero-power gap [5], amplitude correlation function [6,7], carrier phase [8], or constellation [9], often together with machine learning [7-10]. However, most methods require the prior knowledge of the link configuration to take into account its impact on NLI, or significant modifications of the structures for implementation. Many of them, moreover, may not be applicable for DSCM signals. For instance, the zero-power gap method becomes less effective as the power inside the gap no longer properly reflects the NLI due to insufficient pulse broadening [5].

In this paper, we propose an OSNR and NLI monitoring technique suitable for DSCM signals based on amplitude modulation pilot tone (PT). This method takes advantage of the existence of the spectral valleys between subcarriers to extract the information and improve the monitoring performance. The monitoring capability on a per-subcarrier basis could facilitate more flexible and efficient network management using, for example, PCS and waterfilling techniques.

Amplitude modulation PTs for DSCM signals

In PT-based channel monitoring, an intensity modulation with a small modulation index and relatively low frequency (kHz to MHz) is applied to the signal at the transmitter. Each subcarrier in a DSCM signal may be assigned with a unique pilot tone frequency, providing "finger printing" information. The PT-modulated signal in time domain for *i*-th subcarrier is $E_i^{\mathrm{PT}}(kT) = E_i(kT) \times [1 + m\sin(2\pi f_{\mathrm{PT},i} kT)]$, where E_i, m, and $f_{\mathrm{PT},i}$ are the signal before PT modulation, modulation index, and PT frequency of *i*-th subcarrier, respectively. An exemplary implementation of amplitude modulated PT in transmitter DSP is shown in Fig.1. Since we need to assign different PT frequencies for each subcarrier, the PT is applied in frequency domain before the subcarriers are combined. Following FFT and pulse shaping, $h_{\mathrm{PT,i}}(f) = 1 + m\sin\phi_{\mathrm{PT},i}$ is multiplied to the input signal. Here, $\phi_{\mathrm{PT},i} = \phi_0 + 2\pi f_{\mathrm{PT},i}\Delta t$, where ϕ_0 is $\phi_{\mathrm{PT},i}$ of previous FFT block and Δt is the time duration per FFT block. Considering the fact that $f_{\mathrm{PT},i}$ is much smaller than $1/\Delta t$, the pilot tone phase can be regarded as constant over a FFT block. Therefore, this process is equivalent to the amplitude modulation PT applied in time domain and does not require any additional hardware. The pilot tones can be detected by either tapping off a small portion of the signal power into a pilot tone detector (PTD) [11] or using a conventional coherent receiver

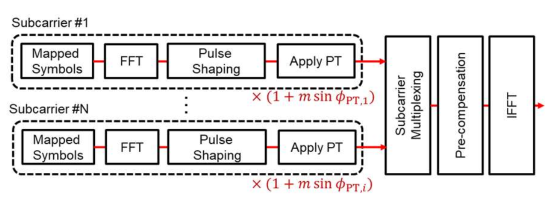

Fig. 1: Implementation of amplitude modulation pilot tones for a DSCM signal

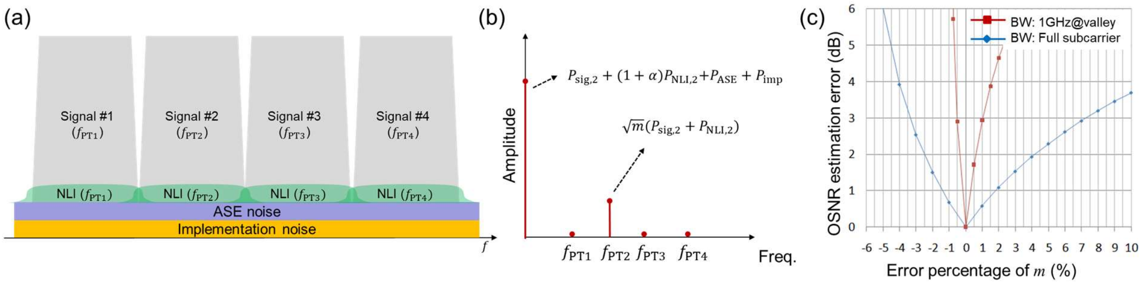

Fig. 2: (a) Noise contributions in a 4-subcarrier DSCM signal, (b) a spectrum after FFT of power waveform for subcarrier #2, and (c) OSNR estimation error induced by the use of erroneous $\boldsymbol{m}$ for two different approaches (@OSNR = 24 dB).

followed by DSP.

OSNR monitoring based on pilot tones

For DSCM signals, it is important to monitor the OSNR of each subcarrier separately because of the dependency of signal degradation on the spectral frequency. This might be caused by non-uniform filtering effects, signal power imbalances, etc. In [12], we have demonstrated an in-band OSNR monitoring based on PT for a single-carrier optical signal. A similar technique can be used for DSCM signals even with an improved robustness. Fig. 2(a) illustrates the noise contributions to a DSCM signal composed of 4 subcarriers. We assume that each subcarrier is amplitude-modulated with a unique frequency (i.e., $f_{\mathrm{PT}i}$ for *i*-th subcarrier). After transmission, the received signal may be contaminated by ASE, NLI, and implementation noises. As opposed to the signal and NLI noise, the ASE and implementation noises are unmodulated. Fig. 2(b) shows the power spectrum of subcarrier #2 as an example. The amplitude of the main peak at DC represents the total power while that of a sub peak at f_{PT2} is proportionate to the sum of signal and NLI noise power. The amplitudes of the main and sub peaks of *i*-th subcarrier are described as

$$A_{\mathrm{main},i} = P_{\mathrm{sig},i} + (1+\alpha)P_{\mathrm{NLI},i} + P_{\mathrm{ASE}} + P_{\mathrm{imp}}, \quad (1)$$

$$A_{\mathrm{sub},i} = \sqrt{m}(P_{\mathrm{sig},i} + P_{\mathrm{NLI},i}), \quad (2)$$

where $P_{\mathrm{sig},i}$, $P_{\mathrm{NLI},i}$, P_{ASE}, and P_{imp} are the power of signal, NLI, ASE, and implementation noise within the band, respectively. α is a factor used to take into account the NLI power leakage from the neighboring subcarriers. If $\alpha P_{\mathrm{NLI},i} \approx 0$ (i.e., NLI is negligible), ASE power level is derived by

$$P_{\mathrm{ASE}} = (\frac{1}{R} - \frac{1}{\sqrt{m}})A_{\mathrm{sub},i} - P_{\mathrm{imp}}, \quad (3)$$

where $R = A_{\mathrm{sub},i}/A_{\mathrm{main},i}$. It should be noted that noise power in conventional definition of OSNR only refers to ASE. Since P_{imp} can be readily measured during transceiver testing process, it is possible to obtain P_{ASE} as well as OSNR. However, in the presence of NLI, a considerable power leakage (i.e., $\alpha P_{\mathrm{NLI},i}$ in Eq. (1)) may exist due to the spectral broadening, resulting in an underestimation of monitored OSNR. To cope with this problem, the value of α needs to be estimated so that we can calibrate the OSNR with a correction factor. The value is directly related to the NLI of the signal and can be obtained in a similar way to NLI power estimation, which will be discussed in the next section.

A drawback of the PT-based method is that the monitoring accuracy is vulnerable to the potential error of m and P_{imp}. As shown in Eq. (3), the sensitivity of P_{ASE} to m or P_{imp} reduces when R is small (i.e., low SNR). A favorable feature of DSCM signals in this regard is the fact that there are spectral valleys where SNR is relatively low. Fig. 2(c) shows the reduction of monitoring error when a narrow spectral slice at a valley is used for ASE noise estimation.

NLI noise monitoring based on pilot tones

When generating a DSCM signal, its subcarriers are usually designed not to be overlapped with each other. Thus, the power inside a spectral valley is mostly NLI, ASE, and implementation noises. To estimate NLI noise power, other noise

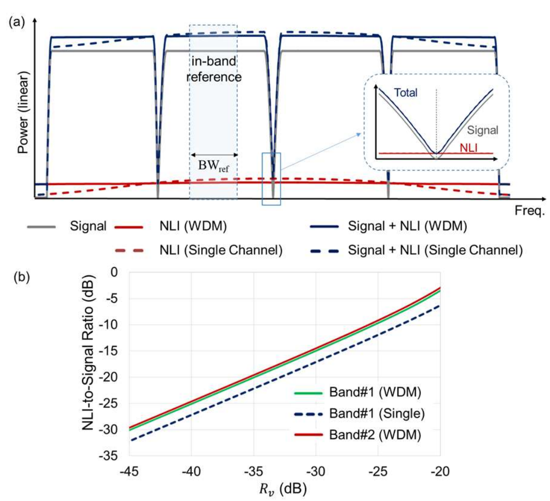

Fig. 3: (a) Simulated power spectra of a DSCM signal for two different channel configurations. Similar NLI-to-signal ratio is assumed for both cases. (b) Relationship between NLI-to-Signal ratio and $\boldsymbol{R_v}$ ($\mathrm{BW_{ref}}$ = 5 GHz)

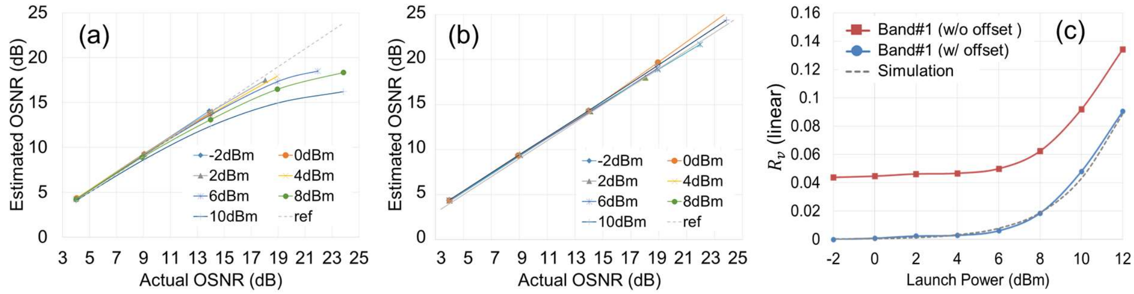

Fig. 4: OSNR monitoring for various launch power (a) without and (b) with NLI correction. (c) $\boldsymbol{R_v}$ measured at the spectral valley between subcarriers #1 and #2 as a function of launch power (BW:1GHz)

factors need to be subtracted but might pose a risk of error propagation. Thus we propose a direct NLI power detection using PT method.

Fig. 3(a) shows a simulated power spectra depicting both signal and NLI contributions. We assume DSCM signals, each of which has 4 subcarriers with a roll-off factor of either 0.04 (outer subcarriers) or 0.08 (inner subcarriers). The noise factors other than NLI are omitted because those are excluded in PT amplitude detection. It is shown that NLI is the major contributor in spectral valleys. For NLI monitoring, we define a parameter as $R_v = (A_{\text{sub1},v} + A_{\text{sub2},v})/A_{\text{sub},ref}$ where $A_{\text{sub1},v}$ and $A_{\text{sub2},v}$ are the PT amplitudes of the spectral slice in a valley and $A_{\text{sub},ref}$ is that of an in-band reference spectral slice (bandwidth: BW_{ref}). The solid lines in Fig. 3(b) show the relationship between R_v and NLI-to-signal ratio. Since the NLI level is relatively flat, the relationship remains almost unchanged for different subcarriers. The flatness of NLI level can be weaken in different channel configurations (e.g., no neighbouring WDM channels) especially for outer subcarriers. The results of the single-channel case are depicted by dashed lines in Fig. 3(a) and (b). Despite this discrepancy, the estimation error between the two extreme cases (i.e., single channel and WDM) are less than ~2 dB.

The normalized spectral shape of NLI is mainly dependent on the signal spectrum itself. Since the signal information such as roll-off factor, subcarrier spacing is already known at TRx, pre-calculated data sets (e.g., NLI-to-signal ratio vs. $\boldsymbol{R_v}$) for different signals can be used to estimate an exact NLI power regardless of the link condition.

Experimental demonstration

For experimental verification, we used a 4-subcarrier DSCM signal having a total baud rate of 63.2 Gbaud. Each subcarrier was modulated with 16QAM-PCS format whose PCS rate is 3.95. The roll-off factor of outer and inner subcarriers were 0.04 and 0.08, respectively. The PT was applied to each subcarrier (m = 0.1), and the PT frequencies were set to be 16.4, 24.2, 19.3, and 29.0 MHz, respectively, from lower to higher wavelengths. The generated signal was sent to transmission link consisting of 6 spans of 75-km long SSMF. To evaluate various conditions with different NLI noise levels, we varied the launch power, P_{in}, into each span from 0 to 12 dBm. After transmission, an additional ASE source was used to adjust the received signal's OSNR. The signal was filtered by an optical filter ($\text{BW}_{3\text{dB}}$: ~90 GHz), and then detected and captured by a conventional coherent receiver and a 4-channel digital sampling oscilloscope operating at 160-GSamp/s, respectively. In Rx DSP, a desired spectral portion was digitally filtered (e.g., bin selection after FFT) and then PT amplitudes were extracted. Fig. 4(a) shows the estimated OSNR versus actual OSNR measured by an optical spectrum analyser (OSA) for various P_{in}. Without the correction of NLI (i.e., $\alpha = 0$), the accuracy was degraded under nonlinear regime. In order to estimate α, we first measured R_v and then used the relationship between α and R_v obtained by simulation. As shown in Fig. 4(b), the accuracy was greatly improved after this correction. In the experiment, we set the bandwidth of the spectral slices (at the valleys) used to estimate R_v to be 1 GHz, which was too broad to discriminate only NLI. To evaluate the change of NLI power as a function of launch power, we applied an offset (i.e., subtraction of the signal contribution) to the measured PT amplitudes. The results are shown in Fig. 4(c) and are in good agreement with the simulation results.

Conclusion

We have proposed a technique, based on amplitude-modulated PT, to estimate OSNR and NLI noise of a DSCM signal simultaneously. The PT amplitude measured at the spectral valley was used as a critical indicator for NLI noise estimation as well as robust and nonlinearity-insensitive OSNR monitoring. The proposed method was experimentally demonstrated using a 4-subcarrier DSCM signal.

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