Joint mitigation of laser phase noise and fiber nonlinearity for polarization-multiplexed QPSK and 16-QAM coherent transmission systems

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Abstract: We propose the use of pilot-aided (PA) transmission, enabled by single-sideband-subcarrier modulation of both quadratures in the DSP-domain, in single-carrier systems to mitigate jointly laser phase noise and fiber nonlinearity. In addition to tolerance against laser phase noise, we show that the proposed scheme also improves the nonlinear tolerance of both polarization-division-multiplexed (PDM) QPSK and 16-QAM coherent transmission systems by increasing the maximum allowable launch power by 1 dB and 1.5 dB, respectively. The improved nonlinear performance of both systems also manifests itself as an increase in the maximum reach by 720 km and 480 km, respectively. Finally, when digital-to-analog converters (DACs) with lower bit resolutions are used at the transmitter, PA transmission is shown to preserve the same performance improvement over the non-PA case.

References and links

1. Introduction

Coherent detection combined with M-ary quadrature amplitude modulation (M-QAM) has emerged as a promising candidate in future optical transport systems because it meets the ever-increasing need for high spectral efficiency [1–10]. Enabled by high speed digital-to-analog converters (DACs) [11] and analog-to-digital converters (ADCs) [12] that can now operate at speeds commensurate with optical line rates, a DSP-based coherent transceiver can pre-compensate or post-compensate transmission impairments by processing the in-phase and quadrature (I and Q) signals on both polarizations [3–5]. Linear impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) are compensated by means of fractionally spaced equalizers with negligible optical signal-to-noise ratio (OSNR) penalties [6–8]. In addition, laser phase noise (PN) can be mitigated by carrier recovery (CR) techniques with OSNR penalties depending on the transmitter (Tx) and receiver (Rx) laser linewidth-to-symbol rate ratio [13]. Feedforward CR techniques are often preferred over feedback counterparts since they provide better laser linewidth tolerances when implemented in a parallelized and pipelined architecture for real-time operation [14]. As the interest in high order M-QAM modulation formats is incessantly growing [15–17], binary phase search (BPS) was proposed in [14] as a feedforward CR scheme suitable for any QAM order (M) with excellent linewidth tolerances that are much needed for such dense constellations. However, BPS is highly complex and its computational requirement increases significantly as the QAM order M increases, i.e., \( M = \{16, 32, 64, \ldots\} \). Other variants of BPS were more recently proposed in [18–20] to reduce the computational complexity while maintaining the excellent performance; however, these techniques are still quite complex and only mitigate laser phase noise and not fiber nonlinearity (NL). These NL impairments caused by fiber Kerr effect are still a problem in long-haul transmission systems since they limit the maximum allowable launch power, which in turn reduces the maximum achievable system reach. Recently, Essiambre et al. showed that NL impairments limit the capacity of a fiber channel compared to a linear additive white Gaussian noise (AWGN) channel [21]. Many techniques have been proposed to mitigate fiber NL effects, such as digital backpropagation (BP) which has proven to be very effective for compensation of intra-channel NL as investigated by Ip et al. in [22]. However, BP is highly complex and requires knowledge of the exact fiber parameters, which is not suitable for optically routed network scenarios. Moreover, BP cannot compensate for inter-channel NL unless the fields of other WDM channels are known at the Rx. In the context of coherent optical OFDM (CO-OFDM) systems, Jansen et al. previously proposed the use of...
pilot-aided (PA) transmission for laser PN compensation in [23] and Inan et al. then extended the scheme for fiber NL mitigation [24].

In this paper, we propose the use of PA transmission in single-carrier (SC) systems to mitigate jointly both laser PN and fiber NL impairments. Pilot-tone insertion is enabled by single-sideband (SSB) modulation of I and Q signals that can be carried out by the Tx-DSP. Advantageously, the complexity of the proposed PA technique is transparent to the order of modulation format and pulse shaping used. It is also inherently suitable for optically routed network scenarios where link parameters do not need to be known. Our simulation results for single channel transmission scenarios show that the proposed technique is capable of laser PN compensation with very low bandwidth (BW) overhead for both PDM-QPSK and PDM 16-QAM coherent transmission systems. Also with a slightly higher BW overhead, the NL tolerance of both systems are shown to improve by allowing for a 1 dB and 1.5 dB increase in the launch power, respectively compared to non-PA transmission. Using PA transmission, the maximum reach distance of both PDM-QPSK and PDM 16-QAM systems can be increased by 720 km and 480 km corresponding to 9% and 20% reach improvement, respectively. Finally, we study the impact of using DACs with lower bit resolutions at the transmitter. We show that PA transmission can still provide the same performance improvement when a DAC resolution of 4 or 5 bits is assumed.

2. Proposed pilot-aided transmission system architecture and concept

The main idea behind the proposed PA scheme is to insert a pilot tone at the middle of the transmitted spectrum of the SC signal. After propagation through the optical channel, the pilot tone will acquire a phase shift ($\theta_{\text{pilot}}$) equal to the sum of the contributions from Tx laser phase ($\theta_{\text{Tx}}$), NL-induced phase shift ($\theta_{\text{NL}}$), and Rx laser phase ($\theta_{\text{Rx}}$). In a noise-free environment, $\theta_{\text{pilot}}$ should be approximately the same as the phase acquired by data symbols due to fiber NL and laser PN. At the Rx, the pilot is filtered out and its phase is determined. By knowing the phase reference of the transmitted pilot tone, the Rx can calculate the extra phase acquired due to laser PN and fiber NL, and hence can correct this phase in data symbols as well.

The proposed PA scheme is a hybrid pre-compensation/post-compensation technique that requires DSP at both Tx and Rx sides. The architecture of a coherent SC transmission system is shown in Fig. 1, where the detailed tasks carried out by the Tx and Rx DSPs in the proposed PA scheme per polarization are shown in Fig. 2. The Tx-DSP first performs pulse shaping on transmitted data symbols $x_n$. A root-raised cosine (RRC) pulse shape with a roll-off factor ($r$) of 1 is assumed throughout the paper; however, the proposed PA transmission technique should work for other pulse shapes as well. Next, the Tx-DSP performs SSB subcarrier modulation by means of Hilbert filtering separately on both I and Q signals $x[n]$ and $y[n]$ (real signals). The subcarrier frequency ($f_{sc}$) used for SSB subcarrier modulation is an important design parameter as it determines the width of the spectral gap left for the pilot tone in the middle of the spectrum. It has to be large enough so that data and pilot symbols do not spectrally overlap throughout transmission. Also, $f_{sc}$ cannot be too large because the ASE noise in the filtered pilot tone at the Rx will be large. Moreover, increasing $f_{sc}$ means an increase in the overall BW of the transmitted signal which makes the signal more vulnerable to tight optical filtering. After SSB modulation, the Tx-DSP inserts two equal pilot tones in both the I and Q signals to produce $x_{\text{SSB,Pa}}[n]$ and $y_{\text{SSB,Pa}}[n]$ which corresponds to adding a pilot symbol at an angle of $\pi/4$ in the complex plane as shown in the illustrative constellation in Fig. 2a. As long as $f_{sc}$ is carefully chosen, the added pilot symbol is frequency multiplexed with the data symbols irrespective of the order of their constellation as shown in Fig. 2a. The power of the added pilot ($P_{\text{pilot}}$) depends on the pilot-to-signal (PSR) power ratio, which is defined as $\text{PSR}(\text{dB}) = 10\log_{10} (P_{\text{pilot}}/P_{\text{signal}})$. Clearly, there is a trade-off between increasing and decreasing PSR. It should be chosen large enough to ensure that noise does not severely mask the pilot while at the same time, it should be small enough to maintain a sufficient signal power compared to noise. Hence, an optimization for PSR similar to [24] is carried out. Figure 3a shows the spectrum of the I-component on the X-polarization of a 28 Gbaud PDM-QPSK signal with an RRC pulse shape having $r$ equal to 1. The spectrum of the same signal is
shown in Fig. 3b after performing SSB modulation on a subcarrier with $f_{sc} = 1$ GHz and pilot insertion with $PSR = -16$ dB. For clarification, a zoomed version of the spectral region near the added pilot is also shown in Fig. 3c. Also, illustrative constellations of transmitted data and pilot symbols per polarization are shown in Fig. 2a for both QPSK and 16-QAM cases.

Fig. 1. DSP-based coherent transmission system (PBS: Polarization Beam Splitter, PBC: Polarization Beam Combiner).

At the Rx, a coherent front-end integrates polarization beam splitters, optical hybrids, a local oscillator and balanced photodetectors to provide four signals corresponding to the I and Q components on both polarizations. These baseband signals are then sampled at their Nyquist rate by four high speed ADCs and processed by the Rx-DSP. As shown in Fig. 2b, Rx-DSP filters the pilot using a Gaussian low-pass filter (LPF) implemented as an FIR filter with a 3 dB BW that is optimized for each launch power in a way similar to [24]. Figure 3d shows the spectrum of the received PA signal after transmission over 20×80 km of standard single-mode fiber (SSMF) with a 4 dBm launch power and noise loading to set OSNR level to 14 dB. Also, Fig. 3e shows a zoomed version of the pilot spectral region together with the spectrum of a Gaussian LPF with a 3 dB BW of 50 MHz. A scatter plot of the extracted pilot symbols is shown in Fig. 2b when 2 MHz lasers are used at Tx and Rx sides. Clearly, PN and NL rotate pilot symbols from their reference phase at the Tx by a value $\theta_{\text{pilot}}$ that varies from symbol to symbol. Hence, the Rx-DSP derotates each data symbol by $\theta_{\text{pilot}}$ of the corresponding pilot symbol. Remaining tasks of the Rx-DSP include compensation of linear...
transmission impairments by frequency domain filtering, SSB demodulation to translate data symbols to baseband, matched filtering, and symbol decision.

![Fig. 3. Spectrum of I-component on X-Pol. of a 28 Gbaud PDM-QPSK signal a) At Tx before SSB together with the spectrum of a 2nd order super-Gaussian 50 GHz MUX (dashed curve), b) At Tx after SSB and pilot insertion with $f_{sc} = 1$ GHz and PSR = $-16$ dB, c) Zoomed version of pilot spectral gap at Tx, d) At Rx after transmission over 1600 km SSMF, launch power = 4 dBm and OSNR = 14 dB, e) Zoomed version of pilot spectral gap at Rx together with a Gaussian LPF with $B_{LPF} = 50$ MHz.](image)

3. Simulation results and discussion

The performance improvement achieved by PA transmission is verified on 28 Gbaud PDM-QPSK and 14 Gbaud PDM 16-QAM systems both delivering a 112 Gb/s bit rate. 216 random symbols are generated and used for all BER calculations for both systems. All Tx-DSP tasks shown in Fig. 2a are carried out at the Nyquist rate in MATLAB R2010a. Then, the four I and Q signals on both polarizations are upsampled to 8 samples/symbol and launched into OptiSystem 9.0 to simulate the optical layer of the transmission system which includes electrical-to-optical conversion, propagation through the fiber channel, and coherent optical-to-electrical conversion. It should be noted that 8 samples/symbol are used in OptiSystem to provide enough simulation BW. For the optical layer, the Tx and Rx lasers are assumed to have a linewidth of 100 kHz each. The signal is propagated over a dispersion unmanaged SSMF with an 80 km span length, attenuation $\alpha = 0.2$ dB/km, dispersion $D = 17$ ps/(nm.km), dispersion slope $S = 0.075$ ps/(nm$^2$.km), effective area $A = 80$ $\mu$m$^2$, Kerr NL parameter $n_2 = 26 \times 10^{-21}$ $m^2$W, and negligible PMD. An Erbium-doped fiber amplifier (EDFA) with a noise figure NF = 7 dB is placed after every span. Noise loading at the Rx is carried out to sweep the received OSNR level when needed for the simulation. At the Rx, the four signals out of the coherent front-end are launched back into MATLAB where they are first downsampled to their Nyquist rate and then processed as in Fig. 2b. Finally, a forward error correction (FEC) threshold BER of $3.8 \times 10^{-3}$ is assumed in all simulations. Both the non-PA and PA systems use CD frequency domain equalization and RRC matched filtering. For the purpose of FFCR in the non-PA system, Viterbi and Viterbi phase estimation (VVPE) [25] and QPSK partitioning [26] are used for PDM-QPSK and PDM 16-QAM systems, respectively. Also, differential encoding is used for the non-PA system to resolve the angle ambiguity. In the PA system, neither differential encoding nor a dedicated FFCR algorithm is used since laser phase noise is compensated by the pilot itself.

Figures 4a and 4b compare the required OSNR versus launch power of the proposed PA scheme to the non-PA one for both PDM-QPSK and PDM 16-QAM systems, respectively. For the 28 Gbaud PDM-QPSK case in Fig. 4a, a transmission distance of 1600 km is used. Two subcarriers of 250 MHz and 1 GHz corresponding to 0.9% and 3.6% BW overhead, respectively, are simulated for the PA system. For those curves, we assume an infinite DAC resolution. Also, optimum values of PSR and 3 dB BW of the pilot LPF are used. As a reference, theoretical results for a linear AWGN channel are also shown. Examining the curves, the two PA systems outperform the non-PA system for small launch powers (0.3 dB less required OSNR) because of the penalty imposed by differential encoding for the non-PA system compared to absolute phase encoding for the PA system (no phase ambiguity). For such small launch powers, there is no difference between the two PA systems which suggests that using a smaller $f_{sc}$ is clearly the better choice to reduce BW overhead. For high launch
powers above 1 dBm, i.e., the NL regime, the PA system with $f_{sc} = 1$ GHz outperforms both the non-PA system and the PA system with $f_{sc} = 250$ MHz due to improved NL tolerance. Hence, we deduce that a larger pilot spectral gap provides better NL tolerance because fiber NL is a rapidly varying process compared to laser PN, and hence a large spectral gap enables the pilot to acquire the faster variations in NL phase. However, this spectral gap can be increased indefinitely. Quantitatively, the PA system with $f_{sc} = 1$ GHz allows for an increase in the allowable launch power by nearly 1 dB for OSNR levels over 14 dB compared to the non-PA system. Next, Fig. 4b compares the required OSNR versus launch power curves of the non-PA and PA systems assuming 14 Gbaud PDM 16-QAM modulation and a transmission distance of 1200 km. $f_{sc} = 1.5$ GHz is chosen for the non-PA system since there is enough room in the 50 GHz channel to accommodate the pilot spectral gap. Clearly, PA transmission improves the NL tolerance if the system by allowing for more than 1.5 dB increase in the maximum launch power for OSNR levels above 19 dB.

Figures 5a and 5b show the reach improvement achieved by using PA transmission for both PDM-QPSK and PDM 16-QAM systems, respectively. In these figures, no noise loading is performed and the OSNR level is limited only by the contribution of in-line EDFAs. As depicted by the figure, PA transmission allows for a maximum reach increase by 720 km and 480 km for PDM-QPSK and PDM 16-QAM systems, respectively which correspond to 9% and 20% reach increase.

![Fig. 4. Required OSNR versus launch power to achieve a BER = $3.8 \times 10^{-3}$ assuming noise loading at Rx side for: a) 28Gbaud PDM-QPSK system with $L = 1600$ km, and b) 14 Gbaud PDM 16-QAM system with $L = 1200$ km.](image)
Finally, we study the impact of realistic bit resolutions of Tx side DACs on the performance of our proposed PA scheme. Since a 16-QAM signal is inherently more vulnerable to quantization effects resulting from lower bit resolution of DACs compared to a QPSK signal, we only consider how the performance of a PDM 16-QAM system is affected when finite resolution DACs are used in both PA and non-PA cases. Figure 6 shows the required OSNR versus launch power curves for a 14 Gbaud PDM 16-QAM system in both PA and non-PA cases for three different DAC bit resolutions: infinite, 5, and 4. The two curves representing the infinite case are identical to the ones shown in Fig. 4b. As the DAC resolution is reduced to 5 and 4, it is clear that both non-PA and PA systems are affected similarly by more stringent quantization. However, it is clearly seen that the PA scheme still outperforms the non-PA system by the same amount as the infinite DAC resolution case.

Fig. 6. Effect of finite DAC resolution on required OSNR versus launch power to achieve a BER = 3.8 \times 10^{-3} assuming noise loading at Rx side for 14 Gbaud PDM 16-QAM system with L = 1200 km.
4. Conclusion

A novel PA transmission is proposed for mitigating jointly laser PN and fiber NL impairments in SC systems. The proposed scheme outperforms the non-PA system that relies only on compensating linear impairments. This comes at the expense of additional transmission BW that depends on whether the PA scheme compensates primarily laser PN or compensates jointly laser PN and NL impairments. With a very low extra BW, the PA technique was shown to work for laser PN compensation in both PDM-QPSK and PDM 16-QAM systems. The proposed scheme has a computation complexity that is independent of the QAM order $M$. Finally, with a slightly higher BW overhead, the ability of the PA scheme to combat intra-channel NL impairments is also demonstrated for both PDM-QPSK and PDM 16-QAM systems. Using the PA scheme allows for a maximum reach increase of 9% and 20% for both systems, respectively. Finally, PA transmission maintains the same performance improvement over the non-PA transmission when a DAC resolution of 4 or 5 bits is assumed.

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