Experimental Demonstration of Joint SPM Compensation in 44-Gb/s PDM-OFDM Transmission with 16-QAM Subcarrier Modulation

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Abstract *We report the experimental demonstration of a recently proposed joint self-phase modulation compensation scheme in a single-channel 44-Gb/s polarization-division multiplexed OFDM transmission with 16-QAM subcarrier modulation, achieving power tolerance improvement as large as 5 dB.*

Introduction

Polarization-division multiplexed orthogonal frequency-division multiplexing (PDM-OFDM) has recently been under active study for potential applications in future optical transport systems [1-2]. With digital coherent detection, PDM-OFDM brings similar benefits as single-carrier based coherent formats such as high spectral efficiency and high receiver sensitivity, while additionally offering transmitter adaptation capability. However, fiber nonlinear effects are found to cause severe signal degradation in long-haul optical OFDM transmission. In dispersion-managed transmission (DMT), self-phase modulation (SPM) imposes a severe limitation on signal power [3,4]. A simple SPM compensation (S-SPMC) scheme was proposed for single-polarization OFDM [3]. For PDM-OFDM, a novel joint SPM compensation (J-SPMC) scheme that jointly processes two signal polarization components was recently proposed [5]. It was numerically shown that J-SPMC increases the optical power tolerance of a PDM-OFDM signal, whose subcarriers are modulated with QPSK, by about 3.5 dB in a DMT [5]. High spectral-efficiency formats are attractive for high-capacity transmission. Spectral efficiency as high as 7.0 bit/s/Hz was recently demonstrated using PDM-OFDM with 32-QAM subcarrier modulation [6]. Here, we show experimentally that the SPM tolerance of PDM-OFDM with 16-QAM modulation is much lower than that with QPSK modulation in DMT, but J-SPMC is more effective for 16-QAM, thereby reducing the transmission performance gap between 16-QAM and QPSK. The optimum cross-polarization cross-phase modulation (XPM) factor used in J-SPMC is also experimentally found.

Experimental setup

Fig. 1 shows the schematic of the experimental setup. At the transmitter, a data stream consisting of pseudo-random bit sequences of length 2^{11}-1 was mapped onto 80 subcarriers with 16-QAM modulation. The data subcarriers, together with 8 pilot subcarriers and 40 unfilled subcarriers, were converted to the time domain via IFFT with size 128. The unfilled subcarriers consisted of one center subcarrier and 39 edge subcarriers. A cyclic prefix of length 16 samples was used, resulting in an OFDM symbol size of 144. Training symbols (TSs) were inserted for channel synchronization and frequency estimation (FE) [1-2]. The real (I) and imaginary (Q) parts of the OFDM symbol sequence were converted to analog waveforms by two 10-GS/s digital-to-analog converters (DACs) imbedded in an arbitrary waveform generator (AWG). The I/Q signals were amplified before driving an optical I/Q modulator that was biased at null. The transmitter laser was an external-cavity laser (ECL) with 100-kHz linewidth. The maximum net data rate of the signal after the optical modulation was 22 Gb/s. The optical signal was then split into two equal copies, which were then delayed by one symbol period (14.4 ns) with respect to each other and combined by a polarization beam splitter (PBS) to form a PDM-OFDM signal with a data rate of 44 Gb/s. After the polarization multiplexing, the TSs were time and polarization interleaved [2]. The optical bandwidth of the 44-Gb/s PDM-OFDM signal is ~7 GHz. The signal was launched into an 80-km standard single-mode fiber (SSMF) followed by a dispersion-compensating fiber (DCF) that compensates the span dispersion. At the receiver, the PDM-OFDM signal was detected by a digital coherent receiver consisting of a polarization-diversity optical hybrid and four 50-GS/s analog-to-digital converters (ADC's) which are imbedded in a real-time sampling scope. The digitized waveforms were processed offline in a computer. J-PSMC [5] was implemented in the receiver digital signal processing (DSP). The other DSP blocks were similar to those described in Refs. [4,5]. The bit-error ratio (BER) of the recovered data was obtained by direct error counting. To better emulate typical DMT, optical noises were equally added before and after the fiber transmission. The received optical signal-to-noise ratio (OSNR) was fixed at 18 dB, at which the bit error ratio (BER) in the back-to-back case was measured to be 1.3×10^{-3}.

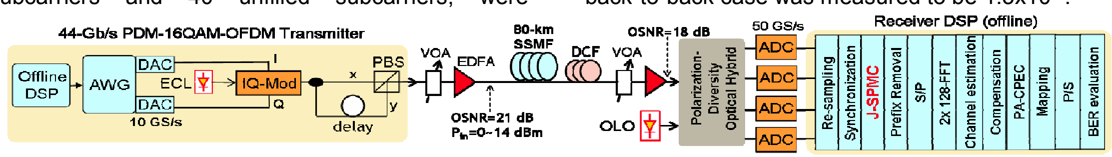

Fig. 1: Experimental setup of a 44-Gb/s PDM-OFDM-16QAM transmission system. VOA: variable optical attenuator.

Experimental results

J-PSMC imposes a compensating phase modulation for each polarization as,

$$\Phi^{x(y)}_{J-SPMC}(t)=\Phi_{SPMC}[P_{x(y)}(t)+BP_{y(x)}(t)]/(\overline{P}_x+\overline{P}_y)$$

where Φ_{SPMC} is the mean compensating phase shift, $P_{x(y)}(t)$ is the instantaneous power of the x(y)-polarization at time t, $\overline{P}_x(\overline{P}_y)$ is the average power of the x(y)-polarization, and B is the cross-polarization XPM coupling factor, which is between 2/3 and 2 depending on the ellipticity of fiber birefringence [7]. To find the optimum value for B, we first set the signal launch power (P_{in}) at 11 dBm, and obtained the signal Q factor, derived from the BER, as a function of Φ_{SPMC} for B=2/3, 1, and 3/2. Fig. 2 shows the results. The Q factors obtained without considering the cross-polarization XPM (B=0), which is effectively equivalent to the S-SPMC case, are also plotted for comparison. Evidently, the inclusion of the B factor greatly improves the SPMC performance, and the optimum B factor is about 1. This is similar to the observation reported recently for SPMC in single-carrier coherent transmission [8].

Fig. 3 shows the measured Q factor of the 44-Gb/s PDM-OFDM signal as a function of signal launch power P_{in}. At 1-dB penalty, the power tolerance is 6 dBm without SPMC. With J-SPMC using B=1, the power tolerance is increased by 5 dB to 11 dBm. With S-SPMC, the power tolerance is only increased by 1 dB to 7 dBm. Notice that without SPMC, the SPM tolerance of PDM-OFDM with 16-QAM modulation is much lower than that with QPSK modulation in DMT [5], but J-SPMC is more effective for 16-QAM and helps to reduce their performance difference.

Fig. 4 shows the constellations of the recovered 44-Gb/s PDM-OFDM symbols in both x and y polarizations after transmission at P_{in}=11 dBm. Without SPMC, the signal Q factor is 4 dB, which is increased to 8.6 dB with J-SPMC using B=1, indicating the high effectiveness of the J-SPMC.

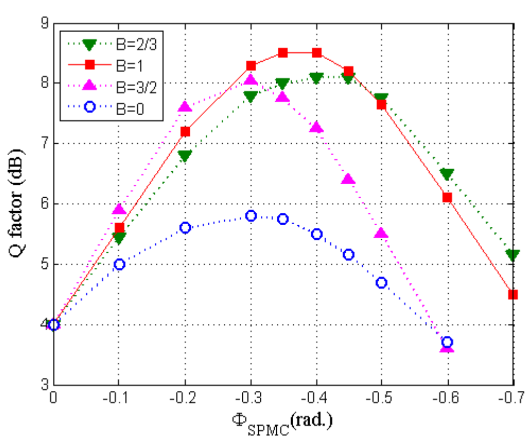

Fig. 2: Measured Q factor versus Φ_{SPMC} with J-SPMC having different cross-polarization XPM factor (B) values. P_{in}=11 dBm. OSNR=18 dB.

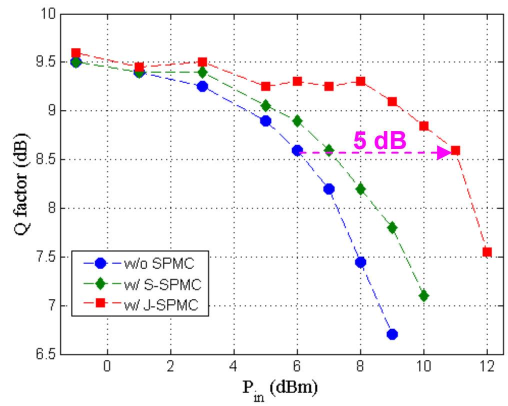

Fig. 3: Measured Q factor of the 44-Gb/s PDM-16QAM-OFDM signal after transmission versus signal launch power (Pin) without and with SPMC. OSNR=18 dB.

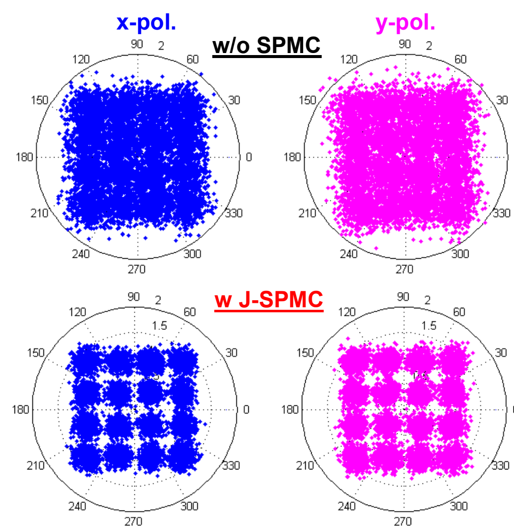

Fig. 4: Constellations of the recovered 44-Gb/s x (left column) and y (right column) PDM-OFDM symbols after transmission over 80-km SSMF without SPMC (upper), and with J-SPMC using B=1 (lower). P_{in}=11 dBm and OSNR=18 dB.

Conclusions

We have demonstrated joint-SPMC in dispersion-managed transmission of a 44-Gb/s PDM-OFDM signal with 16-QAM subcarrier modulation, and achieved a large power tolerance improvement of 5 dB using the optimized cross-polarization XPM factor. This increases the applicability of this highly spectrally efficient format in long-haul transmission where SPM is a major impairment.

References

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