STRATEGIC WHITE PAPER

DEMONSTRATION OF 2.7-PPB RECEIVER SENSITIVITY USING PDM-QPSK WITH 4-PPM AND UNREPEATERED TRANSMISSION OVER A SINGLE 370-KM UNAMPLIFIED ULTRA-LARGE-AREA FIBER SPAN

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Abstract: We demonstrate a record receiver sensitivity of 2.7 photons per bit at 6.23-Gb/s net data rate using PDM-QPSK with 4-ary-pulse-position-modulation. This signal is transmitted over a 370-km unrepeatered ultra-large-area-fiber span with 71.7-dB total loss budget.

OCIS: (060.1660) Coherent communications; (060.5060) Phase modulation; (060.2605) Free-space optical commun.

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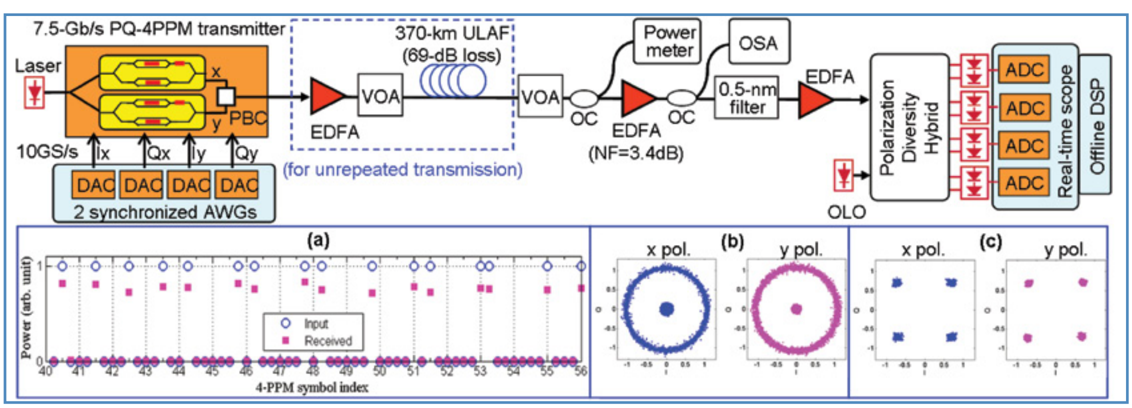
1. INTRODUCTION

Receiver sensitivity is a key performance metric of an optical communication system. Higher receiver sensitivity usually allows for longer transmission reach. In optically pre-amplified receivers, direct-detection binary differential phase-shift keying (DPSK) [1], coherent-detection binary phase-shift-keying BPSK [2], and polarization-division-multiplexed quadrature phase-shift keying (PDM-QPSK) [3-5] are known to provide high receiver sensitivity. Recently, polarization-switched QPSK (PS-QPSK) was proposed [6] to provide ~1 dB higher sensitivity than BPSK at a bit error ratio (BER) of 10-3, and was experimentally demonstrated in an orthogonal frequency-division multiplexing system [7]. More recently, a new power-efficient format based on PDM-QPSK and 16-ary pulse-position-modulation (PPM) was introduced and shown to offer ~3 dB theoretical sensitivity advantage over BPSK at BER=10-3 [8]. A record receiver sensitivity of 3.5 photons per bit (PPB) for Gigabit/s-class systems was experimentally demonstrated at 2.5 Gb/s using a low-overhead pilot-assisted single-carrier frequency-division-equalization (PA-SC-FDE) scheme [8]. Here, we report on the use of PDM-QPSK with 4-ary PPM (PQ-4PPM) to increase the net data rate to 6.23 Gb/s and further improve the receiver sensitivity to 2.7 PPB assuming the use of a 19.25%-overhead forward error correction [9]. Furthermore, we transmit this 6.23-Gb/s PQ-4PPM signal over an unrepeatered 370-km ultra-large-area fiber (ULAF) link with a total link loss budget of 71.7 dB using only Erbium-doped fiber amplifiers (EDFAs) at the transmitter and receiver sites.

2. EXPERIMENTAL SETUP

Figure 1 shows the schematic of the experimental setup. At the transmitter, an external cavity laser (ECL) at 1550 nm with a linewidth of ~100 kHz was used as the laser source, followed by a PDM-I/Q modulator. Each PQ-4PPM symbol contained 6 bits, of which the first 2 bits were encoded through 4-PPM and the remaining 4 bits were encoded through PDM-QPSK. The data bit sequence was a PRBS of length 215-1. The four field components of the encoded PQ-4PPM signal, corresponding to the I and Q components of both x- and y-polarizations, were stored in two synchronized arbitrary waveform generators (AWGs), each having two 10-GS/s digital-to-analog converters (DACs). Twofold oversampling was used, leading to a 4-PPM slot rate of 5 GHz (a symbol rate of 1.25 GHz), which resulted in a raw data rate of 7.5 Gb/s for PQ-4PPM. The DAC outputs were amplified to a peak-to-peak voltage swing of 3.5 V before driving the modulator. The signal has a 3-dB spectral bandwidth of ~6 GHz.

Fig. 1 Schematic of the experimental setup. Insets: (a) power waveform of the 6.23-Gb/s PQ-4PPM signal; (b) signal constellation before PPM demodulation; (c) signal constellation after PPM demodulation and phase compensation.



To measure the receiver sensitivity, the generated 7.5-Gb/s PQ-4PPM signal was attenuated by a variable optical attenuator (VOA) before being split by a 50:50 optical coupler (OC) into two parts, one entering an EDFA with a noise figure (NF) of 3.4 dB, and the other entering a power meter. An optical spectrum analyzer (OSA) was used to measure the optical signal-to-noise ratio (OSNR) of the optically pre-amplified signal. The signal was then filtered by a 0.5-nm optical filter before being received by a digital coherent receiver. For unrepeatered transmission, another EDFA was used to boost the signal power right after the transmitter and the first OC was removed. A VOA was used to adjust the signal power launched into a 370-km ULAF, which had a loss of 69 dB (corresponding to a loss coefficient of 0.187 dB/km) and an effective area of 120 m2. The digital coherent receiver frontend consisted of a 100-kHz-linewidth ECL serving as the optical local oscillator (OLO), a polarization-diversity optical hybrid, four balanced detectors, and four 50-GS/s analog-to-digital converters (ADCs) in a real-time sampling scope. The four sampled waveforms were stored and down-sampled to 10 GS/s before being processed offline. The offline digital signal processing (DSP) used was similar to that described in Ref. [8]. To ensure reliable channel estimation (CE) even in the presence of PPM errors, PA-SC-FDE was used, where the CE is based on known pilot symbols [8]. Inset (a) in Fig. 1 shows a received signal power waveform, indicating that the random locations of the input 4-PPM pulses were correctly identified at the receiver. Inset (b) shows signal constellations in the two original polarization states after channel compensation, but before PPM demodulation, where the points near the origin indicate the slots without PPM pulses. Inset (c) shows signal constellations after PPM demodulation and phase compensation. Clear QPSK constellations were recovered. Figure 2 shows the frame structure of the PA-SC-FDE scheme used for PQ-4PPM. We used similar pilot sequences (T1, T2, and T3) as those used in OFDM [10] for frame synchronization and CE. To minimize overhead, no guard interval (GI) was used for payload symbols although a GI is used in each pilot sequence for accurate CE. The overlap-and-add technique was used during the channel compensation process. For unrepeatered transmission, electronic dispersion compensation [10] was first applied prior to channel synchronization. Additional pilot symbols, each occupying one time slot after 160 slots, were inserted to assist phase estimation (PE). Similar to Ref. [8], the pilot symbols caused a negligible rate overhead of 0.925%. Compared to Ref. [8], the power penalty due to the pilots used for synchronization and CE remained at 0.2 dB, but the power penalty due to the pilots used for PE was reduced from 0.4 dB to 0.1 dB owing to the four-fold reduction in PPM symbol size. Assuming the use of a 19.25% overhead for hard-decision forward error correcting codes (FEC) such as those in [9], which correct BER from 1.5×10−2 to below 10−15, the net data rate of the signal is 6.23 Gb/s.

Fig. 2. Frame structure of the PA-SC-FDE scheme used for PQ-4PPM. CE: channel estimation; PE: phase estimation.

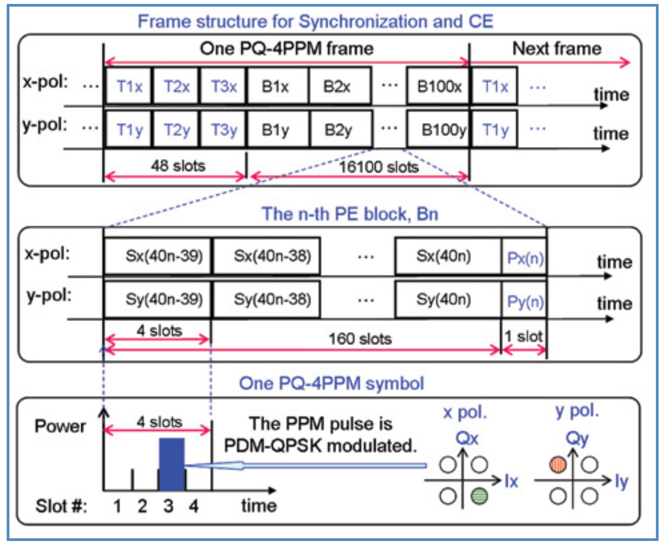
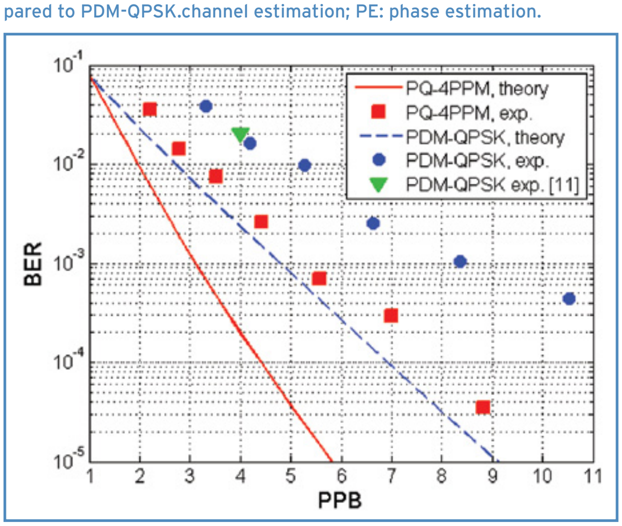


Fig. 3. Theoretical and experimental performances of PQ-4PPM as compared to PDM-QPSK.channel estimation; PE: phase estimation.



2. EXPERIMENTAL RESULTS

Figure 3 shows the experimentally measured BER performance of the PQ-4PPM signal as a function of PPB (referred to the photons per net information bit). Theoretical performance is also shown for comparison. At BER=1.5×10-2, the required PPB is 2.7, which is 1.9 dB away from theory. In the 1.8-dB overall penalty, ~0.8 dB is due to the 19.25% FEC overhead, 0.4 dB is due to the excess EDFA noise, 0.2 dB is due to the pilot sequences used for synchronization and CE, and 0.1 dB is due to the pilot symbols used for PE, leaving only ~0.3 dB to account for the hardware implementation penalty. As a reference, PDM-QPSK performance was also measured by turning off the PPM modulation. The net data rate of the PDM-QPSK signal was 4.15 Gb/s. At BER=2×10-2, the required PPB for the PDM-QPSK signal is ~4, which is essentially the same as that recently reported in Ref. [11]. The 2.7-PPB sensitivity obtained for the PQ-4PPM signal is higher than that obtained for the PDM-QPSK signal by 1.9 dB. The theoretical performances of PQ-4PPM [8] and PDM-QPSK are also shown in Fig. 3 for comparison. It can be seen that PQ-4PPM suffers ~0.6 dB less implementation penalty than PDM-QPSK, probably because the implementation penalty associated with demodulating PPM is lower than with demodulating PDM-QPSK. Compared to the PQ-16PPM demonstration at 2.5 Gb/s [8], this PQ-4PPM demonstration offers a 2.5-fold increase in net data rate and a 1.1-dB reduction in PPB.

Fig. 4. Measured BER performance as a function of signal launch power after transmission over a 370-km ULAF link.

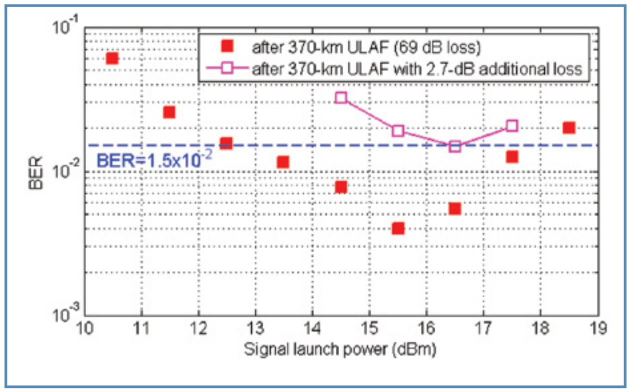


Figure 4 shows the BER performance as a function of signal launch power for the unrepeatered 370-km transmission. Digital self-phase modulation compensation was applied for high input powers. The measured BER is below 1.5×10-2 when the signal launch power is between 12.5 dBm and 17.5 dBm, indicating a substantial power margin of 5 dB. The optimum signal launch power was 15.5 dBm, corresponding to a mean nonlinear phase shift of 2.7 radians for each PPM pulse. At the optimum power, the signal Q factor (derived from the BER) is 8.5 dB, which is 1.7 dB higher than the FEC threshold (1.5×10-2). To assess the maximum allowable link loss, we added 2.7 dB additional loss after the 370-km ULAF, increasing the total link loss to 71.7 dB. The optimum signal launch power was found to be 16.5 dBm, at which the measured BER is just below the BER threshold. At the optimum power, the transmission penalty is estimated to be ~1.5 dB. This allowable link loss budget (71.7 dB) compares reasonably well with the 71.5 dB recently obtained with return-to-zero PDM-BPSK and third-order Raman pumping [12].

4. CONCLUSION

We have experimentally demonstrated a receiver sensitivity of 2.7 PPB by using PDM-QPSK in combination with 4-PPM at 6.23-Gb/s net data rate, outperforming all previously reported Gigabit/s-class sensitivity records. A small implementation penalty was achieved through a low-overhead PA-SC-FDE technique. We have transmitted the 6.23-Gb/s PQ-4PPM signal over a 370-km unrepeatered ultra-large-area with EDFAs only at the transmitter and the receiver sites. A total allowable link loss budget of 71.7 dB has been achieved. This power-efficient modulation format could be attractive in applications where photon efficiency is of critical importance, such as in space communications and unrepeatered fiber transmission.

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