56-Gbaud PDM-QPSK: Coherent Detection and 2,500-km Transmission

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Abstract A 56-Gbaud (224-Gb/s line rate) polarization-division multiplexed quadrature phase shift keyed (PDM-QPSK) signal is transmitted over 2,500 km (32 x 80 km) of fiber and is coherently detected using an 80-GSamples/s oscilloscope with off-line signal processing.

Introduction

With 100-Gb/s transport technologies getting close to commercialization, research is focusing on scaling per-channel bit rates beyond 100 Gb/s, with the goal to develop spectrally efficient solutions for the next Ethernet standards, likely at 400 Gb/s and 1 Tb/s. Approaches include orthogonal sub-carrier multiplexing1 and single-carrier multilevel modulation at high symbol rates2,3. The latter method allows for a simpler transmitter structure at approximately equal receiver and digital signal processing hardware4. Single-polarization quadrature phase shift keying (QPSK) at 53.5 Gbaud and binary modulation at 107 Gbaud have been demonstrated5 using direct detection; the lack of sufficiently fast analog-to-digital converters (ADCs) has prevented coherent detection without resorting to optical time division demultiplexing6 (OTDM), which severely complicates digital compensation of impairments with memory, such as chromatic dispersion (CD). The highest coherently detected symbol rate without OTDM today is7 28 Gbaud for QPSK and 20 Gbaud for 16-QAM2,3.

In this paper, we report the generation, coherent demodulation, and long-haul transmission of 56-Gbaud polarization-division multiplexed (PDM) QPSK, yielding a single-channel line rate of 224 Gb/s.

56-Gbaud PDM-QPSK Transmitter

The experimental setup is shown in Fig. 1. A tunable external-cavity laser (ECL) at 1550 nm with ~100 kHz linewidth is modulated using an integrated LiNbO3 double-nested Mach-Zehnder modulator with 25-GHz 3-dB bandwidth and 4 Vπ. The in-phase (I) and quadrature (Q) branches of the modulator are differentially driven by two 56-Gb/s binary electrical sequences. These are generated by 4:1 multiplexing four delay-decorrelated copies of a 14-Gb/s true pseudo-random bit sequence (PRBS) of length 215–1. Polarization multiplexing is achieved by 3-dB splitting the 56-Gbaud QPSK signal, delaying one copy by 20 ns (1,120 symbols), and combining them in a polarization beamsplitter (PBS), using manual polarization controllers (PCs). The delay is adjusted such that the symbols in the two polarizations are aligned. Eye diagrams and optical spectrum of the 56-Gbaud QPSK signal are shown in the inset to Fig. 1.

56-Gbaud Coherent Intradyne Receiver

At the receiver, the signal is combined with an ECL local oscillator (LO) in a polarization-diversity 90-degree hybrid, followed by 4 balanced detectors. The free-running LO is tuned to within ±1 GHz of the signal carrier. The 4 signal components (Ix, Qx, Iy, Qy) are asynchronously sampled and digitized using two-channel 80-GSamples/s real-time scopes; the frequency response is given in Fig. 2. The high bandwidth and sampling rate are based on digital bandwidth interleaving8 (DBI). The effective number of bits (ENoB) is > 4.5.

To capture the exact same time window on both scopes, as required for intradyne signal processing, a high-speed trigger signal from a 50-Gb/s logic gate is applied to both instruments. We characterized the residual timing skews by simultaneously sampling a

![Fig. 1: Experimental setup of 224-Gb/s PDM-QPSK transmitter and coherent receiver. Inset: Optical spectrum and eyes.](image-url)
fast reference signal. The inset to Fig. 2 shows histograms of ~1000 measurements for the skew within a scope (a) and between the two scopes (b). The intra-scope skew standard deviation is ~1 ps, and the inter-scope skew can be as large as ±1.5 samples (±19 ps). Both random skews are readily compensated within the intradyne receiver algorithm.

As for the sampling rate, we note that the 80-GSamples/s ADCs oversample the 56-Gbaud signal by a factor of 1.4. Since the oscilloscope front-end acts as an anti-aliasing filter that limits the signal spectrum to <30 GHz, sampling at >60 GSamples/s satisfies Nyquist’s criterion. (This process is equivalent to filtering the 56-Gbaud optical signal with a 60-GHz wide optical filter, followed by twofold oversampling at 112 GSamples/s. A 60-GHz window is shown in relation to the signal spectrum in Fig. 1.)

A block diagram of the intradyne receiver algorithm is shown in Fig. 1. We first correct for front-end imperfections, e.g., sampling skew and hybrid phase errors. We then perform CD compensation in the frequency domain. The subsequent clock recovery oversamples a portion of the signal by a factor of 3 using zero-padding in the frequency domain and extracts the tone at the symbol rate (1/T) from the spectrum of the magnitude-squared signal. Using the recovered clock, we synchronously upsample the signal from 1.4 to 2.

Blind source separation, adaptive equalization, and timing recovery are done by a butterfly filter with 16-tap T/2-spaced FIR filters ($H_{xx}$, $H_{xy}$, $H_{yx}$, $H_{yy}$) using the constant-modulus algorithm. Frequency and phase estimation are done by the Viterbi-Viterbi algorithm, followed by decision and differential decoding.

**Back-to-back Characterization**

Figure 3 shows the back-to-back bit error ratio (BER) vs. optical signal-to-noise ratio (OSNR, 0.1-nm reference bandwidth, noise in both polarizations). The circles represent single-polarization 112-Gb/s QPSK signals with a ~0.5-dB difference between x and y polarization due to front-end imperfections. The 224-Gb/s PDM-QPSK signal (squares) has no excess PDM penalty and exhibits a sensitivity of ~20.5 dB at BER = 10^{-3}, ~4 dB off the theoretical limit (dashed). All measurements were error-free (EF) at high enough OSNR (within the statistical limits of ~2.5 million bits used to calculate the BER from 1 million recorded samples per polarization and quadrature).

**Transmission over 2,500 km of Fiber**

Single-channel 56-Gbaud PDM-QPSK transmission was performed in a recirculating loop (Fig. 1) of four ~80-km standard single-mode fiber spans (SSMF, 16 to 17 dB loss/span, 315-km loop length), a gain-equalizing filter (GEF), and no in-line dispersion compensation. Backward Raman amplification (10-dB net gain) and EDFAs with ~5-dB noise figures were used. The signal launch power was -2 dBm, which we found to be close to optimum up to 3000 km.

Triangles in Fig. 4 represent the BER (as Q-factor) versus transmission distance. With a forward error correction (FEC) threshold of 2 x 10^{-3}, 2,500 km can be bridged. Circles give the delivered OSNR, showing ~2.5-dB transmission penalty at 2,500 km.

**Conclusions**

We have demonstrated the first 56-Gbaud coherent detection experiment with full digital impairment compensation. Our 224-Gb/s PDM-QPSK signal has a back-to-back OSNR sensitivity of 20.5 dB and can be transmitted over 2,500 km at BER < 2 x 10^{-3}.

**References**

2. X. Zhou et al., Proc. ECOC’09, 10.3.5 (2009).
4. B. Spinnler, Proc. ECOC’09, 7.3.6 (2009).