# Transmission and Reception of 17×480 Gbit/s PDM-16QAM with Tx/Rx I/Q Imbalance Compensation and Simplified MLSE for Metro-Regional 400G Optical Communications

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**Abstract:** We experimentally demonstrate a single-carrier 400G Metro/regional communications based on 60-GBaud PDM-16QAM over 430-km SMF-28. Joint GPD and GSOP and 4×4 MIMO LMS equalizer are adopted to compensate Rx/Tx I/Q imbalance, and simplified MLSE with 99.61% computational complexity reduction is employed to mitigate channel bandwidth constraint.

## 1. Introduction

Driven by emerging broadband services, such as metaverse, self-driving cars and online machine learning et al., single carrier 400G optical communication standardization has been extensively studied and discussed in industry and academia research community to satisfy continuous explosive growth of data traffic in Ethernet [1-3]. 400G ZR and ZR+ coherent pluggable optics have become new solutions for high-density networks with data rates from 100G to 400G featuring low power and small space from DCI to metro/regional communication [1, 2]. Polarization division multiplexing (PDM) and coherent detection have been adopted to support QPSK signal transmission to meet the previous signal carrier 100G line-side optical interface. It is challenging to upgrade single carrier capacity to 400G with >100 GBaud PDM-QPSK signal transmission utilizing bandwidth limited commercialized opto-electronics components [4]. To address this problem, dual-carrier transmission scheme and high spectrum modulation formats, such as 8QAM [5], 16QAM [3], 32QAM [6], 64QAM [7-9] and even 256QAM [10, 11], are experimentally demonstrated to achieve single carrier 400G. Furthermore, probabilistic shaping is discussed in high-order QAM transmission to further improve system noise tolerance. The other two issues associated with high symbol rate high-order QAM transmission are transmitter (Tx)/Receiver (Rx) I/Q imbalances induced signal distortions and residual ISI cancellation with ultra-high computational complexity maximum likelihood sequence estimation (MLSE).

In this paper, we experimentally demonstrate a single-carrier 400G metro/regional communications based on 60-GBaud PDM-16QAM over 430-km SMF-28. To well address the bandwidth limitation induced inter-symbol interference, MLSE adopted in 100G/200G to suppress the enhanced noise in high frequency domain [12] is also used in 400G PDM-16QAM signal transmission, while simplified MLSE is proposed by adaptively adjusting its number of transfer status and path in Trellis to meet the low power-consumption criterion of 400G transponders. Goard phase detector (GPD) and 4×4 MIMO least-mean-square (LMS) equalizer are utilized to compensate Rx and Tx I/Q imbalance, respectively. By adopting I/Q imbalance compensation and simplified MLSE, the transmission distance over SMF-28 can be extended from 80km to 430km, and simplified MLSE can achieve 99.61% computational complexity reduction compared with conventional MLSE.

## 2. System Configuration

Figure 1 shows the experimental setup of 17×480 Gbit/s PDM-16QAM transmission, together with Tx and Rx digital signal processing algorithms. 17 tunable external cavity lasers (ECLs) with 0.6nm (75-GHz grid) channel spacing are used as the optical carriers to carrier 60Gbaud PDM-16QAM signal. The output power and linewidth of each optical carrier are 16dBm and less than 100KHz, respectively. Two High-Bandwidth Coherent Driver Modulators (HB-CDMs) are adopted in the transmitter to realize the generation of PDM-16QAM optical signal. One optical carrier is input into one HB-CDM and another 16 coupled optical carriers are injected into another HB-CDM to emulate untested WDM channels. It is worth noting that the channel to be measured in optical back to back (OBTB) WDM is the 8$^{th}$ channel, and a polarization maintaining EDFA is used to compensate the average power differences between single optical carrier and each optical carrier of coupled 16 optical carriers. The measured pulse shaped 60Gbaud 16QAM signal with 0.1 roll-off factor of root raise cosine (RRC) shaping pulse is generated with 4-channel differential outputs arbitrary waveform generator (AWG) under 64GSa/s sampling rate and 20GHz -3dB bandwidth working conditions. The signal from the output of two HB-CDMs is coupled together to get 17 channels 480 Gbit/s WDM PDM-16QAM signal. The coupled WDM signal is launched into several cascaded fiber link spans to verify the optical fiber transmission performances. One EDFA and 80km SMF-28 are consisted in one span. EDFA can be used to compensated the loss of 80km SMF-28 and the launch power into fiber link is adjusted by the gain of the EDFA in the first span. After fiber transmission, the tested wavelength is filtered out by the programable wavelength selective switch (WSS). After that the tested wavelength and local oscillator (LO) laser are connected to a 40-G class integrated coherent receiver (ICR) to realize coherent detection. The output 4-channel electrical signal from ICR are captured and restored in digital oscilloscope with 80GSa/s sampling rate and 36GHz bandwidth. Rx DSP algorithms are implemented to recover 16QAM symbols including resampling, chromatic dispersion compensation (CDC), Godard phase detector (GPD)-based receiver side skew compensation, Gram-Schmidt orthogonalization procedure (GSOP) for compensation of quadrature imbalance in phase and amplitude, blind equalization based on constant modulus algorithm (CMA) and constant multiple modulus algorithm (CMMA), frequent offset estimation (FOE), carrier phase estimation (CPE), 4×4 multiple-input-multiple-output (MIMO) based transmitter side imbalance compensation, poster filter cascaded MLSE and direct error counting.

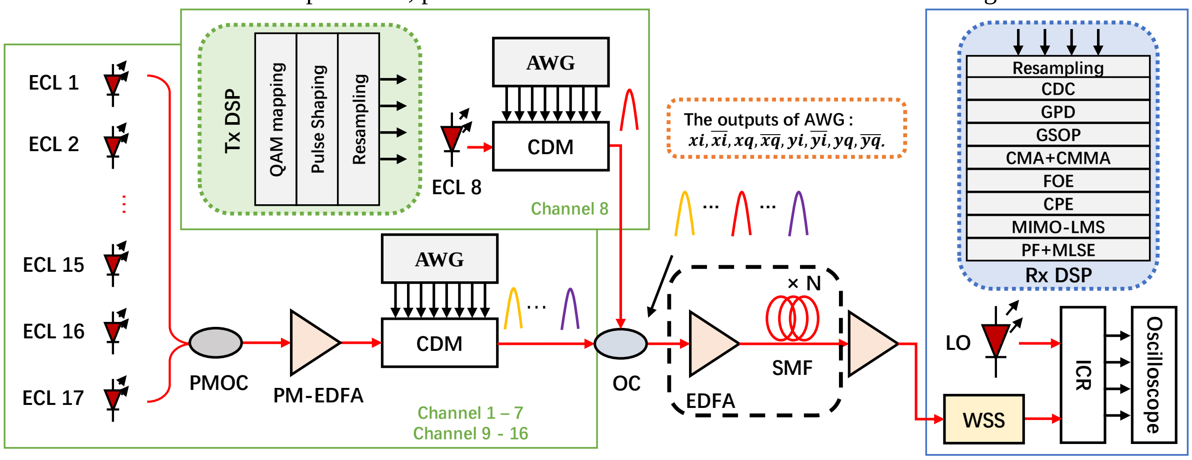


Fig. 1. Experimental setup of 17×480 Gbit/s PDM-16QAM transmission. Insets: Tx and Rx DSP.

The simplification of MLSE is achieved by the threshold detector and slicer. The equalized symbols after delay and adding post-filter is sent into MLSE for symbol detection. The coefficients of post-filter are obtained with the Yule-Walker equations. The mechanism of threshold detector is shown in Fig. 2(a), which can decrease the number of states from 4 to 2. The mechanism of slicer is to filter out those symbols that are close to the standard level as shown in Fig. 2(b). The symbols in yellow area will be filtered out and the size of yellow area can be controlled by adjusting a defined parameter *W*. The compression of transitions in MLSE trellis depends on the output of slicer (S_Seq) as shown in Fig. 2(c). There are four possible compressed transitions trellis diagrams based on different combinations of S_Seq(n) and S_Seq(n-1).

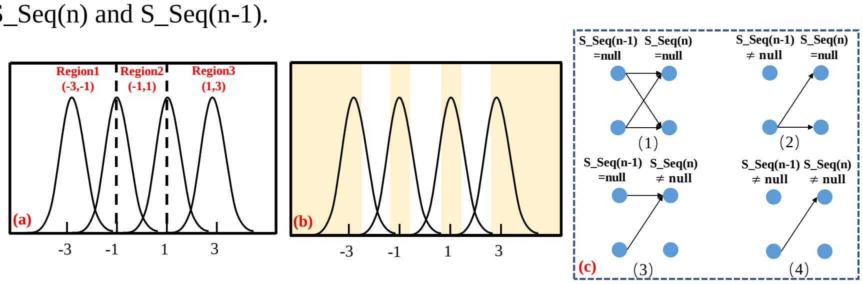


Fig. 2. Simplified MLSE. Insets (a) Threshold detector, (b) Slicer, and (c) Transitions compression in Trellis.

## 3. Experimental Results

To verify the effectiveness of proposed Rx/Tx I/Q imbalance compensation and simplified MLSE in the transmission of 17-channel WDM PDM-16QAM signal transmission, BER versus OSNR in single channel and WDM situation are both measured in OBTB and shown in Fig. 3, the measured channel in WDM OBTB is the 8$^{th}$ channel. As shown in Fig. 3(a), 4 dB receiver sensitivity is achieved with proposed 4×4 MIMO-LMS equalizer for TX IQ imbalance compensation in the single channel transmission measurement, and additional 1.2 dB receiver sensitivity can be obtained after MLSE is utilized for symbol detection. The constellations of equalized symbols after CMMA and 4×4 MIMO-LMS equalizers @40 dB OSNR are shown in Fig.3(a) as insets (i) and (ii), respectively. The convergence characteristic of equalized symbols can be significantly improved by the proposed 4×4 MIMO-LMS after CMMA. To effectively reduce the computational complexity of MLSE detector to meet 400G ZR+ low power consumption requirement, the *W* parameter in the slicer of simplified MLSE is adjusted by taking both the OSNR penalty and computational complexity reduction into consideration. The optimized *W* parameter is 0.9, in which we can achieve 99.61% computational complexity reduction compared to conventional

MLSE with only 0.2dB OSNR penalty at hard-decision FEC threshold (HD-FEC). There is still 1 dB receiver sensitivity improvement existing with simplified MLSE detector. To improve the spectrum efficiency of WDM signal transmission system, the channel spacing is set at 75 GHz, and the measured BER of the 8$^{th}$ channel versus OSNR is also shown in Fig. 3(b). No OSNR penalty is observed in WDM compared with corresponding single channel in OBTB, and the simplified MLSE can still work well in WDM.

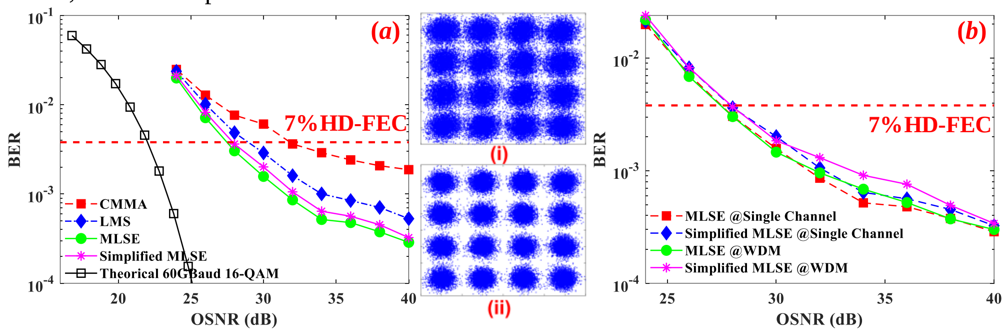


Fig. 3. BER versus OSNR of (a) single channel and (b) the 8$^{th}$ channel of WDM channels 480Gbit/s PDM-16QAM signal transmission in OBTB.

Total launch power versus BER in WDM after 400km SMF-28 transmission is shown in Fig. 4(a), powers of all channels are maintained as the same, the optimized total launch power for both conventional MLSE and simplified MLSE are both 13 dBm (~0.7dBm/channel). In the following fiber transmission test, the total launch power of combined WDM channels is set at 13dBm. Fiber transmission distance versus BER are measured and given in Fig. 4(b), to satisfy the BER of recovered 16QAM symbols below the HD-FEC threshold, the maximum fiber transmission after CMMA, 4×4 MIMO-LMS and simplified MLSE are <80km, 320km and 430km, respectively, which indicate that the proposed 4×4 MIMO-LMS and simplified MLSE can effectively increase the transmission distance of optical fiber. BERs of all 17 channels 480Gbit/s PDM-16QAM signal with proposed 4×4 MIMO-LMS and simplified MLSE are measured and shown in the Fig. 4(c), all the measured BERs are below the HD-FEC threshold, and the optical spectra of 17-channel WDM signal in OBTB and after 400-km SMF-28 transmission in Fig. 4(c) as an inset.

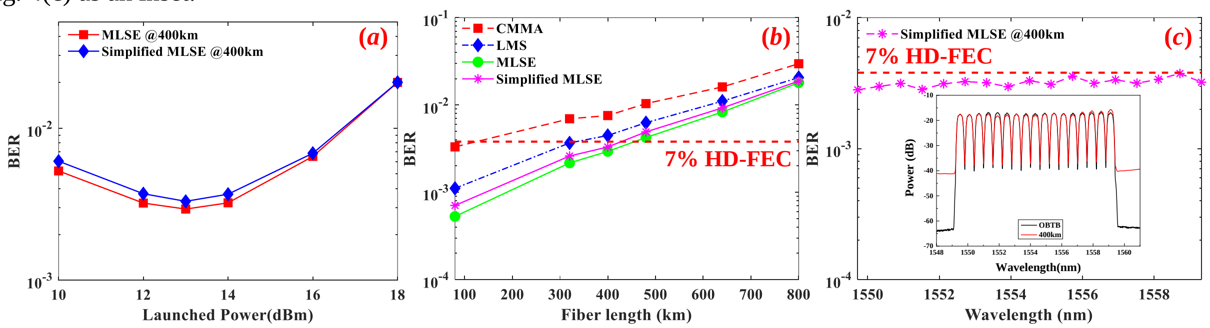


Fig. 4. (a) Total launch power versus BER in WDM transmission, (b) Fiber transmission versus BER in WDM transmission, and (c) Measured BERs of all 17 channels in WDM transmission.

## 4. Conclusion

To improve the receiver sensitivity of signal carrier 400G signal transmission, joint GPD and GSOP and 4×4 MIMO LMS equalizer are adopted to compensate Rx/Tx I/Q Imbalance, and 99.61% computational complexity reduction MLSE is employed to mitigate channel bandwidth constraint. The experimental results of 17×480 Gbit/s PDM-16QAM signal transmission show that 4-dB and 1-dB receiver sensitivity improvements are achieved with 4×4 MIMO LMS equalizer and simplified MLSE, respectively. The total achievable fiber transmission distance under HD-FEC threshold is extended from less than 80km to 430km, the proposed scheme provided a feasible scheme for Metro-regional 400G optical communications.

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