

# Transmission of 400G PM-16QAM Channels over Long-Haul Distance with Commercial All-Distributed Raman Amplification System and Aged Standard SMF in Field

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**Abstract:** Transmission of eight dual-carrier 400G PM-16QAM channels over 1,504-km aged SSMF in field is demonstrated with high-coding-gain FEC and commercial all-distributed-Raman amplification system. The result shows 16QAM can be used for deployed long-haul fiber networks.

**OCIS codes:** (060.2330) Fiber optics communications; (060.1660) Coherent communications.

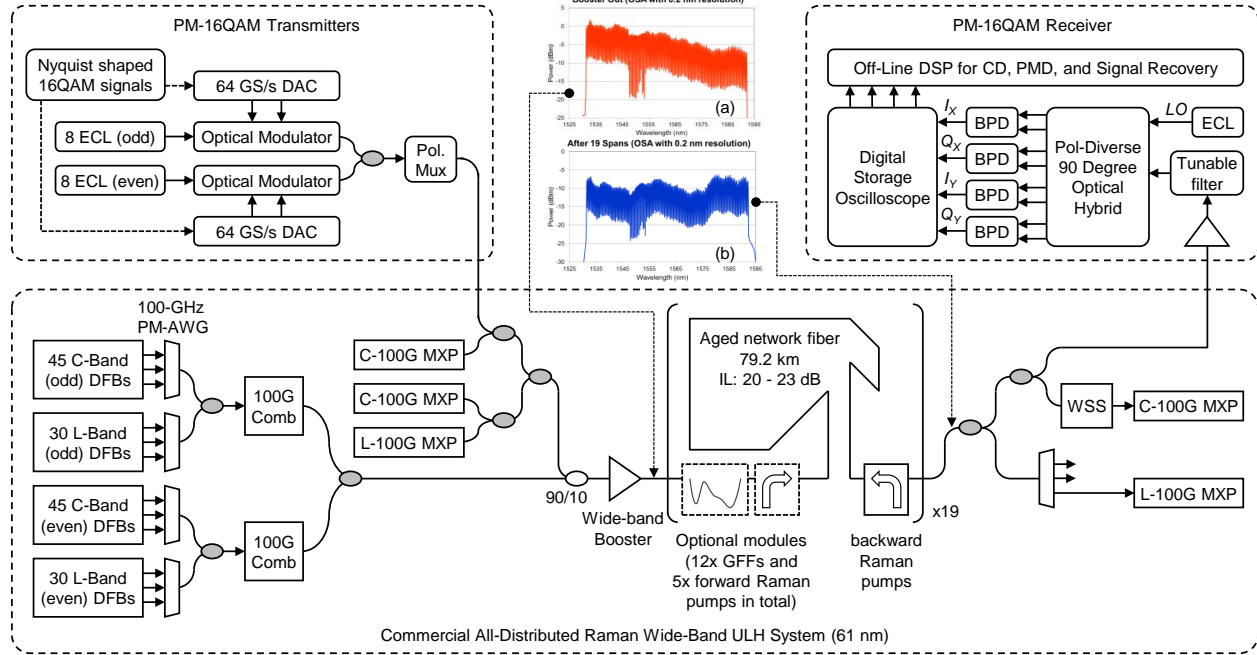
## Introduction

PM-QPSK has become the standard long-haul transmission modulation format for practical carrier networks while PM-16QAM has been considered for practical metro and regional networks [1, 2]. Since much higher SNR is required for 16QAM signals compared with QPSK signals it has not been considered so far to run 16QAM signals for long-haul distance in a real field environment with lossy and aged fiber. Transmission of PM-16QAM signals over 6,600 km and 9,100 km have been just reported [3, 4]; however, the reported experiments are conducted in a lab environment using ultra-low loss and ultra-large core fiber, which have not been deployed in field in any reasonable scale. The transmission distance of the latest reported field trial of PM-16QAM with a commercial transmission system in field is 412 km, which covers only regional distances [5]. It is desired to test if 16QAM signals are able to run for long-haul distances in large carrier existing networks. In this paper we demonstrate that PM-16QAM signals are able to be transmitted over long-haul distances in deployed networks with aged fibers. The result is obtained by using an all-distributed Raman amplification system combined with high coding gain FEC.

## Experimental set-up

Figure 1 shows the experimental configuration. For 400G signal generation, a total of eight dual-carrier 400G PM-16QAM channels were generated by the PM-16QAM transmitter. 16 external cavity lasers (ECLs) were separated into two groups at 100-GHz channel spacing followed by two optical dual-nested Mach-Zehnder modulators (or I/Q modulators) for independent 16-QAM modulation of the odd and even subcarriers within each 400G channel. The I/Q modulators were driven by 32-GBaud Nyquist rate signals using a 64-GS/s digital-to-analog converter (DAC). After passively combining the odd and even subcarriers at 50-GHz spacing, polarization multiplexing was performed by delaying one copy of the combined signal by  $\sim 250$  symbols. Each dual-carrier 400G PM-16QAM signal has a raw data rate of  $32 \text{ (Gbaud)} \times 2 \text{ (polarization)} \times 4 \text{ (bit/symbol)} \times 2 \text{ (subcarriers)} = 512 \text{ Gb/s}$ , occupying a spectral width of 100 GHz as shown in Figure 2(a). The 28% overhead reserved is enough for implementing the 2nd Gen. Soft-Decision Forward Error Correction (SD-FEC) with 25.5% FEC overhead and 12-dB coding gain [6]. With the SD-FEC, the PM-16QAM transmitter has a back-to-back OSNR tolerance at 16.5 dB for each subcarrier. The eight 400G channels were then multiplexed in wavelengths with  $134 \times 100\text{G}$  PM-QPSK signals using an optical coupler before the WDM mixed line-rate signal was transmitted. The signal launch power per subcarrier for PM-16QAM was adjusted to be the same level as the co-propagating PM-QPSK signals. At the receiver side, two cascaded couplers were used to drop the 400G 16QAM signals to the corresponding receiver. At the PM-16QAM receiver, an optical tunable filter with 1-nm bandwidth was used to filter out each 400G channel for data measurement. The filtered signal is sent to a polarization-diversity  $90^\circ$  optical hybrid, where one of the two subcarriers was down-converted each time to baseband by tuning the optical frequency of the local oscillator (LO) laser. The outputs of the optical hybrid were detected using four balanced photodetectors (BPDs), recovering the I and Q signals in both X and Y polarizations. These signals were sampled and digitized by a four-channel real-time oscilloscope with 50-GS/s sampling rate and 18-GHz bandwidth. The data were then processed using offline DSP, which includes a fixed frequency-domain equalizer (FDE) for chromatic dispersion compensation, followed by an

adaptive time-domain equalizer (TDE) to compensate non-stationary effects. The TDE first uses a multi-modulus algorithm (MMA) to initialize the equalizer then transfers the process to decision-directed least-mean-square (DD-LMS) algorithm. For BER computation, 10 data sets of 120,000 symbols were captured and processed for each subcarrier in each 400G channel ( $9.6 \times 10^6$  bits per subcarrier), and the BERs of the odd and even subcarriers are combined to produce the value for the 400G channel.



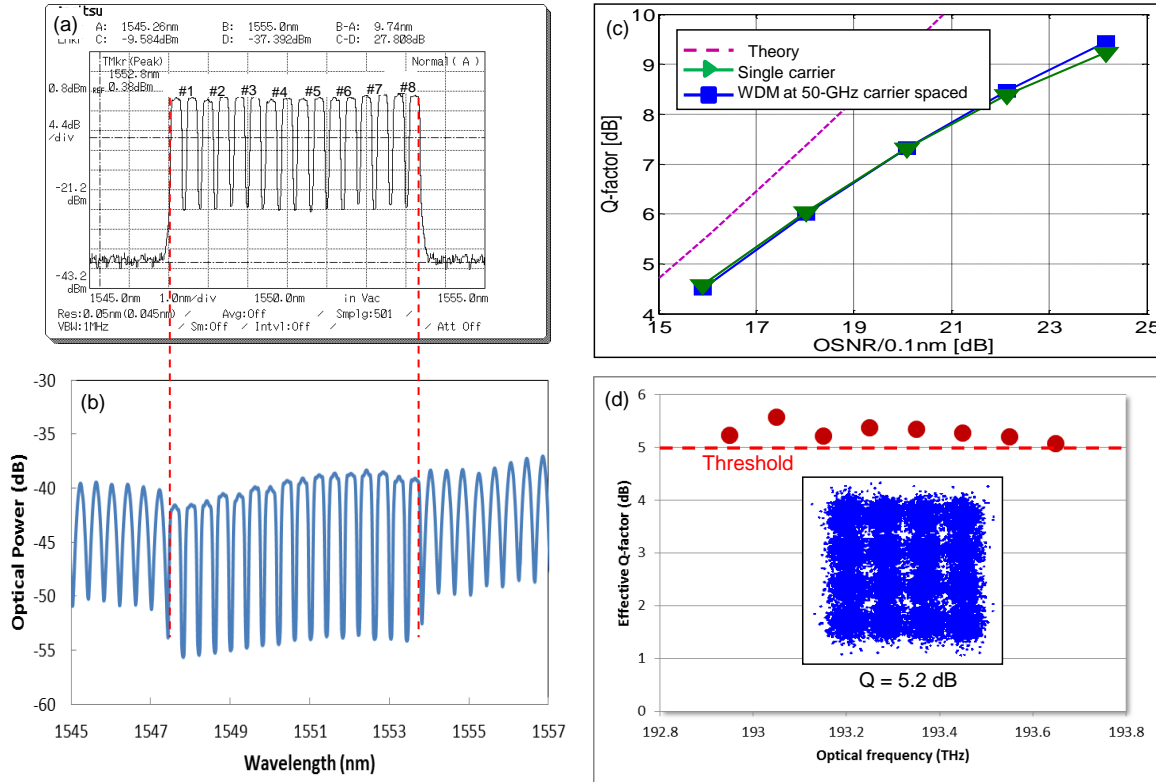
**Figure 1** Experimental set-up for long-haul PM-16QAM channels transmissions with field deployed fiber. Insets: system spectrum at boost amplifier (a) and after transmission (b).

For the commercial all-distributed Raman wide-band transmission system, two modified 100G line cards (hereafter referred to as comb modulators) are used to generate multiple modulated 100G loading channels. A comb modulator accepts an input CW comb generated from a bank of external signal sources and outputs a 120 Gb/s PM-QPSK modulated comb with signals spaced 100 GHz apart. External distributed feedback (DFB) lasers in the C-band (1531.51 nm ~ 1567.13 nm) and L-band (1567.54 nm ~ 1592.10 nm) are separated into two groups with 100 GHz spacing (odd and even) and combined through a 100 GHz PM-AWG and PM 3dB coupler. The channels in each group are modulated by a comb modulator and then combined with a 3dB coupler to generate 50-GHz spaced channels. Three additional production 100G cards (with real-time processing; one in the L band and two in the C-band) are combined with a second 90/10 coupler. In this experiment, all of the channels are modulated at 120 Gb/s, which accounts for the 15% overhead of the SD-FEC. The SD-FEC can correct a BER of  $1.9 \times 10^{-2}$  to less than  $10^{-15}$ . A wide-band hybrid erbium / Raman amplifier is used to boost the signals on the transmit side. The experiment is carried over the Verizon network fiber which was deployed around Dallas more than ten years ago. It is a G.652 fiber with multiple splice points as a result of construction activities in the metropolitan area. Each span is 79.2 km and the average span loss is 21.8 dB. Most of the span losses are compensated by backward Raman pumping and the occasional use of forward Raman pumping. The production backward Raman pump module consists of 5 pump wavelengths in the 1420 to 1500 nm and can deliver up to 1.9 W of distributed pump power. The production forward pump module includes 3 pump wavelengths (1430 ~ 1480 nm) and can deliver up to 0.85 W. Total five forward pump modules and 12 passive gain-flattening filters (GFFs) are used in the system. Due to multiple-pump wavelengths in the Raman pump modules, the gain ripple of the channels can be controlled without any additional active gain flattening devices. At the receiver end, the C-band channels are selected and filtered by a wavelength selective switch (WSS) and the L-band channels are filtered by an L-band demultiplexer.

## Results and Discussion

The transmit channels are pre-emphasized to achieve approximately flat Q-factor over all channels at the receiver, as shown in Figure 1(a). The spectrum after transmission is shown in Figure 1(b). The signal power ripple is measured to be 4.5 dB after 1,504 km transmission. The average OSNR over selected channels (every ten channels) is measured to be about 19.6 dB. The enlarged optical spectrum for eight 400G PM-16QAM channels after

transmission is plotted in Figure 2(b). The average subcarrier OSNR (with 0.1-nm noise resolution) was 19.5 dB after 1,504 km. Figure 2(c) shows the back-to-back performance of the 400G transceivers, for single carrier and multiple-carriers with 50-GHz carrier spacing. Our implementation penalty is about 1.5 dB at 5-dB FEC threshold. The impact of multiple-channel WDM to the back-to-back performance is negligible. Figure 2(d) plots the effective Q-factors, derived from BER counting, for all dual-carrier 400G channels at the receiver, where the inset shows a particular constellation map with  $Q = 5.2$  dB. All eight dual-carrier 400G PM-16QAM channels obtained results above the SD-FEC Q-factor threshold of 4.95 dB, which corresponds to  $BER = 3.8 \times 10^{-2}$  [6]. The Q-factor of all the PM-QPSK 100G channels is measured with real-time processing 100G line cards. During the Q-factor measurement, each individual transmit channel from the comb modulators is replaced by the 100G line card tuned to that channel. Q values of all channels are roughly equalized and show average value of 11.4 dB which is 5 dB higher than SD-FEC threshold of 6.4 dB.



**Figure 2** Results of the experiment: spectrum of eight dual carrier PM-16QAM 400G channels before transmission (a); the spectrum after transmission of 1,504 km (b); back-to-back PM-16QAM transceiver performance (c), and Q-factors of received 400G PM-16QAM channels transmitting over 1,504 km (inset: exemplary constellation map) (d).

## Conclusion

We have successfully performed a transmission experiment of eight dual-carrier 400G PM-16QAM channels with 50-GHz over a long haul distance of 1,504 km in field with aged fiber. All-distributed Raman amplification and high-gain FEC codes play the key roles in this test. The result shows that 16QAM signals can be supported by existing long haul fiber networks by reducing OSNR degradation during signal propagation and by increasing FEC coding gain. This experiment demonstrates that to double the fiber capacity and spectral efficiency of the current industry norm of carriers' long haul network is feasible by using 16QAM signals.

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