Real-Time Transmission Measurements from 200 Gb/s to 600 Gb/s over Links with Long 122 km Fiber Spans

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Abstract: We present results for real-time coherent transmission with data rates from 200 Gb/s to 600 Gb/s in 50 Gb/s increments over a re-circulating loop with 122 km spans of ultra-low loss, large effective area fiber. © 2020 The Author(s)

1. Introduction

According to the latest industry estimates, data traffic continues to grow exponentially in various parts of optical networks, and current predictions point to the continuation of this trend [1]. In the context of long-haul transmission, this necessitates the industry to increase available transmission capacity via putting more fibers in a cable, using C+L band technology, increasing signal-to-noise ratio, and performing network optimization. There have been several recent demonstrations of real-time transmission of advanced modulation formats and higher baud rate signals including lab experiments [2-5] and field trials [6-10]. Some of the recent demonstrations have been with single-carrier data rates of 200 Gb/s or less [4,6,9,10], while others have shown real-time transmission results with single-carrier signals at 400 Gb/s and up to 600 Gb/s [2,3,5,7,8]. Most of the 400G and higher demonstrations have been over relatively short links of a few hundred km.

In this paper, we present results for real-time transmission over an ultra-low loss, 150 μm^2 effective area fiber with a high baud rate (69-72 Gbaud) flex-rate transponder operating at data rates from 200 Gb/s up to 600 Gb/s over a system with span lengths of 122 km. We achieve an error-free reach of more than 3600 km for 400 Gb/s, while 300 Gb/s and 200 Gb/s signals show trans-Atlantic and trans-Pacific reaches, respectively. Signals at 500 and 600 Gb/s are shown to have regional and metro reaches. We also demonstrate that the achievable distance depends on system margin, and that transmission capacity can be increased significantly by employing low margin (<1 dB) network design.

2. Transceiver Characterization

The transceiver used in these experiments is a flex-rate transceiver using Indium Phosphide (InP) narrow linewidth laser, Mach-Zehnder modulator and receiver [11] allowing a wide range of symbol rates and modulation formats. Further, the transceiver may be operated in a mode that transmits and receives half blocks of two adjacent quadrature amplitude modulation (QAM) formats in a defined block length of 128 symbols to adjust the Baud rate and the net data rate in increments of 50 Gb/s. The modulation formats evaluated in these experiments were polarization multiplexed (PM)- QPSK, 8QAM, 16QAM, 32QAM, and 64QAM. Before beginning the transmission experiments, we evaluated the transceiver performance in back-to-back operation by measuring the minimum optical signal to noise ratio (OSNR) values with 0.1 nm noise bandwidth that produce error-free signal recovery after forward error correction (FEC) for the data rates of 200, 300, 400, 500, and 600 Gb/s. These minimum required OSNR values may be converted into gap-to-Shannon values by the following approach to illustrate the distance in SNR space between the real-time transceiver performance and the theoretical Shannon signal capacity.

The gap-to-Shannon data for each data rate were estimated by first converting the minimum required OSNR values to minimum required SNR values as

$$SNR(dB) = OSNR(dB) - 10\log\left[\frac{R_{sym}\cdot(1+\alpha)}{\Delta\nu_{res}}\right] \qquad (1)$$

where R_{sym} is the symbol rate, α is the roll-off factor for the root-raised cosine (RRC) filtered signal, and $\Delta\nu_{res}$ is the resolution noise bandwidth (12.5 GHz) in the OSNR measurements. Then the information rate (b/sym) is calculated as (net data rate/symbol rate) for the transmitted signal. The difference between the minimum SNR required for the signal and the theoretical SNR for that information rate given by the Shannon formula is then taken as the gap-to-Shannon value. Results for the gap-to-Shannon values from 200 Gb/s to 600 Gb/s are shown in Fig. 1.

For 200-500 Gb/s, the symbol rate (baud rate) was 69.4 Gbaud and the FEC overhead was 27%. For the 600 Gb/s signal, the baud rate was 71.9 Gbaud, the FEC overhead was 15%, and this data rate was achieved by a hybrid combination of 32QAM and 64QAM symbols. The RRC roll-off factor was 0.1 for all signals. The results in Fig. 1 show that the gap-to-Shannon values generally increase with modulation format complexity and net data rate but was only 2.6 dB for a 200 Gb/s PM-QPSK signal, and less than 4 dB for 300 (PM-8QAM) and 400 Gb/s (PM-16QAM) signals.

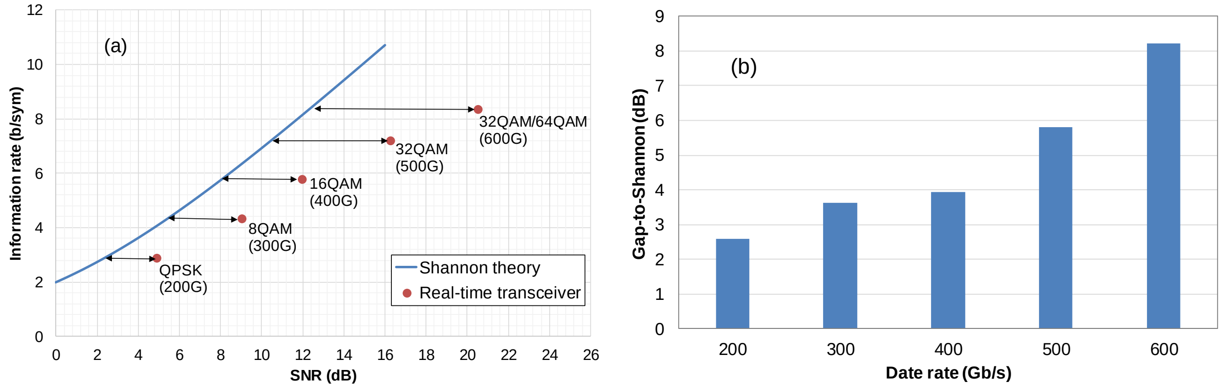

Fig. 1: a) Information rate vs. required SNR for measured modulation formats and theory. b) Summary of gap-to-Shannon data as a function of data rate.

3. Transmission Experiments over a Re-Circulating Loop

Long-haul transmission system experiments were conducted next with the real-time transceiver. A schematic diagram of the re-circulating loop system is shown in Fig. 2a. The real-time transceiver module had two independent transmitters and receivers, with each transmitter tunable over the C-band. Two channels from the module at 1550.12 and 1550 .92 nm were combined with 14 other 64 Gbaud PM-16QAM channels generated by laboratory equipment and spaced by 100 GHz before all channels were launched into the loop. The two real-time channels were located in the center of the 16 channel spectrum. The loop was comprised of 5 spans of ultra-low loss, very large effective area optical fiber (Corning® Vascade® EX3000 fiber), with an average span length of 122.2 km. The fiber effective area was about 150 μm^2. The average total span loss was 19.3 dB including connectors and splices. Each span was followed by an erbium doped fiber amplifier (EDFA) and a variable optical attenuator (VOA) to control the launch power in the following span. A loop synchronous polarization scrambler (LSPS) was used to mitigate loop effects and a gain equalization filter (GEF) was employed at the end of the loop to flatten the spectrum. The two real-time channels from the transceiver module were selected by an optical bandpass filter at the loop output and were directed to the real-time receivers 1 and 2 with a wavelength selective switch (WSS) after amplification. The real-time module was operated in a gated fashion to work in the re-circulating loop environment and the received signals were detected and processed according to the loop circulation number and total transmission distance under test. A minimum of 10^{12} bits was detected and evaluated for all bit error rate (BER) measurements in the transceiver. The spectrum for the 400 Gb/s channels after 3666 km is given in Fig. 2b.

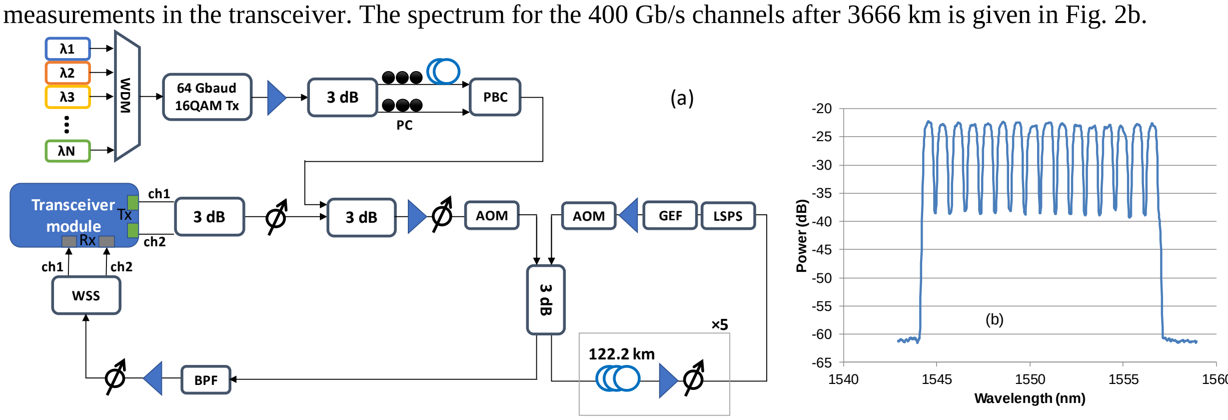

Fig. 2: a) Schematic illustration of the transmission system. PC: polarization controller, AOM: acousto-optic modulator, BPF: band-pass filter (2 nm). b) Optical spectrum of 400 Gb/s signals after 3666 km transmission.

Transmission experiments were performed with the flex-rate real-time transceiver module with data rates from 200 Gb/s to 600 Gb/s in increments of 50 Gb/s. The data rates of 200, 300, 400, and 500 Gb/s were achieved with 69.4 Gbaud signals using the PM modulation formats QPSK, 8QAM, 16QAM, and 32QAM, respectively. Data rates of 250, 350, and 450 Gb/s were generated with mixed constellation blocks using the formats on each side, e.g. 450 Gb/s was comprised of 16QAM and 32QAM symbols in equal proportion per block. The 550 and 600 Gb/s signals were both generated with combinations of 32QAM and 64QAM symbols. The 550 Gb/s signals had a 69.4 Gbaud symbol rate and the 600 Gb/s signal had a 71.9 Gbaud symbol rate. All signals used 27% FEC overhead except the 600 Gb/s signal which had 15% overhead rate. The optimal channel launch power was determined using the 400 Gb/s PM-16QAM signal at a distance of 1833 km and was found to be about 3.5 to 4 dBm. Using channel launch powers in this range, we performed transmission tests for all formats. Results for the transmission of signals with data rates of 200 Gb/s to 450 Gb/s taken over the re-circulating loop are shown in Fig. 3a in the form of Q margin as a function of distance, where Q was calculated from raw detected BER values before FEC. The margin is defined relative to the maximum distance at which both real-time signals were error-free after FEC. We then measured the performance of signals with data rates of 500, 550, and 600 Gb/s over links comprised of as many individual spans as possible, up to five. The results of all transmission measurements are summarized in Fig. 3b as the maximum reach lengths with error-free transmission achieved over these long 122 km spans given the loop and span granularity. We expect that straight-line transmission for a system built with similar span lengths could provide somewhat longer reach lengths than measured here given the extra losses and impairments inherent in a re-circulating loop. We also note that the reach of the 500 Gb/s PM-32QAM signal could be artificially low given our five span constraint.

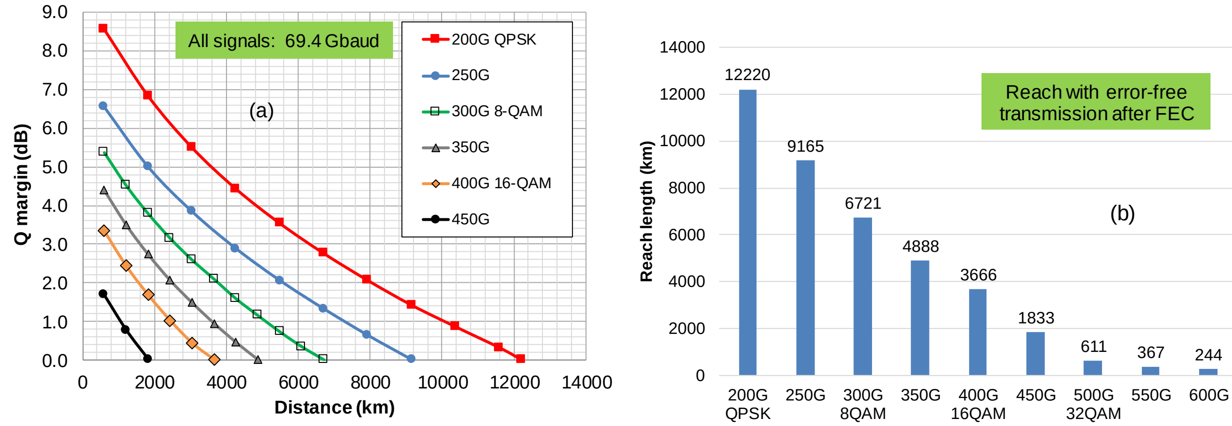

Fig. 3: a) Q margin vs. distance for data rates up to 450 Gb/s taken over re-circulating loop. b) Summary of all reach lengths achieved within the loop and span granularity for all data rates up to 600 Gb/s.

4. Summary

We have experimentally measured the transmission performance of a flex-rate real-time transceiver in a re-circulating loop system with long 122 km spans of ultra-low loss, large effective area optical fiber. We measured the reach length of signals ranging in net data rate from 200 Gb/s to 600 Gb/s in increments of 50 Gb/s. In this long-span system, error-free reach lengths were achieved of more than 3660 km for 400 Gb/s signals, over 6700 km for 300 Gb/s, and over 12,000 km for 200 Gb/s. Metro and regional distances of 244 km for 600 Gb/s, and more than 600 km for 500 Gb/s signals were achieved. We also characterized the real-time transceiver in back-to-back operation, measuring the gap-to-Shannon as a function of information rate, and found that it ranged from 2.6 dB for 200 Gb/s signals to just over 8 dB for 600 Gb/s signals. The gap-to-Shannon number was less than 4 dB for the very important data rate of 400 Gb/s.

5. References

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