The Trade-off Between Transceiver Capacity and Symbol Rate

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Abstract: The achievable throughput using high symbol rate, high order QAM is investigated for the current generation of CMOS-based DAC/ADC. The optimum symbol rate and modulation format is found to be 80GBd DP-256QAM, with an 800Gb/s net data rate.

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1. Introduction

A key goal when designing a new optical transmission system is to increase the amount of data sent for a given cost. One way to reduce the cost-per-bit is to increase the channel symbol rate, which will maximise the amount of information sent over one channel and reduce the number of transceivers for a given transmission bandwidth.

Currently, the upper limit on the available signal-to-noise ratio (SNR), and therefore channel highest achievable information rate (AIR) in a coherent optical transmission system, in the absence of fiber nonlinearity, is bounded by the transceiver subsystems, such as digital-to-analog converter (DAC) and analog to digital converter (ADC). The SNR of an ideal DAC / ADC is defined by the number of bits (N) which sets the quantization noise floor of the device [1]. In practical converters, other distortion sources will add to this noise floor, leading to an effective number of bits (ENOB) smaller than N bits, resulting in a lower SNR. Additionally, mainly due to clock jitter, the ENOB is a function of frequency, and is reduced at high frequencies, which consequently diminishes the SNR as the channel symbol rate is increased. An impressive symbol rate of 100 GBd was demonstrated in [2], achieving 1.2 Tb/s channel line rate and 1 Tb/s after 300 km. In [3], an AIR of 8.3 b/sym and 9.35 b/sym (with probabilistic shaping) for a channel symbol rate of 66 GBd was demonstrated, achieving 680 Gb/s after transmission over 400 km. Both demonstrations used an arbitrary-waveform generator (AWG) based on high-speed SiGe DACs. Todays commercial systems are deployed using CMOS-based DAC / ADC with typical symbol rates on the order of 35 GBd.

In this paper, we investigate the optimum channel symbol rate using commercial off-the-shelf 92 GS/s DACs with CMOS technology. The trade-off between transceiver symbol rate and channel SNR for a given transceiver system is also studied, and its implications on the overall system capacity for a given bandwidth is analyzed.

2. Experimental Setup

The experimental setup used in this work is illustrated in Fig. 1. The multi-level drive signals required for mQAM, where m = 4, 16, 64, 256, were generated offline and digitally filtered using a root raised cosine (RRC) filter and the channel symbol rate was varied from 15 GBd to 90 GBd in increments of 5 GBd. Digital preemphasis was applied to the signal to compensate for the frequency response of the transmitter components.

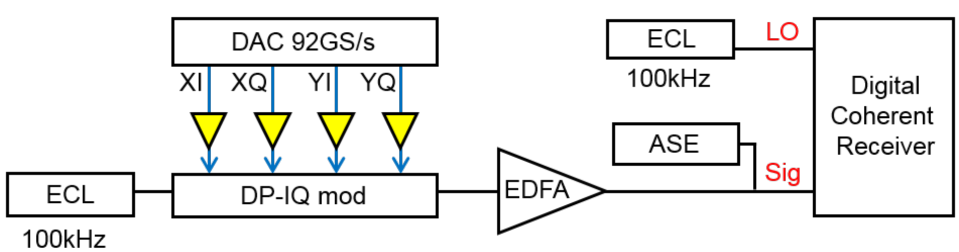

Fig. 1. Nyquist-shaped DP-mQAM experimental setup.

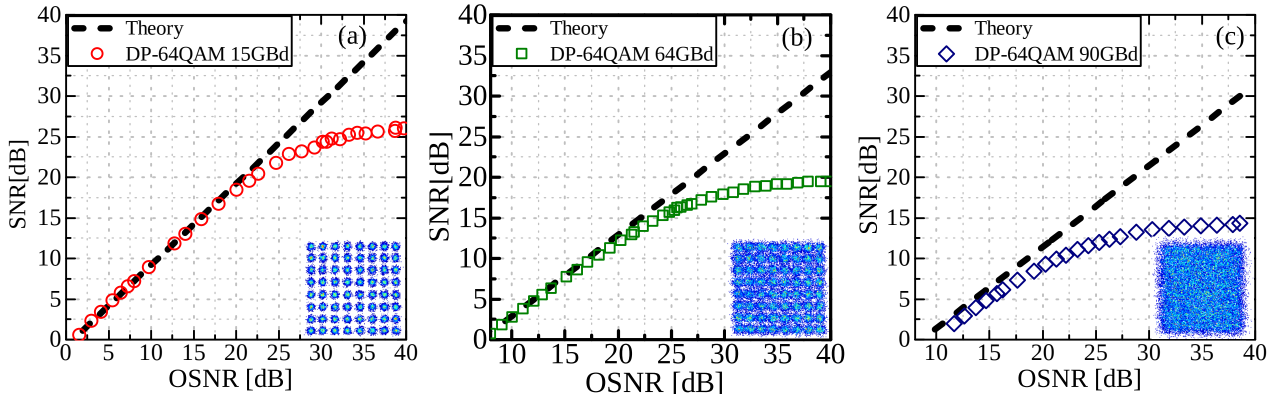

Fig. 2. Measurements of received SNR as a function of OSNR for (a) 15 GBd (b) 64 GBd and (c) 90 GBd DP-64QAM. Inset: constellation diagram from the highest SNR.

The resulting in-phase (I) and quadrature (Q) signals for each polarisation were output using four CMOS-based DACs with typical 3 dB analog bandwidth at 32 GHz, operating at 92 GSa/s and subsequently amplified using four linear amplifiers with 55 GHz electrical bandwidth and typical noise figure of 6 dB, before being applied to the Oclaro high bandwidth dual-polarisation (DP) IQ-modulator. The output of an external cavity laser (ECL) with a 100 kHz linewidth was passed directly into the modulator before being optically amplified to form Nyquist shaped DP-mQAM optical carrier. The DP-mQAM signal was passed into the signal port of the digital coherent receiver, comprised by a 90° optical hybrid, followed by 70 GHz balanced photodiodes and a real-time digital sampling oscilloscope with a sampling rate of 160 GS/s (63 GHz electrical bandwidth). The local oscillator (LO) laser was a 100 kHz linewidth ECL. Amplified spontaneous emission noise was added to the signal to vary the received optical signal-to-noise ratio (OSNR).

The digital signal processing (DSP) was applied off-line. The DP-mQAM signal was initially compensated for receiver skew and the different responsivities of the balanced photodiodes. Each polarisation was resampled to 2 Sa/sym before matched RRC filtering. A blind 21-tap radially directed equaliser (RDE) was used to equalise the signal and to undo polarisation rotations, with the constant modulus algorithm (CMA) equaliser used for pre-convergence. The frequency offset (FO) was subsequently removed prior to blind carrier phase estimation (CPE). The total received SNR was evaluated as the ratio between the variance of the transmitted symbols $E[|X|^2]$ and the variance of the noise σ^2, where $\sigma^2 = E[|X-Y|^2]$ and Y represents the received symbols. The mutual information or achievable information rate (AIR) was estimated from the received data via Monte Carlo integration and provides an upper bound on the performance for any coded system based on DP-mQAM signal.

3. Results

Fig. 2 shows the received SNR as a function of OSNR for DP-64QAM signal with a symbol rate of (a) 15 GBd (b) 64 GBd and (c) 90 GBd. The OSNR was recorded by adding ASE noise to the signal. The theoretical calculation of OSNR = SNR + 10 $\log_{10}(R_s{=}B)$, where R_s is the symbol rate and B is the noise bandwidth, is shown to provide a performance reference relative to the experimental results. If there was no practical SNR limit within the transceiver, the measured data points would follow that of the theoretical curve. However, it is evident that there is a saturation in the highest achievable SNR, and it diminishes as the channel symbol rate is increased. For instance, SNR limits of 27, 19 and 14.5 dB were measured for the 15, 64 and 90 GBd signal, respectively. This practical SNR limit, dominated by the effective number of bits (ENOB) of DACs and ADCs, noise figure of the drive amplifiers and DSP implementation, places an upper limit on the largest achievable information rate (AIR) for this experimental transceiver. Therefore the aim is to understand the degradation in SNR and achievable information rate (AIR) as the channel symbol rate increases.

Fig. 3 illustrates the back-to-back experimentally measured of (a) received SNR and (b) AIR, without ASE noise loading, as a function of channel symbol rate, over both polarizations of the mQAM signal. The SNR and the AIR were recorded for 16 different channel symbol rates; from 15 GBd to up to 90 GBd. As illustrated in Fig. 3(a), for each channel symbol rate, a small variation of the received SNR was measured between the modulation formats. For a channel with 25 GBd, the received SNRs for DP-4QAM and DP-256QAM were 26.3 dB and 25 dB respectively; 1.3 dB lower received SNR for DP-256QAM. For a 90 GBd channel, this difference in received SNR was only 0.2 dB (14.5 dB for DP-4QAM and 14.3 dB from DP-256QAM). This small difference in SNR at higher symbol rate may be due to the system performance being dominated by the receiver noise.

Fig. 3(b) shows the AIR as a function of channel symbol rate for all four formats. DP-256QAM recorded the highest

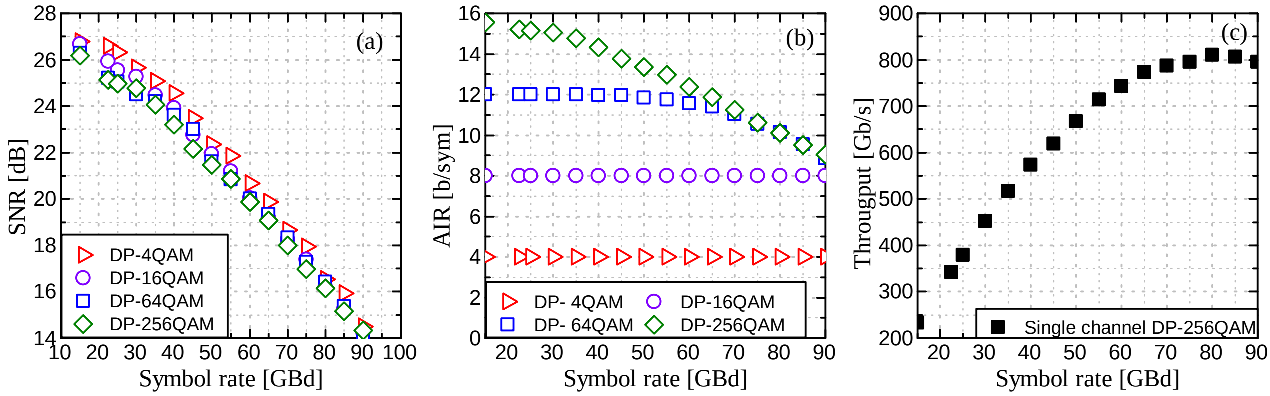

Fig. 3. DP-mQAM back-to-back measurements without ASE noise loading of (a) received SNR (b) mutual information (c) data throughput for different channel symbol rate; from 15 GBd to 90 GBd.

achievable information rate for a channel symbol rate up to 70 GBd. For symbol rates between 70 GBd and 90 GBd either DP-256QAM or DP-64QAM provided the same AIR. The AIR was 15.6 b/sym for a 15 GBd channel, decreasing to 13.8 b/sym for a 45 GBd channel, and further decreasing to 9 b/sym as the channel symbol rate approached 90 GBd. This system has enough SNR margin to maintain the highest AIR of 4 b/sym from DP-4QAM and 8 b/sym from DP-16QAM across all channel symbol rates. For DP-64QAM an AIR of 12 b/sym was maintained for symbol rates of up to 45 GBd and it dropped to 9 b/sym for a 90 GBd channel. Due to system SNR margin, if higher order QAM such as DP-1024QAM was generated with this transceiver setup, the ultimate performance in terms of bits per symbol would be higher than the DP-256QAM for channel symbol rates of up to 30 GBd.

Fig. 3(c) illustrates the net data throughput for different channel symbol rates. This was obtained by multiplying the corresponding DP-256QAM MI of each channel symbol rate (as shown in Fig. 3(b)) by the channel bandwidth. As expected, there was an increase in channel throughput as the channel symbol rate was increased; from 200 Gb/s to 810 Gb/s for channel symbol rates of 15 GBd and 80 GBd, respectively. However there is no further benefit of increasing the channel symbol rate beyond 80 GBd, due to a sharp decrease in the transceiver SNR towards 90 GBd which achieves a net data rate of 795 Gb/s.

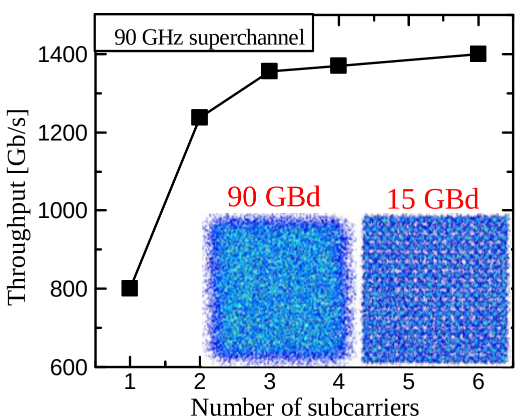

Fig. 4. Throughput versus number of subcarriers

Finally, we analyzed the overall data throughput for DP-256QAM with fixed channel bandwidth. The impact of varying subcarrier bandwidth on achievable data rate for a transceiver-noise limited system was investigated. As illustrated in Fig. 4, the channel bandwidth was fixed at 90 GHz and the performance of a 90 GBd Nyquist-spaced superchannel with different numbers of subcarriers (such as 6x15 GBd, 4x22.5 GBd, 3x30 GBd, 2x45 GBd and 1x90 GBd) was investigated. Inset are the 256QAM constelation for 90 GBd and 15 GBd channels. A sharp drop in the overall channel throughput was found for 1x90 GBd. For instance, the gross data throughput for 6x15 GBd was 1.4 Tb/s, decreasing to 1.25 Tb/s for 2x45 GBd with a further decrease to 795 Gb/s for 1x90 GBd channel.

4. Conclusion

For a fixed superchannel bandwidth of 90 GHz a reduction of 57% in the net channel rate was found for 1x90 GBd compared to 6x15 GBd subcarriers Nyquist-spaced. An optimum symbol rate 80 GBd was found for a CMOS-based DAC / ADC.

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