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### Abstract

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# Transceiver-Limited High Spectral Efficiency Nyquist-WDM Systems

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## Abstract:

We experimentally examine the maximum achievable transmission performance of a 7 channel Nyquist-WDM system with 10GBd per carrier. Back-to-back, a maximum of 11.9 bit/sym and 13.8 bit/sym can be transmitted for DP-64QAM and DP-256QAM respectively, while after 2 spans of transmission, a maximum of 12.4 bit/sym and 11.6 bit/sym can be achieved.

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## 1. Introduction

In recent years, the push for higher spectral efficiency in transmission systems has resulted in several research trends. Amongst these, Nyquist wavelength division multiplexing (WDM) [1] and dual polarization (DP) quadrature amplitude modulation (QAM) [2] have emerged as candidates for implementation in commercial products. While the gains available from highly spectrally efficient modulation seem to be endless when we consider short links, reported systems with more than 10 bit/s/Hz have been dominated by systems with less than 5 Gbaud [3, 4]. By reducing the symbol rate in these systems, the effective jitter (relative to the symbol rate) is reduced, therefore increasing the effective resolution of the digital-to-analog convertor (DAC) and analog-to-digital convertor (ADC), and therefore signal to quantization noise ratio (SQNR). While these results indicate that good performance may be achieved with high effective resolution in the transmitter (resulting from lower effective jitter), they are also a snapshot of performance of a particular example system. This system is defined both in terms of optical and electrical performance, but also in terms of receiver digital signal processing (DSP), coding, decoding and demodulation strategies.

In this paper, we experimentally examine the performance of a transmission system with a highly idealized receiver, in order to determine an upper bound on achievable performance with linear DSP and an AWGN channel model at the receiver, regardless of coding, decoding and demodulation strategy. By performing highly optimized data-directed DSP, followed by mutual information analysis of the received signal, we determine that DP-64QAM can achieve 11.6 bit/sym Nyquist-WDM after 2 spans of transmission compared with 11.9 bit/sym Nyquist-WDM back-to-back. DP-256QAM however, can achieve 12.4 bit/sym after 2 spans transmission, compared with 13.8 bit/sym Nyquist-WDM back-to-back.

## 2. Experimental Setup

The setup used in this experiment was identical to that reported in [5]. An external cavity laser (ECL) with 100 kHz linewidth was used to seed an optical comb generator, resulting in 7 carriers spaced at 10.01 GHz. The carriers were then separated into odd and even channels by cascaded interleavers, before modulation using single polarization I/Q modulators. Two field-programmable gate arrays (FPGAs) were used to send the in-phase and quadrature components of the desired waveforms to a pair of DACs, operating at 20 GSa/s. The 10 GBd, eight and 16 level signals were generated from decorrelated pseudo-random binary sequences of length  $2^{15} - 1$ , which were filtered with a root-raised-cosine (RRC) finite impulse response (FIR) filter with 201 taps and a roll-off of  $10^{-3}$ . After modulation and decorrelation in the optical domain, the odd and even channels were combined, before passive polarization multiplexing emulation. In the single channel case, the seed ECL was sent directly to an I/Q modulator, before passive polarization multiplexing emulation. For noise-loading in the back-to-back configuration, an amplified spontaneous emission (ASE) source was coupled into the optical signal before detection. The link used for transmission was a single span recirculating loop consisting of 80 km of standard single mode fiber (SSMF) with loss of 0.19 dB/km, and

chromatic dispersion (CD) of 17 ps/nm/km. A loop synchronous polarization scrambler was also used. The optical receiver used was a discrete micro-optic 2x8 hybrid with 4 unamplified, balanced photodiodes used for detection (with bandwidth 70 GHz). The local oscillator was an ECL with linewidth 100 kHz, tuned to within 100 MHz of the transmitter seed laser. The electrical signals were digitized using an oscilloscope with 160 GSa/s and 63 GHz of bandwidth, before being processed offline using Matlab.

### 3. Receiver Digital Signal Processing

After normalization and deskewing of each quadrature, the signal was low-pass filtered to select the central channel, and resampled to two samples per symbol. CD was (where required) then compensated in the frequency domain. After intradyne frequency recovery, a matched RRC filter was applied. A 301 tap  $2 \times 2$  multiple-input multiple-output (MIMO) equalizer with radially-data-directed least mean square (LMS) updating was then used to equalize polarization rotations and filtering impairments, and to recover the timing phase. The convergence parameter was gradually reduced from an initial value of  $10^{-3}$  to  $10^{-5}$  in order to minimize tap noise, while still providing enough bandwidth to track slow polarization rotations. Carrier phase estimation (CPE) was then performed with a data directed feed-forward algorithm, with an averaging filter of 31 taps. Mutual information was calculated by the Monte-Carlo integration method over  $2^{18}$  symbols, assuming symbol-by-symbol detection with AWGN impairment. Whilst this assumption is not strictly justified from an information-theoretic perspective [6], it has been shown to be a good approximation for uncompensated links with symbol-by-symbol detection [7, 8]. Using an AWGN channel model at the receiver with MI as a metric also provides an upper bound on performance assuming a symbol likelihood calculation method with reasonable computational complexity while not excluding coding strategies such as iterative demodulation and non-binary coding.

### 4. Results

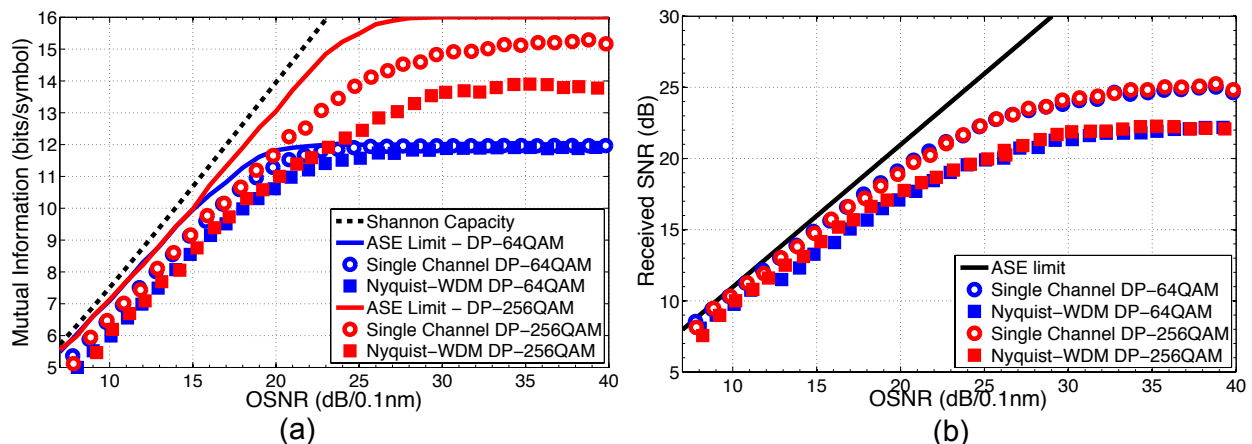


Fig. 1. Back-to-back performance for both DP-64QAM and DP-256QAM single channel and Nyquist-WDM. Mutual information is presented in (a), while evolution of received SNR with OSNR is shown in (b).

Initially, we swept OSNR back-to-back, for DP-64QAM and DP-256QAM for single-channel and 7 channels Nyquist-WDM. The results of this measurement are plotted in Fig. 1(a), along with the Shannon capacity, and the OSNR limited performance for both DP-64QAM and DP-256QAM. We note that single channel results for both modulation formats exhibit a small penalty for low OSNR, due to in-band electrical noise and distortion, while the two examined modulation formats offer near-identical performance in terms of MI. As OSNR increases, the discrepancy between the ASE noise limit and the measured performance of both DP-64QAM and DP-256QAM becomes larger, due to the increased relative contribution of in-band noise compared with ASE noise. DP-64QAM approaches an MI of more than 11.9 bit/sym for high OSNR, while DP-256QAM approaches only 15.2 bit/sym due to the effects of in-band noise. For the Nyquist-WDM system, the same trends are repeated, while the in-band noise component is increased, due to the additional amplifiers and lossy optical components required in the transmitter. Again, both formats offer near-identical performance at low OSNR, albeit with a slightly increased penalty when compared with the single channel case. We note that DP-64QAM diverges earlier from the ASE limit, but still achieves an MI of more than 11.9 bit/sym for high OSNR. As single channel DP-256QAM is already limited by in-band noise in MI performance, we

note that the increased in-band noise for the Nyquist-WDM case results in a significant loss in MI performance for high OSNR, approaching only 13.8 bit/sym. To illustrate this limitation in SNR, we have plotted the received SNR (defined as the ratio of signal to all noise and distortion components, including both broadband and in-band noise sources) against OSNR for each of the four cases previously described in Fig. 1(b). Also plotted is the ASE limit, which is the SNR due to ASE only. We note that the received SNR is independent of modulation format, and converges at high SNR to 25 dB for the single channel system, and 22.2 dB for the Nyquist-WDM system.

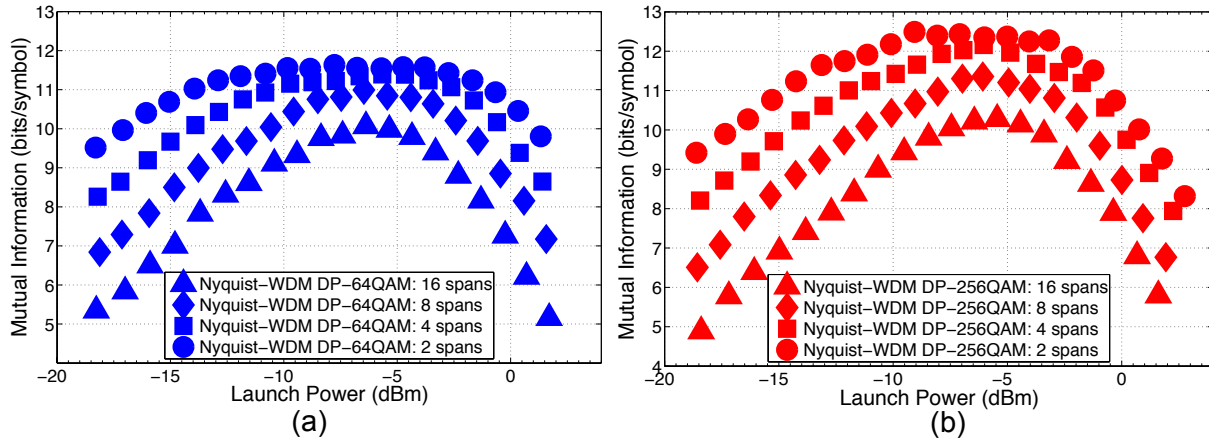


Fig. 2. Transmission performance of Nyquist-WDM super-channel with (a) DP-64QAM modulation, and (b) DP-256QAM modulation. Span length is 80 km.

We then transmitted our Nyquist-WDM signal over a recirculating loop, consisting of a single 80km span of SSMF. The results for 2, 4, 8 and 16 recirculations with DP-64QAM modulation are shown in Fig. 2(a), while those for DP-256QAM are shown in Fig. 2(b). We note that for 16 spans transmission, both formats are almost identical in performance, with most impairments coming from ASE and fiber nonlinearity, with an optimal performance of 10 bit/sym for DP-64QAM and 10.2 bit/sym for DP-256QAM. As expected from the GN model [7], with increasing power, performance degrades more rapidly in the highly nonlinear region than it improves in the linear region, due to the cubic dependance of nonlinear distortion on launch power. We note from Fig. 2(a) that performance in the optimal power region for DP-64QAM starts to become saturated at 8 spans, with both 4 and 2 spans exhibiting a flat region near optimal launch power. We also note that the performance at two spans is limited to approximately 11.6 bit/sym, due to the optical noise introduced by additional lossy optical components and amplifiers necessary for transmission. By comparison, Fig. 2(b) shows that DP-256QAM transmission begins to saturate at only 4 spans, and exhibits only a somewhat flat top at 2 spans. Despite this, the optimal performance at 2 spans is reduced to only 12.4 bit/sym due to the increased noise floor arising from the additional optical components and amplifiers required for transmission.

## 5. Conclusions

In this paper, we have analyzed the back-to-back and transmission performance of DP-64QAM and DP-256QAM at 10 GBd both single channel and 7 channels Nyquist-WDM. By examining MI of the received signal for a highly idealized receiver, we have demonstrated the limitation of transceiver performance on maximum achievable transmission rates, assuming linear receiver DSP and an AWGN channel. DP-64QAM can achieve 11.6 bit/sym Nyquist-WDM after 2 spans of transmission compared with 11.9 bit/sym single channel and back-to-back. Contrastingly, DP-256QAM performance is reduced from 15.3 bit/sym in single channel back-to-back configuration to 12.4 bit/sym after 2 spans of Nyquist-WDM transmission.

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