Effect of Clipping on the Performance of Nyquist-Shaped Dispersion-Precompensated Subcarrier Modulation Transmission with Direct Detection

M.S. Erkılınç(1), S. Pachnicke(2), H. Griesser(3), P. Bayvel(1), B.C. Thomsen(1), and R.I. Killey(1)

(1)Optical Networks Group, Department of Electronic and Electrical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK, m.erkilinc@ee.ucl.ac.uk
(2)ADVA Optical Networking SE, Maerzenquelle 1-3, 98617 Meiningen, Germany
(3)ADVA Optical Networking SE, Fraunhoferstr. 9a, 82152 Martinsried, Germany

Abstract *We investigate the effect of signal waveform symmetric clipping on the performance of dispersion-precompensated subcarrier modulated Nyquist-QPSK in uncompensated direct detection links. OSNR gains of 0.7 dB and 1.2 dB are achieved over 400 and 800 km of SSMF, respectively.*

Introduction

Multilevel modulation to meet the demand in capacity has become more attractive for access, metro and regional links. To achieve a high spectral efficiency, the data is encoded onto the optical phase and amplitude with a coherent receiver to detect and recover the signal. However, due to optical complexity at the receiver, a coherent detection scheme may not be the most efficient solution for short- and medium-haul links. For this reason, spectrally-efficient modulation formats in direct-detected links have attracted much interest. The typical approach for this is to modulate the data onto multiple RF-subcarriers, referred to as orthogonal frequency division multiplexing (OFDM) if the subcarriers are orthogonal [1, 2]. Although, OFDM allows a relatively simple mitigation of linear optical transmission impairments, some bandwidth is sacrificed due to the requirement for a cyclic-prefix, and it also suffers from a high peak-to-average power ratio (PAPR). These drawbacks can be avoided using single subcarrier modulation (SCM) where a single subcarrier is employed to achieve multilevel modulation. Proposed in [3] without Nyquist (N) pulse shaping and in [4–6] with Nyquist pulse shaping, high spectral efficiency in WDM transmission (1.3 b/s/Hz) was recently demonstrated [7].

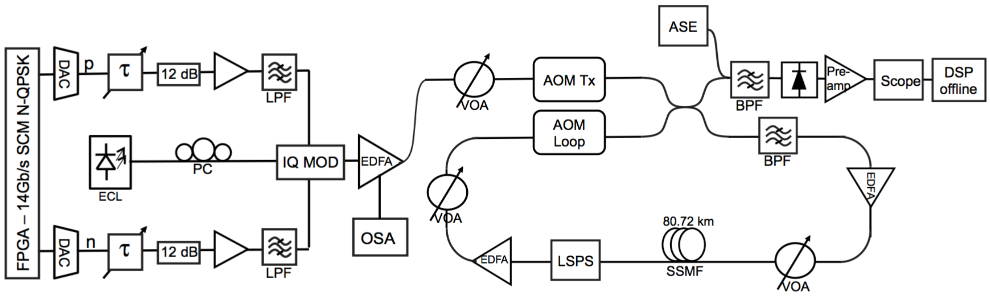
The second key feature is dispersion tolerance for metro/regional links which can be effectively achieved by electronic pre-dispersion (EPD) or pre-compensation [8, 9], which avoids the problem of the loss of phase information in the detected signal limiting receiver based electronic compensation schemes. However, applying EPD increases the PAPR of the transmitted signal and subsequently the required dynamic range of a digital-to-analogue converter (DAC) [10]. In this paper, the effect of clipping on the bit error rate (BER) performance of dispersion pre-compensated single-sideband (SSB) SCM Nyquist-QPSK is experimentally assessed for transmission distances up to 800 km.

Experimental Setup

The optical transmission test-bed used to examine the symmetric clipping effect on the pre-dispersed driving signals is shown in Fig. 1. The SSB subcarrier modulated Nyquist-QPSK transmitter consisted of a pair of Xilinx Virtex 5 FPGAs and a 28 GSa/s DAC (Micram VEGA DACII) with a nominal resolution of 6 bits (measured effective number of bits (ENOB) of 3.5 bits at 10 GHz). The driving signals were linearly amplified and passed through electrical anti-imaging filters (5th-order Bessel low-pass filter with a bandwidth of 7 GHz) to remove the images generated by the DACs.

The generation of the driving signals was performed offline in MATLAB before uploading them to the FPGA-RAM memory. The Nyquist-QPSK signal with a symbol rate of 7 GBaud (f_s) was generated using two 2^{15} de Bruijn bit sequences, de-correlated by 1/4 of the pattern length, and a pair of 128-tap root-raised cosine (RRC) pulse-shaping filters with a roll-off factor (α) of 0.3 and a stop-band attenuation of 40 dB, as shown in Fig. 2. The Nyquist-QPSK baseband signal was then up-converted to a passband signal by RF-subcarrier modulation with a subcarrier frequency (f_{sc}) of 5.25 GHz, followed by a digital SSB filter removing the lower sideband. To mitigate the chromatic dispersion of 6720 and 13340 ps/nm accumulated during the fiber transmission for 400 and 800 km, respectively, the signal was first pre-dispersed by the inverse of the channel (by simply negating the sign of the dispersion parameter D_{SMF}=16.8 ps/(nm.km)) and then hard clipping was applied to reduce the required dynamic range of the DACs, thus reducing DAC quantization noise.

Finally, the waveforms were quantized to 6 bits and uploaded to the memories of the FPGAs driv-



ECL: External cavity laser, DAC:Digital-to-analog converter, LPF: Low-pass filter, EDFA: Erbium-doped fiber amplifier, PC: Polarization controller.

AOM: Acoustic optical modulator, VOA: Variable optical attenuator, LSPS: Loop synchronous polarization scrambler, ASE: Amplified spontaneous noise, BPF: Band-pass filter.

Fig 1. Optical transmission test-bed.

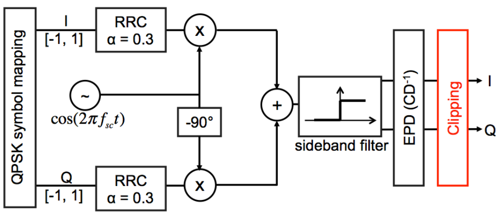


Fig 2. DSP at the transmitter where $f_{sc} = 0.75 \times f_s$ =5.25GHz.

ing the I and Q DACs. The sample probability distributions of the dispersion-precompensated (EPD applied) signals for a range of transmission distances are plotted in Fig. 3(a). The back-to-back SSB SCM Nyquist-QPSK signal is fairly uniform over the range of 6-bit quantization levels. The PAPR gradually increases as the signal is predispersed up to 10 spans (800 km) as presented in Fig. 3(b). Beyond this point, the change in probability distribution and the increase in corresponding PAPR is less significant as illustrated in Fig. 3.

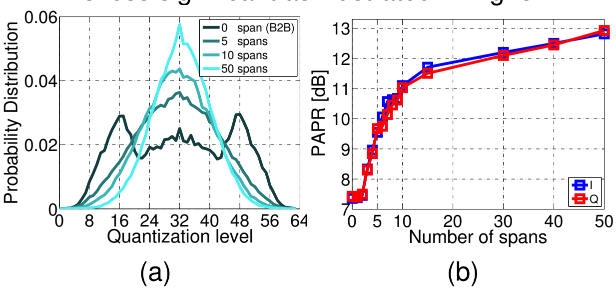


Fig 3. (a) Probability distribution without any clipping for various pre-dispersed signals vs quantization levels and (b) PAPR vs number of spans.

An external cavity laser (ECL) with a linewidth of 100 kHz at 1550 nm was used as a laser source for the IQ-modulator (with which the optical carrier was also added to the modulated signal by appropriate biasing), followed by an erbium-doped fiber amplifier (EDFA) and transmission. Note that the modulators were operated at the quadrature point to achieve linear mapping from the electrical to the optical domain. The non-clipped and clipped signals were transmitted over 400 and 800 km of standard single-mode fiber (SSMF) to evaluate and compare their OSNR performance.

A recirculating fiber loop with a single 80.72 km span of uncompensated SSMF (15.4 dB loss and 16.8 ps/(nm.km) dispersion) was used to transmit the pre-dispersed signal as shown in Fig. 1. The total span loss was compensated by EDFAs with a noise figure of 4.5 dB.

The transmitted signal was first filtered by a tunable band-pass filter (Yenista Optics XTM50-Ultrafine) with a centre frequency of ∼193.55 THz and a 3-dB bandwidth of 11 GHz (filter edge gradient of 800 dB/nm). It was detected by the single-ended PIN photodiode, digitized by a single analogue-to-digital converter (ADC) with a sampling rate of 50 GSa/s, an electrical bandwidth of 16 GHz and a nominal resolution of 8 bits (ENOB of 5 bits at 10 GHz) as shown in Fig. 1. After the signal was digitized, resampling to 2 Sa/s, normalization and down-conversion followed by a matched filter (a RRC filter with α of 0.3) were applied offline in MATLAB. A 5-tap CMA-LMS equalizer to increase the convergence rate and then a DD-LMS equalizer to recover the symbol clock were applied. Finally, the BER was calculated by error counting, using 2^{17} symbols.

Results

The optical signal-to-noise ratio (OSNR) values at the receiver and the corresponding BER values for back-to-back and over the link were measured after noise loading at the receiver. The simulated and experimental optical spectra, monitored after the transmitter, with and without different clipping threshold values for 800 km dispersion-precompensated signals, are presented in Fig. 4. The clipping ratio (CR) is defined as the ratio of the maximum allowable amplitude divided by the average power of the normalized input signal [11] where a clipping threshold (CT) is the maximum allowable amplitude, *i.e*, a CT of 1 corresponds to no clipping. It can be observed from Fig. 4 that the spectrum broadens due to clipping below the CT value of 0.7. Excessive spectral broadening would lead to additional penalties in the case of spectrally-efficient WDM.

Fig. 5 shows the results of simulations quantifying the improvement in required OSNR that can

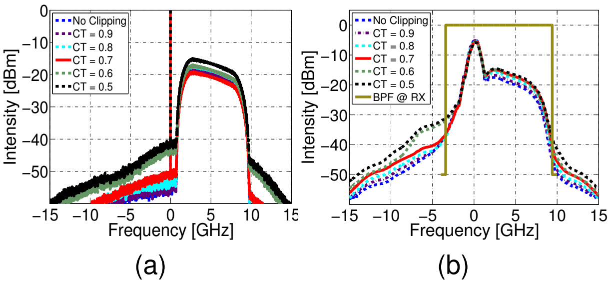


Fig 4. (a) Simulated and (b) experimental optical spectrum.

be obtained by clipping the pre-dispersed signal assuming DAC ENOB values of between 3 and 6. The gain is highest when the ENOB is 3 bits. Note that the DAC utilized in our transmitter had a 6-bit nominal resolution and its measured ENOB is 3.5 bits at 10 GHz. The optimum CT was found to be 0.7 for both 400 km and 800 km.

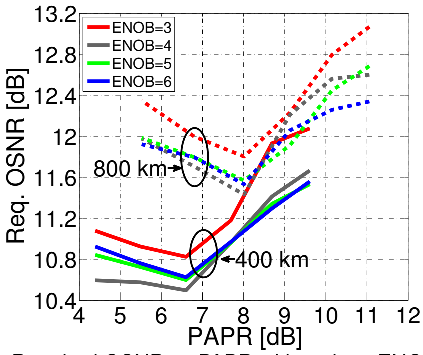


Fig 5. Required OSNR vs PAPR with various ENOB values.

Before noise loading, the CR was varied to obtain PAPR values from 5 to 11 dB and the required OSNR at the hard-decision forward error correction (HD-FEC) limit (assumed to be BER = 3.8×10^{-3}) is plotted in Fig. 6 to determine the optimum CR. After transmission over distances of 400 and 800 km, the optimum performance was obtained at PAPR values of 6.7 and 8 dB, respectively. For both 400 and 800 km, the CT of 0.7 simultaneously achieves good OSNR performance as shown in Fig. 6 while preserving the spectrum shape.

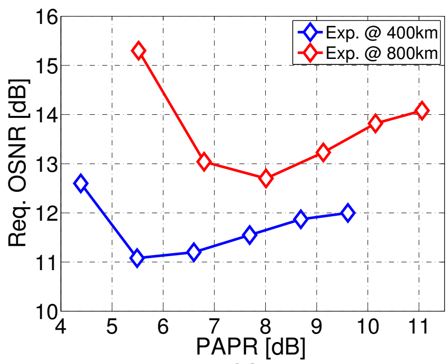


Fig 6. Required OSNR vs PAPR.

The receiver sensitivity performance for back-to-back, 400 and 800 km, is presented in Fig. 7. The implementation penalty at the HD-FEC limit for the back-to-back case was found to be 0.9 dB compared to the simulation due to the DAC quantization noise. In transmission over 400 km of SSMF, a 0.7 dB improvement was observed at a clipping ratio of 6.7 dB compared to the non-clipped pre-dispersed signal. Furthermore, the required OSNR was reduced by 1.2 dB compared to non-clipped pre-dispersed signal at a clipping ratio of 8 dB over 800 km as shown in Fig. 7.

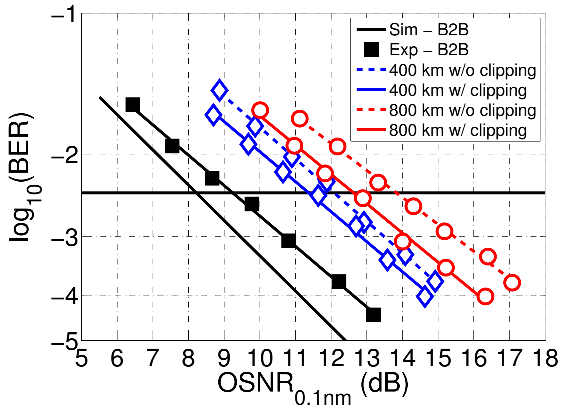


Fig 7. BER vs OSNR with and without clipping.

Conclusion

The effect of symmetric clipping on the BER performance of dispersion-precompensated single-sideband subcarrier modulated Nyquist-QPSK at a bit rate of 14 Gb/s was experimentally assessed in a direct-detected, uncompensated SSMF link up to 800 km. It was shown that at the optimal clipping ratios of 6.7 dB and 8 dB for the 400 km and 800 km pre-dispersed signals, the required OSNR improved by 0.7 dB and 1.2 dB, respectively.

Acknowledgments

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