Spectrally-Efficient Single-Sideband Subcarrier-Multiplexed Quasi-Nyquist QPSK with Direct Detection

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Abstract. We propose and experimentally assess SSB SCM quasi-Nyquist QPSK for spectrally-efficient direct detection links. Nine channel 10.7 GHz-spaced WDM signal generation at 14 Gb/s per channel is demonstrated with a subcarrier frequency of 5.25 GHz.

Introduction

While systems with coherent detection offer the higher performance for long haul transmission, direct detection (DD) systems may provide a cost advantage in some metro, backhaul and access applications. Subcarrier multiplexed (SCM) QPSK or QAM signalling is a good candidate for spectrally efficient wavelength division multiplexing (WDM) direct detection (DD) systems. Multiple subcarriers can be used, e.g. DD-orthogonal frequency division multiplexing (OFDM). However, the high peak-to-average-power-ratio (PAPR) of OFDM results in penalties due to the need for high optical carrier power to avoid clipping [1]. An alternative approach is to use single carrier SCM which has lower PAPR than OFDM.

In conventional single subchannel SCM, the subcarrier frequency is larger than the symbol rate. However, this approach reduces the spectral efficiency. Therefore, there has been recent work reported on the use of subcarrier frequencies equal to (single cycle [2]) or lower than the symbol rate such as half-cycle SCM [1,3]. Half-cycle SCM is particularly attractive because of its spectral efficiency.

Encoding the data on RF-carriers causes doubling in optical spectrum since the subcarriers will appear on both sides of the optical carrier with a spacing equal to the subcarrier frequency. This results in double side band (DSB) signals that reduce the optical spectral efficiency by 50%. Therefore, further improvement in WDM spectral efficiency can be achieved by generating single side band (SSB) SCM signals which can be implemented by using a digital Hilbert transform (HT) filter and conventional IQ-modulators.

To enable narrow spacing between the subchannel and the optical carrier, quasi-Nyquist (qN) (sinc-like) pulse shaping is applied using a root raised cosine (RRC) filter. Varying the roll-off factor of the RRC filter and the subcarrier frequency allows a trade-off between spectral efficiency and the required OSNR. Half-cycle SCM Nyquist QPSK would require a roll-off of zero which results in a high PAPR [1]. Hence, in this paper, we investigated qN-WDM with a roll-off factor parameter greater than zero, and experimentally demonstrated 14 Gb/s per channel SSB-SCM signal quasi Nyquist signal generation with 10.7 GHz WDM channel spacing.

Experimental Setup

The WDM signal is generated by an optical comb generator (OCG) using cascaded intensity and phase modulators [4]. Data is modulated using two IQ modulators and detected by pre-amplified direct detection as presented in Fig. 1. A noise loading analysis is performed for the back-to-back case.

Two FPGA-DAC (Micram VEGA DACII) pairs, with a nominal resolution of 6-bits and a sampling rate of 28 GSa/s, were utilized to drive the IQ-modulators. The driving signals were generated offline as shown in Fig. 2 and uploaded to the FPGAs' memory. Two de-correlated 2^{15} de Bruijn bit sequences decorrelated by 1/4 of the pattern length were used to generate the in-phase (I) and quadrature (Q) driving signals.

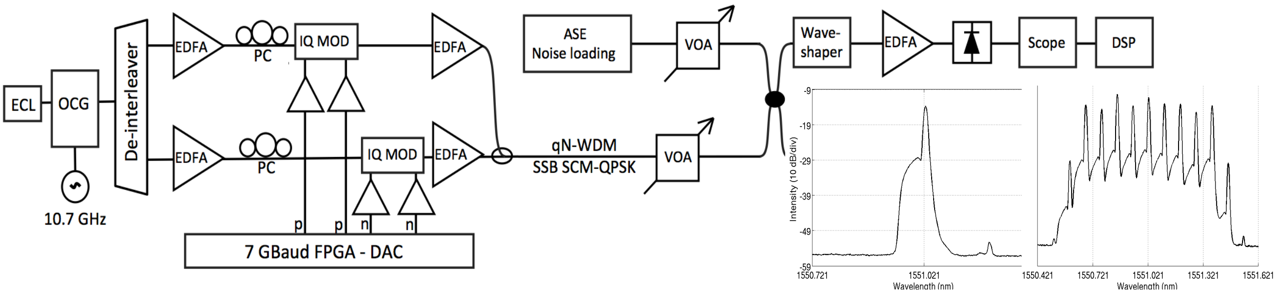

Figure 1. Experimental Setup. ECL: External cavity laser, OCG: Optical comb generator, EDFA: Erbium-doped fiber amplifier, PC: Polarization controller, DAC:Digital-to-analog converter, ASE: Amplified spontaneous emission, VOA: Variable optical attenuator. Inset: Optical spectra, single channel (left) and 9 channels (right)

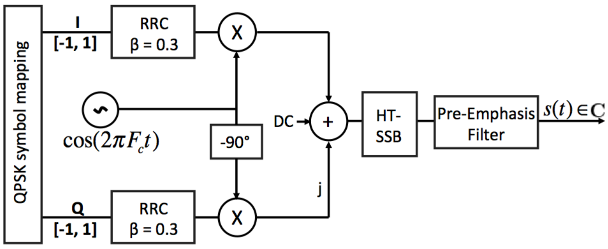

Figure 2. Offline waveform generation. HT: Hilbert transform, $F_c = 0.75 \times F_b$, F_c:Subcarrier frequency, F_b:Symbol rate, $s(t)$:Complex signal

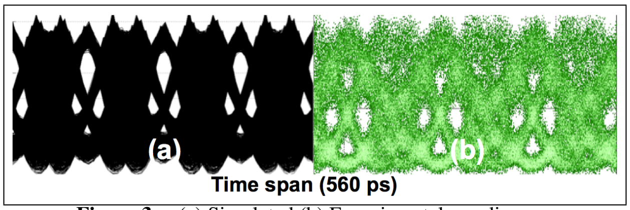

Figure 3. (a) Simulated (b) Experimental eye diagram

Since a roll-off factor of zero yields a high peak-to-average-power ratio (PAPR) which would cause a degradation in the receiver sensitivity, a RRC filter with a roll-off factor of 0.3 and a subcarrier frequency of 5.25 GHz (0.75 of the symbol rate) were chosen considering the trade-off between spectral efficiency and the required OSNR. The driving signals were first electrically modulated on a single subcarrier. Afterwards, I and Q parts were added to each other with a DC bias. A digital Hilbert transform filter was applied to the signal to generate the SSB signal electrically. Since, anti-imaging filters (5th order Bessel low pass-filter with a bandwidth of 7 GHz) were used after the DACs, a digital pre-emphasis filter was then applied to compensate the impairments caused by transmitter elements. The optical setup of the transmitter consisted of an OCG and cascaded interleavers. The nine lines from the comb generator were separated using the cascaded interleavers to allow odd and even channels to be modulated independently (see Fig. 1 for single and 9 channels optical spectra).

Two IQ Mach-Zehnder modulators (MZM) were driven by the positive and negative outputs of the two DACs. Their outputs were coupled to produce 9 modulated channels before the additive noise loading. Simulated and experimental eye diagrams are shown for comparison in Fig. 3.

A programmable optical filter (Finisar 4000S Waveshaper) was used to de-multiplex the central channel before detection. A single-ended PIN photodiode with an integrated TIA was used to detect the transmitted signal, and the signal was digitized by a 50 GSa/s and 16 GHz bandwidth Tektronix DPO 72004 scope. The digitized signal was down-converted after normalization and resampling to 2 samples/symbol. A matched pulse shaping filter was then applied. In order to recover the subcarrier phase, a constant modulus algorithm (CMA) equalizer with seven taps was used. Finally, the error vector magnitude (EVM) was calculated, and the bit error rate (BER) was measured by error counting.

Results

The BER and EVM were calculated using 2^{17} symbols at the receiver end. Additive noise loading was applied to measure the receiver sensitivity. A noise-free constellation diagram of the received signal in the back-to-back case with the corresponding electrical spectrum after detection is presented in Fig. 4. The symbol distortion with an EVM of 8.77 % is incurred by frequency roll-off and quasi-Nyquist pulse shaping.

The system performance for single channel, 5 and 9 channels with 21.4 and 10.7 GHz channel spacing respectively is shown in Fig. 5. As a benchmark performance, the theoretical On-Off-Keying (OOK) BER at the same bit-rate (14 Gbits/s) is shown alongside SSB SCM quasi-Nyquist QPSK as well. The detailed explanation of the theoretical BER curve for

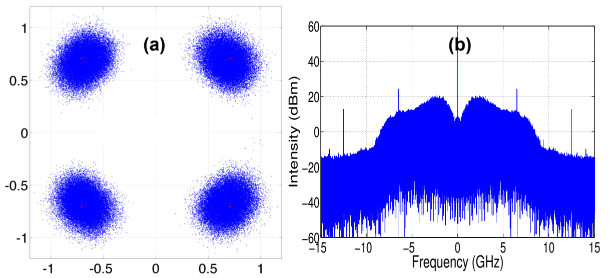

Figure 4. (a) Constellation diagram (b) Electrical spectrum for back–to-back

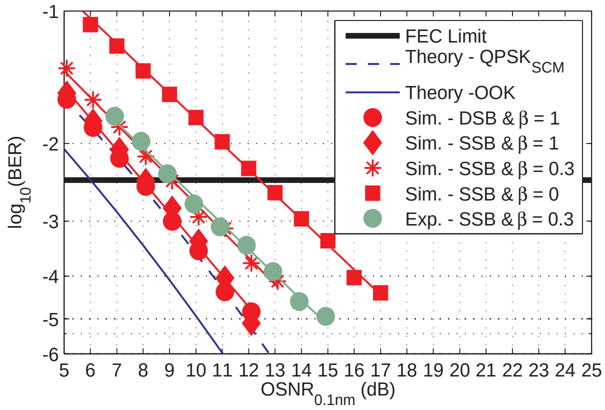

Figure 5. BER vs OSNR for single channel

SCM-QPSK can be found in [5]. At the forward error correction (FEC) limit of 3.8×10^{-3}, the SSB modulation gives only 0.15 dB penalty compared to DSB modulation. Additionally, quasi-Nyquist pulse shaping with a roll-off factor of 0.3 gives an additional 1.13 dB penalty compared to a single cycle SCM with a RRC filter roll-off factor of 1. However, it provides a 3 dB gain over half-cycle SSB SCM-QPSK where the roll-off factor has to be set to 0. The penalty in the half-cycle case is mainly incurred because of the high PAPR, which requires a higher optical carrier power to avoid clipping. It is worth noting that simulations are performed assuming 6-bit resolution at the transmitter. Finally, 7 GBaud SSB SCM quasi-Nyquist QPSK with a roll-off factor 0.3 is experimentally demonstrated for the back-to-back case.

For WDM signalling, BER vs OSNR curves are presented for 5 channels with a channel spacing of 21.4 GHz and 9 channels with a channel spacing of 10.7 GHz to observe the impact of crosstalk in Fig. 6. Each channel occupies 9.8 GHz and with 10.7 GHz channel spacing, the guard band between channels is 0.9 GHz wide. No significant penalty is observed in the 5 channel case since the channels are demultiplexed using the waveshaper which has a 2nd order

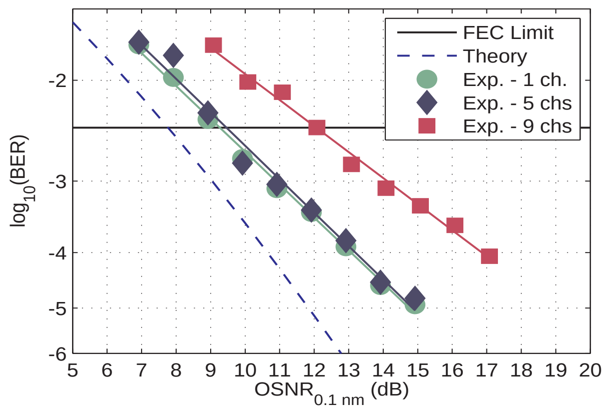

Figure 6. BER vs OSNR for WDM

super-Gaussian frequency response with 10 GHz FWHM. On the other hand, the 9 channel configuration gives an additional 3 dB penalty. The optical carrier of the neighbourhood channels interfere with the detected channel. With a narrower optical filter for wavelength demultiplexing, the penalty could be significantly reduced and this will be assessed in future work. At the FEC limit, 12.1 dB was found to be the required OSNR for 9 channels SSB SCM quasi-Nyquist QPSK.

Conclusions

Nine channel SSB SCM quasi-Nyquist QPSK with a bit rate of 14 Gb/s and WDM channel spacing of 10.7 GHz was experimentally assessed. This yields a spectral efficiency of 1.4 bits/s/Hz. To our knowledge, this is the first demonstration of WDM SSB SCM quasi-Nyquist QPSK with direct detection.

Acknowledgments

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