# 168 Gb/s/λ Direct-Detection 64-QAM SSB Nyquist-SCM Transmission over 80 km Uncompensated SSMF at 4.54 b/s/Hz net ISD using a Kramers-Kronig Receiver

Z. Li, M.S. Erkılınç, K. Shi, E. Sillekens, L. Galdino, B.C. Thomsen, P. Bayvel, and R.I. Killey

Optical Networks Group, Department of Electronic & Electrical Engineering, UCL (University College London), London, WC1E 7JE, UK, zhe.li@ee.ucl.ac.uk

**Abstract** *Using the recently-proposed Kramers-Kronig receiver DSP scheme, we achieved 4×168 Gb/s 35 GHz-spaced WDM single-polarization direct-detection 64-QAM SSB Nyquist-SCM transmission over 80 km of uncompensated SSMF at a record net ISD of 4.54 b/s/Hz.*

## Introduction

Metro, backhaul and inter-data centre networks are experiencing unprecedented traffic growth, mainly driven by the demands of cloud services, broadband video streaming and mobile technologies. Such traffic growth brings the requirement for high-capacity, spectrally-efficient and low-cost optical transceivers. Transceivers achieving record spectral efficiencies and transmission capacities have been realized using coherent detection. However, they come at the expense of significantly increased optical hardware complexity. Spectrally-efficient single polarization single photodiode-based direct-detection (DD) transceivers, offering ≥100 Gb/s per channel over transmission distances of ≥ 40 km, would be attractive for such applications. For such systems, single-sideband (SSB) quadrature amplitude modulation (QAM) Nyquist subcarrier modulation (Nyquist-SCM)[1] can be utilized to achieve high information spectral density (ISD) with reasonably low peak-to-average power ratio (PAPR ~7dB). However, signal-signal beat interference (SSBI) due to square-law detection severely degrades such systems' performance, unless receiver linearization is performed.

To overcome this problem, the Kramers-Kronig (KK) scheme has been proposed[2], in which DSP carried out at the receiver accurately reconstructs the optical phase of the transmitted signal from its detected intensity, making the assumption of minimum phase single-sideband signalling. This approach was assessed for optical SSB DD systems in Refs. 2 and 3 through numerical simulations, and was experimentally demonstrated with a 2.8 b/s/Hz WDM 16-QAM SSB Nyquist-SCM system[4], and subsequently demonstrated with single-channel 218 Gb/s SSB OFDM over an extended-reach single span link[5], confirming its outstanding capability to suppress the SSBI penalty. In this paper, we explore the ISD limits of this approach, through experiments with higher-order QAM format and narrower channel spacing. We successfully transmitted four WDM channels with 35 GHz channel spacing to achieve 3.17 b/s/Hz net ISD over 240 km using 112 Gb/s/λ 16-QAM, and a record net ISD of 4.54 b/s/Hz over 80 km (exceeding the previous record of 3.58 b/s/Hz for this distance[6]) using 168 Gb/s/λ 64-QAM SSB Nyquist-SCM. All experiments employed DCF-free standard SMF, since the KK scheme enables effective electronic dispersion compensation (EDC) at the receiver as well.

## Experimental Setup and Kramers-Kronig Method

The experimental setup is shown in Fig. 1(a). Odd and even channels were generated using two IQ-modulators, driven by two arbitrary waveform generators (AWGs), operating at 92 GSa/s with 33 GHz 3-dB bandwidth. In the transmitter DSP (Tx DSP), 28 GBd (112 Gb/s 16-QAM and 168 Gb/s 64-QAM) SSB Nyquist-SCM signals were generated using a subcarrier frequency of 14.28 GHz (0.51×symbol rate) and Nyquist pulse-shaping (root-raised-cosine) filters with a roll-off factor of 0.01. Four WDM channels were transmitted, with the channel spacing set to 35 GHz (Fig. 1(a) inset (I)), giving gross optical ISDs of 3.2 (b/s)/Hz and 4.8 (b/s)/Hz for 16-QAM and 64-QAM SSB Nyquist-SCM, respectively. For the optimum system performance, the optical carrier-to-signal power ratio (CSPR) value was optimized at each value of optical signal-to-noise ratio (OSNR). Transmission experiments were carried out by utilizing a straight-line multiple span fibre link with 80 km span length using standard SMF followed by EDFAs with a 5 dB noise figure. At the receiver, the channel of interest was demultiplexed using a 31 GHz FWHM 4$^{th}$-order super-Gaussian optical band-pass filter (OBPF), and then detected using a single PIN photodiode with a 40 GHz 3-dB bandwidth followed by a single ADC, operating at 80 GSa/s.

The receiver DSP (Rx-DSP), including the Kramers-Kronig scheme followed by EDC, is depicted in Fig. 1(b). Based on the Kramers-

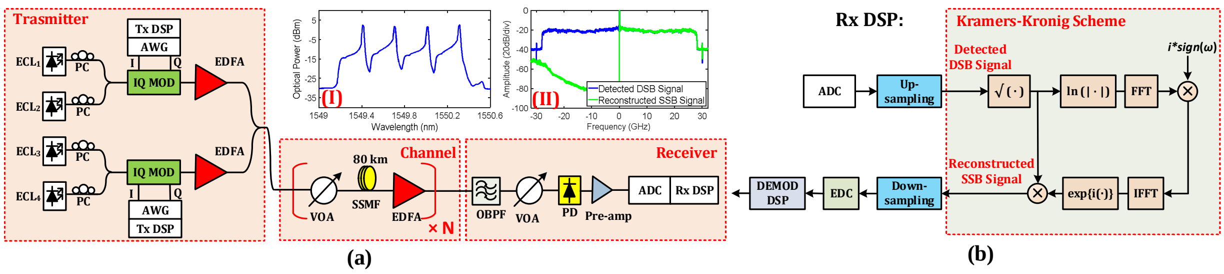


**Fig. 1:** (a) Optical transmission experimental test-bed. Insets: (I) experimental transmitted WDM spectrum, (II) detected digital DSB signal spectrum (blue line) and reconstructed digital SSB signal spectrum (green line) obtained using the KK scheme. ECL: External cavity laser. PC: Polarization controller. AWG: Arbitrary waveform generator. EDFA: Erbium-doped fibre amplifier. VOA: Variable optical attenuator. SSMF: Standard single-mode fibre. OBPF: Optical band-pass filter. PD: Photodiode. (b) Receiver DSP including KK scheme. EDC: Electronic dispersion compensation, DEMOD DSP: Demodulation DSP for SSB Nyquist-SCM signal.

Kronig relation, if the transmitted signal fulfils the condition of minimum phase (assuming the optical signal is single-sideband with the optical carrier having an amplitude larger than that of the SSB signal), the phase of the transmitted signal, $\varphi(n)$, is linked to its amplitude, $h(n) = (V_{DD}(n))^{1/2}$, where $V_{DD}(n)$ is the detected signal voltage. Hence, following direct detection of the total field intensity, the complex-valued SSB signal (Fig. 1(a) inset (II)) can be extracted from the measured photocurrent ($V_{KK}(n) = h(n)exp\{i\varphi(n)\}$). The recovered phase of the optical signal waveform can be written as:

$$\varphi(n) = \mathcal{F}^{-1}\{i \cdot sign(\omega)\mathcal{F}\{ln[|h(n)|]\}\} \qquad (1)$$

where $n$ is the discrete time index, $sign(\omega)$ is the sign function, which is equal to 1 for $\omega > 0$, to 0 for $\omega = 0$, and to -1 for $\omega < 0$, and $\mathcal{F}\{\bullet\}$ and $\mathcal{F}^{-1}\{\bullet\}$ are the Fourier and inverse Fourier transform operators. In contrast to the previously demonstrated SSBI cancellation techniques, which treat the SSBI as a perturbation to the signal which they reconstruct and, subsequently, subtract from the detected signal, the KK scheme enables to reconstruct the transmitted single-sideband signal without SSBI terms, and consequently, provides superior performance[4]. Note that, due to the broadened bandwidth resulting from the square-root and logarithm ($ln(|h(n)|)$) operations, it is required to perform digital upsampling (4 Sa/symbol was used in this study) prior to the KK scheme.

## Experimental Results

The performance of both 4×112 Gb/s 16-QAM and 4×168 Gb/s 64-QAM SSB Nyquist-SCM DD systems was evaluated in optical back-to-back and WDM transmission operations, with the results plotted in Figs. 2 and 3, respectively. The optical back-to-back performance was evaluated by measuring BER versus OSNR using ASE-noise loading at the receiver, for WDM without receiver linearization, and for both single channel and WDM with the KK scheme (using channel #2 in the case of WDM). The results for 16QAM are shown in Fig. 2(a). The results were compared with those of simulations using the KK scheme, assuming ideal transceivers using ideal electrical and optical components, *i.e.* no quantization or other electrical noise, linear modulator and ideal 'rectangular' shaped OBPF. The optimum system performance was achieved by sweeping the CSPR and setting it at the optimum value at each OSNR level. In all back-to-back and transmission experiments, the optimum CSPR values when utilizing the KK scheme were found to be approximately 5 dB lower than those for the system without linearization. For example, at an

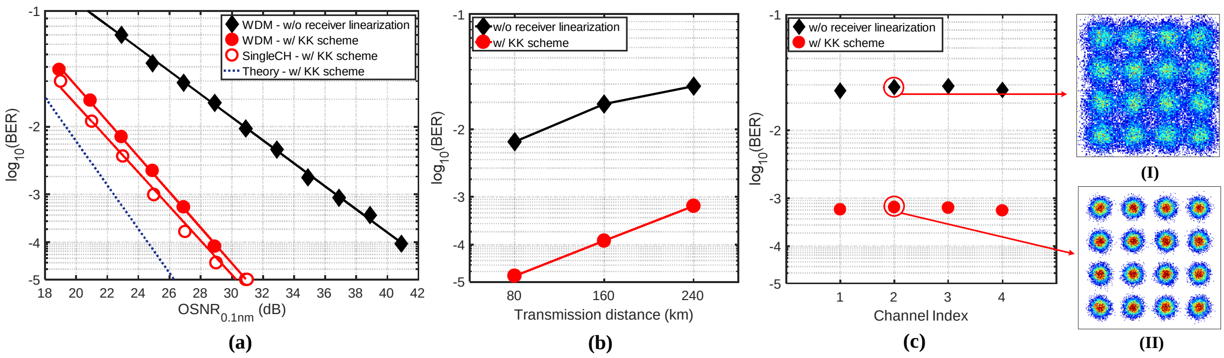


**Fig. 2:** 16-QAM SSB Nyquist-SCM WDM system performance: (a) Back-to-back BER vs OSNR. (b) BER vs transmission distance. (c) BER for each WDM channel after 240 km. Insets: Received constellations (I) without receiver linearization (EVM = 23.6%) and (II) with Kramers-Kronig scheme (EVM = 13.7%) at 240 km transmission.

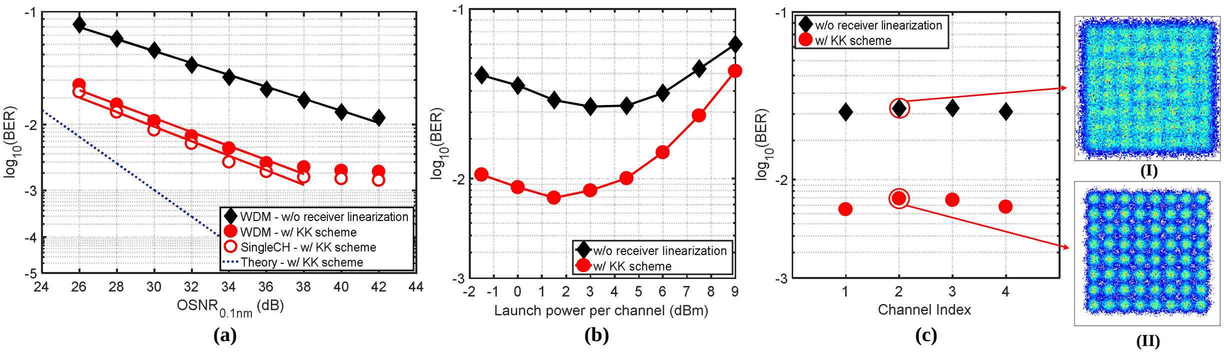


**Fig. 3:** 64-QAM SSB Nyquist-SCM WDM DD system performance: (a) Back-to-back BER vs OSNR. (b) BER vs optical launch power per channel at 80 km transmission. (c) BER for each WDM channel after 80 km. Insets: Received constellations (I) without receiver linearization (EVM = 23.1%) and (II) with Kramers-Kronig scheme (EVM = 13.8%) at 80 km transmission.

OSNR of 25 dB, the optimum CSPR value was reduced from 10 dB to 5 dB using the KK scheme. Compared to the ideal system simulations (shown as 'Theory' in Fig. 2(a)), the penalty caused by transceiver noise and practical OBPF was 3 dB at BER = $10^{-3}$. Additionally, the penalty caused by linear WDM channel crosstalk was approximately 1 dB. At an OSNR of 25 dB, the BER was reduced from $4.3\times10^{-2}$ to $2.5\times10^{-3}$ using the KK scheme. The system was further assessed through WDM transmission over SSMF links of lengths from 80 km to 240 km without and with the KK scheme. The BER versus transmission distance is plotted in Fig. 2(b). The transmission performance was significantly improved at all distances, with the BER at 240 km transmission being reduced by more than an order of magnitude (from $2.9\times10^{-2}$ to $6.7\times10^{-4}$) through using the KK scheme. The performance of all four WDM channels in transmission over 240 km is shown in Fig. 2(c). The average BER across the channels was decreased from $2.8\times10^{-2}$ to $6.3\times10^{-4}$, and, based on the theoretical hard-decision decoding bound at this BER, the achieved net optical ISD was calculated to be 3.17 b/s/Hz.

Next, the system performance with the higher modulation format (64-QAM) and higher channel bit rate (168 Gb/s) was evaluated. In optical back-to-back operation, as shown in Fig. 3(a), it can be seen that the 64-QAM system is more sensitive to transceiver noise and linear WDM channel crosstalk, compared to 16-QAM. The BER at 36 dB OSNR was decreased by approximately one order of magnitude (from $2.5\times10^{-2}$ to $2.8\times10^{-3}$) using the KK receiver, with a corresponding reduction in the optimum CSPR value from 14 dB to 9 dB. As shown in Fig. 3(b), in WDM transmission over 80 km transmission, the BER at the optimum launch power was reduced from $3.2\times10^{-2}$ to $6.9\times10^{-3}$. The BER of all four WDM channels after 80 km transmission is plotted in Fig. 3(c). The average BER across the channels was decreased from $3.1\times10^{-2}$ to $6.1\times10^{-3}$ giving an achieved net optical information spectral density (based on the theoretical hard-decision decoding bound) of 4.54 b/s/Hz, to the best of our knowledge the highest reported net optical ISD for a single-polarization single-photodiode based DD transceiver for metro reach transmission.

## Conclusions

We reported the experimental demonstration of 35 GHz-spaced 4×28 GBd (112 Gb/s/λ 16-QAM and 168 Gb/s/λ 64-QAM) SSB Nyquist-SCM direct-detection signal transmissions over 240 km and 80 km SSMF links, respectively. Record WDM net spectral efficiencies were achieved over these distances. This achievement has been enabled through the use of the recently-proposed Kramers-Kronig receiver DSP scheme. Such technology is a promising solution for future high-capacity metro networks.

## Acknowledgements

This work is supported by the UK EPSRC UNLOC project, and Semtech Corporation.

## References


[1] M.S. Erkılınç et al., "Spectrally-efficient WDM Nyquist pulse-shaped 16-QAM subcarrier modulation transmission with direct detection," J. Lightw. Technol., Vol. **33**, no. 15, p. 3147-3155 (2015).

[2] A. Mecozzi et al., "Kramers-Kronig coherent receiver," Optica, Vol. **3**, no. 11, p. 1220-1227 (2016).

[3] C. Antonelli, et al., "Kramers-Kronig PAM transceiver," Proc. OFC, Tu3I.5 (2017).

[4] Z. Li et al., "SSBI mitigation and Kramer-Kronig scheme in single-sideband direct-detection transmission with receiver-based electronic dispersion compensation," J. Lightw. Technol., Vol. **35**, no. 10, p. 1887-1893 (2017).

[5] X. Chen, et al., "218-Gb/s single-wavelength, single-polarization, single-photodiode transmission over 125-km of standard single-mode fiber using Kramers-Kronig detection", Proc. OFC, Th5B.6 (2017).

[6] R. Hirai, et al., "High-spectral efficiency DWDM transmission of 100-Gbit/s/lambda IM/DD single sideband-baseband-Nyquist-PAM8 signals," Proc. OFC, Th3D.4 (2017).