

# A Low-Loss Split-Carrier Transmitter Architecture for Intra-Datacentre Communications

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**Abstract** A split-carrier transmitter is proposed to increase the loss budget for intra-datacentre links by reducing modulator insertion loss. Transmission of 28 GBd subcarrier modulated 16-QAM (112 Gb/s) over 2 km SSMF is shown to be possible with an optimised modulator loss of <4.4 dB.

## Introduction

To meet the growing bandwidth requirements of cloud data services, datacentre intraconnects will be inevitably upgraded from 100 to 400 Gb/s. To achieve this, 56 GBd 4-level pulse amplitude modulation (4PAM) using four wavelengths or fibres has been favoured as a low cost, low complexity solution<sup>1</sup>. However, 4PAM offers a relatively low loss budget, leaving little margin for system variation and future data rate improvements. The loss budget determines the continuous wave (CW) laser power required, defined here as

$$P_{\text{CW,req}} = P_{\text{mod,loss}} + P_{\text{fibre,loss}} + P_{\text{Rx,req}}, \quad (1)$$

where  $P_{\text{mod,loss}}$  is the dynamic modulator loss in dB,  $P_{\text{fibre,loss}}$  is the fibre transmission loss in dB, and  $P_{\text{Rx,req}}$  is the power required at the receiver, in dBm, for a specified bit error rate (BER).

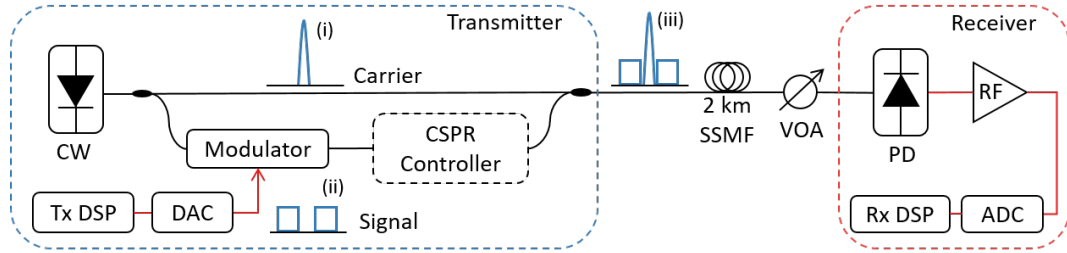
The CW launch power should be kept as low as possible to minimise the equipment and operational costs. To realise this, reduction of  $P_{\text{mod,loss}}$  has been demonstrated using direct modulation, but requires nonlinear Volterra equalisation<sup>2,3</sup>. Alternatively, externally modulated lasers have enabled receiver sensitivities as low as  $-7.1$  dBm at a BER of  $3.8 \times 10^{-3}$ , but typically incur a 10 dB modulation loss<sup>4</sup>. Nyquist-shaped subcarrier modulation (N-SCM) has also been proposed<sup>5,6</sup>, using 16-ary quadrature amplitude modulation (16-QAM) to achieve 112 Gb/s at 28 GBaud per channel. However, these also incur significant modulation losses and, hence, have high CW power requirements.

In this paper, an alternative transceiver design that uses a split-carrier to improve loss budget is presented. The split-carrier method has been recently used to improve the transmitter signal to noise ratio<sup>7</sup>; in this experiment, shown in Fig. 1, its ability to reduce loss is showcased. The CW

output is split into a carrier branch, inset (i), and signal branch, inset (ii). When recoupled, the transmitter output, inset (iii), is dominated by the carrier, which only suffers coupling losses. The power preserved in the carrier is transferred to the signal at the receiver through direct detection employing only a single photodiode. Using this method, the loss budget is improved and advanced modulation formats become feasible; significantly reducing the transceiver bandwidth requirements. To demonstrate this, a 16-QAM N-SCM signal is used to achieve 112 Gb/s with a calculated loss budget of 5.2 dB, including the modulator loss.

## Experimental configuration

A CW laser with an output power of 11 dBm emitting at 1551 nm was split using a 3 dB polarisation maintaining coupler (PMC) into an upper carrier path and a lower signal path, as shown in Fig. 1. To maintain coherence between the signal and carrier, a narrow-linewidth laser (approximately 10 kHz) was used at the transmitter; this would not be required in an integrated device, in which differential path length could be controlled. An IQ modulator with a measured dynamic insertion loss of 26.5 dB was used to modulate the signal. To emulate a simpler design, the four modulator inputs were driven using the same data using a 92 GS/s digital-to-analogue converter (DAC), generating a 28 GBd N-SCM signal. To investigate the optimum carrier-to-signal power ratio (CSPR), the signal was passed through a CSPR controller, comprising an erbium doped fibre amplifier (EDFA) with a noise figure of 5 dB, followed by an optical bandpass filter and a variable optical attenuator (VOA). It is critical to maintain the relative state of polarisation between the carrier and the signal branch. Again, in an integrated device, the CSPR would be defined by the loss of

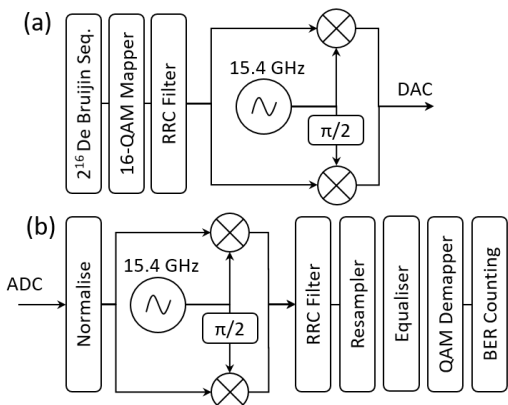


**Fig. 1:** Experimental setup to investigate the N-SCM split-carrier transceiver. The CSRR controller consists of an EDFA, a bandpass filter and VOA (not required in a final design). The schematic of Fourier spectra are shown in the insets (i)-(iii).

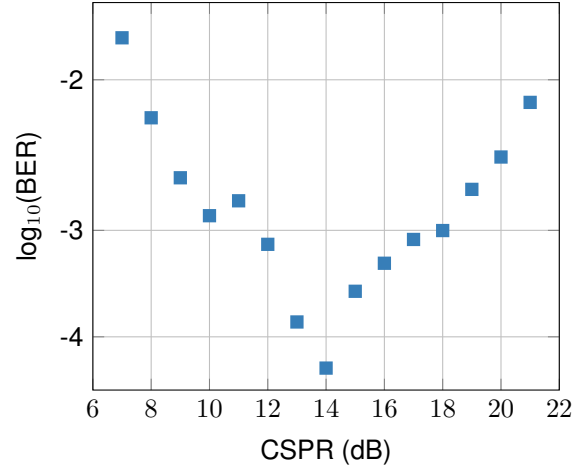
the modulator and the coupling coefficients of the PMCs, with no controller required.

The signal path was then recoupled with the split-carrier using a second 3 dB PMC, leading a measured total carrier loss of 6.4 dB. The recoupled signal was passed through 2 km of standard single mode fibre (SSMF) and a VOA prior to detection and RF amplification using a 40 GHz bandwidth photodiode and RF amplifier providing 17 dB gain, respectively. Finally, the signal was digitised using a 160 GS/s analogue-to-digital converter (ADC) before the offline digital signal processing (DSP) was performed.

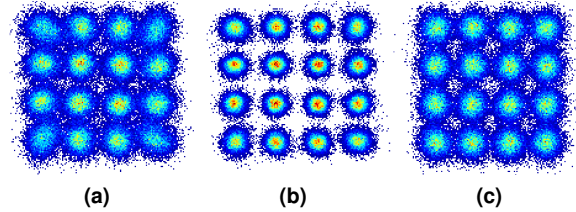
The DSP used to generate the N-SCM waveforms is shown in Fig. 2(a). A  $2^{16}$  De Bruijn sequence was mapped to 16-QAM symbols before being shaped using a Nyquist root raised cosine (RRC) filter with a roll off factor of 0.05. The baseband signal was digitally upconverted using a subcarrier with a frequency of 15.4 GHz, leading a subcycle ratio of 0.55. The receiver-side DSP is shown in Fig. 2(b). Following normalisation, the received signal was digitally downconverted using a second 15.4 GHz clock tone. The baseband signal was passed through a RRC filter and resampled to two samples per symbol. An 11-tap equaliser was used to remove inter symbol interference and recover the symbol samples. Finally, the 16-QAM symbols were demapped and passed to a BER estimator.



**Fig. 2:** DSP performed at the (a) transmitter and (b) receiver. A digital clock tone is used to up- and down-convert the data.



**Fig. 3:** Variation in system performance for a fixed received power of  $-1$  dBm when varying carrier to signal power ratio.

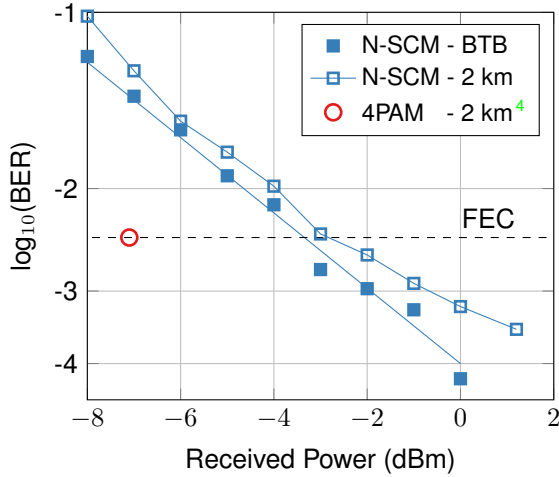


**Fig. 4:** Received 16-QAM N-SCM constellations at a received power of  $-1$  dBm at a CSRR of (a) 8, (b) 14, and (c) 21 dB.

## Results

To determine the optimum PMC coefficient for the split-carrier, the CSRR controller was used to vary the CSRR and back-to-back (BTB) BER measurements taken at a fixed received power of  $-1$  dBm. The results are shown in Fig. 3, in which the optimum CSRR is found to be 14 dB. The effect of this variation on the received 16-QAM constellation can be observed in Fig. 4. Note that in Fig. 4(a), a low CSRR causes amplitude distortions on the outermost symbols due to their high amplitude, shifting the DC bias of the carrier which effectively draws the carrier towards the signal.

To achieve a split-carrier transceiver with a CSRR of 14 dB, the ideal carrier-signal PMC coefficient is 60:40. Assuming both this split ratio, and a typical Mach-Zehnder modulator loss of  $\sim 10$  dB, then creating the split-carrier scheme establishes a CSRR of 13.5 dB. Crucially, this efficient configuration leads to only 4.4 dB of cou-

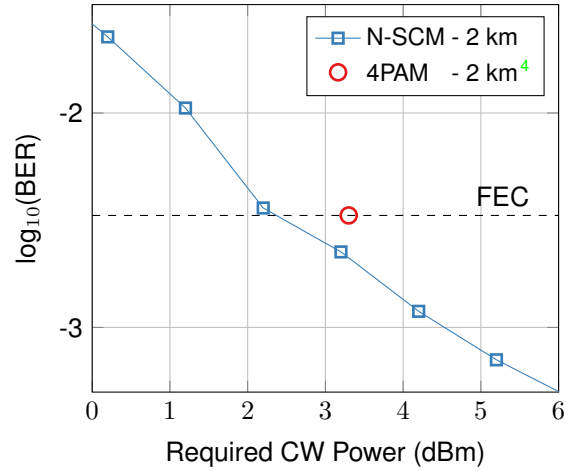


**Fig. 5:** Performance of the 112 Gb/s N-SCM split-carrier system. A 112 Gb/s 4PAM result is included for comparison.

pling loss for the carrier. For the remainder of this paper, the use of 60:40 PMCs is assumed such that the power lost over the split-carrier is 4.8 dB, with an extra 0.4 dB added to account for the measured excess coupler losses.

For the transmission experiment, the CSPR was set to 14 dB and the power received at the photodiode was varied. BTB and transmission over 2 km of SSMF performance was evaluated and the results are shown in Fig. 5. Applying heuristic fits to the data, a hard-decision forward error correction (FEC) at a BER of  $3.8 \times 10^{-3}$  is achieved at a received power of  $-3.3$  dBm (BTB case) and  $-2.7$  dBm (after 2 km).

The red ring marker in Fig. 5 corresponds to the achieved received power at the FEC threshold after 2 km of SSMF for a 56 GBd 4PAM signal reported in<sup>4</sup>. It offers 4.4 dB higher sensitivity compared to the split-carrier reported here. However, it is important to consider this in terms of overall system requirements. Using Eq. (1), the data in Fig. 5 is re-expressed in terms of required CW power, where the  $P_{\text{mod,loss}}$  of 10 dB reported in<sup>4</sup> is used, while the split-carrier results adopt the optimum 4.8 dB loss discussed above. A  $P_{\text{fibre,loss}}$  of 0.4 dB is assumed for both cases. The result is seen in Fig. 6. This shows that despite the lower sensitivity, the power-efficient modulation scheme outperforms the 56 GBaud 4PAM result by 0.8 dB in terms of CW power requirements. Therefore, the split-carrier N-SCM proof-of-concept presented here achieves 112 Gb/s with a higher loss budget than the 56 GBaud 4PAM technique reported in<sup>4</sup>, but with reduced bandwidth requirements.



**Fig. 6:** CW output power required for 112 Gb/s over 2 km using the N-SCM split-carrier system and 4PAM.

## Conclusions

A proof-of-concept split-carrier transmission method envisaged for 400G intra-datacentre connections is proposed to improve loss budget. The results indicate that optimised coupling coefficients allow a laser-to-photodiode loss budget (over 2 km) of 5.2 dB. This was found to outperform a recent, high-sensitivity 112 Gb/s 4PAM result by 0.8 dB. Although it is expected that transmitter pre-emphasis and accurate path matching would both improve the receiver sensitivity, the results demonstrate the feasibility of the split-carrier method to reduce the required CW power of externally modulated transmitters.

## Acknowledgements

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