Digital Subcarrier Multiplexing 4-D Set-Partitioning QAM Signals

Meng Xiang[1,2], Qunbi Zhuge[2,3], Meng Qiu[2], Thang M. Hoang[2], Mohamed M. Osman[2], Xingyu Zhou[2], Fangyuan Zhang[2], Ming Tang[1], Changjian Ke[1], Deming Liu[1], Songnian Fu[1*], David V Plant[2]

[1] School of optical and electronic information, Huazhong University of Sci&Tech (HUST), 1037 Luoyu Road, Wuhan, China 430074, *songnian@mail.hust.edu.cn
[2] Department of Electrical and Computer Engineering, McGill University, Montréal, Qc, H3A 2A7, Canada
[3] Ciena Corporation, Ottawa, Ontario, Canada, K2H 8E9

Abstract We experimentally investigate 4-D set-partitioning formats in digital subcarrier multiplexing systems. The proposed 4-D set-partitioning of signals across two subcarriers outperforms the conventional approach implemented across two polarizations in terms of both nonlinearity and optical filtering tolerance.

Introduction

To meet the ever-growing capacity demands in optical networks, four-dimensional (4-D) modulation formats have gained considerable attention recently due to their ability to achieve fine granularity in spectral efficiency (SE) and improved transmission performance[1-4]. Conventional polarization-division multiplexed (PDM) two dimensional M-quadrature amplitude modulation (QAM) formats normally deliver an even number of encoded bits per symbol. 4-D formats implemented across two polarizations can be derived from the PDM M-QAMs by utilizing the Ungerboeck set-partitioning (SP) scheme. As a result, they can encode odd numbers of bits per symbol and thus enable a granularity of 1 bit/symbol for flexible adaptation of SE. For example, the SP-512-QAM and SP-128-QAM formats yield 9, and 7 bits/symbol, respectively.

At present fiber nonlinearities limit additional increases of optical network capacity. In order to improve the nonlinear tolerance, digital subcarrier multiplexing (SCM) has been proposed in which several low symbol-rate non-overlapping Nyquist subcarriers are digitally generated for signal transmission[5,6]. SCM schemes also suffer from less chromatic dispersion (CD) and polarization mode dispersion. Therefore they can reduce the digital signal processing (DSP) complexity.

In this paper, we investigate the performance of 4-D SP formats in SCM systems. Particularly, we propose to encode the 4-D SP format implemented across two subcarriers in order to improve the tolerance to fiber nonlinearities and the cascaded reconfigurable optical add-drop multiplexers (ROADMs) induced optical filtering, compared with the conventional 4-D SP format encoded across the two polarizations. The performance improvement is experimentally demonstrated in a 34.94 Gbaud SP-128-QAM 4-subcarrier SCM transmission experiment.

Encoding of SCM 4-D signals

In this work we focus on the SP-128-QAM format. For the encoding of SP-128-QAM, an XOR operation on seven information bits is first applied to generate the 8th bit. Then the resulting eight bits are mapped to two gray coded 16QAM constellations, which are typically assigned to the two polarizations for the same time slot in the single carrier system[1]. This 4-D encoding scheme across polarizations can be readily extended to SCM systems, denoted by SCM-SP-POL. Alternatively, we propose the encoding of the 4-D format across two subcarriers, denoted by SCM-SP-SC in order to increase the tolerance to fiber nonlinearity and optical filtering. Fig. 1(a) illustrates the 4-D SCM-SP-POL (top) and SCM-SP-SC (bottom) signals in the frequency domain, and Fig. 1(b) shows the corresponding constellation.

Experimental setup

A schematic of the experimental setup is shown in Fig. 1(d). Before being converted into analog

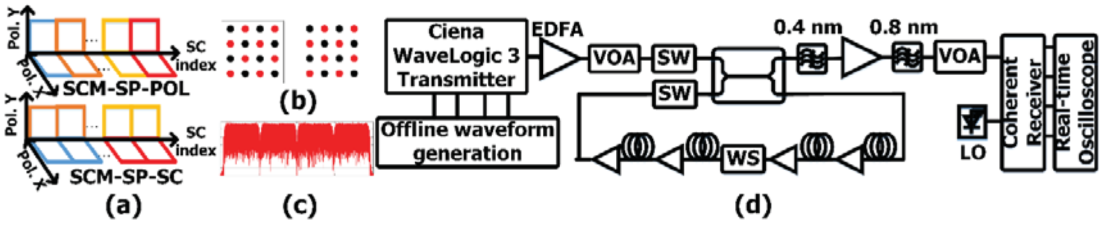

Fig. 1: (a) Illustration of the two set-partitioning schemes in SCM systems. (b) The constellation of SP-128-QAM. (c) Spectrum of the SCM signal. (d) Experimental setup. SW: switch. WS: wave-shaper

ISBN 978-3-8007-4274-5

signals by the digital-to-analog converters (DACs), the SCM 4-D signals are first generated offline in MATLAB. In our experiment, the aggregate baud rate is 34.94 GBaud for the 4-subcarrier SCM signals. A root raised cosine (RRC) pulse shaping filter with a roll-off factor of 0.1 is used for each subcarrier. No guard band is used in the SCM SP-128-QAM signal spectrum, as shown in Fig. 1(c). Then, the generated real and imaginary components of the SCM SP-128-QAM signals are loaded to the transmitter module of a Ciena WaveLogic 3 transmitter, which incorporates a low-linewidth external-cavity laser (ECL), four high-speed DACs with a 6-bit nominal resolution and a DP IQ modulator. The wavelength of the laser is set to 1554.54 nm. The output of the transmitter is boosted by an Erbium-doped fiber amplifier (EDFA). A variable optical attenuator (VOA) controls the launch power before the signals enter the re-circulating loop. The loop contains 320 km of standard single mode fiber (SSMF), and the EDFAs are employed after every 80 km fiber to compensate the loss. When evaluating the performance against the optical filtering, a Finisar wave-shaper (WS) is inserted after the second EDFA. After the loop, the signals are filtered, amplified and filtered again. An ECL is employed as the local oscillator (LO) for the coherent detection. The optical-to-electrical conversion is achieved by 4 balanced photodiodes, and a four-channel real time oscilloscope with a sampling rate of 80 GSa/s per channel is used to digitize the waveform. Finally, the captured waveforms are processed offline in MATLAB. The receiver DSP includes the CD compensation, coase frequency offset (FO) compensation, subcarrier de-multiplexing, matched filtering, adaptive equalization, phase recovery and symbol decision[3,5]. The BER is calculated by counting the bit errors across all the 4 subcarriers.

Results and discussion

Fig. 2 shows the BER versus OSNR (0.1 nm) for the two SCM 4-D signals in the back-to-back (B2B) case. The single carrier scheme with conventional 4-D format (SP-POL) is also shown as a reference. First, the two SCM 4-D SP schemes achieve identical performance in B2B transmission. While compared to the single carrier scheme, a performance penalty is observed especially in the high OSNR region for both of them, which is mainly due to the limited DAC resolution and the residual FO induced offset-filtering by the matched RRC filters. Compared to the theoretical performance, the two SCM 4-D SP schemes suffer from about 1 dB B2B penalty.

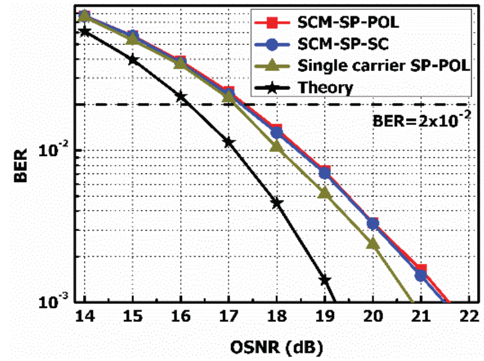

Fig. 2: Back-to-back performance.

Next we investigate the performance after fiber transmission. Fig. 3 shows the BER as a function of the launch power over 2560 km fiber transmission. At low launch power, i.e. from -5 to -3 dBm, the systems are mainly limited by the noise and the BER is approximately the same for the three schemes. However, as the launch power increases, fiber nonlinearities become significant and dominant. In this situation, both SCM signals achieve a lower BER than the single carrier signal. In terms of the optimum launch power, an increase from -1 dBm to 0 dBm is observed for both SCM signals. Furthermore, we demonstrate that the SCM-SP-SC scheme outperforms the SCM-SP-POL scheme in the nonlinear region. This improvement can be explained by the fact that the correlation between polarization symbols in SCM-SP-POL due to 4-D encoding is maintained during transmission, while the correlation between subcarrier symbols in SCM-SP-SC due to 4-D encoding is quickly eliminated by the CD-induced walk-off during transmission. The increase in nonlinear tolerance is also demonstrated in Fig. 4, which shows the achievable transmission distance at BER = 2×10^{-2} as a function of the launch power. For the single carrier scheme, the maximum reach of ~2960 km is achieved at -1 dBm launch power. The SCM-SP-POL scheme and SCM-SP-SC scheme increase the distance by 11.6% and 15.2% to 3305 km and 3410 km, respectively.

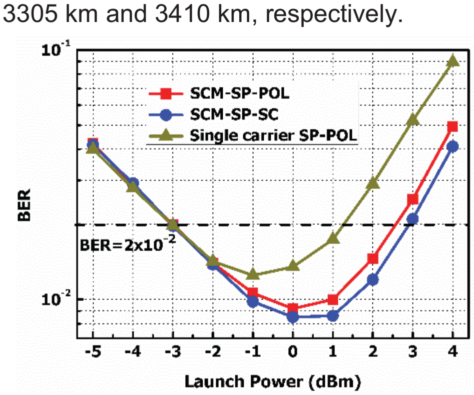

Fig. 3: BER versus the launch power after 2560 km SSMF transmission (no WS in the loop).

ISBN 978-3-8007-4274-5

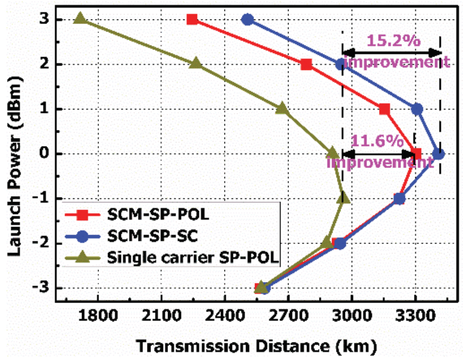

Fig. 4: Achievable transmission distance versus the launch power with a BER limit of 2×10^{-2} (no WS in the loop).

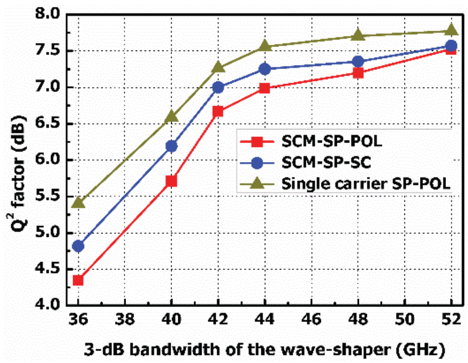

Fig. 5: Transmission performance over 2560 km SSMF (8 loops) with different WS 3 dB bandwidths.

ROADMs are the key elements in meshed optical networks. However, they reduce the available bandwidth for each wavelength-division multiplexing (WDM) channel with cascaded optical filtering. In this section, we insert a WS in the loop with a variable 3-dB bandwidth to emulate the cascaded optical filtering effect and investigate the filtering tolerance of the SCM 4-D signals. First, the measured Q^2factor ($Q^2(\mathrm{dB}) = 20log_{10}(\sqrt{2}erfc^{-1}(2\mathrm{BER}))$) versus the 3-dB bandwidth of the WS after 2560 km SSMF transmission (8 loops) is shown in Fig. 5. The launch power is set to -5 dBm to eliminate the impact of fiber nonlinearities. Obviously, the SCM schemes demonstrate reduced tolerance to the cascaded WSs induced optical filtering compared to the single carrier scheme, since the two edge subcarriers are severely filtered in the SCM cases. As a result, the large performance penalties on these edge subcarriers limit the overall system performance even though the BER is calculated across all subcarriers. On the other hand, the two SCM schemes show similar performance when the 3-dB bandwidth is wide, e.g., 52 GHz. However, as the 3 dB bandwidth decreases, the SCM-SP-SC scheme shows better performance than SCM-SP-POL scheme since the 4-D signal decoding is implemented across the edge and middle subcarriers which mitigates the optical filtering effect. On the contrary, in SCM-SP-POL scheme the 4-D signal decoding is applied to the same subcarrier across polarizations and the performance of edge subcarriers is significantly degraded by the optical filtering.

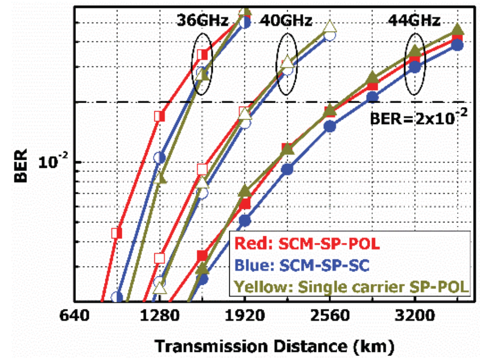

Fig. 6: BER versus transmission distance with various WS 3-dB bandwidths.

Finally, Fig. 6 compares the transmission performance with a 3-dB WS bandwidth of 36, 40 and 44 GHz, respectively. With 36 GHz 3-dB bandwidth, the filtering induced penalty is large and the achievable transmission distance is limited to less than 1500 km for all schemes at BER = 2×10^{-2}. In this scenario, the single carrier scheme is the optimum choice since it is more tolerant to optical filtering. As the 3-dB bandwidth increases, i.e. 40 GHz and 44 GHz in Fig. 6, the transmission distance extends for all three schemes and the penalty due to fiber nonlinearity becomes comparable to the filtering penalty. In this case, the SCM-SP-SC scheme achieves longer distances than the other two schemes.

Conclusion

In this work, we propose to encode a 4-D modulation format across subcarriers in digital subcarrier multiplexing (SCM) systems. We experimentally demonstrate improvement in tolerance to both fiber nonlinearity and optical filtering when compared to a conventional 4-D format across polarizations in a 34.94 Gbaud set-partitioning 128 QAM transmissions.

This work was partially supported by, the 863 High Technology Plan (2015AA016904), and National Natural Science Foundation of China (61307091,61331010), China Scholarship Council (CSC, 201506160024).

References

[1] J. K. Fischer et al., J. Lightwave Technol , vol. 33, no. 7, p. 1445 (2015).
[2] H. Sun et al., Proc. ECOC, Th.2.D.3 (2013).
[3] J. Renaudier et al., Proc. ECOC, We.1.C.5 (2012).
[4] A. S. Kashi et al., Proc. ECOC, ID. 0295 (2015).
[5] M. Qiu et al., Proc. OFC, Tu3J. 2 (2014).
[6] H. Nakashima et al., ECOC , ID. 0391 (2015).