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DOI:
10.1109/ECOC.2017.8345962

Document status and date:
Published: 21/09/2017

Document Version:
Accepted manuscript including changes made at the peer-review stage

112-Gbit/s Single Side-Band PAM-4 Transmission over Inter-DCI distances Without DCF Enabled by Low-complexity DSP

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Abstract We present a *chromatic dispersion and bandwidth pre-compensated 112-Gbit/s single side band signal transmitter over 93 km SSMF at 1550 nm using a dual-drive MZM. The proposed scheme is computationally efficient utilising only 21 linear and 11 quadratic taps.*

Introduction

Rapid developments in datacenter traffic is driving up the requirements for inter-datacenter link capacity. Currently ongoing discussions for 400 gigabit Ethernet (GbE) standard in short-reach capacity require significant migration from 25Gb/s line rates towards 100Gb/s. One solution for 400GbE is the use of four parallel single mode fibers (PSM4) as a promising candidate for delivering link capacity in inter-data center interconnects[1] (inter-DCI). For this transmission scheme, high-bitrate single wavelength (100-Gbit/s/λ) intensity modulated direct detection (IM/DD) links are being developed. Due to cost, these links need to have as few optical components as possible. Therefore, the use of dispersion compensating fibers (DCF) or modules (DCM) needs to be avoided. Digital signal processing (DSP) is key in relaxing the requirements on the components used. Techniques such as pre-compensation for bandwidth limitations[6] and chromatic dispersion[7] and powerful equalizers[3] are required to reach inter-DCI distances with sufficient performance. However, at the same time, DSP complexity needs to be limited to reduce energy and cost.

Recently, there has been a lot of interest in single sideband (SSB) for single wavelength 100-Gbit/s transmission[2-5,8]. These experiments use 4-level pulse amplitude modulation PAM-4[3,6,9], subcarrier multiplexing[2,8] (SCM), duo-binary[4] PAM-4 or discrete multitone[9] (DMT). The sideband is suppressed using DSP and an IQ-modulator[2,5] or a dual-drive Mach-Zehnder modulator[4,8-10] (DD-MZM). Pre-compensation of the chromatic dispersion (CD) is used as well[2-4,6-8] to omit the use of dispersion compensating fibers (DCF).

In this work we demonstrate 112-Gbit/s SSB PAM-4 transmission over 93 km of fiber without DCF using a DD-MZM to modulate a single sideband onto a single wavelength. The transmitted signal is pre-compensated for bandwidth limitations and CD, resulting in distinguishable levels at the receiver. A clear description of the optical signal-to-noise ratio (OSNR) in the IM/DD system is given here as this is not trivial in an IM/DD scenario. Focusing on DSP complexity, the amount of taps is limited for both the transmitter and receiver side implementation. A total of only 19 taps (up to 25 km of fiber) up to 56 taps (93 km), were used for CD pre-compensation, pulse shaping and Hilbert transform in total. Note that a separate filter of 9 taps was used for bandwidth pre-compensation. Finally, a full 2D tap-sweep was carried out for a blind feedforward equalizer with added quadratic taps[3] indicating the optimal selection of 21 linear taps and 11 quadratic taps for the equalizer, a significant improvement over previous works of similar reach[3].

Experimental setup

Fig. 4 shows the experimental setup with the digital signal processing (DSP) functions. Two PRBS-sequences are combined to create a Gray-coded 56-GBaud PAM-4 sequence that is subsequently resampled to 84 GS/s. A single complex filter is created to apply raised cosine pulse shaping with roll-off 0.2, Hilbert transformation and CD pre-compensation[7]. Tap number minimization resulted in using only 19 taps for up to 25 km transmission and 56 taps for 93 km, as it needed more taps to be able to pre-compensate for the larger amount of chromatic dispersion. The real and imaginary (Hilbert) parts of the waveform are combined, pre-compensated for bandwidth limitations of the channel caused by transmitter and receiver components using a 9-tap filter[6], and uploaded to a Keysight M8196A arbitrary waveform generator (AWG) running at 84 GS/s. Note that the Keysight channel correction software to pre-compensate for channel impairments is not used. The two electrical signals are amplified by SHF807 RF-amplifiers. A DD-MZM modulates the SSB PAM-4 signal onto a 1550 nm optical carrier. The optical signal is amplified by an

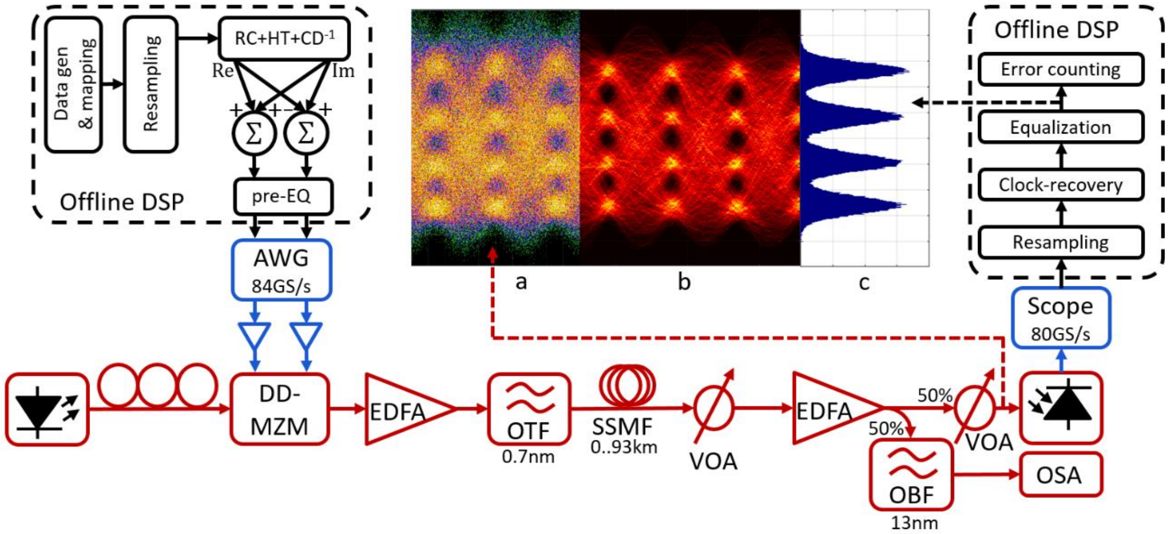

Fig. 1: Experiment setup. Inset shows optical eye diagram right before the detector (a), eye diagram after equalization (b) and the corresponding histogram (c). (RC: Raised Cosine, HT: Hilbert Transform, CD: Chromatic Dispersion, pre-EQ: pre-equalization, AWG: arbitrary waveform generator, DD-MZM: Dual-Drive Mach-Zehnder Modulator, EDFA: Erbium Doped Fiber Amplifier, OTF: Optical Tunable Filter, SSMF: Standard SingleMode Fiber, VOA: Variable Optical Attenuator, OBF: Optical Bandpass Filter, OSA: Optical Spectrum Analyzer)

erbium doped fiber amplifier (EDFA) and filtered by an optical tunable filter (OTF) with a passband of 0.7 nm.

Fig. 2 shows that the OTF suppresses the sideband 5 dB further. The spectrum was measured with an optical spectrum analyser (OSA) with 0.05 nm bandwidth. In recent literature it has not been clear how OSNR and carrier-to-signal power ratio (CSPR) measurements for SSB are done. When a normal OSNR measurement is performed using an OSA, it actually measures the carrier-to-noise power ratio, because IM/DD is not carrierless. As a consequence, the measured OSNR would be independent of the modulation depth, even though it directly controls signal power. To counter this, we measured CSPR with the same resolution (0.05 nm) as used for the OSNR measurement (0.05 nm resolution with 0.1 nm noise bandwidth) and subtracted this value (16.9 dB) from the measured carrier-to-noise power ratio. Note that CSPR is dependent on resolution of the OSA as we calculated the difference between peak carrier power density and the signal power density. Our definition for OSNR and CSPR in an IM/DD system is hence depicted in Fig. 2. The optical signal is launched into fiber of different lengths up to 93 km with 6.3 dBm launch power. A variable optical attenuator (VOA) is employed to control the input power at the EDFA and a second VOA controls the power into the PIN photodiode. To show optical eye at this point, an optical sampling oscilloscope is inserted before the photodiode. Fig. 1 (inset a) shows unskewed eyes, indicating no residual dispersion and confirms the impact of CD pre-compensation.The signal is digitized by an 80-GS/s Keysight MSOV334A oscilloscope and DSP is performed offline employing resampling, clock-recovery, equalization and error counting. A feedforward equalizer with both linear and quadratic taps is used[3]. The quadratic taps help to combat non-linear effects such as signal-signal-beating interference (SSBI). In an effort to minimize complexity, a full two-dimensional tap-sweep was performed to determine the amount of linear and quadratic taps. Fig. 3 depicts the

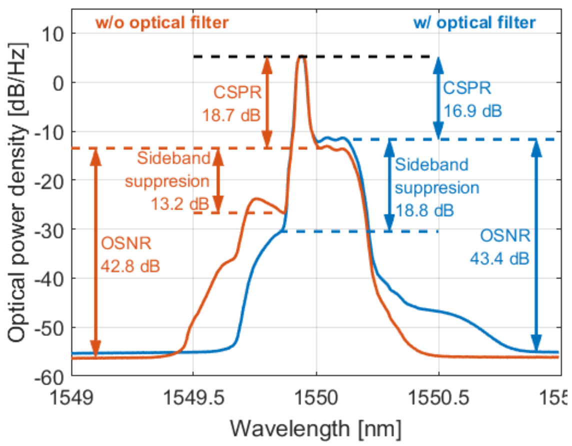

Fig. 3: Optical spectrum (back-to-back), with and without the optical tunable filter, showing carrier-to-signal power ratio (CSPR), sideband suppression and optical signal-to-noise ratio (OSNR). Measured with 0.05nm resolution.

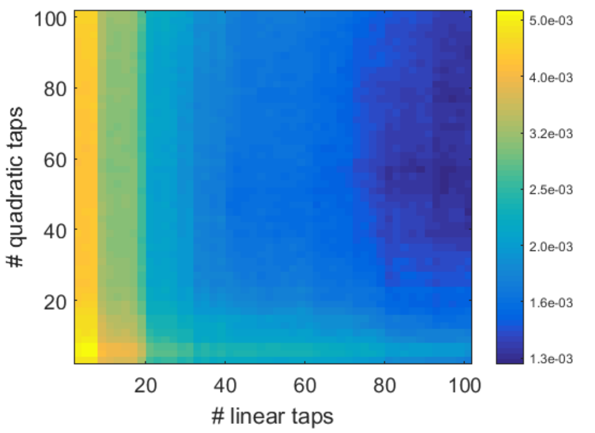

Fig. 4: Full two-dimensional tap-sweep for a blind feedforward equalizer with added quadratic taps[2] working on the received signal after 93 km of transmission with 23 dB OSNR. An equalizer with 21 linear taps and 11 quadratic taps was used in the transmission experiments.

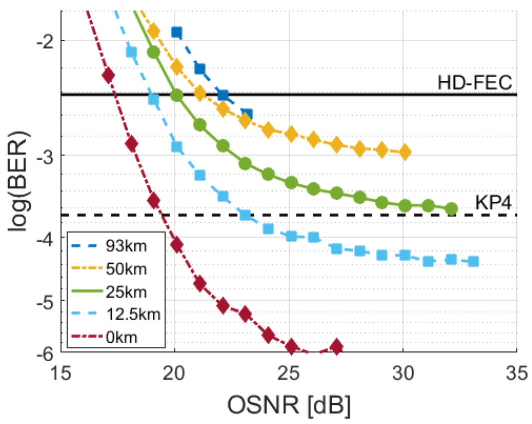

Fig. 5: BER vs OSNR performance

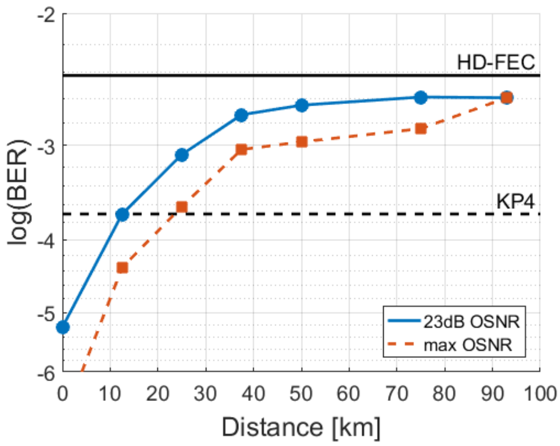

Fig. 6: BER vs distance performance for 23 dB OSNR and the maximum measured OSNR for each respective distance.

results of this tap-sweep. An equalizer using 21 linear and 11 quadratic taps proved to be a good trade-off between performance and complexity.

Results

Fig. 4 shows the BER versus OSNR performance of the 112-Gbit/s SSB PAM-4 system. Bit error rates below HD-FEC ($3.8x10^{-3}$) are achieved for all measured distances. BER measurements were performed using 2.2 million received bits. The penalty with respect to back-to-back increases with distance, but seems to converge, as with each extra reach little penalty is added. This effect is emphasized in Fig. 5, which shows BER versus distance. The BER at a given OSNR (23 dB), flattens out after 50 km of transmission. This shows inter-DCI distances are possible with this system if high enough OSNR can be provided. Due to an error floor present in our system, bit error rates below or near KP4 ($2x10^{-4}$) is possible up to 25 km of fiber and up to 93km at HD-FEC.

Conclusions

A 112-Gbit/s single sideband PAM-4 signal was transmitted over up to 93km of fiber in the C-band with bit error rates below HD-FEC. Although digital signal processing is key for reaching inter-DCI distances with 112 Gbit/s transmission, minimizing complexity is a key target. Digital pre-compensation of both bandwidth impairments and chromatic dispersion was done to improve bit error rate performance. Also, a feedforward equalizer with additional quadratic taps[3] was used. Efforts were made to limit the amount of DSP complexity, resulting in only 19 (up to 25 km) to 56 (for 93 km) taps for pulse shaping, sideband filtering and chromatic dispersion pre-compensation and only 9 taps for bandwidth pre-compensation. Receiver equalizer taps were limited to 21 linear and 11 quadratic taps. The proposed system is shown to be capable of transmitting 112-Gbit/s signals modulated on a single wavelength over inter-DCI distances and thus enables 400 Gbit/s transmission in a PSM4 transmission scheme.

Acknowledgements

The authors wish to acknowledge Keysight Technologies for supplying their M8196A AWG and MSOV334A DSO.

References

[1] S. Bhoja, PAM4 Signaling for Intra-data Center and Data Center to Data Center Connectivity (DCI), W4D.5, OFC (2017)

[2] Z. Li et al., "112 Gb/s/λ WDM Direct-Detection Nyquist-SCM Transmission at 3.15 (b/s)/Hz Over 240 km SSMF Enabled by Novel Beating Interference Compensation," OFC (2017).

[3] N. Kaneda et al., "Nonlinear Equalizer for 112-Gb/s SSB-PAM4 in 80-km Dispersion Uncompensated Link", OFC (2017)

[4] E. Zhou et al., "Single-Lane 180 Gb/s SSB-Duobinary-PAM-4 Signal Transmission over 13 km SSMF", OFC (2017)

[5] N. Kukuchi et al., "Quasi Single-Sideband (SSB) IM/DD Nyquist PAM Signaling for High-Spectral Efficiency DWDM Transmission", OFC (2016)

[6] A. Napoli et al., "Digital Compensation of Bandwidth Limitations for High-Speed DACs and ADCs", JLT (2016)

[7] R.I. Killey et al., "Electronic dispersion compensation by signal predistortion using digital Processing and a dual-drive Mach-Zehnder Modulator", PTL (2005)

[8] M. Erkilinc et al., "Dispersion-precompensated direct-detection nyquist pulse-shaped subcarrier modulation using a dual-drive Mach-Zehnder modulator", OECC (2015)

[9] Q. Zhang et al., "Transmission of single lane 128 Gbit / s PAM-4 signals over an 80 km SSMF link, enabled by DDMZM aided dispersion pre-compensation", Optics Express (2016)

[10] L. Zhang et al., "C-band Single Wavelength 100-Gb/s IM-DD Transmission over 80-km SMF without CD compensation using SSB-DMT", OFC (2015).