Field Recovery at Low CSPR Using Interleaved Carrier Assisted Differential Detection

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Abstract: We propose an interleaved subcarrier loading scheme for double-sideband signals to relax the high CSPR requirement for self-coherent detection systems. Experimental result demonstrates a successful 100-Gb/s OFDM signal transmission over 160-km SSMF at 3.5-dB CSPR.

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1. Introduction

Due to its low cost and low power consumption, intensity modulation with direct detection (IM-DD) systems are dominant for commercial optical short-reach links, such as data center interconnects (DCI). However, its data rate is limited by the dispersion-induced power fading problem. In the meanwhile, self-coherent detection (SCD) receivers [1-4] are considered as a promising solution because of its capability of recovering the full optical field. Among these systems, single sideband (SSB) modulation is usually utilized and a carrier is inserted at the edge of the signal spectrum co-propagating with the information bearing signal. After square-law detection of a single-ended photodiode (PD), signal can be retrieved from the signal-carrier beat term, however, an undesired term is also generated, which is termed as signal-signal beat interference (SSBI). Although frequency gap between the carrier and signals or interleaved subcarrier loading scheme can be used to accommodate SSBI [5,6], they will reduce the spectral efficiency (SE) by half. Alternatively, Kramers-Kronig (KK) [3] or SSBI iterative cancellation (IC) receiver [2] can be utilized to mitigate SSBI without sacrificing spectral efficiency. It should be noted that the power of inserted carrier in these two systems has to be high enough to meet the minimum phase condition for KK relation or avoid error propagation during iteration in IC receiver [2,3,7]. Since high carrier to signal power ratio (CSPR) may limit the power efficiency and increase the nonlinear effects, it would be quite advantageous to have the similar sensitivity and electrical SE with a low CSPR.

Recently, we have proposed a carrier assisted differential detection (CADD) receiver that can recover field information of complex-valued double sideband (DSB) signals [8]. In this paper, we propose an interleaved subcarrier loading scheme for DSB signal in CADD receiver. The scheme has two distinct advantages: (i) it achieves a relatively low CSPR with almost the same electrical SE as SSB self-coherent systems; (ii) it reduces the computational complexity as it does not require complicated iterations to cancel SSBI because the SSBI resides in different frequencies than the signals. We experimentally demonstrate a 16 QAM modulated raw data rate of 100Gb/s (net data rate 77.37 Gb/s counting all the overheads) signal transmission over 160-km standard single mode fiber (SSMF). The experimental result shows the proposed interleaved CADD has a much-reduced requirement of CSPR compared to conventional SSB self-coherent systems.

2. Principle of interleaved CADD

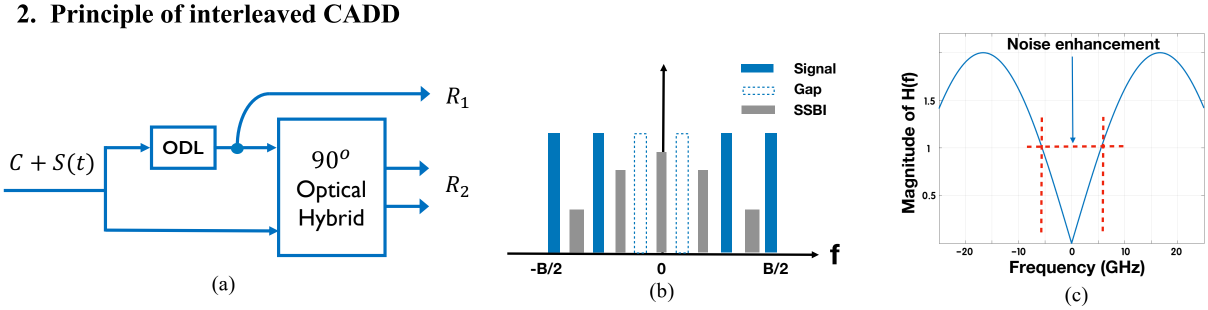


Fig.1 (a) Structure of CADD receiver. ODL: Optical delay line; (b) Proposed subcarriers loading scheme; (c) Magnitude of transfer function $H(f)$, τ=1.5/B, B: bandwidth of signal.

Fig. 1 depicts the structure of our recently proposed CADD receiver. We denote the carrier and signal field as C and S, respectively. Detected by a single-ended photodiode (PD), R_1 can be expressed as (assuming the responsivity of PD equals to 1 for simplicity),

$$R_1 = |C + S(t-\tau)|^2$$
$$= |C|^2 + |S(t-\tau)|^2 + C[S(t-\tau) + S^*(t-\tau)] \quad (1)$$

where '*' stands for conjugation, τ is the time of optical delay generated by optical delay line (ODL). After a standard balanced receiver, a complex-value signal R_2 can be reconstructed as

$$R_2 = [C + S(t-\tau)]^*[C + S(t)]$$
$$= |C|^2 + S(t)S^*(t-\tau) + C[S(t-\tau) + S^*(t-\tau)] \quad (2)$$

Subtracting R_1 from R_2, we obtain

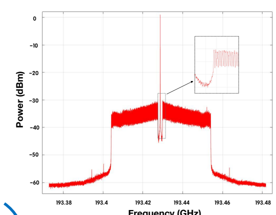
$$R = R_1 - R_2 = C[S(t) - S(t-\tau)] + S_2 \quad (3)$$

where $S_2 = S(t)S^*(t-\tau) - |S(t-\tau)|^2$, which is the 2nd-order SSBI. Signal can be retrieved from the signal-carrier beating term $C[S(t) - S(t-\tau)]$ in the frequency domain as

$$\mathrm{S}(f) = \frac{1}{H(f)}\mathrm{F}\left\{\frac{R-S_2}{C}\right\} \quad (4)$$

where $S(f)$ is the Fourier transform of $S(t)$, $H(f)$ is the transfer function of CADD receiver, which equals to $1 - e^{j2\pi f\tau}$. It is worth mentioning that the transfer function $H(f)$ has a null point at zero frequency as shown in Fig. 1(c), leading to a severe noise enhancement. Therefore, a small frequency gap (e.g. 5% of the signal bandwidth) is inserted to avoid the singularity when recovering signal using Eq. 4. Fig. 1(b) shows the interleaved subcarrier allocations for DSB signal, odd-subcarriers relative to the direct current (DC) carrier are loaded with data while even subcarriers are left unused. In addition, a few data subcarriers near DC carrier need to be vacant for frequency gap. After CADD receiver, 2nd-order SSBI (S_2) will fall on those even subcarriers. As a result, signal can be extracted without interfered by the SSBI, which makes our scheme possible to recover optical field with a low CSPR, as well without computation-heavy iterative cancellations.

3. Experimental setup



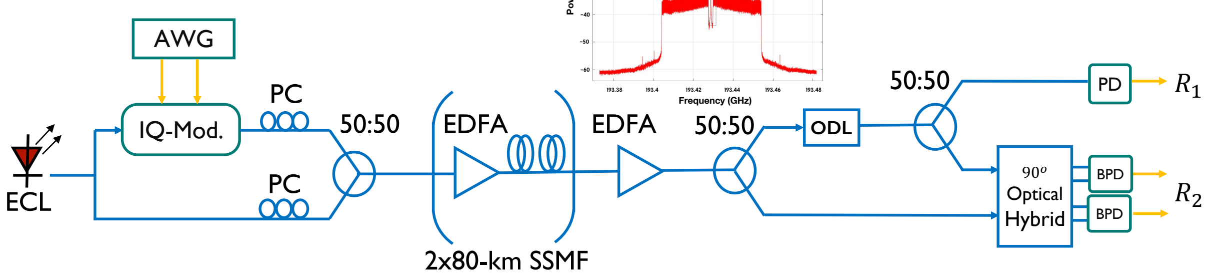


Fig.2 Experiment setup for interleaved CADD (inset: optical spectrum after 160-km transmission). ECL: External cavity laser; AWG: Arbitrary waveform generator; IQ-Mod.: I/Q Modulator; PC: Polarization controller; EDFA: Erbium-doped fiber amplifier; SSMF: standard single mode fiber; ODL: Optical delay line; PD: Photodiode; BPD: Balanced photodiode.

Fig. 2 shows the experimental setup to verify our proposed interleaved CADD. The CW signal of an external cavity laser is first split into two branches for the signal and carrier, respectively. For the signal branch, an I/Q modulator, biased at null point, driven by a 92-GSa/s arbitrary waveform generator (AWG) is used for data generation and modulation. We digitally generate 25-Gbaud interleaved OFDM signals with a 16-QAM modulation as described in Sec. 2, covering a bandwidth from -25GHz to 25GHz. The filled subcarrier number of the OFDM signal is 610 and is zero-padded to an IFFT size of 2048. A cyclic prefix of 128 points is applied for channel synchronization and for mitigating the inter-symbol interference (ISI) caused by chromatic dispersion (CD). The raw date rate is 25x4=100 Gb/s. Counting the gap and CP, the transmitted data rate is decreased to 89.71 Gb/s. The fiber length of lower branch is matched with the upper line to mitigate the phase noise between signal and carrier. Polarization controllers are used in both branches to ensure the polarization of carrier and signal are aligned with each other. Signal and carrier are combined by a 3-dB coupler and then launched into 2-span 80-km SSMF link. CSPR is adjusted before coupler and the total optical power after coupler is set to 6 dBm. The inset in Fig. 2 shows the optical spectrum after 160-km transmission. At the CADD receiver, the optical signal is split into two paths, the upper branch goes through an optical delay line generating an optical delay of τ. According to the magnitude to transfer function $H(f)$, the optical delay is preferred between 1/B and 2/B (B: bandwidth of signal) and there exists an optimum delay in terms of a certain CSPR value and frequency gap. For example, in our experiment, we found the optimum delay is around 1.5/B for 3.5-dB

CSPR and 5% frequency gap. Port 1 is fed into a single-ended PD. Ports 2 and 3 are fed into a 90° optical hybrid to generate the complex-value signal R_2. The electrical signal is sampled by a real-time oscilloscope with a bandwidth and sampling rate of 33 GHz and 80 GSa/s, respectively.

4. Results and discussion

We firstly conduct a back to back (BtB) 25-Gbaud 16-QAM simulation for both KK receiver (bandwidth: [0, 25GHz]) and interleaved CADD (bandwidth: [-25GHz, 25GHz]). Fig. 3(a) shows the simulation result of optimum CSPR for KK and the proposed interleaved CADD with different frequency gaps. Based on the BER threshold of 2.4e-2, the optimum CSPR for KK receiver is around 6 dB, while it is only 3 dB for interleaved CADD (5% gap). We further verified this in our experiment using the same parameters as simulation. Shown in Fig. 3(b) is the mutual information as a function of CSPR with different OSNR values of 28, 32 and 36 dB after 160 km SMMF transmission link. The CSPR of ~3.5 dB is found to be the optimum for our system, which agrees relatively well with the result in simulation. Specifically, this optimum CSPR is different from the previous result of 0 dB for interleaved subcarrier loading systems. This disagreement is mainly caused by the noise enhancement in the vicinity of zero frequency as described in Sec. 2. This can be validated in simulation – as shown in Fig. 3(a), the optimum CSPR decreased to 2 dB when frequency gap is increased to 15%. This means interleaved CADD can have much better CSPR and OSNR sensitivity improvement relative to KK receiver with a slight increase in bandwidth of 5-15%. In an extreme case, when the frequency gap (i.e., 25%) is larger than the noise enhancement region which is shown in Fig. 1(c), the optimum CSPR will achieve around 0 dB.

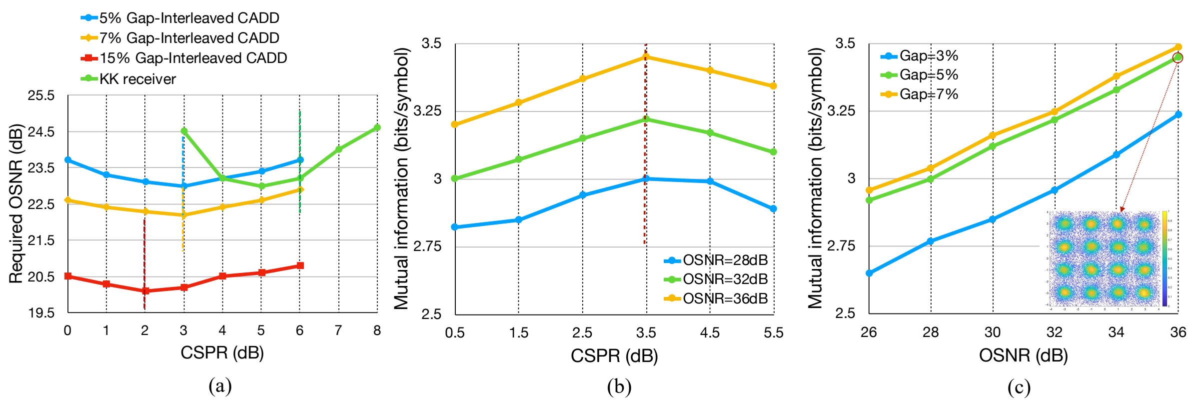


Fig. 3 (a) Simulation result of optimum CSPR for KK and interleaved CADD. (b) Experiemntal result of optimum CSPR for interleaved CADD after 160-km SSMF transmission link. (c) System performance after 160-km SSMF transmission with different frequency gaps.

Fig. 3(c) illustrates the system performance after 160-km SSMF transmission with different frequency gaps. All the results are at their optimum CSPR regarding to frequency gap and optical delay is set to 30 ps. The inset in Fig. 3(c) is a constellation measured at an OSNR of 36 dB with mutual information of 3.45 bits/symbol. After counting all the overheads, the net data rate is computed to be 77.37 Gb/s. There is a sizable improvement of performance when frequency gap is increased from 3% to 5%, while little from 5% to 7%. This indicates that the amplified noise by transfer function $H(f)$ will gradually become a non-dominant factor in signal with the increase of frequency gap. In this case, 5% frequency gap, which is acceptable in short-reach applications, is enough for mitigating the noise enhancement effect.

5. Conclusion

We have proposed and experimentally demonstrated an interleaved subcarrier allocation of double-sideband signal. Using the previously proposed CADD receiver, 100-Gb/s signal can be retrieved with field recovery after 160-km SSMF transmission at CSPR of 3.5 dB. In addition, 5% frequency gap is adequate for avoiding noise enhancement induced from transfer function of CADD.

6. Reference

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