Sidelobe Suppression using Cancellation Sub-Carriers for OFDM Superchannels

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Abstract *We mitigate the inter-channel-interference (ICI) in orthogonal frequency division multiplexing (OFDM) superchannel by adding cancellation sub-carriers (CCs). We experimentally show that CC-OFDM outperforms conventional OFDM by 0.4-dB in a dual-polarization 400-Gbps 3360-km OFDM superchannel.*

Introduction

Superchannels based on concatenating lower-rate orthogonal-frequency division multiplexing (OFDM) channels have been demonstrated to provide 400-G and 1-Tb/s transmission[1,2]. Compared with Nyquist wavelength division multiplexing (N-WDM)[3,4], OFDM system can use simple one-tap equalization at the receiver, but have a drawback of higher sidelobe powers[5]. Unless the sub-carriers on the adjacent bands that constitute the superchannel are carefully controlled in frequency[6], this sidelobe power will degrade the system performance. Thus, sidelobe suppression could be a critical issue for the successful deployment of OFDM-superchannels.

Windowing of OFDM symbols (or filtering the OFDM spectrum) is a common method to suppress its sidelobes, but this destroys the orthogonality of the sub-carriers[7].

In this paper, we propose suppressing the sidelobes by inserting cancellation sub-carriers (CCs) at the edges of the OFDM channels, which are specially designed by using linear least squares algorithm[8]. The implementation complexity of this approach is small as it only needs to design two or four extra sub-carriers; it also maintains the sub-carrier orthogonality. We experimentally demonstrate a 400-Gb/s 4-channel OFDM-superchannel system using the CC technique to reduce inter-channel-interference (ICI). By inserting 4 CCs into a 302 sub-carriers quaternary phase shift keying (QPSK)-OFDM signal, 8-dB sidelobe suppression and more than 0.4-dB performance improvement after 3360-km is successfully demonstrated.

Principle of CC-OFDM

Fig. 1(a) illustrates the conceptual block diagram of the CC-OFDM system transmitter (Tx) for one sub-channel. After bit-to-symbol mapping and serial-to-parallel (S/P) conversion, the k^{th} block contains N complex data symbols, $d_{n,k}$. In contrast to conventional OFDM, before the inverse fast Fourier transform (IFFT) operation a few CCs are appended to the edge of the band for the purpose of sidelobe suppression. These CCs carry complex weighting values, $g_{m,k}$, which are calculated from the data symbols within each IFFT block. The optimal number of CCs has been suggested[8] to be 4, thus we chose 4 CCs through our paper. After zero padding, the IFFT size becomes S.

The design criterion of CCs aims to minimize the superposition of the sidelobe spectra of the weighted CCs and the original Tx signal, the sidelobe are defined as the spectra range outside the Nyquist frequency, as highlighted in Fig. 1(b). For IFFT block k, the optimization of

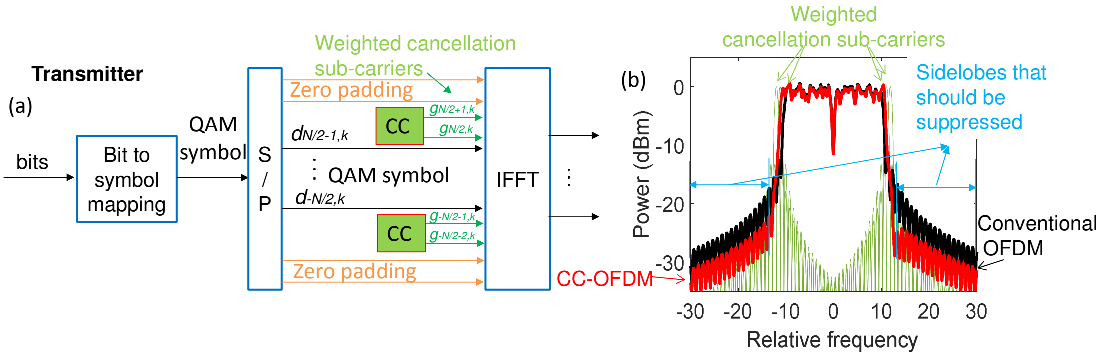

Fig. 1: (a) Block diagram of a CC-OFDM transmitter. (b) Comparison of QPSK-OFDM spectra with and without CCs (N = 20, the number of OFDM symbol is 60, VPItransmissionMaker simulation with 10 MHz frequency resolution).

CCs can be formulated as a linear least squares problem[8]:

$$\min_{\mathbf{g}} \left\| \sum_{n=-N/2}^{N/2-1} d_{n,k} \cdot \mathrm{sinc}_n + \sum_{m\in\mathbf{M}} g_{m,k} \cdot \mathrm{sinc}_m \right\|^2$$

subject to the constraint:

$$\left\| g_{m,k} \right\|^2 \le \alpha \qquad (1)$$

with $d_{n,k}$ (n = -N/2,..., N/2-1) and $g_{m,k}$ ($m \in \mathbf{M}$, $\mathbf{M}$ = {-N/2-1, -N/2-2, N/2, N/2+1}) representing the data and CC symbols, respectively. The sinc_x represents the unit sinc-shape transfer function of each sub-carrier, with its subscript indicating the sub-carrier spectrum frequency. The constraint limits the power of the CCs to that of each sub-carrier, α, to limit the added Tx power. The solutions of the Eq. (1) would be:

$$g_k = \mathrm{inv}\left(\mathrm{sinc}_{\mathbf{M}}^{\mathrm{H}} \cdot \mathrm{sinc}_{\mathbf{M}} + \lambda \mathbf{I}\right) \cdot \mathrm{sinc}_{\mathbf{M}}^{\mathrm{H}} \cdot \sum_{n=-N/2}^{N/2-1} d_{n,k} \cdot \mathrm{sinc}_n \qquad (2)$$

Where $(\cdot)^{\mathrm{H}}$ is the matrix transpose, $\mathbf{I}$ is a 4×4 identity matrix, λ is a scalar selected by Bisection method such that the solutions meet the constraints. $\mathrm{sinc}_{\mathbf{M}}$ is an S×4 matrix that contains four CC sub-carriers.

Fig. 1 (b) shows the optical spectra of the baseband CC-OFDM and conventional OFDM systems with N = 20 sub-carriers each modulated with QPSK symbol; clear sidelobe suppression can be visualized. The insertion of CCs maintains the main lobe of the OFDM spectrum, but strongly suppresses the sidelobes. Also, it only costs small amount of power and does not break the sub-carriers orthogonality.

Experiment

Fig. 2(a) shows the experimental setup. The transmitter comprised 2 external cavity lasers (ECLs), spaced at 50 GHz, externally modulated by signals generated from an Keysight arbitrary waveform generator. The baseband electrical signal had either 302 or 302 + 4 CCs data-sub-carriers for conventional OFDM and CC-OFDM systems, respectively. The IFFT size was set to 1112 to allow the 90 Gsamples/s AWG to generate a 25-Gbaud QPSK-OFDM signal. The number of OFDM symbols is 200. Subsequently, the CP of 8 samples was added at the beginning of each OFDM symbol. The baseband spectra of the CC-OFDM and a single-channel OFDM are shown in Fig. 2(a); the CC-OFDM system shows 8-dB reduction of the sidelobes by adding two CCs at each edge of the conventional OFDM signal respectively, which leads to less crosstalk when formed into a superchannel. The two modulated optical channels were de-correlated by first deinterleaving using an Avanex 50-G interleaver, delaying by one symbol, then recombining. The signal was then again split into two paths, one arm delayed and frequency shifted by 25 GHz then recombined with the through paths. Therefore, a single polarization 4-channel OFDM-superchannel with 2% guard-band was created, with all the channels are fully-decorrelated to assess the effects of ICI. Polarization controllers (PC) were used in each interleaver output path and the frequency shifter output, to align the polarizations for four channels. Finally a polmux superchannel was formed by a polarization beam combiner (PBC). The transmitted optical spectra, (Agilent 83453B high-resolution spectrophotometer), of the combined superchannel for CC-OFDM and OFDM with a

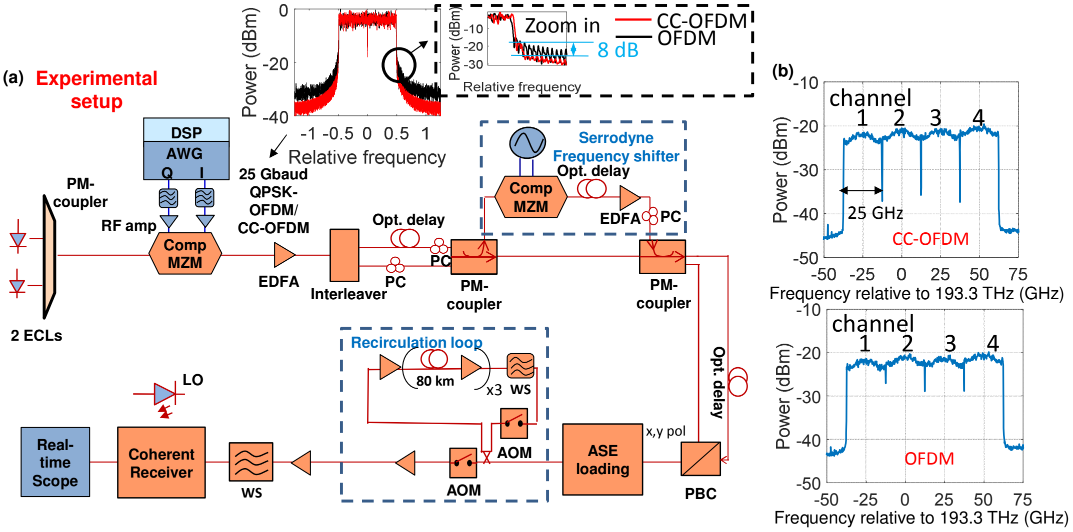

Fig. 2: (a) Experimental setup for 400 Gb/s four-channel CC-OFDM and OFDM superchannel transmission. (b) Optical spectra with and without CCs after the PBC (MZM: Mach-Zehnder modulator, PM: polarization maintaining, LO: local oscillator, ASE: amplified spontaneous emission).

2% guard band is shown in Fig. 2(b). The signals were then launched into a recirculating loop, consisting of two acousto-optic modulators (AOM), three 80-km spans of standard single mode fibre, a Waveshaper (WS) for gain flattening and 4 erbium doped fibre amplifiers (EDFAs). At the receiver, after an optical band-pass filter for channel selection, a standard coherent receiver was used to detect the optical signals, which were then sampled by a real-time scope for off-line processing.

Results

Fig. 3(a) compares the back-to-back optical signal to noise ratio (OSNR) performance of Sub-channel 2 of the superchannels. The *Q*-factor is derived from the variance of the equalized signals over 200 OFDM symbols[9]. For OSNRs of 10-20 dB, the CC-OFDM superchannel gives 0.4-0.5 dB improvement over the normal OFDM superchannel. Fig. 3(b) plots the signal quality versus the index of the sub-carriers within Sub-channel 2. The signal quality at the edges of this band is reduced by the crosstalk from the tails of the adjacent bands. The 4th degree polynomial fitted curves (solid lines) show that the signal quality at the edges of the band is improved by 1.2 dB when CC-OFDM is used. However, there is still a reduction in signal quality for the outer sub-carriers. This is due to the unflatness of the sub-carriers that could be improved by Tx side pre-emphasis.

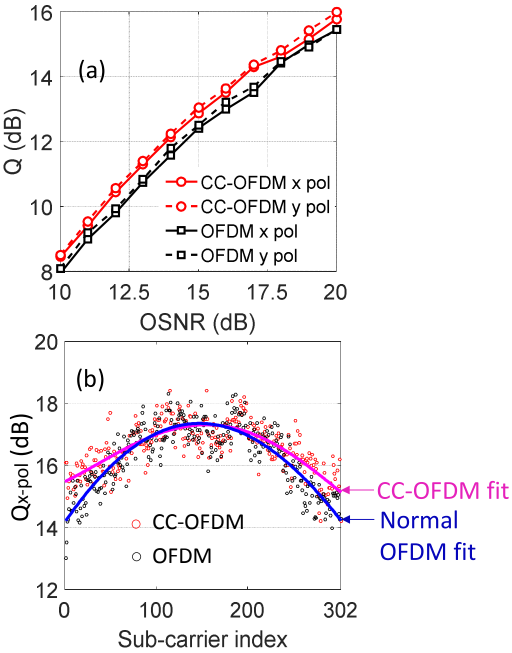

Fig. 3: (a) Signal quality versus OSNR; (b) $Q_{x\text{-pol}}$ versus sub-carriers index for OSNR = 20 dB (0.1 nm).

Fig. 4 plots the performance versus transmission distance; the CC-OFDM superchannel always has better performance than conventional OFDM in both polarizations.

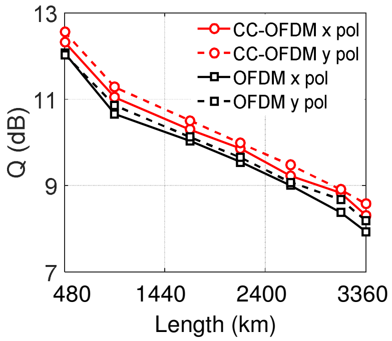

Fig. 4: Performance of CC-OFDM and OFDM with respect to different lengths of the transmission system.

Conclusions

In this paper, we have experimentally demonstrated the insertion of CCs at both sides of the OFDM spectrum to reduce out-of-band power. Results show that a significant reduction of the sidelobe power can be achieved, which reduces ICI and so improves signal quality.

Acknowledgements

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References

[1] X. Liu *et al.*, "Digital signal processing techniques enabling multi-Tb/s superchannel transmission: an overview of recent advances in DSP-enabled superchannels," IEEE Sig. Proc. Mag., Vol. **31**, no. 2, p.16-24 (2014).

[2] S. Chandrasekhar *et al.*, "OFDM based superchannel transmission technology," Journal of Lightwave Technol., Vol. **30**, no. 24, p. 3816-3823 (2012).

[3] G. Bosco, *et al.*, "Investigation on the robustness of a Nyquist-WDM terabit superchannel to transmitter and receiver non-idealities," Proc. ECOC, Tu.3.A.4, Turino (2010).

[4] G. Bosco, *et al.*, "On the performance of Nyquist-WDM terabit superchannels based on PM-BPSK, PM-QPSK, PM-8QAM or PM-16QAM subcarriers," J. Lightwave Technol., Vol. **29**, no.1, p. 53-61 (2011).

[5] A. J. Lowery, *et al.*, "Optical orthogonal division multiplexing for long haul optical communications: A review of the first five years," Optical Fiber Technol., Vol. **17**, no. 5, p. 421-438 (2011).

[6] Q. Yang *et al.*, "107 Gb/s coherent optical OFDM reception using orthogonal band multiplexing," Proc. OFC, PDP7, San Diego (2008).

[7] T. Weiss, *et al.*, "Mutual interference in OFDM-basedspectrum pooling systems, " Proc. VTC, 1873-1877, Los Angeles (2004).

[8] S. Brandes, *et al.*, "Reduction of out-of-band radiation in OFDM systems by insertion of cancellation carriers," Comm. Lett., Vol. **10**, no. 6, p. 420-422 (2006).

[9] A. J. Lowery, *et al*, "Performance of optical OFDM in ultralong-haul WDM lightwave systems," J. Lightwave Technol., Vol. **25**, no. 1, p. 131-138 (2007).