Enhanced Asymmetrically Clipped Optical ODFM for High Spectral Efficiency and Sensitivity

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Abstract: Using ‘musical’ chords at octaves, EACO-OFDM increases ACO-OFDM’s spectral efficiency to 87.5% of DC-biased OFDM, while providing a 7-dB SNR advantage for the same optical power. Nonlinear methods and matched filtering provide near theoretical performance.

OCIS codes: (060.4510) Optical communications; (060.2360) Fiber optics links and subsystems; (060.2605) Free-space optical communication; (060.4080) Modulation.

1. Introduction

Odd-subcarrier ACO-OFDM (asymmetrically clipped optical OFDM) provides better signal quality per unit optical power than DC-biased optical OFDM (DCO-OFDM), by removing all negative going peaks of the transmitted waveform (clipping at zero) rather than adding a bias [1]. The resulting strong clipping distortion is discarded by the receiver’s Fourier transform (FT), because it falls on the even-frequencies, which are not used as information-bearing subcarriers. This reduces the spectral efficiency (SE) by half, which is undesirable in electrical-bandwidth-limited systems. Recently, methods of cancelling the distortion products of one group of subcarriers [2-4], so that other groups can be decoded at the receiver, aim to restore spectral efficiency while preserving the unipolar nature of the signal. Unfortunately, these all have noise penalties, either because they reuse subcarrier frequencies [3], or because slicing/thresholding is not used when estimating then cancelling the clipping distortion [2, 4].

In this paper, I introduce nonlinear separation of ACO-OFDM signals that are grouped into chords at octave intervals, so that no subcarrier frequencies are re-used. This gives close-to-theoretical performance, and supports high-order QAM, enabling high data rates over low-electrical-bandwidth channels, such as for visible light-wave communications and compact short-haul links. Also, in contrast to Flip/Unipolar [5,6] based techniques [3,4] all subcarriers are periodic within a common OFDM symbol, allowing for simple 1-tap channel equalization, bit-loading and optimum matched filtering. Simulations show that 1024-QAM has a 7-dB SNR advantage over DCO-OFDM at 10^{-3} BER for an SE loss of only 12.5%. This outperforms other methods of increasing spectral efficiency.

2. Description of the method

At the transmitter, subcarriers (*notes*) are arranged into *chords*. Each chord is asymmetrically clipped before being combined. The subcarriers’ allocations (the *notes* in *chords*) enable the receiver to cancel the clipping distortion from lower chords, in order to recover higher chords. As shown in Fig. 1 (upper-left), the lowest chord, C0, uses only odd harmonics of its lowest subcarrier (musically, e.g.: harmonic/**note**: 1=**C**, 3=**G’**, 5=**E’’**…). A chord, C1, at double the frequency (musically, an octave above the first) will fill some of the even frequencies of C0 (2=**C’**, 6=**G’’**, 10=**E’’’**…), and a chord, C3, at quadruple the frequency will fill yet more even subcarriers (4=**C’’**, 12=**G’’’**, 20=**E’’’’**…). The spectral utilization is therefore $\frac{1}{2} + \frac{1}{4} + \frac{1}{8} = \frac{7}{8}$, compared with $\frac{1}{2}$ for ACO-OFDM.

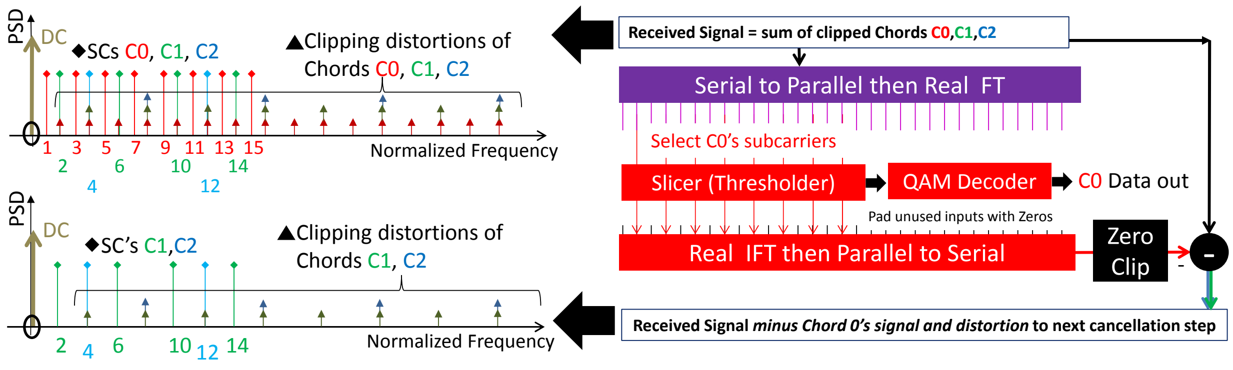

Fig. 1: (left) Electrical spectra before (top) and after (bottom) cancellation of Chord 0’s signal and distortion; (right) cancellation circuit for C0. Only 15 subcarriers are shown for clarity: the simulations use 56 subcarriers.

Fig. 1 (left) shows that the clipping distortion of the lowest chord pollutes the frequencies used by higher chords. Thus, the receiver must first remove this distortion before the second and third chords are revealed (lower left). Fig. 1(right) shows how this is achieved by: (1) matched-filtering the odd-subcarriers of C0 with a FT, (2) slicing the signals to quantize the subcarriers' symbols, (3) recreating the transmitted waveform with an inverse FT followed by a clipper. This signal is then subtracted from the received waveform, removing both the subcarriers and distortion of C0, to reveal the higher chords. The slicing also provides the QAM symbols. This process is repeated to reveal higher-octave chords and their data. Tsonev and Haas used similar processing [3], but after recovering the OFDM symbols by subtraction of sequential positive and negative Flip-/Unipolar [5,6] symbols; however, their spectral allocation placed the subcarriers of their deeper 'depths' at exactly the same frequencies as the original subcarriers, so that slicing errors in the decoding of a 'shallow' depth cause large error-vectors on the deeper subcarriers – leading to a strong possibility of multiple bit errors for one slicing error. In contrast, in EACO-OFDM, slicing errors in, say, C0 have less effect on C1 and C2 as only the clipping distortion from C0 falls on the subcarriers of C1 and C2, and furthermore this is distributed over several subcarriers. Neither Dissanayaki and Armstrong [2], nor Elgala and Little [4] used slicing, so noise propagates from one set of subcarriers to others via the receiver's clipping and cancellation, which degrades performance. A quantitative comparison will be made in Section 4.

3. Example of 1024-QAM over 3-bands

Using VPItransmissionMaker™, DCO-OFDM and EACO-OFDM were compared, on the basis of equal optical powers, numbers of subcarriers, bit rates, and equivalent receivers. The receiver's SNR is adjusted by scaling its noise, with unit (0 dB) SNR giving 0-dB Error Vector Magnitude (EVM) for 4-QAM ACO-OFDM (17.5 Gbit/s). The EVM is calculated using the average power over all symbols; e.g. for 1024-QAM, a BER of 10^{-3} requires an EVM < -34.2 dB. The bias level was swept for DCO-OFDM, to identify the optimum, for a fair comparison.

Fig. 2 plots the EVM versus SNR for each of the three chords in EACO-OFDM and for single-chord DCO-OFDM. At low SNRs there are relatively constant cancellation penalties for C1 and C2, with a cascading effect degrading C2 by 5 dB. As the SNR is increased, the cancellation penalties rapidly decrease, until there is only 0.8-dB EVM difference of the three chords at a BER of 10^{-3}. The performance of ACO-OFDM is 7-dB better than DCO-OFDM at this SNR, and this difference increases at approximately 0.2 dB per 1-dB SNR. Note, however, as with other schemes [3,4], the spectral efficiency is only 87.5% of DCO-OFDM for the same constellation size.

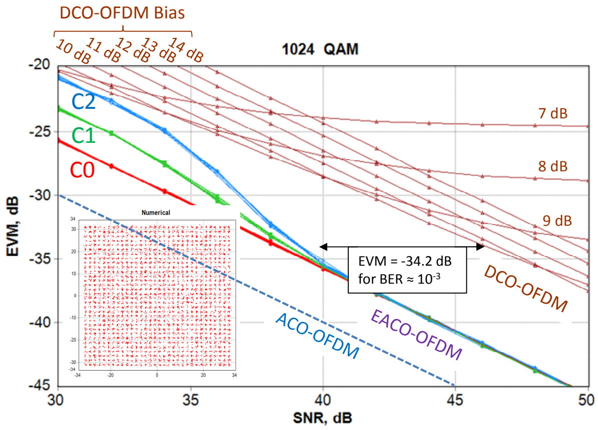

Fig. 2a (left): EVM versus SNR for EACO-OFDM, ACO-OFDM and DCO-OFDM for 1024-QAM.

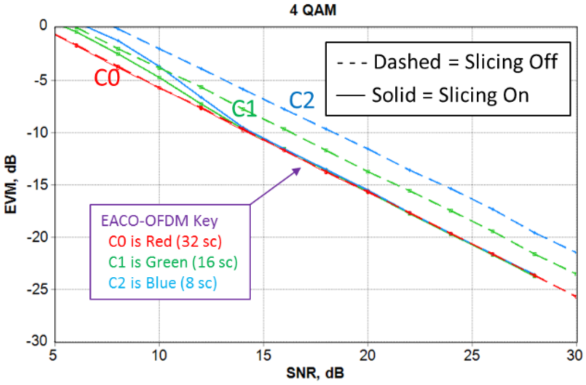

Fig. 2b (right): Effect of slicing on performance of Chords 1 and 2 for 4-QAM.

Compared with conventional ACO-OFDM at the same data rate – but obviously lower SE – there is a 4.5-dB sensitivity penalty, because the mean optical power is proportional to the sum of the chords' individual r.m.s. signal voltages, which scale as the square-root of the number of subcarriers in a particular chord. Thus, to support $7N/4$ subcarriers requires three chords with N, $N/2$, $N/4$ subcarriers, with an optical power $(\sqrt{N}+\sqrt{N}/\sqrt{2}+\sqrt{N}/2)/\sqrt{(7N/4)} \approx 1.668\times$ that of ACO-OFDM, or +4.45 dB electrical SNR. An obvious alternative way to improve the spectral efficiency is to increase the order of the QAM; however, as noted in the earlier papers, doubling the SE requires the constellation size to be squared, from say 16-QAM to 256 QAM. For the same data rate, this gives a penalty of ≈ 9 dB, favoring the EACO-OFDM method by at least 4 dB, noting a 15% increase in required channel bandwidth.

Fig. 2b illustrates the effectiveness of the slicing on the performance of the higher chords in a 4-QAM system. Without slicing there is an EVM increase for C1 and C2, being 2 and 4-dB, respectively, for all SNRs. With slicing, the penalty is halved at low SNRs and becomes negligible at EVM's < -10 dB (BER ≈ 10^{-3}). Although this result is for 4-QAM, as Fig. 2a showed, the threshold where the performances of the chords converge is always close to the EVM value where a BER of 10^{-3} can be obtained, even for high-order constellations.

4. Comparisons with other systems for increasing spectral efficiency

Fig. 3 plots the electrical SNR cost of increasing the spectral efficiency for constant bit rates and optical powers, to maintain a BER of 10^{-3}, with some results extracted from [2,4]. PAM has the highest cost. At SEs < 2 bit/s/Hz ACO-OFDM has the lowest cost (and is the reference SNR for 4 QAM); however, its cost increases rapidly with SE, as it has to use m^2-QAM. SEE-OFDM [4] is best for an SE of 3 bit/s/Hz; but for higher SEs, EACO-OFDM obviously has the lowest cost. ADO-OFDM [2] follows a similar trend to EACO-OFDM, but has a penalty due to noise added to its DCO-OFDM subcarriers in the cancellation process. EU-OFDM [3] reports SNRs 1.5, 2, & 3-dB below their optimally biased DCO-OFDM for 64, 256 and 1024-QAM at 87.5% of the DCO's SE. As shown in Fig. 3, EACO-OFDM offers 5.5, 6.9 and 7.1-dB less cost, respectively, than our optimum-bias DCO-OFDM results.

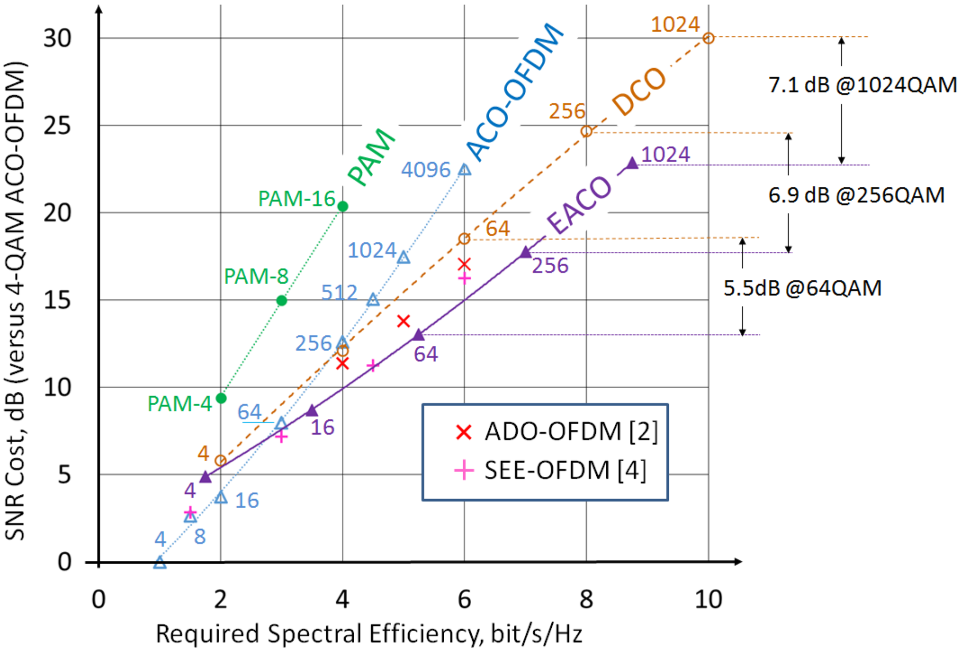

Fig. 3. The costs of increasing spectral efficiency in terms of receiver SNR.

5. Conclusions

Enhanced ACO-OFDM offers the highest spectral efficiencies at the lowest SNR cost. Its effectiveness is due to: the slicing used when cancelling the lower chords to reveal the higher chords, the allocation of subcarriers to unique frequencies, and the use of the FTs as matched filters. EACO-OFDM preserves OFDM concepts such as frequency-domain equalization and also allows bit-loading. Because EACO-OFDM incurs the lowest SNR cost to gain a high SE, it is very attractive for providing high data rates over low-bandwidth channels, such as in directly-modulated short-haul links and visible lightwave communications systems.

Acknowledgements

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