Improving the Sensitivity of Direct-Detection Optical OFDM Systems by Pairing of the Optical Subcarriers

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Abstract: This paper introduces subcarrier pairing to optical OFDM systems and shows, using simulations, that the OSNR sensitivity of DDO-OFDM systems can be improved by 0.7 dB using only simple computations.

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1. Introduction

Direct-Detection Optical Orthogonal Frequency Division Multiplexing (DDO-OFDM) [1,2] allows simpler receivers to be used than for Coherent Optical OFDM (CO-OFDM) [3,4], but requires around 7-dB more Optical Signal to Noise Ratio (OSNR) at the receiver [5]. An interesting feature of the electrical noise spectrum of DDO-OFDM is that, theoretically, the noise decreases at higher frequencies. This is due to the subtleties of the intermixing of the optical noise spectrum with the subcarrier spectrum [5]. Thus the higher-frequency subcarriers should, in theory, offer a better BER performance than the lower-frequency subcarriers. This scenario is similar to multiple-input multiple-output (MIMO) wireless systems using singular value decomposition (SVD) precoding [6,7]. After SVD processing, the MIMO channels are transformed into parallel subchannels with different signal and interference to noise ratios (SINRs). Pairing of the subchannels then improves BER performance [8]. In particular, subchannels with different SNRs and different diversity gains are paired together, then jointly pre-coded using signal constellation rotations and component interleaving [9]. The essential idea is to make the real and imaginary components of the received symbols affected by two independent channels. If one channel loses one component due to deep fading, the other component is still valid. This is also more robust against the effect of noise [8].

Pairing has not yet been explored for optical OFDM, as the dependence of noise on subcarrier frequency is a subtle feature of DDO-OFDM. Furthermore, if CO-OFDM systems exhibit frequency-dependent noise in practice, due to electronic and optical filtering for example, then pairwise coding may also be suitable for CO-OFDM. In this paper we exploit the idea of subcarrier pairing. Since joint pre-coding is performed only across a pair of subcarriers, the complexity of the joint maximum likelihood detection (MLD) is low. We show that simple additional computations can increase the sensitivity of the system by 0.7 dB.

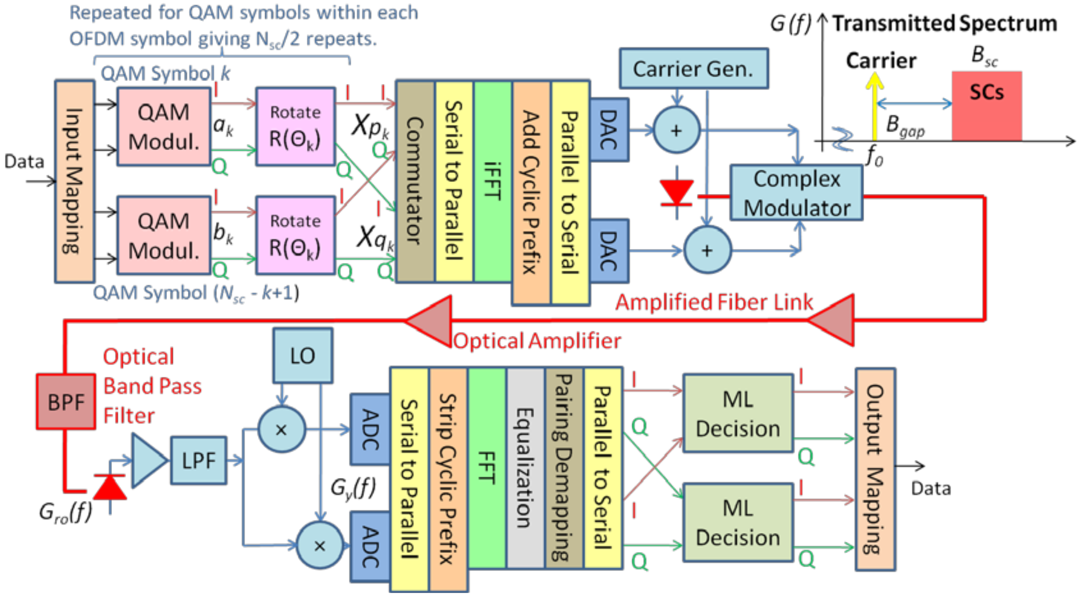

Fig. 1. Direct detection optical OFDM schematic. The Rotate and ML Decision blocks are new additions to standard DDO-OFDM systems. Note the peculiar mapping of the I and Q signals from the Rotate block to the commutator, which is needed to realize component interleaving.

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2. System Description

Figure 1 shows a diagram of the complete system, including pairwise coding, which will be described mathematically later. For each OFDM symbol, data bits are coded as 4-QAM, and interleaved using a rotator, then collected as a vector and sent to an inverse Fast Fourier Transform (FFT). This generates a time-waveform, which is a superposition of QAM modulated subcarriers. A Cyclic Prefix (CP) is usually added to each OFDM symbol, to accommodate symbol-spreading due to dispersion without a penalty. The resulting OFDM symbol is converted to inphase (I) and quadrature (Q) analog waveforms using DACs. Inphase and quadrature components of a high-frequency carrier are added to the I, Q waveforms, to create a virtual carrier by frequency-down-shifting the laser line. These waveforms drive a complex optical modulator to create the DDO-OFDM spectrum shown in the inset. This is transmitted over an amplified optical link, which adds ASE. The bandwidth of the ASE is limited by an optical bandpass filter. The photodetector causes intermixing of the carrier, ASE and subcarrier, giving a subcarrier-dependent signal to noise ratio [5]. Two microwave mixers down-convert the electrical spectrum so that the subcarriers lie either side of DC. The CP is stripped from the signal. An FFT acts as a matched filter for all of the subcarriers, producing a complex number for each subcarrier. Phase offsets are added to each subcarrier to equalize the phase distortion accumulated along the link, chiefly due to chromatic dispersion. The pairing is then undone by demapping and the bits detected by MLD. This process is repeated for each OFDM symbol to give continuous data transmission.

3. DDO-OFDM with pairing of "good" and "bad" subcarriers

We consider the set of pairs $\Psi = \{(p_k,q_k), k=1,\ldots,N_{sc}/2\}$ forming a partition of the N_{sc} subcarriers, where k is the index of pairs. According to [8], good sub-channels with high SINR should be paired with bad sub-channels with low SINR, so that the pairing of the corresponding subcarriers should be [9]: $\Psi = \{(p_k,q_k) = (k, N_{sc} - k+1), k = 1,\ldots, N_{sc}/2\}$. The actual coding is performed across a pair (indexed by k) of M-QAM information symbols a_k and b_k by multiplying by rotation factor $\exp(j\theta_k)$, yields two rotated complex symbols $a_k\exp(j\theta_k)$ and $b_k\exp(j\theta_k)$, where θ_k is the rotation angle for the k-th pair. The optimal rotation angle [9], denoted by θ_k^{opt}, has been derived analytically for 4-QAM, to minimize the total error probability and is given by

$$\theta_k^{opt} = \begin{cases} \pi/4 & \beta_k \le \sqrt{3} \\ \tan^{-1}\left[(\beta_k^2 - 1) - \sqrt{(\beta_k^2-1)^2 - \beta_k^2}\right] & \beta_k > \sqrt{3} \end{cases} \tag{5}$$

where $\beta_k = \lambda_{q_k}/\lambda_{p_k}$ is called *condition number* of the pair of subcarriers (p_k, q_k), and

$$\lambda_{p_k} = \sqrt{\mathrm{SINR}_{p_k}} \qquad \lambda_{q_k} = \sqrt{\mathrm{SINR}_{q_k}} \tag{6}$$

The condition number describes the SINR unbalance between the two subcarriers. For reasonable OSNRs, the optimum rotation angle for $\eta = 0.5$ varies over a small range between 39° and 45° and is exactly 45° for >90% of the subcarriers. After rotation, IQ component interleaving is used over the two precoded symbols, $a_k\exp(j\theta_k)$ and $b_k\exp(j\theta_k)$. The IQ component interleaver described in [9] exchanges the real part of $b_k\exp(j\theta_k)$ and the imaginary part of $a_k\exp(j\theta_k)$, to obtain two transmitted complex symbols:

$$X_{p_k} = Re\left(a_k e^{j\theta_k}\right) + jRe\left(b_k e^{j\theta_k}\right) \qquad X_{q_k} = Im\left(a_k e^{j\theta_k}\right) + jIm\left(b_k e^{j\theta_k}\right) \tag{7}$$

As a result of the OFDM transmitter-receiver process (see Fig. 1 and [1] for the details), the transmitted complex symbols go through separate sub-carriers with different SINRs, so that the received complex symbols are given by

$$\begin{cases} Y_{p_k} = \lambda_{p_k} X_{p_k} + n_{p_k} \\ Y_{q_k} = \lambda_{q_k} X_{q_k} + n_{q_k} \end{cases} \tag{8}$$

where n_{p_k}, n_{q_k} are unit variance complex Gaussian noise samples. Then IQ component deinterleaving is used to obtain two complex symbols $Re(Y_{p_k}) + jRe(Y_{q_k})$ and $Im(Y_{p_k}) + jIm(Y_{q_k})$. Finally, the ML detection is conducted to obtain the estimates:

$$\begin{cases} \hat{a}_k = \operatorname{argmin}_{a_k} \left|Re(Y_{p_k}) - \lambda_{p_k} Re(X_{p_k})\right|^2 + \left|Re(Y_{q_k}) - \lambda_{q_k} Re(X_{q_k})\right|^2 \\ \hat{b}_k = \operatorname{argmin}_{b_k} \left|Im(Y_{p_k}) - \lambda_{p_k} Im(X_{p_k})\right|^2 + \left|Im(Y_{q_k}) - \lambda_{q_k} Im(X_{q_k})\right|^2 \end{cases} \qquad (10)$$

In the encoding and decoding process, constellation rotation and component interleaving both play important roles. For example, to decode a_k, if one channel loses one component, say $\mathrm{Re}(X_{pk})$, due to a small coefficient λ_{pk}, the other component $Re(X_{qk})$ is still valid and available to be decoded [9].

4. Simulation of the required OSNR with and without pairing

Fig. 2 compares the OSNRs at which the systems can achieve BER of 10^{-3} as a function of the carrier-to-signal power ratio, η. These results were obtained using MATLAB® Monte-Carlo simulations of the receiver with the variance of the random electrical noise for each subcarrier set by the calculated SINR [5]. Also included are 3 points (◊) obtained using a VPItransmissionMaker™ simulation without pairing, where optical noise is added before the photodiode. These points validate the MATLAB model's results (•) and confirm the quality of the Gaussian approximation of the interference terms. When pairing is added to the MATLAB simulation (□), the required OSNR is reduced over a wide range of carrier to subcarrier power ratios. If the carrier power is equal to the subcarrier power, the required OSNR can be reduced by 0.5 dB; however, pairing produces its best performance when the carrier power is lowered to 60% of the subcarrier power. This reduces the required OSNR by a further 0.2 dB.

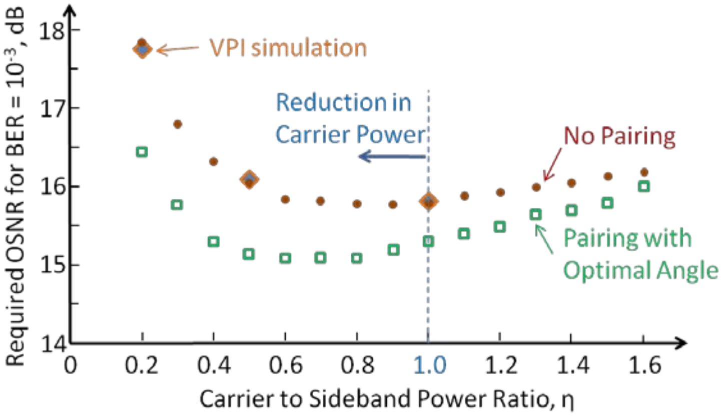

Fig. 2. Required OSNR for BER= 10^{-3} versus the ratio of carrier power to sideband power.

5. Conclusions

This paper has demonstrated that pairwise coding is beneficial to direct-detection optical OFDM systems, giving a performance 0.7 dB gain in a system where the subcarriers have a 3.2 dB difference in SINR across the band. The carrier power can be reduced below the sideband power. The results are also applicable to any optical OFDM system where subcarriers with bad SINR can be paired with subcarriers of good SINRs.

Acknowledgements

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