Precoding Based Peak-to-Average Power Ratio Reduction for Optical OFDM demonstrated on Compatible Single-Sideband Modulation with Direct Detection

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Abstract: Clipping-aided precoding is suggested for effective PAPR reduction to improve performance of OFDM. Up to 3.7 dB PAPR reduction is shown. Performance improvements in required OSNR and dispersion tolerance are demonstrated on compatible SSB.

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1. Introduction

Orthogonal frequency-division multiplexing (OFDM) is a promising modulation technique well known from wireless and wired communications and part of standards as WiMax, WLAN, DVB and DAB [1]. OFDM is also discussed for optical long-haul communications especially for the reason that it can be designed to be extremely tolerant to chromatic dispersion (CD) [2-4]. However, a major drawback of OFDM is high peak-to-average power ratio (PAPR). Therefore, a high dynamic range of power amplifiers and DA/AD-converters is required for distortionless transmission. The effect of high PAPR becomes worse for higher number of subcarriers (SCs), since PAPR of an OFDM symbol can be up to \(10 \log_{10}(N)\) in the worst case, given \(N\) as the number of subcarriers. As OFDM with high number of SCs is desirable for systems with high data rates like optical OFDM systems, PAPR reduction schemes are of particular interest.

Among a number of proposed schemes, precoding [5] is a promising one-shot process which is efficient, signal independent and distortionless. It has neither an overhead as in Selected Mapping (SLM), Partial Transmit Sequence (PTS), and Coding nor complex iterations as in Tone Reservation (TR) and Active Constellation Extension (ACE) [6]. The overhead of SLM and PTS, which is the side information to be sent per data block, is vital to recover the data block at the receiver and loss of the side information may cause the loss of whole data block. Coding can effectively reduce PAPR (PAPR can be limited to 3 dB); however, the code rate (number of information bits divided by total number of transmitted bits) is already low for low number of SCs, and vanishes for high number of SCs [7].

The efficiency of precoding is investigated on a recently discussed approach for optical OFDM, capable of direct detection based on compatible single-sideband modulation (CompSSB) [8,9]. This approach applies the signal to the amplitude of the transmitted SSB-signal [10]. In this method an optical carrier is transmitted whose relative power depends on the PAPR of the OFDM signal. In addition to formerly stated disadvantages of high PAPR, this has a dramatic effect on the system performance. To further improve the system performance, a clipping-aided precoding scheme is also considered at the expense of small distortion. Since CompSSB suffers a lot from PAPR, and is spectrally efficient, CompSSB is preferred for demonstration to another SSB modulation scheme using direct detection [2] which is referred to as OffsetSSB in this paper.

2. Precoding Based PAPR Reduction Scheme

To reduce the PAPR, a precoding matrix \((P)\) with dimension \(N \times N\) is constructed based on Zadoff-Chu perfect sequence which has ideal autocorrelation function and hence PAPR reduction capability [5]. The constellation symbols are precoded in advance of Inverse Fast Fourier Transform (IFFT) at the transmitter and the received symbols are de-precoded after Fast Fourier Transform (FFT). This property enables easy channel equalization in the frequency domain, contrary to other PAPR reduction schemes as for example companding transform [11]. Another major advantage of precoding is the increasing PAPR reduction capability for increasing number of subcarriers (SCs). Complementary Cumulative Distribution Functions (CCDFs) which denote the probability that the PAPR of an OFDM symbol exceeds a given threshold \(\text{PAPR}_0\) are shown for different number of SCs in Fig. 1. The reductions of 2.5 dB and 3.7 dB are observed at \(10^{-3}\) level of CCDFs for 15 SCs and 1023 SCs, respectively.
3. Compatible Single-Sideband Modulation and Clipping

An ideal SSB signal \( m(t) \) of an arbitrary real baseband signal \( \sigma(t) \) is known to be

\[
m(t) = \sigma(t) + jH\{\sigma(t)\},
\]

where \( H\{\sigma(t)\} \) is the Hilbert transform of \( \sigma(t) \). As we want to apply the information not to real or imaginary part but the envelope of the signal, we define the transmitted signal

\[
n(t) = e^{m(t)} = a(t)e^{j\varphi(t)},
\]

which still is an SSB-signal, as \( e^x \) can be expanded in a power series [8]. Amplitude \( a(t) \) and phase \( \varphi(t) \) are interdependent via (1). By identifying the information bearing signal with the signal envelope \( a(t) \), the phase \( \varphi(t) \) that turns \( n(t) \) into an SSB signal follows directly from combining (1) and (2):

\[
\varphi(t) = H\{\ln(a(t))\}.
\]

The signal applied to the envelope \( a(t) \) is thus limited to positive values. To modulate the resulting signal \( n(t) \), onto an optical carrier \( f_0 \), an optical IQ-modulator is required, which generates the optical field of \( n(t) \exp(j2\pi f_0 t) \). The introduced signal is not perfectly compatible for direct detection. For ideal demodulation a square root has to be applied to the received signal to compensate for the squaring of the photodiode. This allows complete reconstruction of the original signal. The big advantage of CompSSB is the highly spectrally efficient signal which is capable of incoherent detection with a single photodiode. Since the amplitude \( a(t) \) in (2) has to be unipolar, a carrier has to be added to allow the transmission of a usual bipolar signal like an OFDM-signal (Fig. 1a). On the other hand, OffsetSSB utilizes a spectral gap between optical carrier and signal with the same width as the signal itself (Fig. 1b).

In order to guarantee system performance and decrease PAPR further, clipping is also applied to the precoded signal after IFFT. Signal \( a(t) \) in (3) is derived from the root-mean-square normalized double-sideband OFDM signal \( g(t) \) by multiplying with clipping factor \( c_{\text{lin}} \), and clipping. Addition of a DC part ensures positive values,

\[
a(t) = 1 + k \begin{cases} +1 & \text{for } c_{\text{lin}} \cdot g(t) > +1 \\ -1 & \text{for } c_{\text{lin}} \cdot g(t) < -1 \\ c_{\text{lin}} \cdot g(t) & \text{otherwise} \end{cases}
\]

Factor \( k \) is required to avoid zeros in any case and was set to 0.99. In the following \( c \) denotes the logarithmic clipping factor which is related to \( c_{\text{lin}} \) by \( c = 20 \log_{10}(c_{\text{lin}}) \).
4. Simulation Results and Discussion

Simulations were carried out considering a bandwidth of 5 GHz filled with 15 and 1023 QPSK-modulated SCs, respectively. As one SC is not used the resulting data rate is a bit smaller than 10 Gbit/s, depending on the number of SCs. After generation, the signals are modulated onto an optical carrier with \( f_0 = 193.1 \) THz using an ideal optical IQ-modulator. The signal is transmitted over a linear optical fiber adding a certain amount of CD to the signal. At the receiver the required OSNR for \( \text{SER} = 10^{-3} \) is determined by noise loading. The receiver employs an optical 10th-order Gaussian filter of 6 GHz FWHM bandwidth. After detection of the signal using a single photodiode, the squaring characteristic of the photo diode is compensated by taking the square root. Then, the signal is demodulated in the OFDM receiver including equalization. Influence of DA- and AD-converters is not considered.

![Fig. 3. Required OSNR at \( \text{SER} = 10^{-3} \) vs CD for CompSSB transmission. Results are shown for 15 a), and 1023 b) SCs.](image)

The results for CompSSB with various combinations of precoding and clipping as well as the results for unmodified CompSSB are shown in Figure 3. For \( c = -13 \) dB (practically no clipping) CompSSB requires at least 13 dB OSNR for 15 SCs and 14.7 dB for 1023 SCs. When pure precoding is applied to CompSSB the minimum required OSNR values are decreased by 1 dB for 15 SCs and 3.1 dB for 1023 SCs. At 1 dB OSNR penalty of unmodified CompSSB (OSNR = 14 dB for 15 SCs and 15.7 dB for 1023 SCs) CD tolerance of pure precoding is almost same as that of unmodified CompSSB for 15 SCs; however, it outperforms unmodified CompSSB by more than 2300 ps/nm for 1023 SCs. In case of pure clipping with \( c = -9 \) dB, the minimum required OSNR is same for 1023 SCs compared to pure precoding. However, the CD tolerance of pure clipping at 1 dB penalty remains the same around 2500 ps/nm regardless of the number of SCs. The CD tolerance of pure precoding increases from 3000 ps/nm to 5500 ps/nm as the number of SCs increases. Further improvement in minimum required OSNR can be obtained by applying clipping-aided precoding (clipping factor is -9 dB) at the expense of decreased CD tolerance caused by the clipping distortion. By this the required OSNR can be lowered by another 0.6 dB for 1023 SCs. A complexity reduction of 4.5% for pure precoding is gained by replacing the precoding matrix elements with randomly distributed zeros (at most 50 per row and column), cf. less complex precod. in Fig. 1b. However, this small amount of complexity reduction already leads to 0.5 dB OSNR penalty and 800 ps/nm CD tolerance reduction.

5. Conclusion

A precoding based PAPR reduction approach is suggested to increase the performance of optical OFDM and demonstrated on CompSSB. Remarkable required minimum OSNR gain up to 3.7 dB can be achieved. Compared to pure clipping, the CD tolerance can be extended by 3000 ps/nm. The efficiency of this scheme is shown to be better for higher number of SCs and its CD tolerance characteristic is similar to that of unmodified CompSSB.

References