Spectrally Efficient Compatible Single-Sideband Modulation for OFDM Transmission With Direct Detection

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***Abstract*—A combination of orthogonal frequency-division multiplexing (OFDM) and compatible single-sideband modulation (CompSSB) using a standard direct-detection scheme is suggested to overcome chromatic dispersion without explicit compensation. Since the proposed type of SSB modulation does not require a spectral gap between optical carrier and subcarriers, it is highly spectrally efficient and the complexity in the analogue part is reduced compared to known direct-detection schemes for OFDM.**

***Index Terms*—Compatible single-sideband (SSB) modulation, optical fiber communication, optical modulation, optical short-haul communication, orthogonal frequency-division multiplexing (OFDM).**

I. Introduction

ORTHOGONAL frequency-division multiplexing (OFDM) is a modulation technique well known from wireless communications and part of various standards as, e.g., wireless local area network (WLAN) [1]. Information symbols are interpreted as weights of consecutive subcarriers in frequency domain and translated to time domain via an inverse Fourier transform. At the receiver, the blocks are translated back to the frequency domain.

Recently, OFDM has also been discussed for optical fiber communications especially because of its high tolerance to chromatic dispersion (CD) and flexibility [2]–[5]. However, to overcome CD in case of direct detection, it is important to avoid receiving the two interfering sidebands. Therefore, for direct detection single-sideband (SSB) modulation has to be applied. To correctly detect SSB signals, usually a coherent receiver is required. However, special signal designs also allow for the use of the much simpler and thus cheaper direct detection. One scheme [2] uses a spectral gap between carrier and signal of the same width as the signal itself [Fig. 1 (left)]. This method is referred to as OffsetSSB in the following. After the photodiode, the signal-carrier beating terms (the useful signal) can be found undistorted adjacent to the gap interval [Fig. 1 (right)]. The drawback of this approach is the excess bandwidth occupied by the gap-interval, which cannot be used for data transmission. It counts, however, for the required bandwidth of digital-to-analog (DA) and analog-to-digital (AD) converters. Alternatively, converters with only the fourth of the bandwidth can be used, but at the expense of additional components (compare [2], [3]).

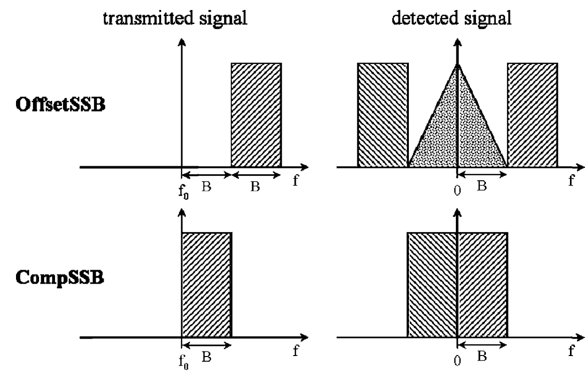

Fig. 1. Spectra of OffsetSSB and CompSSB signals before and after square-law detection. The useful signal remains undistorted at its relative position to the carrier in the frequency range $[B, 2\cdot B]$ for OffsetSSB and $[0, B]$ for CompSSB. In the case of OffsetSSB distortions can be found within $[0, B]$.

A way to overcome this problem is to modulate the envelope of the power by the signal instead of the amplitude of the field. This can be achieved by using compatible SSB modulation (CompSSB), a technique developed years ago for spectrally efficient audio broadcasting compatible with common squaring receivers at that time [6]. This technique was first discussed in [7] as an approach for optical OFDM. Here, an improved setup is discussed, in which the information is coded in the envelope of the field combined with digital compensation for the squaring photodiode and clipping for reduction of the high carrier-to-signal power ratio. After a brief explanation of this method, simulation results show the performance of this approach compared to OffsetSSB.

II. OFDM-Signal Generation

A serial digital data stream is converted into 4-QAM symbols and divided into blocks with length N, which is the number of independent subcarriers. Based on these blocks, a conjugate complex symmetric spectrum is built. This leads to a real-valued

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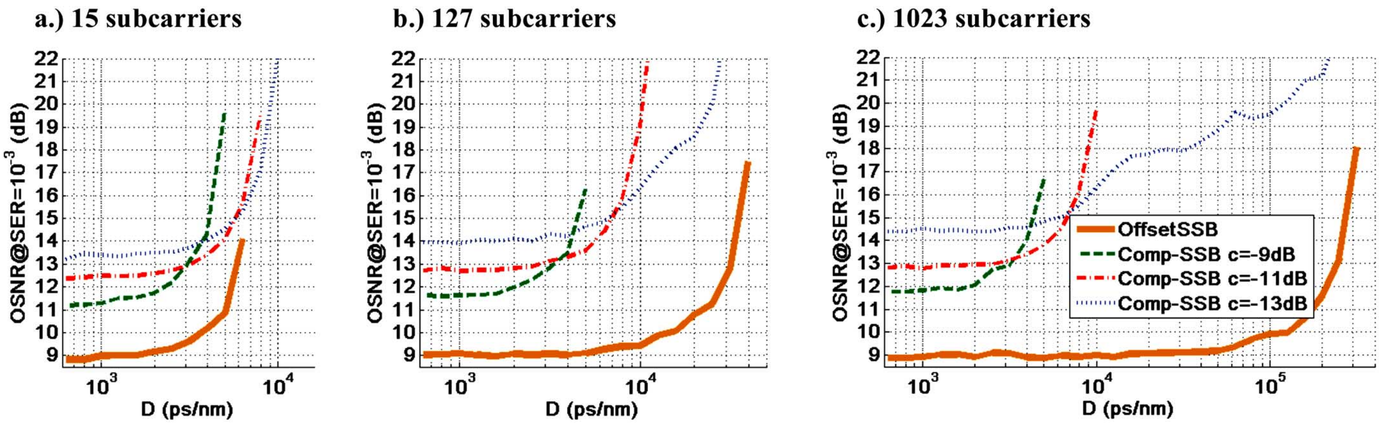

Fig. 2. Required OSNR for SER $= 10^{-3}$ for OffsetSSB transmission (10-GHz total bandwidth) and CompSSB transmission (5-GHz total bandwidth) with different clipping of the CompSSB signal. Results are shown for (a) 15, (b) 127, and (c) 1023 subcarriers. By increasing the clipping factor, it is possible to reduce the OSNR penalty for CompSSB compared to OffsetSSB to below 3 dB. However, this can reduce the tolerance against CD remarkably.

time-domain signal $g(t)$ after inverse Fourier transform. Clipping was applied to $g(t)$ in order to reduce the peak-to-average power ratio (PAPR). After normalization of the signal $g(t)$ with clipping factor c

$$g'(t) = 10^{c/20} \cdot \frac{g(t)}{\sqrt{\overline{|g(t)|^2}}} \tag{1}$$

the signal is clipped and results in

$$a(t) = 1 + k \cdot \begin{cases} +1, & \text{for } g'(t) > +1 \\ -1, & \text{for } g'(t) < -1 \\ g'(t), & \text{otherwise.} \end{cases} \tag{2}$$

The added dc part and factor k, which was set to 0.99, are required to ensure a signal greater than zero. Note that no further clipping is applied to the transmitted signal, for OffsetSSB clipping is not considered at all. The next step is to apply compatible SSB modulation to $a(t)$.

III. Compatible SSB Modulation

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

$$m(t) = \sigma(t) + jH\{\sigma(t)\} \tag{3}$$

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

$$n(t) = e^{m(t)} = a(t)e^{j\varphi(t)} \tag{4}$$

which is still an SSB signal, as e^x can be expanded in a power series [6]. Amplitude $a(t)$ and phase $\varphi(t)$ are interdependent via (3). By modulating the envelope of the transmitted signal $n(t)$ with signal $a(t)$, a phase $\varphi(t)$ over this interdependency results, which transforms $n(t)$ into an SSB signal. This phase directly results from (3) and (4) to

$$\varphi(t) = H\{\ln(a(t))\}. \tag{5}$$

It is important to note that the signal applied to the envelope $a(t)$ has to be limited to positive values only. This constraint also makes sense when one considers the aimed direct-detection receiver, which can only recognize absolute values of the envelope and ignores the phase. To modulate the resulting signal $n(t)$ onto an optical carrier f_0, an optical inphase/quadrature (IQ) modulator is required, which generates the optical field $E(t) = n(t) \cdot \exp(j2\pi f_0 t)$.

The introduced signal is not inherently compatible with direct detection. For ideal demodulation, a square root has to be applied to the received signal in order to compensate for the squaring of the photodiode. This allows for complete reconstruction of the original signal as long as it had been constrained to positive values. On the other hand, the signal would be inherently compatible with direct detection by applying the square root of the information to the envelope of the signal, which is equal to applying the information to the envelope of the signal power (compare [7]). The main problem of this approach seems to be an increased dc part of the signal due to the square root and therefore an increased carrier-to-signal power ratio.

The big advantage of CompSSB is its highly spectrally efficient signal compatible with direct detection. However, the high power in the dc part (carrier) of the signal reduces the sensitivity remarkably. Its relative power compared to the signal is determined by the PAPR of the OFDM signal $a(t)$ which can be controlled by clipping as discussed above. In the past, the success of CompSSB mainly was limited by the complicated analogue signal generation according to (5). With digital signal processing, the implementation is easy. Compared to other optical OFDM techniques, however, the complexity of digital processing is increased.

IV. Simulation Results

To compare the performance of CompSSB to OffsetSSB simulations have been carried out considering a wanted signal with a bandwidth of 5 GHz including 15, 127, or 1023 subcarriers modulated with QPSK symbols. As the fast Fourier transform requires the number of samples for the Fourier transform to be

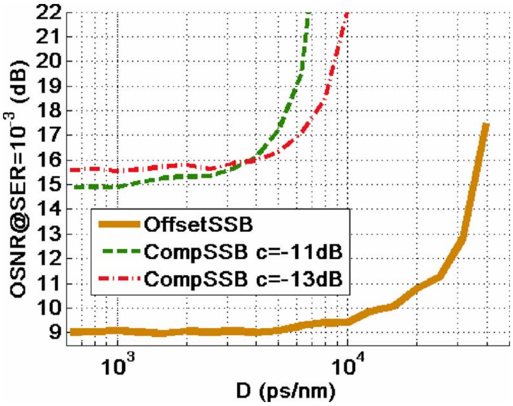

Fig. 3. For 127 subcarriers, CompSSB and OffsetSSB are compared exemplarily for omitted compensation of square-law detection in case of CompSSB. Because of the high carrier-to-signal ratio of CompSSB, the required OSNR increases only by 1.5 to 2 dB (compare Fig. 2). However, the tolerance to CD is also reduced.

a power of two, one subcarrier is not used for data transmission. The resulting data rate is, therefore, slightly smaller than 10 Gb/s, depending on the number of subcarriers. The electrical signals are modulated onto an optical carrier with $f_0 = 193.1$ THz using an ideal optical IQ modulator. The nonlinearity of the optical IQ modulator has been precompensated completely. The signal is then transmitted over a linear single-mode fiber adding a certain amount of CD to the signal. At the receiver, the required optical signal-to-noise ratio (OSNR) for a symbol error ratio (SER) equal to 10^{-3} is determined by adding noise and filtering the signal with an optical tenth-order Gaussian filter of 6 (CompSSB) or 11 GHz (OffsetSSB) full-width at half-maximum. After detection using a single photodiode, the signal is first optionally equalized in the time domain by taking the square root (CompSSB only) and afterwards demodulated in the OFDM receiver including equalization. Note that no influence of DA and AD converters is considered and clipping is only applied to the source OFDM signal $g(t)$ before CompSSB modulation. In none of the simulations, a cyclic prefix (CP) was used. OffsetSSB would benefit much more from CP in terms of dispersion tolerance, but in order to consider a system with minimum overhead and complexity, this setup was chosen.

The results for CompSSB compared to OffsetSSB are shown in Fig. 2. It is clearly visible that both lowest required OSNR and maximum CD tolerance cannot be reached simultaneously and depend on the clipping factor. For strong clipping of $c = -9$ dB, CompSSB shows a minimum required OSNR, which is only 2.2 to 3 dB higher than for OffsetSSB. Independent of the number of subcarriers, the CD tolerance for 1-dB OSNR penalty compared to the best value is about 2000 ps/nm. For $c = -11$ dB, the required OSNR without CD is about 1 dB higher, but the CD tolerance increases to about 5000 ps/nm in return. For only 15 subcarriers, the dispersion tolerance remains smaller and is limited by the low number of subcarriers. For $c = -13$ dB, which implies hardly any clipping, the CD tolerance increases to about 7000 ps/nm at the cost of another 1- to 1.5-dB OSNR penalty (also not for 15 subcarriers). However, it is interesting to note, that the OSNR requirement does not increase as fast as for OffsetSSB. The decrease of dispersion tolerance of CompSSB can be explained by the modified spectrum due to the applied phase modulation from (3).

Results for omitting the square-root equalization in the receiver are exemplary shown for a configuration with 127 subcarriers in Fig. 3. Besides an OSNR penalty between 1 and 4 dB compared to the configuration with square root for small CD, a further limitation of the dispersion tolerance can be observed. The reason for the relatively small gain of the square-root operation is the high carrier of the signal. The carrier-signal beating products after the photodiode dominate the signal whereas distorting signal–signal products are small.

The suggested method of CompSSB in combination with square-root compensation of the photodiode at the receiver allows for data transmission in half the bandwidth required by OffsetSSB but at the cost of 5-dB OSNR penalty. With clipping of the signal before phase modulation for the CompSSB signal, the OSNR penalty can be reduced to 3 dB and less at the expense of a smaller CD tolerance. The dispersion tolerance compared to OffsetSSB without clipping is reduced, especially when a high number of subcarriers are used. However, the required OSNR for CompSSB tends to increase much slower than for OffsetSSB. This highly bandwidth-efficient technique combined with a cheap receiver and reduced analogue requirements compared to OffsetSSB combined with limited tolerance to noise and CD is a promising technique for short- to medium-haul connections.

V. Conclusion

A novel approach for transmission of OFDM signals has been presented for optical medium-haul systems with direct detection. Compared to another approach capable of direct detection, only half the bandwidth is required. However, a 2.2- to 5-dB higher OSNR is needed at the receiver.

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