Performance of Asymmetrically Clipped Optical OFDM in AWGN for an Intensity Modulated Direct Detection System

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Abstract- **Orthogonal frequency division multiplexing (OFDM) is used in many wired and wireless broadband communication systems because of its resilience in the presence of signal dispersion or multipath distortion. OFDM has not been used in practical optical communication systems because the bipolar waveform cannot be used in intensity-modulated direct detection (IM/DD) systems. A new unipolar form of OFDM, asymmetrically clipped optical OFDM (ACO-OFDM), has recently been developed. For the case of an AWGN channel, we compare ACO-OFDM and other modulation schemes. It is shown that ACO-OFDM with 4-QAM subcarrier modulation has the same bandwidth efficiency but requires 2 dB less energy per bit than on-off keying. ACO-OFDM with larger constellation sizes gives higher bandwidth efficiencies and lower optical power than other modulation schemes. Unlike existing methods, the performance of ACO-OFDM is limited by the bandwidth of the transmitter and receiver not the dispersion of the channel.**

I. INTRODUCTION

In this paper we present results for the performance of asymmetrically-clipped optical OFDM (ACO-OFDM) in an additive white Gaussian noise (AWGN) channel [1, 2]. OFDM is used in many new and emerging broadband wired and wireless communication systems because it is an effective solution to intersymbol interference (ISI) caused by multipath transmission or by a dispersive channel. However it has not been used in any commercial optical communication systems. This is because OFDM signals are bipolar, while in optical systems that use intensity modulation (IM), only unipolar signals can be transmitted [3-5]. In the papers that describe the use of OFDM in IM optical communications, a large DC bias is usually added to the OFDM signals but this results in an optical signal with a high mean optical power [5-9]. This is very inefficient and makes conventional OFDM impractical in the many optical systems in which the average transmitted optical power is limited due to eye safety or other considerations. Recent work by the authors has shown that by asymmetrically clipping particular classes of bipolar OFDM signals, power efficient Optical OFDM signals can be derived [1, 2]. ACO-OFDM signals retain the properties that make OFDM resilient in a dispersive or multipath channel. For coherent optical systems carrier suppressed optical OFDM (CSO-OFDM) has been shown to be an effective solution to chromatic dispersion in single mode fibers [10, 11].

In this paper we compare ACO-OFDM and DC biased OFDM with the modulation techniques that are commonly used in intensity modulated direct detection (IM/DD) optical communications such as pulse position modulation (PPM) and on-off keying (OOK). We show that for a given average transmitted optical power and signal bandwidth ACO-OFDM gives better performance than PPM and OOK. This result has significant practical implications for both wireless optical and optical fiber communications. In many optical systems the achievable data rate is limited by a combination of maximum transmitted optical power and multipath distortion, ACO-OFDM solves the multipath problem as well as giving a 2 dB reduction in optical power for an AWGN channel.

II. SYSTEM DESCRIPTION

A. *Intensity Modulated – Direct Detection (IM/DD) System*

Fig. 1 shows the block diagram of the intensity modulated direct detection (IM/DD) optical communication system being considered in this paper. The data is modulated onto an electrical signal, $s(t)$. Depending on the details of the electrical system, $s(t)$ may be represented by either current or voltage; however in either case the electrical power is proportional to $s^2(t)$. The optical intensity modulator generates an optical signal with intensity (not amplitude) $\varsigma s(t)$. This means that the optical power is proportional to $s(t)$ (not $s^2(t)$). It also means that $s(t)$ can take only positive values and so modulation techniques commonly used in radio communications cannot be used without modification. The signal is passed through an optical channel with impulse response, $h(t)$. The signal $r(t) = h(t) \otimes s(t)$ is received by a direct detection receiver which converts the optical intensity signal back to an electrical signal (voltage or current), $R\, r(t)$.

The system model shows AWGN being added in the electrical domain. This is the model commonly used in wireless infrared communication systems [12] where the main impairment is due to high level ambient infrared radiation. The ambient signals are mainly at DC and can be filtered out, however they cause shot noise in the detector, which is accurately modeled as AWGN. The received noisy signal is

$$z(t) = Rr(t) + w(t) \tag{1}$$

where $w(t)$ is AWGN. The data is recovered from $z(t)$ using a matched filter.

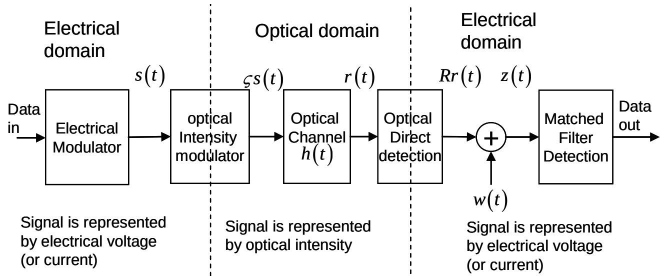


Figure 1. Intensity modulated/ direct detection optical communication system.

In this paper we are comparing the relative performance of different modulation schemes in AWGN, so without loss of generality we assume that $\varsigma = h(t) = R = 1$. Thus the BER of the system depends on $z(t) = s(t) + w(t)$

In many optical communication systems, the average transmitted optical power, given by,

$$E\{s(t)\} = \lim_{T' \to \infty} \frac{1}{2T'} \int_{-T'}^{T'} s(t)\, dt \tag{2}$$

is constrained by eye safety considerations. This means that while the main constraint on signal design is the value of $E\{s(t)\}$, the BER depends on the electrical SNR which in turn depends on $E\{s^2(t)\}$, Therefore the performance of a system depends not only on the type of modulation (orthogonal, bipolar etc.) but on the average optical power. In contrast to radio systems where a high peak-to-average ratio is a disadvantage, in optical systems signals with a high peak-to-average ratio in general give better system performance as the ratio $E\{s^2(t)\}$ to $E\{s(t)\}$ is large and so they have a larger received electrical power for a given optical power [12].

B. *OFDM Modulation*

The key feature of OFDM is that data is transmitted in parallel on a number of sinusoidal subcarriers of different frequencies [13]. The frequencies are chosen so that the subcarriers are mutually orthogonal over each OFDM symbol period. Fig. 2 shows a typical OFDM modulator and demodulator. The input data is partitioned into blocks. The i-th block is mapped onto $X_{0,i} \cdots X_{N-1,i}$ which is a vector of length N of complex numbers which represent constellation points for the modulation scheme being used for each subcarrier, typically 4-QAM or 16-QAM. $X_{0,i} \cdots X_{N-1,i}$ is the i-th frequency domain OFDM symbol. An N-point inverse fast Fourier transform (IFFT) of $X_{0,i} \cdots X_{N-1,i}$ generates the complex vector $x_{0,i} \cdots x_{N-1,i}$ which is the i-th time domain OFDM symbol. In one operation the IFFT modulates and multiplexes the subcarriers of the OFDM symbol.

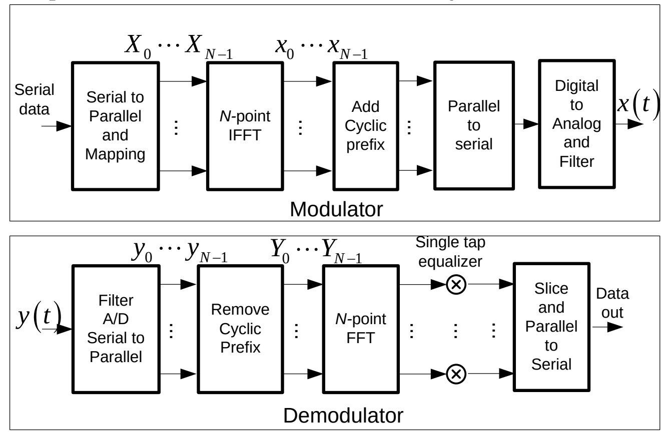


Figure 2. Block diagram of an OFDM communications system.

The resilience of OFDM in a multipath channel is the result of two factors, parallel transmission and the cyclic prefix. Because the data is transmitted in parallel each symbol is much longer and intersymbol interference affects only a small fraction of a symbol period. In most practical OFDM systems a cyclic prefix is also added to each OFDM symbol. As long as the cyclic prefix is longer than the delay spread of the channel and the receiver is correctly synchronized, the use of a cyclic prefix eliminates the residual ISI and ensures that the received subcarriers are orthogonal over the useful symbol period [13]. After the addition of the cyclic prefix, the data is parallel-to-serial converted, converted to analog and filtered to generate a continuous time domain signal $x(t)$.

Except for the 'single tap equalizer', the blocks in the receiver correspond to the blocks in the transmitter. The effect of multipath transmission on an OFDM symbol with cyclic prefix is to cause frequency non-selective fading on each individual subcarrier. This changes the phase and magnitude of each subcarrier but does not cause any ISI or intercarrier interference (ICI). The magnitude and phase of each subcarrier is corrected by the single tap equalizer which performs a single complex multiplication per subcarrier.

In general the output of the OFDM modulator $x(t)$ is complex. In radio systems the real and imaginary components are used to modulate the in-phase and quadrature components of a high frequency carrier. In systems where quadrature modulation is not possible, such as baseband systems or intensity modulated optical systems, the input vector $X_{0,i} \cdots X_{N-1,i}$ is constrained to have Hermitian symmetry so that $x(t)$ is real not complex. This constraint reduces the number of independent complex values transmitted per symbol from N to $N/2$. For 4-QAM modulation this means that N bits can be transmitted per OFDM symbol.

Fig. 3 shows the continuous time domain waveform of a typical OFDM symbol with cyclic prefix and the discrete IFFT output samples from which it was generated. Because normal OFDM signals are bipolar they cannot be used without modification for intensity modulation. The papers which have considered the use of OFDM in IM/DD have added a DC bias to the OFDM signal [5-9, 14-16]. Because of the high peak-to-average power ratio of OFDM signals a bias of at least twice the standard deviation the bipolar signal must be used to minimize clipping of the OFDM signal. Thus in a DC biased system the transmitted signal is given by

$$s(t) = x(t) + 2\sqrt{E\left\{x^2(t)\right\}} \quad (3)$$

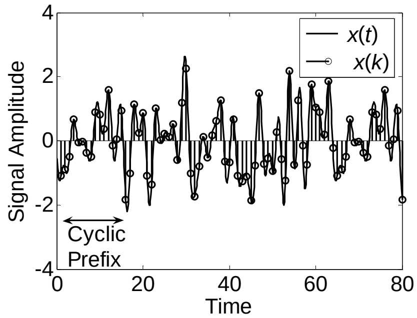


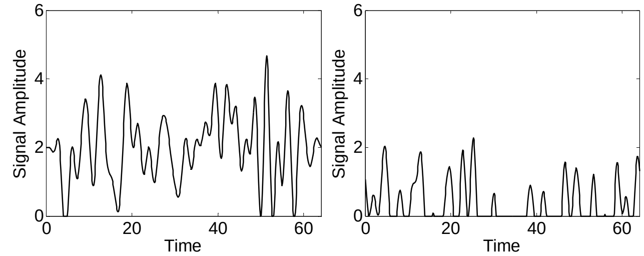
Figure 3. Biipolar OFDM signal (64 subcarriers, cyclic prefix length of 16)

While early work on OFDM suggested that clipping OFDM signals resulted in high levels of intermodulation distortion, more recent work has shown that the main effect of clipping is to reduce the signal amplitude rather than to introduce clipping noise [17]. With ACO-OFDM the signal is made unipolar by simply clipping it at the zero level. If only the odd frequency subcarriers of the unclipped OFDM signal are modulated, it can be shown theoretically [1] that asymmetrical clipping reduces the amplitude of each of the odd frequency subcarriers by exactly half but that they are otherwise undistorted. All of the intermodulation products fall on the even subcarriers. This is the form of ACO-OFDM analyzed in this paper. A similar effect can be achieved if a bandpass, rather than a baseband OFDM signal is clipped [2]. In this case all of the subcarrier frequencies can be used but the carrier frequency must be at least 1.5 times the bandwidth of the OFDM signal. The transmitted signal using ACO-OFDM is given by

$$\begin{aligned} s(t) &= x(t), \quad x(t) \geq 0 \\ &= 0, \quad x(t) < 0 \end{aligned} \quad (4)$$

It is important to note that although the clipped signal is unipolar, the input to the IFFT is still bipolar. As a result increasing the data rate by increasing the constellation size from 4-QAM to 16-QAM causes much less degradation than increasing the data rate of a unipolar signal by changing from OOK to a unipolar four level modulation.

Fig. 4 shows the signal for DC-biased OFDM and ACO-OFDM for an OFDM symbol (without cyclic prefix) and $N = 64$. All subcarriers are modulated for the DC-biased OFDM but only the odd frequency subcarriers for ACO-OFDM. This means that the data rate of the ACO-OFDM is half of the DC-biased OFDM; the odd frequency subcarriers of each ACO-OFDM symbol can carry only $N/4$ different complex values rather than $N/2$ for DC-biased OFDM. However, it is clear that the average optical power is very much reduced for clipped OFDM.



(a) DC-biased OFDM (b) Clipped OFDM

Figure 4. Transmitted optical signal for DC-biased OFDM and ACO-OFDM

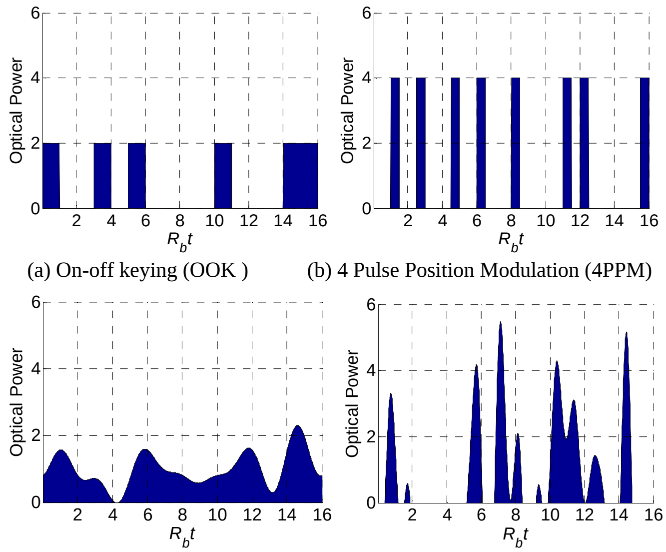
III. Comparison of Different Modulation Schemes

We will now compare the performance of a number of modulation schemes. Fig. 5 shows the time domain waveforms for some of the modulation schemes being considered. The waveforms shown have the same average optical power of unity and the same average transmitted bit rate, R_b. However as we shall show they have very different spectral bandwidths and error rates for a given, optical energy per bit to single sided noise power spectral density, $E_{b(opt)}/N_0$.

A. *Time Domain Waveforms*

Fig. 5(a) shows binary on-off keying (OOK). (This is also known as non return to zero (NRZ) signaling). In each bit period the signal is either +2 or 0, representing binary 1 or 0. Perfectly square pulses are shown and our calculations are based on these. However more realistic pulses would result in a poorer ratio of electrical power to optical power but a smaller signal bandwidth. Fig. 5 (b) shows PPM with four time slots (4PPM). In each symbol period a pulse is transmitted in one of four possible slots, so each 4PPM symbol represents two bits. Comparing figures (a) and (b) it is clear that the shorter pulses of 4PPM give it a wider bandwidth than OOK, but the higher peak-to-average of the signal means that it also has a higher ratio of electrical to optical power, and so has a lower BER for a given average optical power. For this reason PPM is used in many practical optical communication systems such as some of the Infrared Data Association (IRDA) standards.

Figs. 5(c) and (d) show waveforms for OFDM. In this section the results presented are for OFDM with no cyclic prefix. For OFDM with a cyclic prefix, the bandwidth and $E_{b(opt)}/N_0$ for a given BER would be slightly increased. Fig. 5(c) shows DC biased OFDM. The signal has a very low peak-to-average power and as a result a low electrical power for a given optical power. However the smooth, slowly varying waveform make it obvious that is also has a lower bandwidth. Finally Fig. 5(d) shows ACO-OFDM. It has a very high peak-to-average power ratio and this is why, as the simulations will show, it requires less optical power than any of the other waveforms to achieve a given BER. It has a greater bandwidth than DC biased OFDM because only the odd subcarriers are used to carry data, so a larger bandwidth signal is required for a given bit rate.



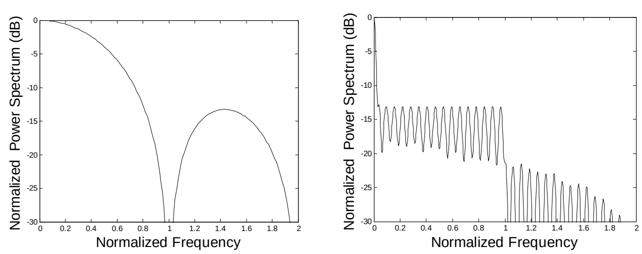
(a) On-off keying (OOK) (b) 4 Pulse Position Modulation (4PPM)

(c) DC-biased OFDM (d) ACO-OFDM

Figure 5. Time domain waveforms

B. *Bandwidth of different modulation formals*

To make a fair comparison between modulation schemes we calculate the bandwidth of each of the signals for a given bit rate. Fig. 6 shows the power spectra of OOK and of ACO-OFDM with only odd subcarriers modulated Following [12] we define the bandwidth of the signal as the frequency of the first nul and define the point of the first null for OOK as unity, and normalize the spectra of other signals for the same transmitted bit rate. For ACO-OFDM the first null occurs at a normalized frequency of $1+2/N$ which is slightly larger than for OOK. The ripple within the OFDM spectrum is because only odd subcarriers are being used to carry data. The intermodulation products on the even subcarriers have much lower power. Because it is a unipolar signal ACO-OFDM also has a large component at zero frequency. The out-of-band power falls away more slowly than for unclipped OFDM but the fall off is still more rapid than for OOK,



(a) OOK

Figure 6. Power spectrum of OOK signal on linear and dB scales.

C. *Bit Error Rates as a function of $E_{b(elect)}/N_0$*

To calculate $E_{b(opt)}/N_0$ for a BER of 10^{-3} we find $E_{b(elect)}/N_0$ for each of the modulation techniques and then calculate the conversion factor between electrical and optical power. Fig. 7 shows BER as a function of $E_{b(elect)}/N_0$. The higher order PPM require the lowest $E_{b(elect)}/N_0$ for a given BER, but this is at the expense of the higher bandwidth required for the short duration pulses. OOK and ACO-OFDM with 4-QAM modulation of the subcarriers require the same $E_{b(elect)}/N_0$ for a given BER, but as we will show the conversion from optical to electrical power is better, so ACO-OFDM outperforms OOK overall. ACO-OFDM with 16-QAM modulation requires the same $E_{b(elect)}/N_0$ for a given BER as DC biased OFDM with only 4-QAM subcarrier modulation. OOK with 4 levels, (rather than only on and off) required the highest $E_{b(opt)}/N_0$.

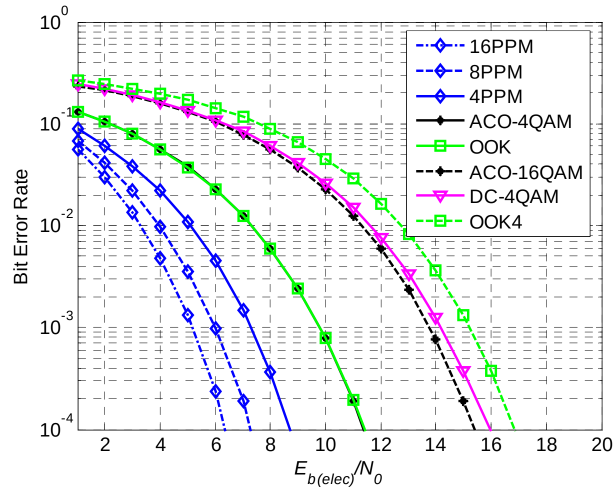


Figure 7. BER as a function of $E_{b(elect)}/N_0$ for PPM, OOK, ACO-OFDM and DC biased OFDM.

D. *Optical power and Normalized Bandwidth*

To make the overall comparison of schemes we need to calculate the relationship between $E_{b(opt)}/N_0$ and $E_{b(elect)}/N_0$. The electrical and optical energy per bit are given by

$$E_{b(opt)} = E\{x\}/R_b \tag{5}$$

and

$$E_{b(elect)} = E\{x^2\}/R_b \tag{6}$$

So

$$\frac{E_{b(opt)}/N_0}{E_{b(elect)}/N_0} = \left(E\{x\}/E\{x^2\}\right) \tag{7}$$

However the ratio depends on the absolute level of the optical power. Using simple proportion it is easy to show that when the signals are normalized for unity optical power.

$$\left(E_{b(opt)}/N_0\right)_{\text{norm}} = \left(E^2\{x\}/E\{x^2\}\right)\left(E_{b(elect)}/N_0\right)_{\text{norm}} \tag{8}$$

Fig. 8 shows the results for a number of modulation schemes. For PPM the values can be calculated by simple algebra. For OFDM the results depend on the properties of Gaussian distributions and Bussgang's theorem. In [1] it was shown theoretically that for ACO-OFDM,

$$E\{x\} = 1/\sqrt{2\pi} \quad \text{for} \quad E\{x^2\} = 0.5 \tag{9}$$

As in [12] we present the results relative to OOK rather than as absolute values. Fig. 8 shows the surprising and significant result that ACO-OFDM with 4-QAM modulation of each subcarrier requires only slightly greater bandwidth than OOK but is 2 dB more efficient in terms of optical power. This is in addition to solving the multipath problem which limits many optical communication systems. ACO-OFDM with 16-QAM modulation requires approximately the same bandwidth as DC biased OFDM and 4 level OOK but is more than 5 dB more efficient in optical power.

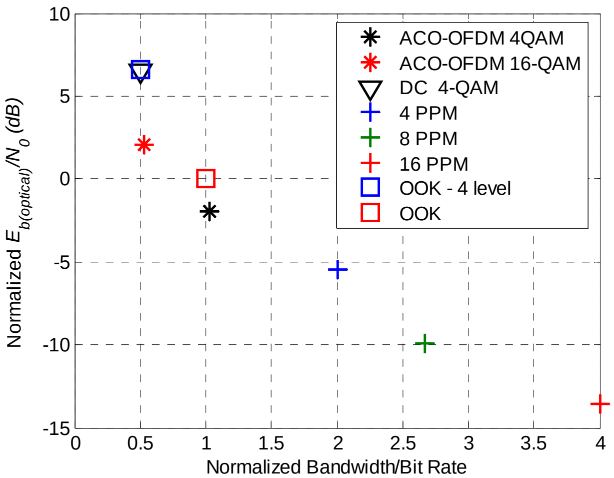


Figure8. $E_{b(opt)}/N_0$ for a BER of 10^{-3} versus normalized bandwidth for PPM, OOK, ACO-OFDM and DC biased OFDM.

IV. Discussion

The invention of ACO-OFDM, an optically efficient modulation scheme which can compensate for distortion caused by signal dispersion or multipath has significant practical as well as theoretical implications. Many of the current limitations on wireless optical communications are directly or indirectly due to the inability of OOK and PPM to compensate for dispersion. For example, transmitted optical power can be increased within eye safety limits if the transmitters are spaced apart – but this causes signal dispersion. ACO-OFDM can readily be used with multiple transmitter systems. Similarly diversity combining techniques in receivers are known to increase performance and bandwidth, but have been limited by multipath effects. It is well known that multiple input-multiple output (MIMO) can be combined with OFDM [18], so ACO-OFDM means that MIMO techniques can now be applied in optical systems.

With ACO-OFDM the limit is set by the electrical bandwidth of the transmitter and receiver and these may be subject to Moore's law. Finally ACO-OFDM requires almost identical digital signal processing as conventional OFDM, so can use the mature OFDM DSP technology [19].

V. Conclusions

We have presented simulation results for ACO-OFDM a new modulation technique based on OFDM but adapted for optical efficiency in an IM/DD system. We have shown that ACO-OFDM has greater optical efficiency than OOK. ACO-OFDM with 4-QAM modulation requires approximately the same normalized bandwidth as OOK but requires 2 dB less optical power. ACO-OFDM with larger constellation sizes allows higher bits per hertz for a given optical power than any previously reported modulation schemes. Performance of ACO-OFDM degrades more slowly with increasing constellation size compared with conventional unipolar modulation schemes. This is because subcarrier modulation occurs in the discrete frequency domain and is bipolar, although the transmitted time domain signal is unipolar.

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