Novel Unipolar Orthogonal Frequency Division Multiplexing (U-OFDM) for Optical Wireless

Dobroslav Tsonev, Sinan Sinanovic and Harald Haas
Institute for Digital Communications, Joint Research Institute for Signal and Image Processing,
The University of Edinburgh, EH9 3JL, Edinburgh, UK
Email: {dtsonev,s.sinanovic, h.haas}@ed.ac.uk

***Abstract*—A novel modulation technique coined U-OFDM is proposed. U-OFDM uses different time sample states and an innovative rearrangement of the Orthogonal Frequency Division Multiplexing (OFDM) frame which allow for the creation of unipolar OFDM signals required for Optical Wireless Communication (OWC) with Light Emitting Diodes (LEDs). In comparison to similar techniques like DC-biased Optical OFDM (DCO-OFDM) and Asymmetrically Clipped Optical OFDM (ACO-OFDM), U-OFDM is both optically and electrically more power efficient in an Additive White Gaussian Noise (AWGN) channel, which is prevalent in an optical wireless system.**

I. Introduction

The demand for wireless data rates is growing exponentially. It is forecast that globally in 2015 more than 6 Exabyte of data will be sent through wireless networks per month [1]. Continuously increasing amounts of data traffic have led to new and refined wireless communication standards that significantly improve the usage, and hence the spectral efficiency of the scarce and limited radio frequency (RF) spectrum. Despite the improvements in current cellular standards, the demand for mobile data throughput outstrips the supply because the available RF spectrum is very limited. Hence, an expansion of wireless communications into a new and largely unexplored physical domain – the visible light spectrum – is very appealing. The main advantages of an optical wireless system are: (a) enormous amount of unregulated bandwidth, (b) no licensing requirements, (c) low-cost front end devices, and (d) no interference with the operation of sensitive electronic systems. Additionally, most of the existing lighting infrastructure can be reused for communication, and there are no known health concerns related to visible light as long as eye-safety regulations are met.

The physical properties of LEDs and Photodiodes (PDs) characterize a Visible Light Communication (VLC) system as an Intensity Modulation/Direct Detection (IM/DD) system. It means that only signal intensity and no phase and amplitude can be conveyed. This limits the set of modulation schemes which can be employed. Techniques like On-Off Keying (OOK), Pulse Position Modulation (PPM), and Pulse Amplitude Modulation (PAM) can be applied in a straightforward fashion for the purpose of OWC. With the increase of transmission rates, however, Intersymbol Interference (ISI) becomes an issue. Hence, the usage of a more resilient technique like OFDM becomes desirable. On one hand, it allows equalization to be performed with single tap equalizers in the frequency domain, which simplifies design. On the other hand, OFDM allows different frequency carriers to be adaptively loaded with bits according to the channel properties. This improves performance, especially in channels where signal attenuation is significant [2]. It is possible to generate real OFDM signals by imposing Hermitian symmetry on the carriers in frequency domain at the expense of half the spectral efficiency. The bipolar nature of OFDM signals, however, introduces an additional problem in VLC since LEDs can only convey unipolar signals in light intensity. The issue can be solved by introducing a DC-bias, which increases the power requirement of the system and cannot be easily optimized for any constellation size if Quadrature Amplitude Modulation (M-QAM) is used to modulate the different OFDM carriers. This technique is known as DCO-OFDM. A power efficient alternative to DCO-OFDM is ACO-OFDM, which uses the properties of the Fourier Transform and asymmetrical clipping to create unipolar signals in time domain [3]. ACO-OFDM, however, has half of the spectral efficiency of DCO-OFDM and a 3 dB performance disadvantage for bipolar signals when compared to OFDM [4]. A third novel modulation approach, in which carrier states are used to convey information is described in [5]. The idea is a modification for improved performance of Subcarrier-Index Modulation OFDM (SIM-OFDM) described in [6]. It has been developed in an attempt to create a modulation scheme with inherently reduced Peak-to-average Power Ratio (PAPR) for the purposes of VLC. The newly proposed modulation scheme, U-OFDM, is inspired by the concept from [5] in an attempt to close the 3 dB gap between OFDM and ACO-OFDM for bipolar signals, whilst generating a unipolar signal, which does not require the biasing of DCO-OFDM for OWC.

The rest of this paper is organized as follows. Section II provides a description of the U-OFDM modulation scheme and its demodulator. Section III describes the new modulation scheme's performance in an AWGN channel. Section IV presents a theoretical approach for assessing the performance of the system. Finally, section V gives concluding remarks.

II. U-OFDM

A typical discrete real bipolar OFDM signal in time domain is illustrated in Fig. 1. A DC shift can be added to the signal, so that DCO-OFDM is obtained for optical wireless communication. This is illustrated in Fig. 2. The DC bias in this example is equal to the absolute value of the lowest sample in the figure. In practice, OFDM has a very high PAPR. The DC shift would have a typical value of a few standard deviations of the original OFDM signal distribution, and any remaining negative values would be clipped. The required bias

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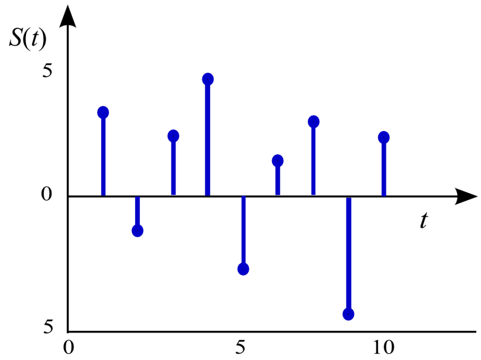

Fig. 1. Typical real OFDM time domain signal

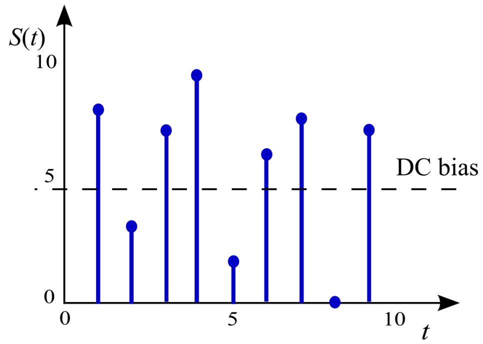

Fig. 2. Typical DCO-OFDM time domain signal

depends on the desired BER and constellation size as described in [4]. In Fig. 2 it is easy to visualize that the power of the signal is being increased by the DC shift when compared to the original signal in Fig. 1.

Unipolar signals do not require a DC shift and lead to higher power efficiency. ACO-OFDM is a state of the art technique for achieving unipolar OFDM signals. As described in [3], the method modulates only odd carriers in the OFDM frame, which leads to a certain symmetry between positive and negative values in time domain. In effect, all negative values can simply be ignored and replaced with zeros. Any distortion, caused by the clipping of the negative values, is projected on the even carriers in frequency domain. The resulting unipolar signal can be used for the purposes of OWC. By ignoring half of the carriers in frequency domain, however, ACO-OFDM has half the spectral efficiency of DCO-OFDM for the same order of M-QAM modulation. In addition, ACO-OFDM has a 3 dB disadvantage in power efficiency for bipolar signals when compared to conventional OFDM for the same M-QAM modulation order.

U-OFDM is a simple alternative technique which provides the benefit of unipolar signals. The modulation process begins with conventional modulation of an OFDM signal. After a real bipolar OFDM signal such as the one in Fig. 1 is obtained, it is transformed into a unipolar signal by encoding each time sample into a pair of new time samples. If the original OFDM sample is positive, the first sample of the new pair is set as "active", and the second sample is set as "inactive". If, on the other hand, the original OFDM sample is negative, the first sample of the new pair is set as "inactive", and the second

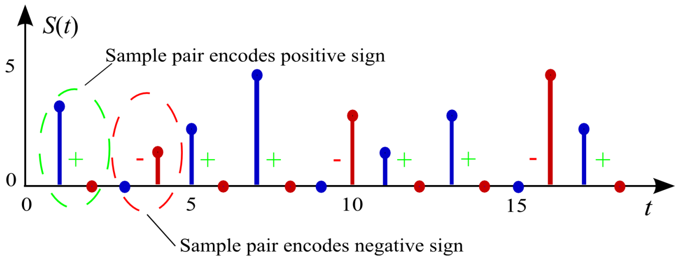

Fig. 3. A unipolar time domain signal

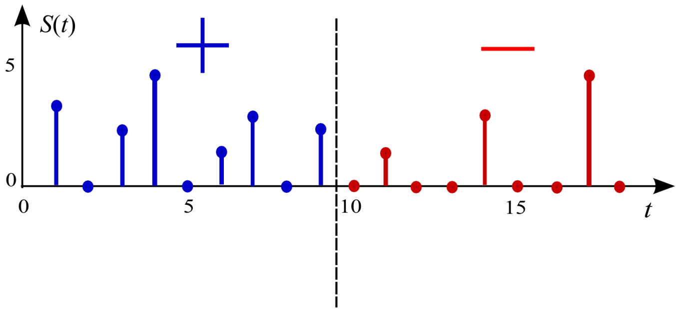

Fig. 4. U-OFDM time domain signal

sample is set as "active". Active samples are set equal to the absolute value of the original OFDM sample they correspond to, and inactive samples are set to zero. That is how the signal illustrated in Fig. 3 is obtained from the signal in Fig. 1. Fig. 3 only illustrates how the signs of the bipolar samples are encoded in the position of the active sample in a pair. The actual U-OFDM signal is obtained when the first samples of each pair are grouped in their original order to form the so called "positive" block while the second samples are grouped in their original order to form the so called "negative" block. The positive block is transmitted first and the negative block is transmitted second. That is how the signal illustrated in Fig. 4 is obtained. It can be used for transmission through the LED. The idea behind the rearrangement procedure is to obtain two blocks which can be linearly combined in order to obtain the original bipolar OFDM signal. This is done so that when both blocks are transmitted through an ISI channel, their frequency components will be attenuated in the same way. The linear recombination will ensure that the symbols encoded in the frequency components of the original bipolar OFDM signal will be subjected to the same attenuation effects by the channel. Cyclic prefixes are not illustrated in the given example. Since the length of the OFDM frame is doubled, the spectral efficiency of U-OFDM is about half the spectral efficiency of DCO-OFDM and the same as the spectral efficiency of ACO-OFDM. There is a necessity for a second cyclic prefix to separate the positive and negative blocks. However, for a large number of carriers its influence on the spectral efficiency will be negligible.

Once the U-OFDM signal is received, there are two ways in which it can be demodulated. The first way consists of subtracting the negative signal block from the positive one, and afterwards continuing the demodulation process with conventional demodulation of an OFDM signal since the result of the subtraction would be identical to the original bipolar

OFDM signal. When demodulated this way, the proposed scheme performs 3 dB worse than bipolar OFDM for the same M-QAM modulation order. This is due to the fact that the subtraction of the negative block from the positive one effectively doubles the AWGN variance at each resulting point. The U-OFDM performance is exactly the same as the reported performance of ACO-OFDM in [4]. An alternative demodulation method allows for a significant improvement of the scheme performance. Each pair of samples as illustrated in Fig. 3 encodes the amplitude and the sign of the original bipolar sample. If the receiver is able to detect which is the active sample in a pair, it can successfully guess the original sign and simply discard the passive sample since it carries no further information. This procedure is ideally expected to remove about half of the noise variance, and hence improve the performance. A simple and efficient way to achieve this is by comparing the amplitudes of the samples in each pair - the one with higher amplitude will be marked as active. A similar approach for ACO-OFDM demodulation has been reported very recently by Asadzadeh et. al. in [7].

III. U-OFDM Performance

Performance of U-OFDM has been simulated in an AWGN channel. No fading is observed in IM/DD systems, and so the AWGN channel is a sufficient model for the evaluation of optical wireless systems. The rest of this work presents only the performance of the improved demodulation scheme for U-OFDM since the other case completely resembles the behavior of ACO-OFDM and is trivial. For comparison purposes the quantities electrical energy per bit ($E_{\mathrm{b,elec}}$) and optical energy per bit ($E_{\mathrm{b,opt}}$) are introduced in [4] as the average electrical and optical energy per bit consumed in the system. Then Electrical Signal-to-noise Ratio ($\mathrm{SNR}_{\mathrm{elec}}$) and Optical Signal-to-noise Ratio ($\mathrm{SNR}_{\mathrm{opt}}$) would be defined as

$$\mathrm{SNR}_{\mathrm{elec}} = \frac{E_{\mathrm{b,elec}}}{N_{\mathrm{o}}} \quad (1)$$

$$\mathrm{SNR}_{\mathrm{opt}} = \frac{E_{\mathrm{b,opt}}}{N_{\mathrm{o}}} \quad (2)$$

where $N_{\mathrm{o}}/2$ is the variance of the AWGN. The bit error rate

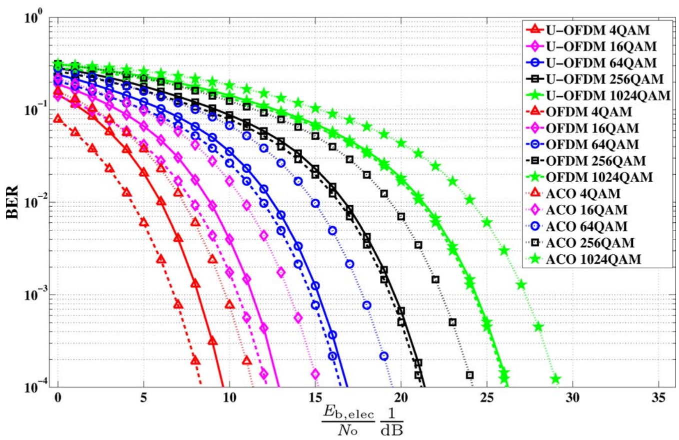

Fig. 5. U-OFDM vs OFDM and ACO-OFDM for bipolar signals

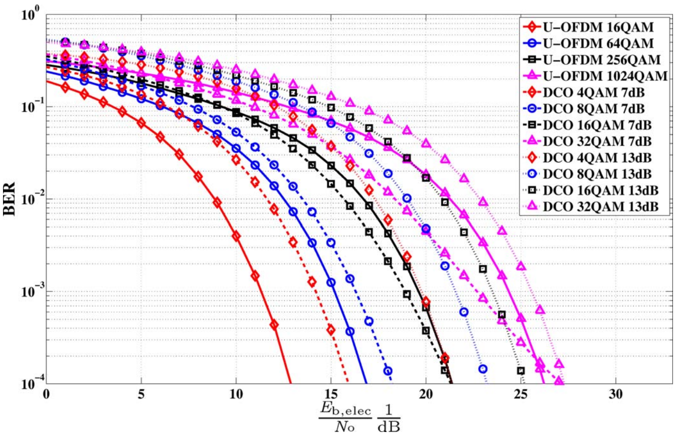

Fig. 6. U-OFDM vs DCO-OFDM performance for different values of $\mathrm{SNR}_{\mathrm{elec}}$

(BER) performance of U-OFDM as a function of $\mathrm{SNR}_{\mathrm{elec}}$ is compared to the performances of OFDM and ACO-OFDM for bipolar signals in Fig. 5. The theoretical BER curves of M-QAM are used for the performance of OFDM, and the same curves with a 3 dB shift are used for the performance of ACO-OFDM in agreement with the analysis from [4]. The new improved ACO-OFDM demodulation technique from [7] is not taken into account. The curves for the improved U-OFDM are obtained with Monte Carlo simulations. The simulations are conducted for 1024 carriers per U-OFDM frame. As expected, U-OFDM cannot surpass conventional bipolar OFDM for the same M-QAM modulation due to the additional detection of active samples in time domain which is not always perfect. However, it has noticeably better performance than ACO-OFDM of the same modulation order. The performance improvement reaches almost 3 dB for higher order M-QAM modulation where U-OFDM approaches conventional OFDM. The difference between U-OFDM and ACO-OFDM curves also illustrates the reduction of the required power caused by the improved demodulator. The performances of U-OFDM and DCO-OFDM are compared in Fig. 6. ACO-OFDM creates unipolar signals. Therefore, its performance does not need to be considered again. The BER curves are plotted against $\mathrm{SNR}_{\mathrm{elec}}$. The energy consumed by DCO-OFDM depends on the choice of a biasing point. Consistence with the work presented in [4] will be kept for comparison purposes. Hence, the DC shift of DCO-OFDM is defined in [4] as

$$B_{\mathrm{DC}} = k\sqrt{\mathrm{E}[S^2(t)]} \quad (3)$$

where $S(t)$ is the bipolar OFDM signal in time domain before the shift and k denotes the ratio of the DC shift and the standard deviation. This is defined in the same work as a bias of $10\log_{10}(k^2+1)$ dB. In consistence with the work in [4], bias levels of 7 dB and 13 dB are chosen for DCO-OFDM. They are not necessarily the optimum biasing points for the different modulation orders. Estimation of the optimum biasing points and a better comparison is a subject of further research. The spectral efficiency of U-OFDM is half the spectral efficiency of DCO-OFDM. That is why the orders of M-QAM modulation are chosen such that the spectral efficiencies of U-OFDM and DCO-OFDM are the same. For example, 16-QAM U-OFDM

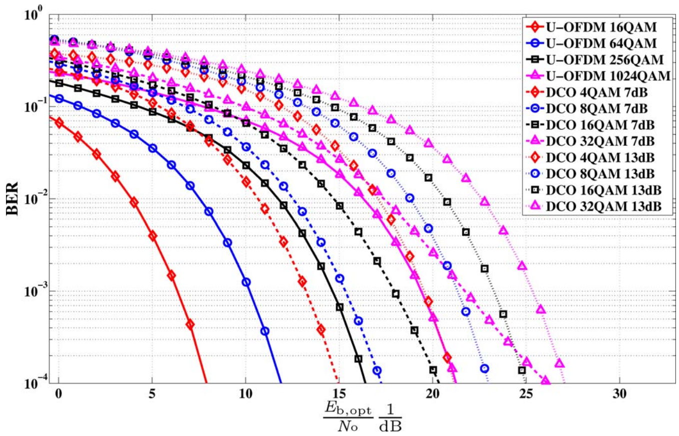

Fig. 7. U-OFDM vs DCO-OFDM performance for different values of $\mathrm{SNR_{opt}}$

should be compared to 4-QAM DCO-OFDM, 64-QAM U-OFDM should be compared to 8-QAM DCO-OFDM, etc. For a $\mathrm{BER} = 10^{-4}$, U-OFDM performs better or the same as DCO-OFDM in all the presented cases.

In order to compare the optical efficiencies of the systems, we adopt the conditions,

$$P_{\mathrm{opt}}^{\mathrm{DCO}} = \mathrm{E}[S_{\mathrm{DCO}}(t)] = 1 \tag{4}$$

$$P_{\mathrm{opt}}^{\mathrm{U}} = \mathrm{E}[S_{\mathrm{U}}(t)] = 1 \tag{5}$$

for consistency with the work done in [4] where subbscripts DCO and U denote time domain signals of DCO-OFDM and U-OFDM respectively. $P_{\mathrm{opt}}^{\mathrm{DCO}}$ and $P_{\mathrm{opt}}^{\mathrm{U}}$ stand for the average optical power of the DCO-OFDM and U-OFDM time domain signals. If these conditions are fullfilled, by using [4], we can write

$$\frac{E_{\mathrm{b,opt}}^{\mathrm{DCO}}}{N_{\mathrm{o}}} = \frac{k^2}{1+k^2}\frac{E_{\mathrm{b,elec}}^{\mathrm{DCO}}}{N_{\mathrm{o}}} \tag{6}$$

$$\frac{E_{\mathrm{b,opt}}^{\mathrm{U}}}{N_{\mathrm{o}}} = \frac{1}{\pi}\frac{E_{\mathrm{b,elec}}^{\mathrm{U}}}{N_{\mathrm{o}}} \tag{7}$$

Using the relations defined in (6) and (7), the performances of U-OFDM and DCO-OFDM for different values of $\mathrm{SNR_{opt}}$ are compared in Fig. 7. U-OFDM surpasses DCO-OFDM in performance for all presented cases, regardless of BER.

It should be noted that the relations in (6) and (7) are only true for the conditions in (4) and (5). The relationship between optical and electrical power efficiency of the system changes as the average power of the signal is varied. The previous remark about the optimum biasing levels of DCO-OFDM applies in this case as well.

IV. Theoretical Performance of U-OFDM

A theoretical approach for analyzing the performance of the improved demodulator for U-OFDM in an AWGN channel is presented in this section. In the context of the following mathematical formulas, σ_{n} is the standard deviation of the AWGN, i.e., $\sigma_{\mathrm{n}} = \sqrt{N_{\mathrm{o}}/2}$, σ_{s} is the standard deviation of the real OFDM signal, $S(t)$, before it is encoded in U-OFDM, i.e., $\sigma_{\mathrm{s}} = \sqrt{E_{\mathrm{b,elec}}\log_2(M)/2}$, $\mathrm{sgn}(s)$ is the sign function, i.e.,

$$\mathrm{sgn}(s) = \begin{cases} -1 & \text{if } s < 0 \\ 0 & \text{if } s = 0 \\ 1 & \text{if } s > 0 \end{cases} \tag{8}$$

$\phi(x)$ is the standard normal distribution probability density function, i.e.,

$$\phi(x) = \frac{1}{\sqrt{2\pi}}e^{-\frac{x^2}{2}} \tag{9}$$

and $Q(x)$ is the tail probability of the standard normal distribution, i.e.,

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{u^2}{2}}\mathrm{d}u \tag{10}$$

Modeling a U-OFDM system analytically is a cumbersome task due to the fact that during demodulation each individual sample in time domain is subjected to a different nonlinear transformation, which depends on two independent random variables from the AWGN. As a starting point, we look at the statistics of the value of a *correctly* detected active sample, which is a random variable. The mean of that variable can be viewed as a nonlinear transform to which the original $S(t)$ sample, s, is subjected. That function has the following form:

$$f_{\mathrm{c}}(s) = \frac{s - \mathrm{sgn}(s)\int_{-\infty}^{\infty}\frac{x}{\sigma_{\mathrm{n}}}\phi\left(\frac{x-|s|}{\sigma_{\mathrm{n}}}\right)Q\left(\frac{x}{\sigma_{\mathrm{n}}}\right)\mathrm{d}x}{\int_{-\infty}^{\infty}\frac{1}{\sigma_{\mathrm{n}}}\phi\left(\frac{x-|s|}{\sigma_{\mathrm{n}}}\right)\left(1-Q\left(\frac{x}{\sigma_{\mathrm{n}}}\right)\right)\mathrm{d}x} \tag{11}$$

In addition, the variance of the *correctly* detected sample has the following value

$$v_{\mathrm{c}}(s) = \frac{\int_{-\infty}^{\infty}\frac{x^2}{\sigma_{\mathrm{n}}}\phi\left(\frac{x-|s|}{\sigma_{\mathrm{n}}}\right)\left(1-Q\left(\frac{x}{\sigma_{\mathrm{n}}}\right)\right)\mathrm{d}x}{\int_{-\infty}^{\infty}\frac{1}{\sigma_{\mathrm{n}}}\phi\left(\frac{x-|s|}{\sigma_{\mathrm{n}}}\right)\left(1-Q\left(\frac{x}{\sigma_{\mathrm{n}}}\right)\right)\mathrm{d}x} - f_{\mathrm{c}}^2(s) \tag{12}$$

Due to the Central Limit Theorem (CLT), that variance will be part of the variance of the AWGN in frequency domain after the Fast Fourier Transform (FFT) is performed in the demodulation process. For the *incorrectly* detected active sample, the mean and variance have the following form

$$f_{\mathrm{w}}(s) = \frac{\mathrm{sgn}(s)\int_{-\infty}^{\infty}\frac{x}{\sigma_{\mathrm{n}}}\phi\left(\frac{x}{\sigma_{\mathrm{n}}}\right)Q\left(\frac{x-|s|}{\sigma_{\mathrm{n}}}\right)\mathrm{d}x}{\int_{-\infty}^{\infty}\frac{1}{\sigma_{\mathrm{n}}}\phi\left(\frac{x}{\sigma_{\mathrm{n}}}\right)\left(1-Q\left(\frac{x-|s|}{\sigma_{\mathrm{n}}}\right)\right)\mathrm{d}x} \tag{13}$$

$$v_{\mathrm{w}}(s) = \frac{\int_{-\infty}^{\infty}\frac{x^2}{\sigma_{\mathrm{n}}}\phi\left(\frac{x}{\sigma_{\mathrm{n}}}\right)\left(1-Q\left(\frac{x-|s|}{\sigma_{\mathrm{n}}}\right)\right)\mathrm{d}x}{\int_{-\infty}^{\infty}\frac{1}{\sigma_{\mathrm{n}}}\phi\left(\frac{x}{\sigma_{\mathrm{n}}}\right)\left(1-Q\left(\frac{x-|s|}{\sigma_{\mathrm{n}}}\right)\right)\mathrm{d}x} - f_{\mathrm{w}}^2(s) \tag{14}$$

Using the Bussgang theorem, introduced in [8], a Gaussian random variable, X, subjected to a nonlinear transformation, $f(X)$, has the following properties

$$f(X) = \alpha X + Y \tag{15}$$

$$E[XY] = 0 \tag{16}$$

$$\alpha = \mathrm{const.} \tag{17}$$

Based on these properties, the constant α and the variance of the noise Y are calculated for the two separate cases we have defined:

$$\alpha_{\mathrm{c}} = \frac{\int_{-\infty}^{\infty} s f_{\mathrm{c}}(s) \frac{1}{\sigma_{\mathrm{s}}} \phi\left(\frac{s}{\sigma_{\mathrm{s}}}\right) \mathrm{d}s}{\sigma_{\mathrm{s}}^2} \tag{18}$$

$$y_{\mathrm{c}} = \mathrm{E}[Y_{\mathrm{c}}^2] = \int_{-\infty}^{\infty} f_{\mathrm{c}}^2(s) \frac{1}{\sigma_{\mathrm{s}}} \phi\left(\frac{s}{\sigma_{\mathrm{s}}}\right) \mathrm{d}s - \alpha_{\mathrm{c}}^2 \sigma_{\mathrm{s}}^2 \tag{19}$$

$$\alpha_{\mathrm{w}} = \frac{\int_{-\infty}^{\infty} s f_{\mathrm{w}}(s) \frac{1}{\sigma_{\mathrm{s}}} \phi\left(\frac{s}{\sigma_{\mathrm{s}}}\right) \mathrm{d}s}{\sigma_{\mathrm{s}}^2} \tag{20}$$

$$y_{\mathrm{w}} = \mathrm{E}[Y_{\mathrm{w}}^2] = \int_{-\infty}^{\infty} f_{\mathrm{w}}^2(s) \frac{1}{\sigma_{\mathrm{s}}} \phi\left(\frac{s}{\sigma_{\mathrm{s}}}\right) \mathrm{d}s - \alpha_{\mathrm{w}}^2 \sigma_{\mathrm{s}}^2 \tag{21}$$

The variance of Y will also be added to the variance of the AWGN in frequency domain. The variances in (12) and (14) are given as functions of the realization of the signal $S(t)$. On average they will be equal to

$$\bar{v}_{\mathrm{c}} = \int_{-\infty}^{\infty} v_{\mathrm{c}}(s) \frac{1}{\sigma_{\mathrm{s}}} \phi\left(\frac{s}{\sigma_{\mathrm{s}}}\right) \mathrm{d}s \tag{22}$$

and

$$\bar{v}_{\mathrm{w}} = \int_{-\infty}^{\infty} v_{\mathrm{w}}(s) \frac{1}{\sigma_{\mathrm{s}}} \phi\left(\frac{s}{\sigma_{\mathrm{s}}}\right) \mathrm{d}s \tag{23}$$

The probability for correct detection of an active time sample, d_{c}, is

$$d_{\mathrm{c}} = \int_{0}^{\infty} \frac{2}{\sigma_{\mathrm{s}}} \phi\left(\frac{s}{\sigma_{\mathrm{s}}}\right) Q\left(\frac{s}{\sqrt{2}\sigma_{\mathrm{n}}}\right) \mathrm{d}s \tag{24}$$

For a large number of samples in a U-OFDM frame, the number of *correctly* and *incorrectly* detected active samples will have a ratio which corresponds to the probabilities for *correct* and *incorrect* detection. Hence, the average gain factor, $\bar{\alpha}$, and the average noise variance in frequency domain, $\bar{N}$, become

$$\bar{\alpha} = d_{\mathrm{c}}\alpha_{\mathrm{c}} + (1 - d_{\mathrm{c}})\alpha_{\mathrm{w}} \tag{25}$$

$$\bar{N} = d_{\mathrm{c}}(\bar{v}_{\mathrm{c}} + y_{\mathrm{c}}) + (1 - d_{\mathrm{c}})(\bar{v}_{\mathrm{w}} + y_{\mathrm{w}}) \tag{26}$$

$$\mathrm{SNR}_{\mathrm{elec}} = \frac{\alpha^2 E_{\mathrm{b,elec}}}{\bar{N}} \tag{27}$$

The achieved average $\mathrm{SNR}_{\mathrm{elec}}$ from (27) can be plugged in the well-known formula for M-QAM BER performance [9]. Hence, the performance of U-OFDM can be calculated as

$$\mathrm{BER}_{\mathrm{U}} = \mathrm{BER}_{\mathrm{QAM}}\left(\frac{\alpha^2 E_{\mathrm{b,elec}}}{\bar{N}}\right) \tag{28}$$

The comparison between theoretical model and Monte Carlo simulations of the system performance is presented in Fig. 8. There is good agreement between the presented model and the conducted simulations.

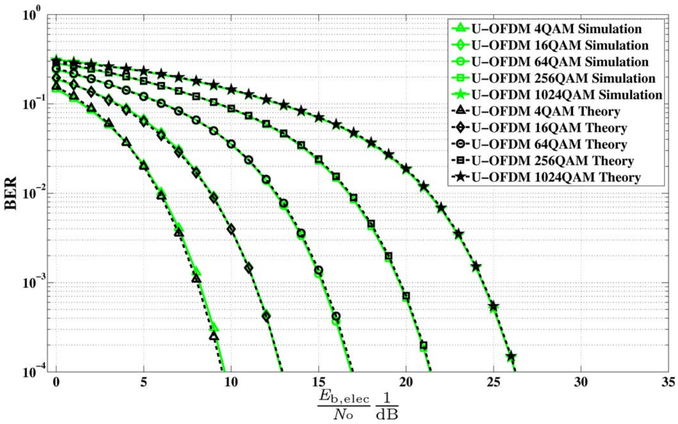

Fig. 8. Theoretical U-OFDM performance vs. Monte Carlo simulations

V. Conclusion

A novel multicarrier modulation scheme for optical wireless communication has been presented in this paper. The new scheme demonstrates improvement over some known multicarrier schemes for OWC. It provides the same benefits as the already known ACO-OFDM modulation scheme as well as an improved demodulation scheme for better power efficiency in an AWGN channel. When compared to DCO-OFDM, it shows better performance in terms of BER for the presented scenarios. The current work additionally provides a good theoretical analysis for the performance of the presented scheme in an AWGN channel.

Acknowledgement

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