Optimum Signal Shaping in OFDM-based Optical Wireless Communication Systems

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***Abstract*—In this paper, a framework for optimum signal shaping in multi-carrier modulation is presented for optical wireless communications (OWC). The two fundamental multi-carrier transmission schemes based on orthogonal frequency division multiplexing (OFDM), direct-current-biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM), are studied. The optimum signal shaping is defined as optimum biasing and optimum scaling of the time domain signal within the optical power constraints of the transmitter front-end. These include the boundaries of the limited linear dynamic range, such as minimum and maximum radiated optical power, and the desired average optical power level. As a result, the minimum required electrical signal-to-noise ratio (SNR) to maintain a target bit-error ratio (BER) is obtained for a desired multi-level quadrature amplitude modulation (M-QAM) scheme and a given combination of optical power constraints. The average optical power is varied over dynamic ranges of 10 dB, 20 dB and 30 dB. With the increase of the dynamic range and for a major portion of the average optical power levels, DCO-OFDM demonstrates a lower minimum electrical SNR requirement for a target BER as compared to ACO-OFDM for modulation orders with similar spectral efficiencies.**

***Index Terms*—Signal shaping, optimization, DCO-OFDM, ACO-OFDM, optical wireless communication.**

I. INTRODUCTION

Optical OFDM (O-OFDM) transmission has proven to be a robust candidate for high-speed data communication over the dispersive optical wireless channel [1]. The data transmission in OWC is achieved through intensity modulation and direct detection (IM/DD). A real-valued non-negative signal modulates the intensity of a light emitting diode (LED) at the transmitter, and it is detected by a photodiode (PD) at the receiver. In the literature, two possible O-OFDM system realizations can be found: DCO-OFDM [2] and ACO-OFDM [3]. A real-valued signal is obtained when Hermitian symmetry is imposed on the OFDM subcarriers. A non-negative signal is obtained in DCO-OFDM by the addition of a direct current (DC) bias. In ACO-OFDM, the odd subcarriers are enabled for data transmission, whereas the even ones are set to zero. Here, the negative part of the time domain signal can be clipped at the transmitter, and the information can be still successfully decoded from the odd subcarriers at the receiver.

Imperfections of the optical front-ends due to the use of off-the-shelf components result in a limited linear dynamic range of radiated optical power [4]. It is shown in [5] that the non-linear transfer characteristic of the LED can be compensated by pre-distortion. A linear characteristic is obtainable, however, only over a limited range. Therefore, the transmitted signal is constrained between levels of minimum and maximum optical power. Furthermore, the average optical power level is constrained by the eye safety regulations [6] and/or design requirements such as signal dimming. An example of the latter is OWC in an aircraft cabin [7] where the cabin illumination serves the dual purpose of visible light communication (VLC). In order to condition the signal in accordance with these constraints, signal scaling in the digital signal processor (DSP) and DC-biasing in the analog circuitry is required. For a large number of subcarriers, *e.g.* greater than 64 [8], the time domain signals in DCO-OFDM and ACO-OFDM closely follow Gaussian and half-Gaussian distributions, respectively. Therefore, scaling and DC-biasing in DCO-OFDM and ACO-OFDM result in a non-linear signal distortion.

In this paper, the analysis of the clipping distortion from [9] is employed in the demonstration of the minimum electrical SNR requirement to achieve a target BER for a given combination of optical power constraints and a desired QAM order, M. Both alternating current (AC) power and DC power are included in the calculation of the electrical SNR requirement for average optical power levels varied over dynamic ranges of 10 dB, 20 dB and 30 dB. For the majority of average optical power levels, DCO-OFDM demonstrates a lower minimum electrical SNR requirement for a target BER as compared to ACO-OFDM for modulation orders with similar spectral efficiencies as the dynamic range increases. Therefore, DCO-OFDM proves to be the more flexible transmission scheme for OWC with an ability to sweep over more than 50% of the dynamic range within a 3 dB SNR margin.

The rest of the paper is organized as follows. Section II presents the O-OFDM system model and the formulation of the optimization problem. Results are discussed in Section III. Finally, Section IV concludes the paper.

II. O-OFDM TRANSMISSION

The conventional discrete model for a noisy communication link is employed in this study:

$$\mathbf{y} = \mathbf{h} * \mathbf{x} + \mathbf{n} \,, \tag{1}$$

where $\mathbf{y}$ represents the received distorted replica of the transmitted signal, $\mathbf{x}$, which is convolved with the channel impulse response, $\mathbf{h}$, and it is distorted by additive white Gaussian noise (AWGN), $\mathbf{n}$, at the receiver. In M-QAM O-OFDM, $\mathbf{n}$ has a zero-mean real-valued Gaussian distribution which after optical-to-electrical (O/E) conversion is transformed into

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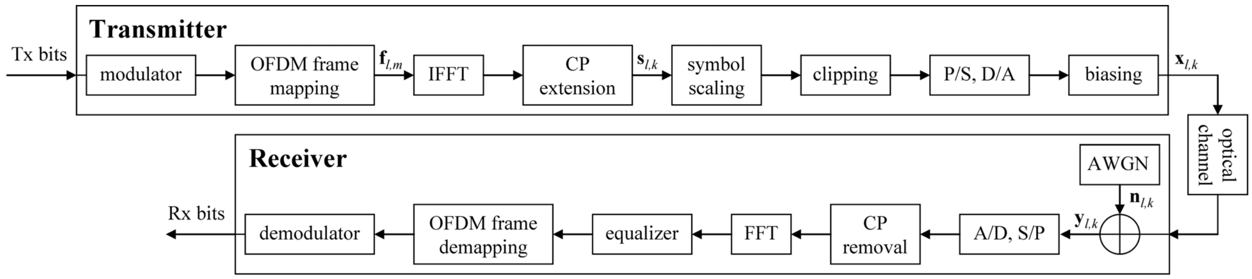

Fig. 1: Block diagram of O-OFDM transmission.

a complex-valued AWGN with an electrical power spectral density (PSD) of $N_0/2$ per complex dimension [10]. Here, $*$ stands for discrete linear convolution. The discrete signal vectors are obtained by sampling of the equivalent continuous-time signals with a sampling period of T. Here, $\mathbf{x}$ contains $Z_{\mathbf{x}}$ samples, $\mathbf{h}$ has $Z_{\mathbf{h}}$ samples, and as a result, $\mathbf{n}$ and $\mathbf{y}$ have $Z_{\mathbf{x}}+Z_{\mathbf{h}}-1$ samples [10]. In multi-carrier systems, a large number of subcarriers and a cyclic prefix (CP) transform the dispersive optical wireless channel into a flat fading channel over the subcarrier bandwidth [10]. In OWC, the flatness of the channel can be extended over all subcarriers for bandwidths up to 20 MHz [11], and it can be primarily characterized by the optical path gain coefficient, $g_{\mathrm{h(opt)}}$ [7]. Single-tap zero forcing (ZF) or minimum mean-squared error (MMSE) equalization are employed to counter the channel effect [10].

The block diagram for multi-carrier O-OFDM transmission is presented in Fig. 1. Here, $\log_2(M)$ bits of the equiprobable input bits modulate the complex-valued information carrying frequency domain subcarrier in an M-QAM fashion. In general, N subcarriers form the l-th OFDM frame, $\mathbf{f}_{l,m}$, $l=0,1,...,L-1$, corresponding to the l-th OFDM symbol, where m, $m=0,1,...,N-1$, is the subcarrier index. Each subcarrier occupies a bandwidth of $1/NT$ in a total OFDM frame double-sided bandwidth of $B=1/T$. Here, the bandwidth utilization factor is denoted by G_{B}, where $G_{\mathrm{B}}=(N-2)/N$ in DCO-OFDM and $G_{\mathrm{B}}=0.5$ in ACO-OFDM. Both systems have the Hermitian symmetry imposed on the OFDM frame, in order to ensure a real-valued time domain signal. Whereas in DCO-OFDM the information carrying subcarriers populate the first half of the frame, leaving the first one set to zero, in ACO-OFDM every even subcarrier is set to zero. Here, the l-th OFDM symbol in the train of L symbols, $\mathbf{s}_l$, is obtained by the inverse fast Fourier transformation (IFFT) of the l-th OFDM frame in the train of L frames, $\mathbf{f}_l$. Next, N_{CP} samples from the end of each OFDM symbol are appended at the beginning of the symbol, creating the CP extension. Here, the time domain sample index within the l-th OFDM symbol with CP, $\mathbf{s}_{l,k}$, is denoted by k, $k=0,1,...,N+N_{\mathrm{CP}}-1$. As a result, the time domain OFDM symbol with CP occupies a double-sided bandwidth of $B=1/T$, and it has a duration of $(N+N_{\mathrm{CP}})T$. Because of the Hermitian symmetry, the spectral efficiency of optical OFDM with M-QAM amounts to $\log_2(M)G_{\mathrm{T}}G_{\mathrm{B}}/2$ bits/s/Hz, where $G_{\mathrm{T}}=N/(N+N_{\mathrm{CP}})$ is the utilization factor for the information carrying time. The train of OFDM symbols, $\mathbf{s}_{l,k}$, follows a close to Gaussian distribution for IFFT sizes greater than 64 [8]. In order to fit the signal within the limited linear dynamic range of the transmitter, $\mathbf{s}_{l,k}$ is scaled and clipped at normalized bottom and top clipping levels of $\lambda_{\mathrm{bottom}}$ and λ_{top} relative to a standard normal distribution [9]. In DCO-OFDM, $\lambda_{\mathrm{bottom}}=\big(P_{\mathrm{Tx,min}}-\beta_{\mathrm{DC}}\big)/\sigma$, whereas in ACO-OFDM, $\lambda_{\mathrm{bottom}}=\max\Big(\big(P_{\mathrm{Tx,min}}-\beta_{\mathrm{DC}}\big)/\sigma,0\Big)$. Here, σ is the target standard deviation of the non-clipped time domain signal to be fit within the minimum and maximum level of radiated optical power, $P_{\mathrm{Tx,min}}$ and $P_{\mathrm{Tx,max}}$, and β_{DC} is the DC bias. In both systems, $\lambda_{\mathrm{top}}=\big(P_{\mathrm{Tx,max}}-\beta_{\mathrm{DC}}\big)/\sigma$. Next, the train of symbols with CPs is subjected to a parallel-to-serial (P/S) conversion, and it is passed through the digital-to-analog (D/A) converter. Here, a pulse shaping filter is applied to obtain the continuous-time signal. In the analog circuitry the signal is DC-biased by β_{DC}. Therefore, the transmitted signal vector, $\mathbf{x}$, with a length of $Z_{\mathbf{x}}=L(N+N_{\mathrm{CP}})$ can be expressed as follows:

$$\mathbf{x}_{l,k}=\mathrm{CLIP}\left[\alpha\mathbf{s}_{l,k}\right]+\beta_{\mathrm{DC}}\ , \tag{2}$$

where

$$\alpha=\sigma\sqrt{\frac{N-1}{\sum\limits_{m=0}^{N-1}|\mathbf{f}_{l,m}|^2}}\ . \tag{3}$$

Before the scaling clock, the average electrical power of the $G_{\mathrm{B}}N$ QAM symbols on the enabled subcarriers amounts to $P_{\mathrm{s(elec)}}=1$. In order to maintain the signal variance of σ^2, the power of the enabled subcarriers is scaled through α to $P_{\mathrm{s(elec)}}/G_{\mathrm{B}}$, where $P_{\mathrm{s(elec)}}=\sigma^2$. Thus, the average bit energy can be expressed as follows: $E_{\mathrm{b(elec)}}=\sigma^2/(\log_2(M)G_{\mathrm{T}}G_{\mathrm{B}}B)$. The non-linear clipping distortion represented by the CLIP $[\cdot]$ operator can be translated into an attenuation factor, K, on the information carrying subcarriers plus a zero-mean complex-valued Gaussian noise component with a variance of σ^2_{clip}. In DCO-OFDM and ACO-OFDM, K is given as follows [9]:

$$K=Q(\lambda_{\mathrm{bottom}})-Q(\lambda_{\mathrm{top}})\ . \tag{4}$$

Here, $Q(\cdot)$ stands for the complementary cumulative distribution function (CCDF) of a standard normal distribution with zero mean and unity variance. The variance of the clipping noise in DCO-OFDM and ACO-OFDM, respectively, can be expressed as follows [9]:

$$\begin{aligned}\sigma_{\text{clip}}^2 = P_{\text{s(elec)}}\Big(K - K^2 - \big(\phi(\lambda_{\text{bottom}}) - \phi(\lambda_{\text{top}})\\ +(1-Q(\lambda_{\text{bottom}}))\lambda_{\text{bottom}} + Q(\lambda_{\text{top}})\lambda_{\text{top}}\big)^2\\ +(1-Q(\lambda_{\text{bottom}}))\lambda_{\text{bottom}}^2 + Q(\lambda_{\text{top}})\lambda_{\text{top}}^2\\ +\phi(\lambda_{\text{bottom}})\lambda_{\text{bottom}} - \phi(\lambda_{\text{top}})\lambda_{\text{top}}\Big)\ ,\end{aligned} \tag{5}$$

$$\begin{aligned}\sigma_{\text{clip}}^2 = P_{\text{s(elec)}}\Big(K\big(\lambda_{\text{bottom}}^2+1\big) - 2K^2\\ -\lambda_{\text{bottom}}\big(\phi(\lambda_{\text{bottom}}) - \phi(\lambda_{\text{top}})\big)\\ -\phi(\lambda_{\text{top}})\big(\lambda_{\text{top}} - \lambda_{\text{bottom}}\big)\\ +Q(\lambda_{\text{top}})\big(\lambda_{\text{top}} - \lambda_{\text{bottom}}\big)^2\Big)\ ,\end{aligned} \tag{6}$$

where $\phi(\cdot)$ stands for the probability density function (PDF) of a standard normal distribution. In addition to the distortion of the information carrying subcarriers, time domain signal clipping modifies the average optical power of the transmitted signal as follows:

$$\begin{aligned}\mathrm{E}\left[\mathbf{x}_l\right] = \sigma\Big(\lambda_{\text{top}}Q(\lambda_{\text{top}}) - \lambda_{\text{bottom}}Q(\lambda_{\text{bottom}})\\ +\phi(\lambda_{\text{bottom}}) - \phi(\lambda_{\text{top}})\Big) + P_{\text{bottom}}\ .\end{aligned} \tag{7}$$

In DCO-OFDM, $P_{\text{bottom}} = P_{\text{Tx,min}}$, while in ACO-OFDM, $P_{\text{bottom}} = \max\Big(P_{\text{Tx,min}}, \beta_{\text{DC}}\Big)$ because of the default zero-level clipping. The eye safety regulations [6] and/or the design requirements such as signal dimming impose the average optical power constraint, $P_{\text{Tx,avg}}$, *i.e.* $\mathrm{E}\left[\mathbf{x}_l\right] \leq P_{\text{Tx,avg}}$.

The signal $\mathbf{x}_{l,k}$ is transmitted over the optical wireless channel. At the receiver, it is distorted by AWGN, $\mathbf{n}_{l,k}$, to obtain $\mathbf{y}_{l,k}$. A matched filter is employed, and at the analog-to-digital (A/D) converter the signal is sampled at a frequency of $1/T$ [10]. Next, the CP extension of each OFDM symbol is removed, and after serial-to-parallel (S/P) conversion the signal is passed through a fast Fourier transformation (FFT) block back to the frequency domain. A single-tap ZF or MMSE equalizer and a hard-decision decoder are employed to obtain the received bits. Thus, the effective electrical SNR per bit in M-QAM O-OFDM is given as follows:

$$\Gamma_{\text{b(elec)}} = \frac{K^2}{\dfrac{G_{\text{B}}\log_2(M)\sigma_{\text{clip}}^2}{P_{\text{s(elec)}}} + \dfrac{G_{\text{B}}\gamma_{\text{b(elec)}}^{-1}}{G_{\text{T}}G_{\text{EQ}}G_{\text{DC}}}}\ , \tag{8}$$

where $\gamma_{\text{b(elec)}} = E_{\text{b(elec)}}/N_0$ is the undistorted electrical SNR per bit. Here, G_{EQ} stands for the equalizer gain, and it is given for ZF and MMSE, respectively, as $g_{\text{h(opt)}}^2$ and $g_{\text{h(opt)}}^2 + \gamma_{\text{b(elec)}}^{-1}$. The gain factor G_{DC} denotes the attenuation of the useful electrical signal power of $\mathbf{x}$ due to the DC component, and it can be expressed in DCO-OFDM and ACO-OFDM, respectively, as follows [9]:

$$G_{\text{DC}} = \frac{\sigma^2}{\sigma^2 + \beta_{\text{DC}}^2}\ , \tag{9}$$

$$G_{\text{DC}} = \frac{\sqrt{2\pi}\sigma^2}{\sqrt{2\pi}\sigma^2 + 4\sigma\beta_{\text{DC}} + 2\sqrt{2\pi}\beta_{\text{DC}}^2}\ . \tag{10}$$

The BER performance of M-QAM O-OFDM in AWGN can be obtained as follows [12]:

$$\text{BER} = \frac{4\big(\sqrt{M}-1\big)}{\log_2(M)\sqrt{M}}Q\left(\sqrt{\frac{3\log_2(M)}{M-1}\Gamma_{\text{b(elec)}}}\right)\ . \tag{11}$$

The choice of the biasing parameters, such as the signal variance, σ^2, and the DC bias, β_{DC}, in consideration of the front-end optical power constraints, $P_{\text{Tx,min}}$, $P_{\text{Tx,max}}$ and $P_{\text{Tx,avg}}$, for a given QAM modulation order, M, can be formulated as an optimization problem. The objective of the optimization is the minimization of the electrical SNR requirement to achieve a target BER which is summarized in TABLE I. Here, the electrical SNR requirement is represented by the electrical SNR per bit, $\gamma_{\text{b(elec)}}$. The analytical approach to solve the minimization problem leads to a system of non-linear transcendental equations which does not have a closed-form solution. Therefore, a numerical optimization procedure

Given: BER, M, $P_{\text{Tx,min}}$, $P_{\text{Tx,max}}$ and $P_{\text{Tx,avg}}$
Find: $\underset{\substack{\sigma\geq 0\\ \beta_{\text{DC}}\geq 0}}{\operatorname{argmin}}\ f(\sigma,\beta_{\text{DC}}) = \gamma_{\text{b(elec)}} \geq 0$ where ZF equalizer $\gamma_{\text{b(elec)}} = \frac{G_{\text{B}}}{g_{\text{h(opt)}}^2 G_{\text{T}} G_{\text{DC}}}\left(qK^2 - \frac{G_{\text{B}}\log_2(M)\sigma_{\text{clip}}^2}{P_{\text{s(elec)}}}\right)^{-1}$ MMSE equalizer $\gamma_{\text{b(elec)}} = \frac{\frac{G_{\text{B}}}{G_{\text{T}}G_{\text{DC}}} - \left(qK^2 - \frac{G_{\text{B}}\log_2(M)\sigma_{\text{clip}}^2}{P_{\text{s(elec)}}}\right)}{g_{\text{h(opt)}}^2\left(qK^2 - \frac{G_{\text{B}}\log_2(M)\sigma_{\text{clip}}^2}{P_{\text{s(elec)}}}\right)}$ $q = \frac{3\log_2(M)}{M-1}\left(Q^{-1}\left(\frac{\text{BER}\sqrt{M}\log_2(M)}{4(\sqrt{M}-1)}\right)\right)^{-2}$
Constraints: $\mathrm{E}\left[\mathbf{x}_l\right] = \sigma\Big(\phi(\lambda_{\text{bottom}}) - \phi(\lambda_{\text{top}}) + \lambda_{\text{top}}Q(\lambda_{\text{top}}) - \lambda_{\text{bottom}}Q(\lambda_{\text{bottom}})\Big) + P_{\text{bottom}} \leq P_{\text{Tx,avg}}$ DCO-OFDM: $\lambda_{\text{top}} > \lambda_{\text{bottom}}$ ACO-OFDM: $\lambda_{\text{top}} > \lambda_{\text{bottom}} \geq 0$

TABLE I: Minimization of $\gamma_{\text{b(elec)}}$ over σ and β_{DC} for given target BER, M, $P_{\text{Tx,min}}$, $P_{\text{Tx,max}}$ and $P_{\text{Tx,avg}}$.

is required, and the minimization can be carried out through a computer simulation for a particular choice of front-end optical power constraints.

III. Results and Discussion

In this paper, the optimum signal scaling and DC-biasing are obtained as a minimization of the electrical SNR requirement of DCO-OFDM and ACO-OFDM for a set of optical power constraints. The following QAM orders are chosen: $M = \{4, 16, 64, 256, 1024\}$. In order to facilitate forward error correction (FEC) coding, a target BER of 10^{-3} is considered. In addition, the average optical power constraint in TABLE I is met with equality, *i.e.* $\mathrm{E}[\mathbf{x}_l] = P_{\mathrm{Tx,avg}}$, in order to illustrate the influence of signal dimming on the electrical SNR requirement. For the sake of generality, the optical power constraints are normalized to $P_{\mathrm{Tx,max}}$ as follows: $P_{\mathrm{Tx,min,norm}} = P_{\mathrm{Tx,min}}/P_{\mathrm{Tx,max}}$, $P_{\mathrm{Tx,avg,norm}} = P_{\mathrm{Tx,avg}}/P_{\mathrm{Tx,max}}$ and $P_{\mathrm{Tx,max,norm}} = 1$. Linear dynamic ranges of 10 dB, 20 dB and 30 dB are considered, and therefore the normalized minimum optical power is set to $P_{\mathrm{Tx,min,norm}} = \{0.1, 0.01, 0.001\}$. For a large number of subcarriers, the inter-symbol interference (ISI) from maximum delay spreads up to 100 ns can be compensated by a CP of 2 samples at a sampling rate of 20 MHz with a negligible reduction of the electrical SNR requirement and the spectral efficiency [13]. In addition, since the optical path gain coefficient, $g_{\mathrm{h(opt)}}$, is merely a factor in the equalization process which equally scales every $\gamma_{\mathrm{b(elec)}}$ minimum from TABLE I, $g_{\mathrm{h(opt)}}$ does not influence the optimum biasing parameters, such as σ^2 and β_{DC}. Therefore, $g_{\mathrm{h(opt)}} = 1$ is assumed for simplicity. An MMSE equalizer is used.

The electrical SNR requirement for a target BER of 10^{-3} is presented in DCO-OFDM and ACO-OFDM for linear dynamic ranges of 10 dB, 20 dB and 30 dB in Fig. 2, Fig. 3 and Fig. 4, respectively. The small slopes of the graphs in the middle of the dynamic range suggest that average optical powers over more than 50% and 25% of the dynamic range

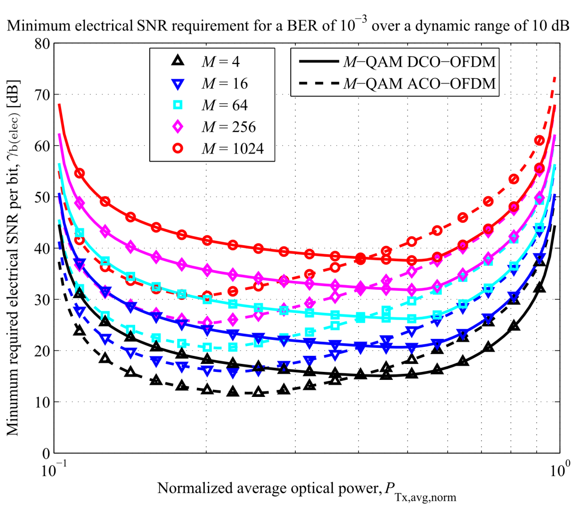

Fig. 2: Minimum electrical SNR requirement for a BER of 10^{-3} *vs.* average optical power over a 10 dB dynamic range.

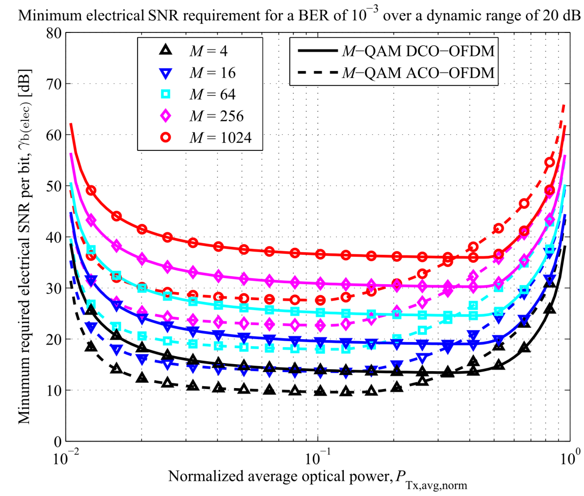

Fig. 3: Minimum electrical SNR requirement for a BER of 10^{-3} *vs.* average optical power over a 20 dB dynamic range.

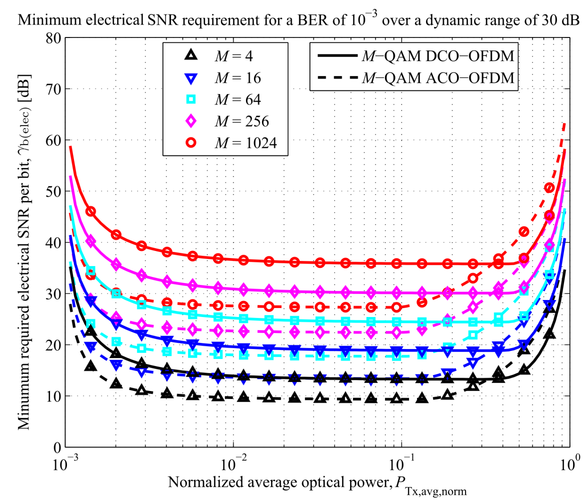

Fig. 4: Minimum electrical SNR requirement for a BER of 10^{-3} *vs.* average optical power over a 30 dB dynamic range.

can be supported by an SNR margin as low as 3 dB in DCO-OFDM and ACO-OFDM, respectively. It is shown that for an equal modulation order, M, DCO-OFDM outperforms ACO-OFDM in terms of minimum electrical SNR requirement in the upper part of the dynamic range, whereas ACO-OFDM prevails for lower average optical power levels because of the respective Gaussian and half-Gaussian distributions of the signals. In addition, the minimum electrical SNR requirement graphs exhibit an absolute minimum. This suggests that there is an average optical power level which allows for the best joint maximization of the signal variance, minimization of the clipping distortion and minimization of the DC-bias penalty from TABLE I. For both systems, the absolute minimum electrical SNR requirement and the corresponding average optical power level are presented in Fig. 5. They decrease with the increase of the dynamic range because of the relaxed $P_{\mathrm{Tx,min}}$ and $P_{\mathrm{Tx,max}}$ constraints in the optimization. In order to find out which system delivers the higher throughput for a given

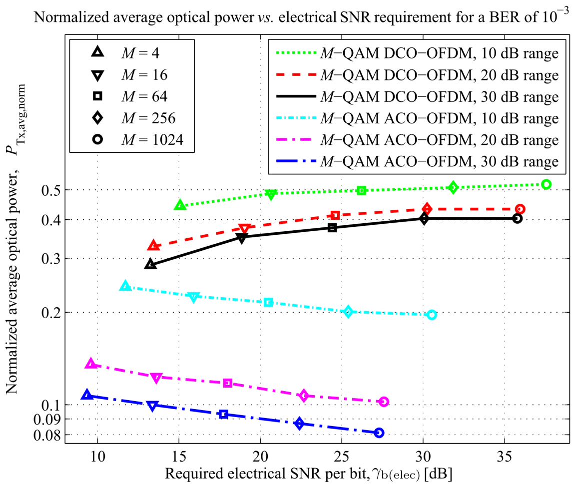

Fig. 5: Normalized average optical power *vs.* absolute minimum electrical SNR requirement for a target BER of 10^{-3}.

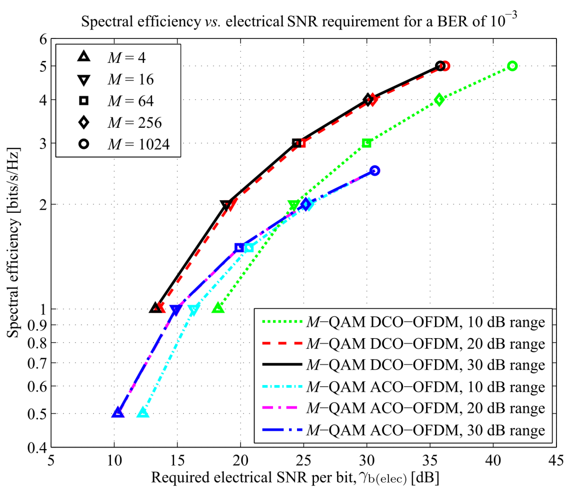

Fig. 6: Spectral efficiency *vs.* minimum electrical SNR requirement for a target BER of 10^{-3}. The average optical power level is set to 20% of the maximum of the dynamic range.

average optical power level, the spectral efficiency and the minimum electrical SNR requirement are shown in Fig. 6 for an average optical power level dimmed down to 20%. DCO-OFDM is expected to have a lower electrical SNR requirement and a superior spectral efficiency as compared to ACO-OFDM for average optical power levels in the upper part of the dynamic range. However, this is shown to be the case also for low average optical power levels, *i.e.* $P_{\mathrm{Tx,avg,norm}} = 0.2$, as the dynamic range increases. Here, LEDs with wider linear dynamic ranges are proven to be the enabling factor for OWC with low optical power radiation. In addition, DCO-OFDM demonstrates a lower minimum electrical SNR requirement for a target BER as compared to ACO-OFDM for modulation orders with similar spectral efficiencies for average optical power levels over more than 85%, 90% and 95% of the dynamic ranges of 10 dB, 20 dB and 30 dB, respectively.

IV. Conclusion

In this paper, a framework for optimum signal scaling and biasing is presented for OFDM-based OWC with minimum, average and maximum optical power constraints. The minimum electrical SNR requirement is obtained in DCO-OFDM and ACO-OFDM for a target BER, M-QAM scheme, and an average optical power constraint varied over dynamic ranges of 10 dB, 20 dB and 30 dB. It is shown that a transmitter front-end with a wide linear dynamic range of 20 dB or higher provides sufficient electrical power for OWC with optical power output close to the boundaries of the dynamic range, where the LED appears to be off or driven close to its maximum. In addition, an SNR margin of 3 dB is sufficient to support an average optical power sweep over 50% and 25% of the dynamic range in DCO-OFDM and ACO-OFDM, respectively. Finally, DCO-OFDM is expected to deliver the higher throughput as compared to ACO-OFDM for average optical power levels over a major portion of the dynamic range.

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