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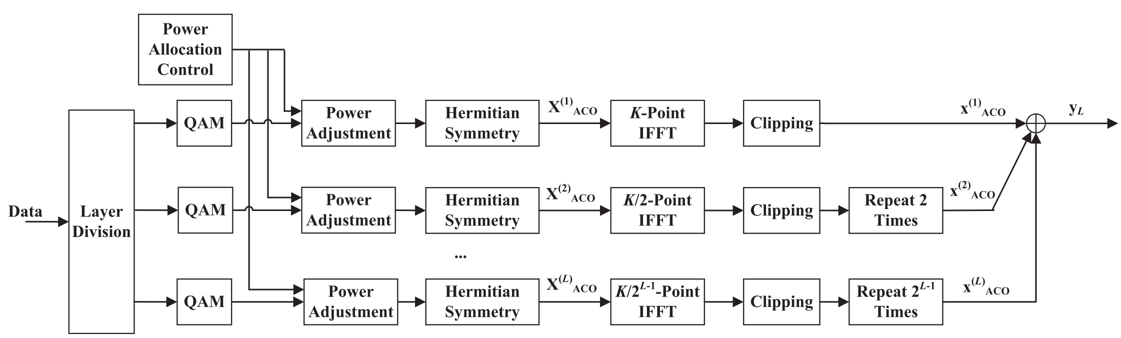

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Adaptive LACO-OFDM With Variable Layer for Visible Light Communication

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Abstract: In this paper, the adaptive layered asymmetrically clipped optical orthogonal frequency division multiplexing (LACO-OFDM) with variable layer is investigated. The channel capacities of the adaptive LACO-OFDM with different layers are formulated to determine the optimal layer amount under different optical signal-to-noise ratio scenarios with electrical or optical power constraint, respectively. Computer simulations verify the validity of the theoretical analysis for the proposed layer assignment scheme.

Index Terms: Visible light communication (VLC), orthogonal frequency division multiplexing (OFDM), layered asymmetrically clipped optical OFDM (LACO-OFDM), layer assignment.

1. Introduction

Visible light communication (VLC) has drawn growing attention as a promising technology, especially for indoor environment, owing to its features such as unregulated bandwidth, low cost, high privacy protection and no health concerns [1]–[3]. Recently, due to its advantages of resistance to inter symbol interference (ISI), orthogonal frequency division multiplexing (OFDM) has been increasingly considered as an emerging modulation technique in VLC [4], due to its high power efficiency compared to single-subcarrier schemes, such as on-off-keying (OOK) and pulse position modulation (PPM) [5], [6].

In VLC systems, intensity modulation with direct detection (IM/DD) is widely adopted, where the transmitted signal is modulated onto the intensity of light [7]. As a result, the OFDM signals in the time domain used for VLC have to be real and unipolar. The Hermitian symmetry property is usually satisfied for the input frequency-domain signal in order to achieve real signals. Several strategies are proposed for the purpose of unipolar signal generation. In DC biased optical OFDM (DCO-OFDM), after inverse fast Fourier transform (IFFT), the signals are guaranteed positive by adding a DC bias [8]. The signals could also be ensured non-negative by clipping the negative part directly based on its anti-symmetric features in asymmetrically clipped optical OFDM (ACO-OFDM) [9] and pulse-amplitude-modulated discrete multitoned (PAM-DMT) [10]. However, the optical power efficiency of DCO-OFDM is low [11], while there is a spectral efficiency loss in ACO-OFDM and PAM-DMT as only half of the subcarriers or signal dimensions are utilized [12].

Recently, a new technique, layered ACO-OFDM (LACO-OFDM) is introduced in [13] combining several orthogonal layers of ACO-OFDM signals and can achieve spectral efficiency improvement by up to 2 times with the increase of the computational complexity, which is also known as spectral and energy efficient OFDM (SEE-OFDM) [14] or enhanced ACO-OFDM (eACO-OFDM) [15]. Moreover, an enhanced unipolar OFDM is also proposed in [16], which is similar to LACO-OFDM and combines multiple layers of unipolar OFDM (U-OFDM) instead.

This paper focuses on the optimal layer assignment of the adaptive LACO-OFDM system. Although higher layers mean high spectral efficiency, the improvement may be not significant when the layer number is too large. Besides, considering the constraints of either the electrical power or optical power, more layers usually lead to less power distributed to each layer, which may cause degraded bit error rate (BER) performance. With the assumption that the sum of electrical power or optical power of the whole layers is limited, the channel capacity of LACO-OFDM with different layers are investigated. The theoretical optimal layer assignment can be obtained based on the simulated maximal channel capacity. Furthermore, considering the effect of the error propagation from the lower layers, the optimal layer assignment is also explored by taking the BER performance, spectral efficiency, and computational complexity into account with simulations.

The rest of this paper is organized as follows. In Section 2, the system model of LACO-OFDM is briefly introduced. Then, the proposed adaptive LACO-OFDM with variable layer is analyzed in detail to find the optimal layer assignment in Section 3 for both electrical and optical power constraint, respectively. In Section 4, simulation results are demonstrated, while the paper concludes in Section 5.

2. System Model

For ACO-OFDM system, considering the Hermitian symmetry, the input signal to the K-point IFFT can be represented as $\mathbf{X} = [0, X_1, 0, X_3, ..., X_{K/2-1}, 0, X^*_{K/2-1}, ..., X^*_3, 0, X^*_1]$, where the odd subcarriers carry data while the even subcarriers are set to zeros in the frequency domain. It has been shown that the time-domain signal x_n has the anti-symmetric property [4], which is given by

$$x_n = -x_{n+\frac{K}{2}}, \quad 0 \le n < \frac{K}{2}. \tag{1}$$

Thus, the negative part can be clipped directly without loss of information, to ensure that the ACO-OFDM signal $x_{\mathrm{ACO},n}$ is non-negative, i.e.,

$$x_{\mathrm{ACO},n} = \begin{cases} x_n, & x_n \ge 0, \\ 0, & x_n < 0. \end{cases} \tag{2}$$

Since the clipping distortion only falls on the even subcarriers, which is proved in [9], the demodulation of the transmitted data will not be affected.

To improve the spectral efficiency, different layers of ACO-OFDM signals are combined, forming a novel hybrid scheme, which is called LACO-OFDM [13]. In general, L-Layer LACO-OFDM denotes an LACO-OFDM with L layers, while the l-th layer in LACO-OFDM is referred as the l-th ACO-OFDM.

In the adaptive LACO-OFDM, as shown in Fig. 1, the transmitted data is divided into several layers, where the layer amount could be variable adaptively according to the system requirement and transmission environment. Multiple layers of the modified signals adopt the ACO-OFDM modulation schemes individually with QAM modulation, power adjustment, Hermitian symmetry, IFFT operation, and clipping strategy, while different layers of signals are repeated different times. Without loss of generality, the constellation sizes for different layers are all the same. First, considering the case where only the $2^{l-1}k$-th ($0 < l < \log_2 K,\ k = 0, 1, ..., K/2^{l-1} - 1$) subcarriers are modulated for the

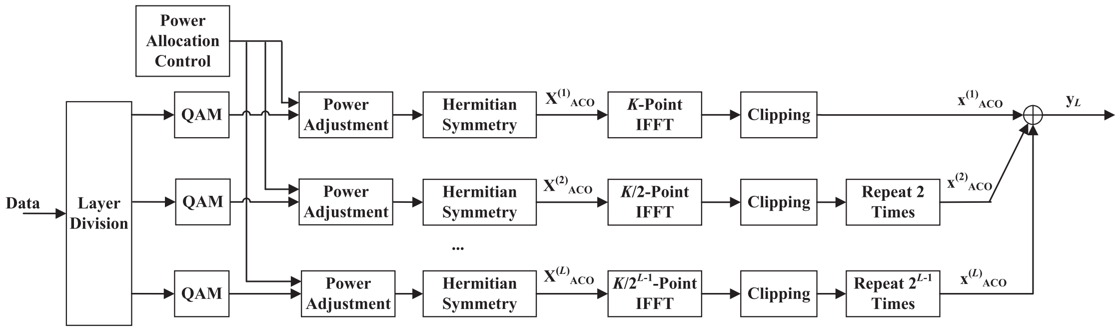

Fig. 1. Block diagram of transmitter for the adaptive LACO-OFDM system.

l-th layer, the time-domain signal is calculated as [13]

$$\begin{aligned} x_n &= \frac{1}{\sqrt{K}} \sum_{k=0}^{K/2^{l-1}-1} X_{2^{l-1}k} \exp\left(j\frac{2\pi}{N} n 2^{l-1} k\right) \\ &= \frac{1}{\sqrt{2^{l-1}}} \frac{1}{\sqrt{K/2^{l-1}}} \sum_{k'=0}^{K/2^{l-1}-1} X^{(l)}_{k'} \exp\left(j\frac{2\pi}{N/2^{l-1}} nk'\right) \\ &= \frac{1}{\sqrt{2^{l-1}}} x^{(l)}_{\bmod (n, K/2^{l-1})}, \quad n = 0, 1, \ldots K-1, \end{aligned} \tag{3}$$

where $x^{(l)}_n$ denotes the $K/2^{l-1}$-point IFFT result of $X^{(l)}_{k'}$. Obviously, x_n is periodic and can be generated by repeating $x^{(l)}_n$ by 2^{l-1} times.

In the l-th ACO-OFDM, only the subcarriers with odd indexes of $X^{(l)}_k$ are utilized, i.e., only the $2^{l-1}(2k+1)$-th $(k = 0, 1, \ldots, K/2^l - 1)$ subcarriers are modulated. Besides, the clipping strategy is applied to obtain the l-th ACO-OFDM signals $x^{(l)}_{ACO,n}$. When the $2^{l-1}k$-th $(0 < l < \log_2 K,\ k = 0, 1, \ldots, K/2^{l-1} - 1)$ subcarriers are modulated, the K-point time-domain signal can be obtained by repeating the $K/2^{l-1}$-point IFFT result. When the $2^{l-1}(2k+1)$-th $(k = 0, 1, \ldots, K/2^l - 1)$ subcarriers are modulated, the K-point time-domain signal generated by repeating the $K/2^{l-1}$-point IFFT result is non-negative, which can be applied to the IM/DD systems. The time-domain signals of different layers are added together for simultaneous transmission. As a result, the adaptive L-Layer LACO-OFDM signals, y_L, can be represented as

$$y_L = \sum_{l=1}^{L} x^{(l)}_{ACO,n}. \tag{4}$$

3. Analysis of Adaptive LACO-OFDM

LACO-OFDM with different layer assignment has different spectral efficiency and BER performance. For LACO-OFDM, higher layers result in high spectral efficiency. However, the improvement may be not notable when the layer number is too large. Besides, the power distributed to each layer will decrease with the increase of layer number since overall power among all layers is constrained in either optical or electrical power, resulting in worse BER performance. Thus, in this section, the optimal layer assignment is explored based on the study of channel capacity with the constraints of electrical power and optical power, respectively.

For a time-domain signal x_n in VLC, the optical power, P_{opt}, is proportional to $E\{x_n\}$ while the electrical power, P_{elec}, depends on $E\{x_n^2\}$. Thus without loss of generality, it can be defined that $P_{opt} = E\{x_n\}$ and $P_{elec} = E\{x_n^2\}$.

Throughout this paper, E_l denotes the ACO-OFDM electrical energy per subcarrier in layer l, i.e., $E_l = E[(X_k^{(l)})^2]$, where $E[\cdot]$ denotes the expectation of the variable. σ_l refers to the root mean square (RMS) of the unclipped time-domain signals in layer l. Since only $K/2^l$ subcarriers are utilized in the l-th ACO-OFDM, the relationship between E_l and σ_l can be derived as

$$\sigma_l^2 = \frac{E_l}{2^l}. \tag{5}$$

3.1 Optimal Layer Assignment for Adaptive LACO-OFDM With Limited Electrical Power

The channel capacity for the l-th ACO-OFDM under AWGN channel, C_l, is given by [17]

$$C_l = W_l \log_2\left(1 + \frac{S_l}{N}\right), \tag{6}$$

where W_l and S_l are the effective bandwidth and electrical signal power for the l-th layer, respectively. Considering the l-th ACO-OFDM utilizes $K/2^l$ subcarriers with equal power allocation on each subcarrier, they can be represented as

$$W_l = \frac{W}{2^l}, \tag{7}$$

$$S_l = \frac{\frac{1}{2^l} S}{\sum_{k=1}^{L} \frac{1}{2^k}} = \frac{\frac{1}{2^l}}{1 - \frac{1}{2^L}} S, \tag{8}$$

where W denotes the whole bandwidth. Thus, the total channel capacity for L-Layer LACO-OFDM is derived as

$$C = \sum_{l=1}^{L} C_l = \sum_{l=1}^{L} \frac{W}{2^l} \log_2\left(1 + \frac{\frac{1}{2^l}}{1 - \frac{1}{2^L}} \frac{S}{N}\right). \tag{9}$$

The signal-to-noise ratio (SNR) for electrical power is defined as $\text{SNR} = S/N$. Thus the channel capacity can be represented as

$$C = \sum_{l=1}^{L} C_l = \sum_{l=1}^{L} \frac{W}{2^l} \log_2\left(1 + \frac{\frac{1}{2^l}}{1 - \frac{1}{2^L}} \text{SNR}\right). \tag{10}$$

The optimal layer assignment can be obtained by maximizing the whole channel capacity. It can be inferred that under low SNR environment, the optimal layer number is small, while large layer number should be applied in high SNR scenario for achieving larger channel capacity.

3.2 Optimal Layer Assignment for Adaptive LACO-OFDM With Limited Optical Power

It has been proved that the optical power of the l-th ACO-OFDM is proportional to the RMS of the unclipped signals as [18]

$$P_{opt,l} = \frac{\sigma_l}{\sqrt{2\pi}}. \tag{11}$$

In practice, the optical power for VLC system is usually limited. Thus, for L-Layer LACO-OFDM, the sum of the optical power of all layers is constrained to be P as

$$P = \sum_{l=1}^{L} P_{opt,l} = \sum_{l=1}^{L} \frac{\sigma_l}{\sqrt{2\pi}}. \tag{12}$$

Under additive white Gaussian noise (AWGN) channel, which is usually adopted by VLC system [11], the optimal performance requires that the electrical power of each subcarrier should be equally distributed [13], [14], [19], which is given by

$$E_1 = E_2 = \cdots = E_L. \tag{13}$$

Therefore, based on (5) and (13), σ_l can be derived as

$$\sigma_l = \frac{\sigma_1}{\left(\sqrt{2}\right)^{l-1}}. \tag{14}$$

Thus, according to (12), the relationship between P and σ_1 is given by

$$P = \frac{\sigma_1}{\sqrt{2\pi}} \frac{1 - \frac{1}{(\sqrt{2})^L}}{1 - \frac{1}{\sqrt{2}}}. \tag{15}$$

Moreover, in order to evaluate the noise level for VLC system with IM/DD, the SNR for optical power instead of the conventional electrical SNR is defined as

$$\text{SNR}_{opt} = \frac{P^2}{N}. \tag{16}$$

S_l, the electrical signal power for the l-th layer, can be represented as

$$S_l = \sigma_l{}^2 = \frac{\sigma_1^2}{2^{l-1}}. \tag{17}$$

Thus, the total channel capacity for L-Layer LACO-OFDM is derived as

$$C = \sum_{l=1}^{L} C_l = \sum_{l=1}^{L} \frac{W}{2^l} \log_2 \left(1 + \frac{\frac{\sigma_1^2}{2^{l-1}}}{N}\right). \tag{18}$$

Therefore, based on (15) and (16), the whole channel capacity C can be rewritten in terms of SNR for optical power as

$$C = W \sum_{l=1}^{L} \frac{1}{2^l} \log_2 \left(1 + \frac{1}{2^{l-1}} \frac{2\pi\left(1 - \frac{1}{\sqrt{2}}\right)^2}{\left(1 - \frac{1}{(\sqrt{2})^L}\right)^2} \text{SNR}_{opt}\right). \tag{19}$$

The optimal layer assignment can be obtained by maximizing the channel capacity, which is dependent on SNR_{opt}. It can be inferred that under low SNR_{opt} environment, the optimal layer number is small, while large layer number should be applied in high SNR_{opt} scenario for achieving larger channel capacity, which will be verified in the simulation section.

4. Simulation Results

In this section, simulation results are demonstrated to verify the theoretical analysis of optimal layer assignment for adaptive LACO-OFDM.

Fig. 2 demonstrates the channel capacity under different SNRs for LACO-OFDM with limited electrical power. The differences of the channel capacities between LACO-OFDM systems composed of different number of layers are drawn, where the channel capacity of 4-Layer LACO-OFDM is subtracted for clear illustration. The labeled number represents the optimal layer number for LACO-OFDM under that SNR region to achieve the maximum channel capacity. When SNR changes from 0 dB to 21 dB, the optimal layer number varies from 1 to 6. When SNR is over 20 dB, the channel capacities between 5-Layer and 6-Layer LACO-OFDM are pretty close. When the whole electrical power is constrained, the optimal layer assignment rises with the SNR of the environment based on the comparison of the channel capacity.

For LACO-OFDM, the normalized bandwidth is given by $1 + 2/K$ [18]. Since only half of the subcarriers carry data in conventional ACO-OFDM, the bit rate is $(\log_2 M)/2$ where M is the constellation size. For L-Layer LACO-OFDM, the bit rate can be derived as

$$\text{bit rate} = (\log_2 M)(1/2 + 1/4 + \cdots + 1/2^L). \tag{20}$$

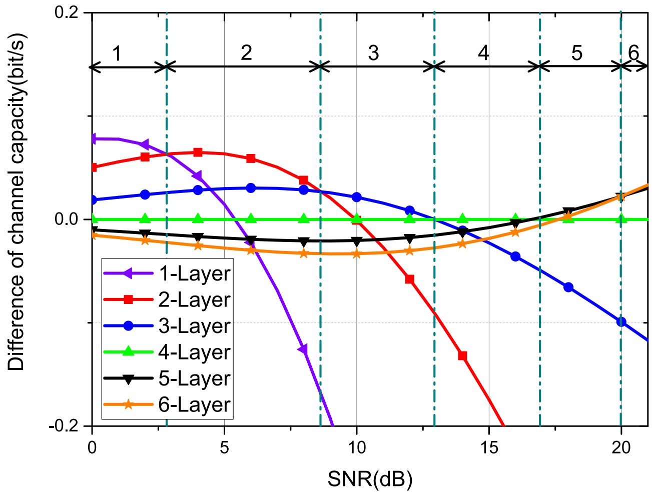

Fig. 2. Difference of channel capacities under different SNR for the adaptive LACO-OFDM with limited electrical power where the channel capacity of 4-Layer LACO-OFDM is subtracted.

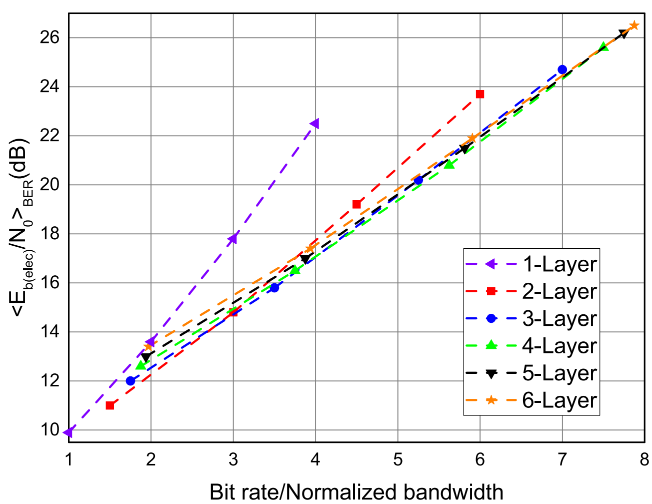

Fig. 3. Comparison of $< E_{b(elec)}/N_0 >_{\text{BER}}$ versus bit rate/normalized bandwidth for the adaptive LACO-OFDM with limited electrical power.

As illustrated in Fig. 3, $< E_{b(elec)}/N_0 >_{\text{BER}}$ versus the average bit rate/normalized bandwidth for LACO-OFDM with 1 to 6 layers are simulated with 4QAM, 16QAM, 64QAM, and 256QAM where the electrical power is constrained. Under low SNR region, with constrained electrical power, the power allocated on each layer will decrease with the increase of the layer number, which may lead to high BER. Thus, as demonstrated in Fig. 3 when the bit rate/normalized bandwidth is less than 3, 1-Layer or 2-Layer LACO-OFDM perform better than LACO-OFDM with higher layers. When the bit rate/normalized bandwidth is around 3.5, 3-Layer LACO-OFDM is shown to be the optimal scheme as it has the lowest $< E_{b(elec)}/N_0 >_{\text{BER}}$. When the bit rate/normalized bandwidth more than 4, it can be seen that with the layer number rising from 2 to 4, there is an improvement in the performance of LACO-OFDM. The effect of error propagation will increase with the higher layers. LACO-OFDM with 4 layers performs almost the same as 5-Layer and 6-Layer LACO-OFDM when the bit rate/normalized bandwidth is larger than 6, which is also verified in Fig. 2. Since 4-Layer LACO-OFDM performs well enough with lower computational complexity compared with 5-Layer and 6-Layer LACO-OFDM [13], 4-Layer is shown to be the optimal option for LACO-OFDM in low noise scenario. It can be seen that the optimal layer number of LACO-OFDM varies according to

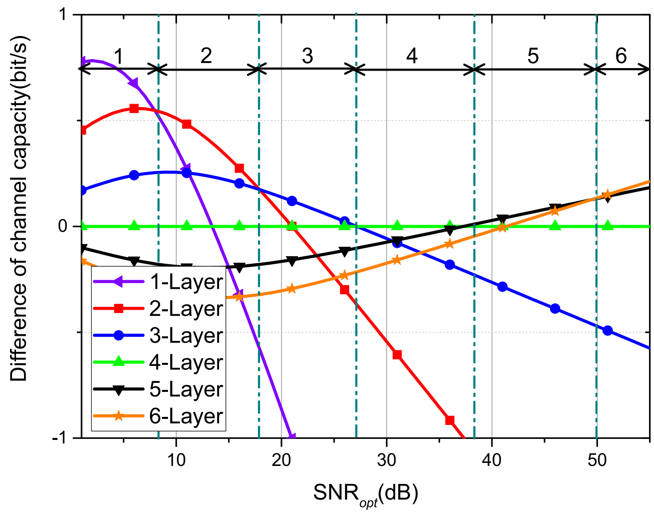

Fig. 4. Difference of channel capacities under different SNR$_{opt}$ for the adaptive LACO-OFDM with limited optical power where the channel capacity of 4-Layer LACO-OFDM is subtracted.

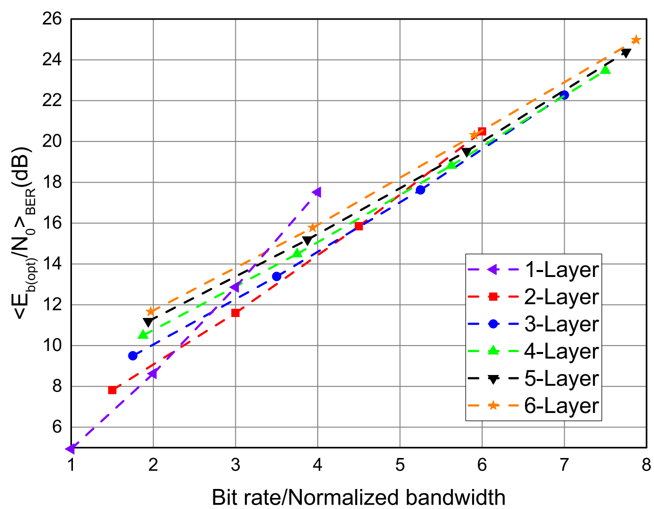

Fig. 5. Comparison of $< E_{b(opt)}/N_0 >_{\text{BER}}$ versus bit rate/normalized bandwidth for the adaptive LACO-OFDM with limited optical power.

the bit rate/normalized bandwidth. Therefore, the optimal layer assignment is dependent on the applied environment.

Simulations of channel capacities are carried out where the optical power is constrained, as shown in Fig. 4. The channel capacity of 4-Layer LACO-OFDM is also subtracted. The labeled number represents the optimal layer number for LACO-OFDM under that SNR$_{opt}$ region to achieve the maximum channel capacity. When SNR$_{opt}$ rises from 1 dB to 55 dB, the optimal layer number changes from 1 to 6. When SNR$_{opt}$ is over 50 dB, the differences between 5-Layer and 6-Layer LACO-OFDM are slight. With the constraint of optical power, the optimal layer assignment also varies with the SNR$_{opt}$.

For limited optical power, the minimum required normalized optical bit energy to noise power for a BER of 10^{-3}, denoted as $< E_{b(opt)}/N_0 >_{\text{BER}}$. $< E_{b(opt)}/N_0 >_{\text{BER}}$ versus the average bit rate/normalized bandwidth is investigated with simulations, as demonstrated in Fig. 5. Under low SNR$_{opt}$, with constrained optical power, the power allocated on each layer will decrease with the increase of the layer number, which may lead to high BER. Thus, as shown in Fig. 5 when the bit rate/normalized bandwidth is less than 3, 1-Layer or 2-Layer LACO-OFDM perform better than LACO-OFDM with higher layers. When the bit rate/normalized bandwidth is around 5, 3-Layer LACO-OFDM is shown to be the optimal scheme as it has the lowest $< E_{b(opt)}/N_0 >_{\mathrm{BER}}$. When the bit rate/normalized bandwidth is more than 5, it can be seen that with the layer number rising from 2 to 4, there is an improvement in the performance of the adaptive LACO-OFDM. It can be seen that the optimal layer number of the adaptive LACO-OFDM varies according to the bit rate/normalized bandwidth. Moreover, LACO-OFDM with 4 layers performs almost the same as 5-Layer LACO-OFDM when the bit rate/normalized bandwidth is larger than 6. Fig. 4 show that LACO-OFDM with higher layers should perform better when SNR_{opt} is over 38 dB, while the SNR_{opt} less than 38 dB since the minimal required $< E_{b(opt)}/N_0 >$ for a BER of 10^{-3} is observed in Fig. 4, which is caused by the error propagation from lower layer ACO-OFDM. Since 4-Layer LACO-OFDM performs well enough with lower computational complexity compared with 5-Layer LACO-OFDM, 4-Layer is shown to be the optimal option for the adaptive LACO-OFDM in low noise scenario.

5. Conclusion

In this paper, the adaptive LACO-OFDM with variable layer is analyzed in terms of channel capacity. The optimal layer assignments with constraints of electrical and optical power are related to SNR and SNR_{opt}, respectively. In these two assumptions, the small layer number applies to low SNR (or SNR_{opt}), since more layers mean less power allocated to each layer, leading to poor BER performance. Under high SNR (or SNR_{opt}), the optimal layer number is large with the advantage of higher spectral efficiency. In practice, performance requirement, application environment, and complexity cost should all be taken into consideration to choose an optimal layer assignment scheme for the LACO-OFDM system adaptively.

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