Optimal Power Allocation in Spatial Modulation OFDM for Visible Light Communications

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***Abstract*—This paper constructs a model for Optical Spatial Modulation Orthogonal Frequency Division Multiplexing (O-SM-OFDM). It investigates the effects of different power allocation schemes on bit error ratio (BER) performance. The experiment is based on an optical 2 $\times$ 1 SM-OFDM system with symmetrical link geometry. Effects introduced by the particular properties of intensity modulation (IM) that the signal has to be real valued and positive are considered in this study. In this work we assume direct current (DC) biased optical communication and take into account light-emitting diode (LED) non-linearities. We consider the information bits that are encoded in the spatial domain in SM and the bits in quadrature amplitude (QAM) modulated signal separately. The former are the "spatial domain bits", and the latter are the "signal domain bits". The optical transmit powers are varied while the total transmit power is kept constant and power imbalances between the different transmitters are created in order to be able to study the trade-off between the accuracy of detecting the spatial domain bits and the signal domain bits. It is shown that transmission power imbalance between transmitters can improve the detection accuracy of the spatial domain bits as expected. However, this will reduce the receiver signal to noise ratio (SNR) of the signals with weaker power. As a consequence, signal domain BER increases, which compromises the BER improvement of spatial domain bits. In this context, the relationship between power imbalance, BER performance and minimum SNR required to achieve a certain BER level are investigated. The optimal point of transmission power difference is determined via computer simulations.**

***Index Terms*—Spatial modulation, OFDM-based indoor optical wireless communication, power allocation**

I. Introduction

Spatial modulation (SM) [1] is a recently proposed multiple-input-multiple-output (MIMO) modulation scheme that utilizes the location of transmitters to carry extra information bits. A good survey of SM technology can be found in [2]. SM can be combined with orthogonal frequency division multiplexing (OFDM) [3] which is heavily used in radio frequency (RF) domain wireless systems such as 3rd generation partnership project long term evolution (3GPP LTE). In [4] it has been demonstrated that through the exploitation of the high peak-to-average power ratio (PAPR) in OFDM, it is also possible to significantly enhance the data rates of IM optical wireless systems. In [5-9] it is demonstrated that SM can be combined with IM in optical wireless communications (OWC) since for the detection of the spatial domain bits only a power signal is needed. However, to the best of our knowledge, SM along with OFDM has not been applied to OWC systems. The advantages of this system configuration are that it enables the scaling of the data rates with the achieved signal-to-noise ratio, and with the number of LEDs used in a transmitter unit.

In order to produce a real valued time domain signal at the output of the OFDM transmitter, Hermitian symmetry is applied to the subcarriers that constitute the input of the inverse fast Fourier transform (IFFT) operation. As a result, only half of the subcarriers can be used for information transmission, but each of these subcarriers can accommodate higher order modulation schemes such as M-level quadrature amplitude modulation (M-QAM) [4]. SM relies on the receiver being able to distinguish the different transmitting LEDs, and for this purpose a maximum likelihood detection algorithm is reported in [10]. Therefore, similarity between the link transfer functions may result in misdetection of the spatial domain bits [9]. This situation is dependent on the actual transceivers link geometry and the design and the characteristics of the optical fronts. In order to counter the similarity of the link transfer functions, power imbalance at the transmitters can be created [11]. Alternatively, asymmetric link geometries can be constructed. In this paper we consider the first method. However, if the total transmit power of the system is kept unaltered, the increase in power imbalance will worsen the receiver SNR of links with lower transmission power since only one transmitter is active at any given time instant. This will increase the probability of signal domain bit errors, and adversely compensate the improvement of the spatial domain bit detection accuracy. Hence, the overall BER performance improvements will degrade. Consequently, it is necessary to study the optimal spatial transmission power difference, and to achieve the best overall system BER performance in a realistic scenario.

The paper is structured as follows. Section II describes the system models. Section III compares the optical domain model with a RF domain correspondence. Section IV provides simulation results for the optimum power imbalance of the

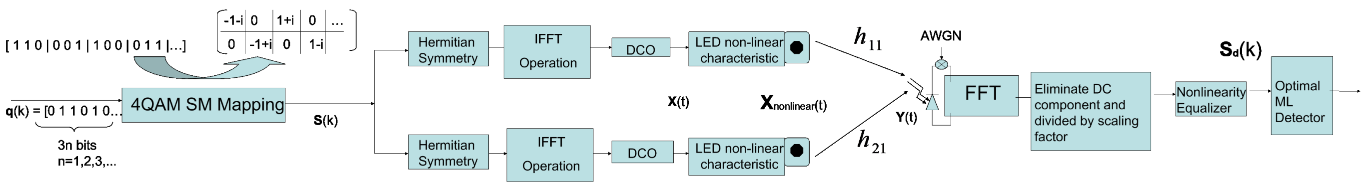

Fig. 1. Block diagram of the optical SM-OFDM system.

system. Finally, conclusions are drawn in Section V.

II. System Model

In this paper, the following notations are used. Bold and small letters '**a**' denote vectors, Bold and capital letters '**A**' denote matrixes. $h_{\upsilon\tau}$ is the channel transfer function between LED transmitter υ and receiver photo-diode τ.

The constructed O-SM-OFDM system model and the link geometry arrangement are shown respectively in Fig. 1 and Fig. 2 in a symmetric setup. The optical system is characterized by a DC-biased optical (DCO) technique [12], electrical-to-optical power conversion, LED non-linearity [13], and a realistic optical channel [14] dominated by free path loss (FPL) and log-normal shadowing.

Under spatial modulation mapping [15], for every three random binary bits, the first one is modulated as spatial domain bit, and the other two are modulated as a 4-QAM symbol. As a result, in our model, a sequence of random binary bits $\mathbf{q}$ with length $3 \times n$ (where n is an integer) is mapped to a 2 rows, $2 \times n$ columns matrix $\mathbf{S}$. Each row of $\mathbf{S}$ contains the 4-QAM symbols transmitted by each transmitter. Each column of $\mathbf{S}$ with only one non-zero element represents a frequency domain subcarrier. Under the SM concept, the spectrum efficiency is increased by the base-2 logarithm of the number of LED transmitters.

For each LED transmitter, i.e. row of $\mathbf{S}$, we perform the Hermitian symmetry operation [4]. After the IFFT operation for each row with Hermitian symmetry, the complex symbols become real valued signals.

In order to ensure a positive signal being transmitted, DC biasing is used. For the purpose of biasing, we add 3 times the standard deviation, σ, of the Gaussian distributed real valued signals on each row of $\mathbf{S}$ and multiply each of them by a scaling factor [12] so as to reduce the clipping effect.

The resulting $2 \times (4n+2)$ real valued matrix $\mathbf{X}$ contains the modulated intensities for the LED of each transmitter. At the receiver, a photon detector accumulates the total optical power received at each sample instant, and then using an optimal maximum likelihood detector [10], the original information bits can be recovered.

A. Non-linearity of LED

The non-linearity of the LED leads to a BER performance degradation. If the forward current is proportional to the forward voltage, then the radiated optical power is proportional to the current [16]. However, since off-the-shelf LEDs have a non-linear transfer characteristic, there is a non-linear relation between the forward current and the radiated optical power.

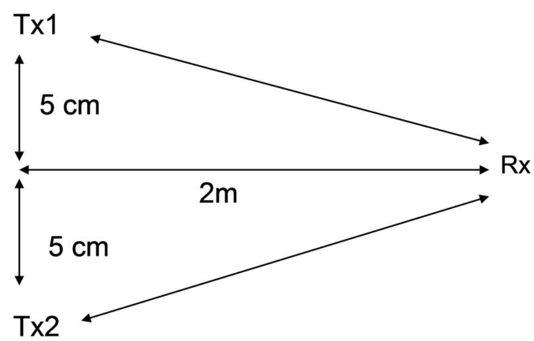

Fig. 2. Setup of two transmitters and a receiver.

As a result, non-linearities shrink the normalized signal constellation and thus reduce the Euclidean distance between symbol points. Moreover, high order QAM in severe non-linearity cases will suffer distortion. Methods to mitigate the non-linearity effect include pre-distortion compensation [16] and non-linear equalization.

In analogy to a solid state power amplifier (SSPA) model for RF domain systems, a LED non-linearity model is proposed in [13]. To model the non-linear effect, the output optical power from a transmitter LED can be represented as [13]:

$$\tilde{x}_j^i = \sqrt{x_j^i \frac{x_j^i}{(1+(\frac{x_j^i}{I_m})^{2k})^{1/2k}}} \tag{1}$$

where $\tilde{x}_j^i$ is the LED intensity after non-linear distortion at sample instant j from transmitter i. x_j^i is the input voltage of LED, i, at sample instant j; k is a parameter to model the degree of nonlinearity [13] (see Fig. 3). In the model, when k = 1.5, the BER performance of the system is close to the ideal linear case. When the non-linear factor k = 0.5, the SNR will lose 3 dB under the same BER (see Fig. 4). We use this value to model practical scenarios.

B. Electrical to Optical Power Conversion

The relationship between the optical power and electrical power is as follows [12]:

$$\frac{\mathrm{E}\left\{x_0^2(t)\right\}}{N_0} = \frac{P_{\text{opt}}^2}{N_0} \frac{K^2}{K^2+1} \tag{2}$$

where N_0 is noise power per subcarrier, K is a constant relating DC-bias and optical power as [12] $B_{DC} = K\sqrt{\mathrm{E}\left\{x_0^2(t)\right\}}$,

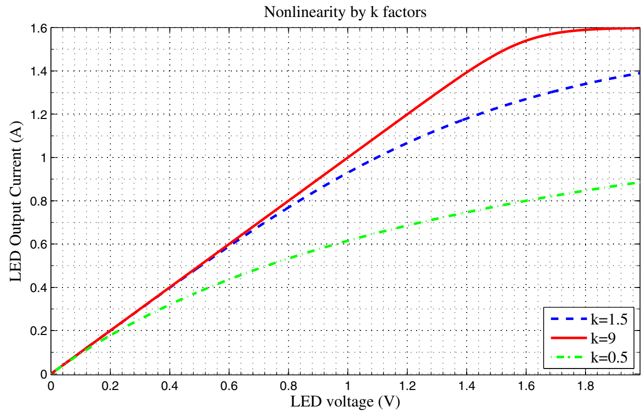

Fig. 3. The non-linear LED model.

and here K = 3 because we make 3 times σ of DC biasing. If we represent the actual electrical power needed for DC-optical transmission in dB, we can see that it increases by a DC bias of $10\log_{10}\left(K^2+1\right)$ dB [12].

C. Optical Channel

Based on the system scenario shown in Fig. 2, optical channels are dominated by shadowing. Using the proposed receiver hardware model in [14], the modified FPL model for fitting the receiver photo diode with certain photosensitive area is given as [14]:

$$L(d) = 10\log_{10}\left(\frac{P_{\mathrm{T}}}{E_{\mathrm{ref}}\cdot A_0}\right) - 10\log_{10}\left(\frac{A}{A_0}\right)$$
$$+10\gamma\log_{10}\left(\frac{d}{d_{\mathrm{ref}}}\right) + X_{\sigma'} \tag{3}$$

where, E_{ref} [W/m^2] is the irradiance at the reference distance d [m], A_0 is assumed to be 1 m^2 and A is the photosensitive area of the receiver photo diode. The shadowing component $X_{\sigma'}$ is modelled by means of a Gaussian random variable with zero mean and standard deviation, $\sigma^{'}$, and γ is the path loss exponent.

We assume that the optical signal be transmitted through line of sight (LOS) enhanced by single reflections optical paths in indoor environments. Using the parameters in Table I of [14], we set d_{ref} = 0.04 m, transmit power P_{T} = 800 mW, E_{ref} = 280036.82 mW/m^2, γ = 1.94 and $\sigma^{'}$ = 0.57. Furthermore, we assume A to be 150 mm^2. This results in an optical FPL of 45.7 dB for the scenario shown in Fig. 2. At each instant, the channel is represented by a 2 $\times$ 1 real matrix $\mathbf{H}$, i.e one channel transfer factor [9] per link at each time.

D. Power Allocation

We assume E_{b} to be the electrical signal power per bit at the receiver from each transmitter. Further more, we assume ρ_i to be the average SNR at the receiver from transmitter i. Then, for the case of equal transmit powers and the scenario in Fig. 2, we have $\rho_1 = \rho_2 = \frac{E_{\mathrm{b}}}{N_0}$. Keeping the total system transmit power unchanged, if transmitter 1 has a relative power surplus of α, then $\rho_1 = \frac{\alpha}{1+\alpha}\frac{E_{\mathrm{b}}}{N_0}$ and $\rho_2 = \frac{1}{1+\alpha}\frac{E_{\mathrm{b}}}{N_0}$.

Therefore, we can present the received signal at instant j as follows:

$$\boldsymbol{y}_j = \mathbf{H}\tilde{\mathbf{X}}_j + \eta_j \tag{4}$$

where η_j is the average additive white Gaussian noise (AWGN) at each receiver. The channel transfer function matrix is $\mathbf{H} = [\frac{L(d_1)\alpha}{1+\alpha}\ \frac{L(d_2)}{1+\alpha}]$ and contains FPL factors for both links defined by (3) in the optical domain. $\tilde{\mathbf{X}}_j$ is the matrix of non-linear distorted LED intensities from transmitters.

E. Optimal Maximum Likelihood Detector

At the receiver, after the fast Fourier transform (FFT) operation with length $4n + 2$ accommodating the number of subcarriers after Hermition symmetry operation, the time domain optical power signal stream is converted to a $1 \times (4n + 2)$ frequency domain signal vector. By eliminating the effects of DC biasing and performing inverse Hermitian symmetry operation [4], the result is a $1 \times 2n$ complex matrix $\mathbf{S}_d$, which contains noise disturbed 4-QAM SM-OFDM modulation symbols.

Assuming the receiver has perfect channel state information and that perfect time synchronization is in place, optimal maximum likelihood detection [10] can jointly detect the spatial domain bits and signal domain bits for each subcarrier of the received signal matrix $\mathbf{S}_d$. The ML algorithm compares every potential symbol from every transmitter with the received symbol from different channel transfer functions to find the one with Minimum Euclidean Distance [10]:

$$\left[\hat{i}_{\mathrm{ML}}, \hat{q}_{\mathrm{ML}}\right] = \arg\max_{i,q} p_{\mathbf{s}_j}\left(\mathbf{s}_j | x_{iq}, \mathbf{H}\right)$$
$$= \arg\min_{i,q} \left|\mathbf{s}_j - \mathbf{H}\cdot x_{iq}\right|^2 \tag{5}$$

where $\mathbf{s}_j$ is j-th column of matrix $\boldsymbol{S}_d$, and x_{iq} represents the potential M-QAM symbol, q, sent by the i-th transmitter device. $p_{\mathbf{s}_j}\left(\mathbf{s}_j | x_{iq}, \mathbf{H}\right)$ is the probability density function of $\mathbf{s}_j$ conditioned on x_{iq} and $\mathbf{H}$. The value of $\hat{i}_{\mathrm{ML}}$ is the estimated index of the transmitting LED. This can be used to recover spatial domain bits by the SM-demapper. $\hat{q}_{\mathrm{ML}}$ is the index of QAM symbol that is used by the QAM slicing function to retrieve signal domain bits.

III. Comparison with RF

To ensure the validity of the model, the investigation starts from an optical single-input-single-output OFDM (O-SISO-OFDM) link, which forms one of the branches in the O-SM-OFDM system (Fig. 1) without spatial modulation. The development of the O-SISO-OFDM model is based on a corresponding RF domain OFDM system model. Before we consider the optical system particularities described in Section

II, we simulate the corresponding RF system BER performance and check its consistency with theoretical QAM OFDM BER curve (Fig. 4) determined as follows:

$$P_{e,b} = \frac{1}{b}\left\{1 - \left[1 - \frac{2(L-1)}{L} Q\left(\sqrt{\frac{3b/2}{L^2-1}\frac{E_\mathrm{b}}{N_0}}\right)\right]^2\right\} \quad (6)$$

in which, for an $M = 2^b = L^2$ square QAM signalling, when $M = 4$, then $b = 2$ and $L = 2$. $Q(.)$ represents Q-function.

Subsequently the Hermitian symmetry block is added as well as the DC offset and the non-linear LED model. At the receiver, the ML is applied. After the conversion from electrical power to optical power, a DC bias of 10 dB (section II.B) results in a shift to the right compared to RF in Fig. 4. By setting the non-linearity factor k to be 0.5, an additional 3 dB BER performance degradation is caused.

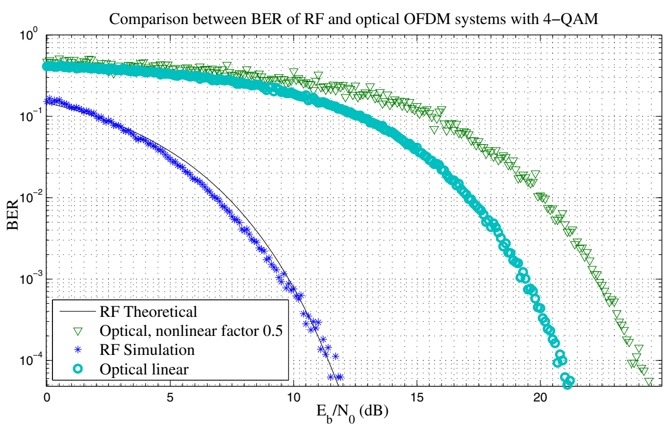

Fig. 4. Single branch of the O-SM-OFDM system is developed by comparing with RF domain correspondence.

Upon validating the O-SISO-OFDM link performance, the SM modulation scheme is applied at the transmitter side to form the 2×1 MISO scheme in Fig. 1. Since we investigate BER against the average signal to noise ratio per bit at the receiver, $\frac{E_\mathrm{b}}{N_0}$, the approximate 45.7 dB average FPL in all the plots of this paper is subtracted.

IV. Simulation Results and Discussion for Optimal Power Allocation

As the link geometry is completely symmetric, we can investigate the effects of different power allocation schemes on BER performance by creating power surplus at one transmitter while keeping the total transmission power the same. Fig. 5 shows the effects of creating power surplus in transmitter 1 on overall system BER performance. In the equal power case, the receiver can hardly determine the transmitter that radiated the OFDM symbol because the channel variations are insufficient. Therefore, only the signal domain bits can be correctly detected while the spatial domain bits will almost be lost. Even with the increase of $\frac{E_\mathrm{b}}{N_0}$, the system total BER cannot converge to zero. An increase of the power surplus of 9 dB counters similarity between the channel links. As a consequence, the receiver can resolve the spatial location of the LEDs. Therefore, with the increase of $\frac{E_\mathrm{b}}{N_0}$, both signal domain bits and spatial domain bits can be recovered. If the weaker link achieves acceptable $\frac{E_\mathrm{b}}{N_0}$, the larger extent to which channel transfer functions differ from each other, the more accurate the spatial domain bits can be recovered. For example, increasing the power surplus to 12 dB results in improved BER performance of SNR values greater than 25 dB compared to a difference of 9 dB. The spatial domain BER performance is analogue to the space shift keying case studied in [9, eqn. (3)]. It provides a relationship between average spatial bit error probability and the difference of the channel transfer functions. However, if the weaker link achieves unacceptably low SNR, symbols transmitted through this link will be lost. Totally switching off one of the transmitters is at the cost of losing spectrum efficiency. As in Fig. 5, when the power surplus in transmitter 1 is increased to 20 dB, the total BER performance of the system becomes worse. Next, the experiment focuses on finding the point where, under the trade-off between signal domain bits detection accuracy and spatial domain bits detection accuracy, the system can provide the best BER performance.

In order to find the optimal point, we plot the error rate of spatial domain bits, signal domain bits and system total bits against power surplus of transmitter 1 while keeping $\frac{E_\mathrm{b}}{N_0}$ at 30 dB to ensure that the BER can drop below 10^{-3} (refer to Fig. 6). Total BER is the weighted sum of spatial domain BER and signal domain BER. As expected, with the increase of transmission power difference between two transmitters, spatial domain bits can be more accurately detected because of more distinct channel transfer functions, while signal domain bits are less likely to be recovered due to worse SNR of weaker link at the receiver end. These two curves intersect at 11.5 dB transmission power surplus of transmitter 1, where the system's total BER has the lowest level.

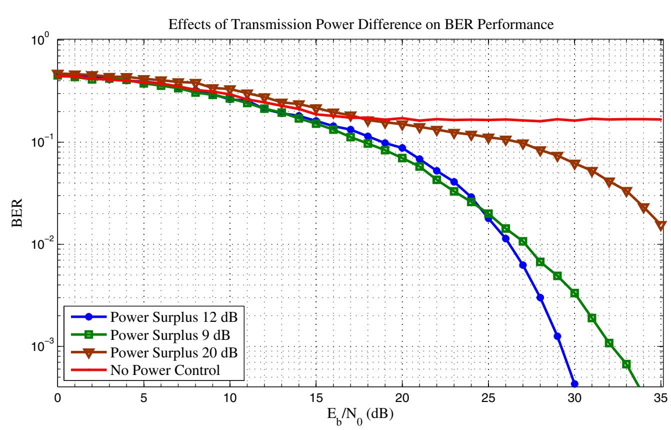

Fig. 5. Effects of the transmission power difference on BER.

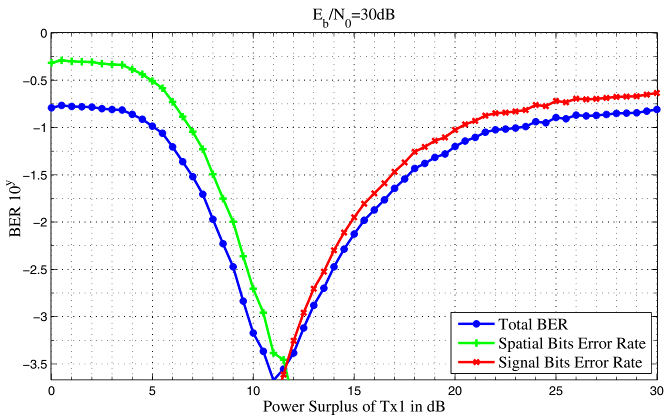

Fig. 6. BER vs. power surplus of Transmitter 1.

In low power surplus regions (below around 11.5 dB), the spatial domain BER is dominant while the signal domain BER is small. And in the high power surplus region (above around 11.5 dB), the spatial domain BER is small while the signal domain BER is dominant. In order to validate this finding, a further experiment fixes the BER at 10^{-3} and inspects the minimum SNR required with the increase of power surplus at transmitter 1.

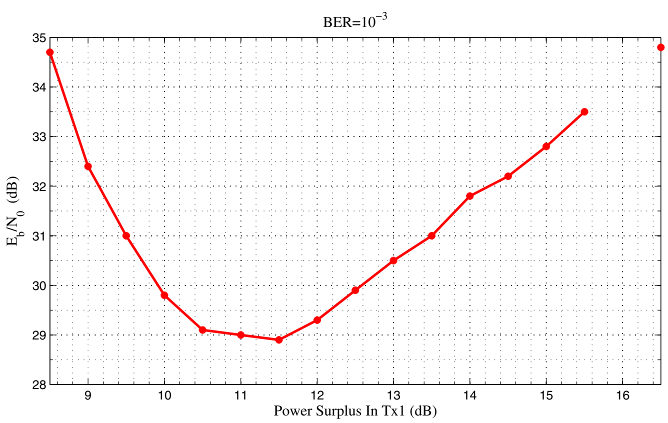

Fig. 7. SNR required to achieve BER=10^{-3} is plotted as a function of power surplus in Transmitter 1.

As seen from Fig. 7, if the power difference is around 11.5 dB, the SNR required for achieving a certain BER level can be minimized. Main factors affecting this optimal power difference are the order of QAM modulation and the non-linearity of LED.

V. Conclusions and Future Work

In this paper, spatial modulation in conjunction with OFDM has been considered for an optical wireless system. It has been found that for constant total transmit power and symmetric wireless link geometry, when the power surplus is below the optimal point, the difference between both links' channel transfer functions is not large enough to allow the receiver to discern spatial domain bits. When the power surplus is above the optimal point, adverse SNR at the receiver of the weaker link results in BER degradation. In order to achieve optimum BER performance, transmission power imbalance or link geometry asymmetry should make a difference among channel transfer functions to be around 11.5 dB. However, this optimal point may be affected by different system scenarios. Further work will be geared towards investigating effects of higher order QAM modulation on the optimal power difference, and to derive a general algorithm to determine optimal power allocation point based on different O-SM-OFDM systems.

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