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Subcarrier intensity modulation for MIMO visible light communications

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ABSTRACT

In this paper, subcarrier intensity modulation (SIM) is investigated for multiple-input multiple-output (MIMO) visible light communication (VLC) systems. A new modulation scheme called DC-aid SIM (DCA-SIM) is proposed for the spatial modulation (SM) transmission plan. Then, DCA-SIM is extended for multiple subcarrier case which is called DC-aid Multiple Subcarrier Modulation (DCA-MSM). Bit error rate (BER) performances of the considered system are analyzed for different MIMO schemes. The power efficiencies of DCA-SIM and DCA-MSM are shown in correlated MIMO VLC channels. The upper bound BER performances of the proposed models are obtained analytically for PSK and QAM modulation types in order to validate the simulation results. Additionally, the effect of power imbalance method on the performance of SIM is studied and remarkable power gains are obtained compared to the non-power imbalanced cases. In this work, Pulse amplitude modulation (PAM) and MSM-Index are used as benchmarks for single carrier and multiple carrier cases, respectively. And the results show that the proposed schemes outperform PAM and MSM-Index for considered single carrier and multiple carrier communication scenarios.

1. Introduction

In recent years, rapid developments and maturing in light emitting diode (LED) technologies has caused the replacement of LEDs instead of the old illumination devices for both indoor and outdoor environments. The driving force behind this replacement is the energy efficiency of LEDs. The other positive side of this replacement is the use of LEDs as transmission sources in VLC systems which is a promising technology for short-range wireless communications. Because of the spectrum shortage of radio frequency (RF) systems, VLC offers a complementary solution to achieve high data rates for indoor communications [1].

Another high data rate solution is MIMO communication has been extensively studied in RF systems and successful MIMO schemes have been proposed. These schemes can provide multiplexing gain to increase the data rate and/or diversity gain to enhance the reliability [2]. MIMO VLC systems have been investigated for the same reasons as in RF counterparts [3–6]. Even though the optical bandwidth of VLC systems is about 400 THz, the electrical 3 dB modulation bandwidth is restricted to several MHz by white LEDs. Therefore, it is substantial to apply spectrally efficient technologies, such as MIMO techniques, for VLC systems. In general, multiple LEDs are utilized for illumination purposes in the same area, so the structure of the LED illumination naturally supports MIMO communication techniques for VLC systems [7]. Hence, MIMO VLC is an efficient way to combine the illumination with high-speed wireless communication [8].

Spatial modulation is relatively a new scheme for MIMO systems [9]. In SM model, a part of the data bits are modulated on the location of the LED, so the minimum distance between symbols depend on correlations of channels. In [10], the authors adapted the spatial modulation concept for optical communication systems and thereafter this concept is investigated for visible light communication indoor environments which have correlated channels under the condition of a direct line of sight (LOS). In SM, only one LED is used at the time of transmission therefore inter-channel interference (ICI) is decreased. However, there is a trade-off between ICI and spatial multiplexing [11]. In [4], multiplexing performances of SM are analyzed and compared with two other MIMO techniques, namely repetition coding (RC), and spatial multiplexing (SMP) for VLC. SM scheme has advantages over SMP in terms of reliable communication in correlated channels, and more spectrally efficient compared with RC. In that study, Fath and Haas obtained MIMO VLC schemes with PAM and evaluated the upper bound BER performances of the schemes.

PAM is a simple modulation technique for intensity modulation direct detection (IM/DD) systems, can be applied in a straightforward

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manner, and achieve good BER performances at lower spectral efficiencies. However, if the spectral efficiency increases, the performance of the PAM system decreases [12]. Optical Orthogonal Frequency Division Multiplexing (O-OFDM) is another popular modulation technique has been investigated for VLC and combined with MIMO schemes [5,12,13]. But, peak to average power ratio (PAPR) is the major disadvantage for OFDM and its modifications. There is a more favorable modulation scheme proposed in the literature which outperforms modulations mentioned above without PAPR problem and has good performances at high spectral efficiencies [14]. Besides, the constellation of the modulation scheme effects the performance of the MIMO systems especially SM [9]. From this point of view, SIM is one of these modulation schemes which was proposed for IM/DD systems [15]. It is formed from sinusoidal signal pairs and a DC signal which makes total electrical signal positive at all times. At the receiver side, DC content of the signal is filtered by the bandpass filter and sinusoidal parts of the signal are demodulated. Demodulation process is performed on the in-phase and quadrature part of the signal. Different from the RF counterpart, SIM needs two fold bandwidth because of the intermediate modulation step of the electrical subcarrier. Another important drawback of SIM is the DC content which consumes power without carrying any information [16]. MSM is the extended version of SIM which uses multiple sinusoidal signal pairs with different frequencies selected to ensure orthogonality between these subcarriers [16]. In [17], Hwang and Cheng proposed SIM/SM-aided free space optical communication with receiver diversity. They compared proposed SIM/SM scheme with conventional SIM scheme in additive white Gaussian noise (AWGN) and outdoor log-normal atmospheric channels. They considered multiple subcarriers and used subcarrier index as an extra dimension of signal constellation, not the position of the optical source. In order to avoid confusion between our MSM scheme and Hwang's approach, we call Hwang's MSM scheme as "MSM-index" throughout the paper.

In this study, BER performances of a MIMO VLC system with SIM modulation are analyzed and new schemes which are called DCA-SIM and DCA-MSM are proposed for SM case. The power efficiencies of DCA-SIM and DCA-MSM are shown in correlated MIMO VLC channels. The upper bound BER performances of the schemes are investigated analytically for PSK and QAM modulation types in order to validate the simulation results. Two different VLC indoor channel models are used with a different correlation between MIMO channel coefficients. The BER performances of SIM modulated MIMO schemes are then compared with PAM modulated counterparts in terms of various spectral efficiencies for single carrier scenarios. Additionally, MSM and DCA-MSM BER performances are compared with MSM-index under SM transmission plan for multiple carrier scenarios. Moreover, the power imbalance method for SIM is investigated to improve the BER results in correlated channels and the best power imbalance factors are obtained by getting the BER versus power imbalance graphs.

The remainder of this paper is organized as follows. In Section 2, the system model under consideration is described. MIMO techniques and the analytical upper bound BER expressions are presented in Section 3. Then, DC-aid schemes and complexity analysis are presented in Section 4 and power imbalance scenarios are introduced in Section 5. Simulation results and discussions on the BER performances for different channel types are presented in Section 6. Finally, the paper is concluded in Section 7.

The following notations are used throughout the paper: lower case bold symbols denote vectors and upper case bold symbols denote matrices. $[.]^T$, $|.|$, and $\|.\|_F$ are used for the transpose operator, the absolute value, and the Frobenius norm, respectively.

2. System model

2.1. Subcarrier intensity modulation

In this study, Subcarrier Intensity Modulation (SIM) is considered as modulation scheme. SIM is formed by sinusoidal signal pairs and a DC signal which makes total electrical signal positive all the time [15]. Moreover, power efficient form of SIM was introduced in [18] which uses symbol-by-symbol bias as a DC content. So, at the transmitter side symbol-by-symbol biased SIM is considered and two different constellations quadrature amplitude modulation (QAM) or phase shift keying (PSK) are used as a modulation scheme for SIM. The spherical demonstration of QAM-SIM symbols in 3-D space is illustrated in Fig. 1. Here, the diameter of spheres is equal to minimum distance of the constellation and the axes indicate in-phase, quadrature and DC components. If M size signal constellation is taken into consideration, then $log_2(M)$ bits are mapped to PSK or QAM symbols, after that these symbols are modulated on sinusoidal carriers and the DC content is determined with respect to these carriers. In-phase carrier, quadrature carrier, and pulse shape $p(t)$ are defined as;

$$\begin{aligned} p(t) &= \sqrt{\frac{2}{T_s}} rect\left(\frac{t}{T_s}\right), \\ In &= \sqrt{\frac{1}{T_s}} \sin(2\pi f_c t), \\ Qd &= \sqrt{\frac{1}{T_s}} \cos(2\pi f_c t), \end{aligned} \tag{1}$$

here T_s is symbol interval, and $f_c = 1/T_s$ is the subcarrier frequency. Rectangular pulse shape $rect(t)$ is defined as;

$$rect(t) = \begin{cases} 1, & 0 \le t \le T_s, \\ 0, & o/w. \end{cases} \tag{2}$$

Inphase, quadrature and dc components are summed up after modulation and formed the transmitted signal $x(t)$.

An extended version of SIM is MSM which is consisted of SIM transmitter blocks with carriers in different frequencies. These frequencies of the SIM blocks are chosen carefully to ensure orthogonality and have to be $1/2T$ multiples of baseband frequency [15]. And symbol-by-symbol DC bias method is implemented to reduce DC power consumption. Finally, MSM signal is formed by the sum of these SIM blocks with DC bias which ensures the positivity of the entire signal. At the receiver side of MSM, parallel SIM receiver blocks are formed to obtain the sink data at different subcarriers [16].

Some advantages of MSM scheme are as follows; it is usual to implement frequency division multiplexing in IM/DD systems through MSM, so this scheme is easily implemented in the multi-user scenarios. Furthermore, each SIM block carries independent data and increases the throughput/capacity of the system. Also, increasing of peak power as the number of subcarriers increase and requiring two fold bandwidth compared to the baseband modulations are said to be the drawbacks of MSM.

2.2. Indoor scenario

A MIMO IM/DD transmission system which uses LEDs as light sources is considered for indoor VLC. N_t LEDs are conceived as transmitters and N_r photo-detectors are conceived as receivers. T_x is the transmitter index and R_x is the receiver index. Optical intensity is received by N_r photo-detectors and the received vector is given by;

$$\mathbf{y} = \eta\rho\mathbf{H}\mathbf{x} + \mathbf{n} \tag{3}$$

here η is electrical-to-optical conversion coefficient, ρ is the photo-detector sensitivity. In this paper, without loss of generality, we assume $\eta\rho = 1$. The shot and the thermal noises at the receiver are modeled as additive white Gaussian noise (AWGN) and are added to the received signal in the electrical domain [4]. $\mathbf{n}$ is zero mean Gaussian random variable with a variance of $N_o/2$ per dimension. $\mathbf{x} = [x_1 \dots x_{N_t}]^T$ is the signal vector to be transmitted. $\mathbf{H}$ is the N_rxN_t channel vector and h_{nrnt} represents the respective channel coefficient of the optical link between transmitter nt and receiver nr. The LEDs are perfectly synchronized