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Visible Light Communication Using Multiuser MIMO Networks

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***Abstract* - To achieve the transmission of data with high data rate and to use the spectrum efficiently, we incorporate the technique of Visible Light Communication using multiuser MIMO networks. For low cost implementation we use intensity modulation with direct detection (IM/DD), where information is conveyed through intensity of LEDs and detected by photodiodes at the receiver. As the distance between multiple transmitter and receiver varies, the delay also varies, resulting in complex channel gain. For each subcarrier in OFDM, precoding matrix is calculated to eliminate the multiuser interface. In order to generate real valued, non-negative signals, minimum DC bias, unified DC bias, asymmetrically clipped optical OFDM schemes are being used. The precoding schemes used are Zero forcing and Minimum-Mean Squared error (MMSE). In our proposed work, we use different techniques to make use of the spectrum efficiently and to implement using power efficient optical OFDM.**

***Index Terms* - Visible light communication (VLC), multiple-input multiple-output (MIMO),orthogonal frequency-division multiplexing (OFDM), multiuser, precoding.**

I. INTRODUCTION

Recently, a worldwide convergence has occurred for the use of *Orthogonal Frequency Division Multiplexing* (OFDM) as an emerging technology for high data rates. In particular, many wireless standards (Wi-Max, IEEE802.11a, LTE, DVB) have adopted the OFDM technology as a mean to increase dramatically future wireless communications. OFDM is a particular form of Multi-carrier transmission and is suited for frequency selective channels and high data rates. This technique transforms a frequency-selective wide-band channel into a group of non-selective narrow band channels, which makes it robust against large delay spreads by preserving orthogonality in the frequency domain. Moreover, the ingenious introduction of cyclic redundancy at the transmitter reduces the complexity to only FFT processing and one tap scalar equalization at the receiver.

(OFDM) is widely used in many digital communication systems due to its advantages such as high bit rate, strong immunity to multipath and high spectral efficiency but it suffers a high Peak-to-Average Power Ratio (PAPR) at the transmitted signal. It is very important to deal with PAPR reduction in OFDM systems to avoid signal degradation.

MIMO technology offers significant increases in data throughput and link range without requiring additional bandwidth or transmit power. This is achieved by higher spectral efficiency and link reliability or diversity (reduced fading). Because of these properties, MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wifi), IEEE 802.16e (WiMAX), 3GPP Long Term Evolution (LTE), 3GPP HSPA+, and 4G systems to come.

Optical wireless technologies, sometimes called visible light communication and more recently referred to as Li-Fi (Light Fidelity), on the other hand, offer an entirely new paradigm in wireless technologies in terms of communication speed, flexibility and usability. This emerging technology offers optical wireless communications by using visible light. Today, it is seen as an alternative to different RF-based communication services in wireless personal-area networks. An additional opportunity is arising by using current state-of-the-art LED lighting solutions for illumination and communication at the same time and with the same module. This can be done due to the ability to modulate LEDs at speeds far faster than the human eye can detect while still providing artificial lighting. Thus while LEDs will be used for illumination,

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communication onto lighting systems. This will be particularly relevant in indoor 'smart' lighting systems, where the light is always 'on'. The premise behind VLC is that because lighting is nearly everywhere, communications can ride along for nearly free. Think of a TV remote in every LED light bulb and you'll soon realise the possibilities of this technology.

The rest of the paper is organized as follows, in Section II, ACO-OFDM, DCO-OFDM systems are analyzed . In Section III, simulation results are shown. The paper concludes in Section IV.

II. SYSTEM MODEL

Assuming a single room equipped with multiple LED units for illumination, we can achieve transmission of data to multiple users simultaneously. Considering N_t LED units in ceiling (Transmitter) and N_r users (Receiver) on the same receiving plane between the ceiling and floor of the room , with a single Photo Diode, where $Nt \geq Nr$.

To eliminate multi user interference, the transmitted data vector **d** is precoded into a transmitted vector **x**. DC bias is added to each LED unit as the transmitted vector **x** should be real-valued and nonnegative, because VLC systems makes use of intensity modulation.

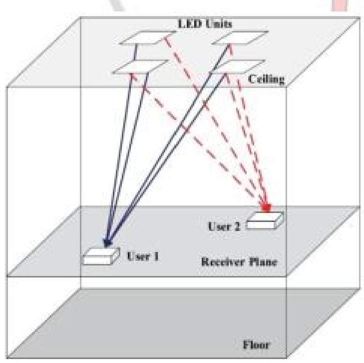

Fig..1 MU-MIMO VLC SYSTEM

The DC gain is expressed as,

$$h^{DC}_{p,q} = \begin{cases} (\rho_p A_p / d^2_{p,q}) R(\phi_q) \cos(\varphi_{p,q}), & \varphi_{p,q} \leq \Psi_{c,p} \\ 0 & \varphi_{p,q} > \Psi_{c,p} \end{cases} \quad (1)$$

ρ_p : responsivity coefficient of Photo diode

$d_{p,q}$: distance between receiver and transmitter at that time

$\varphi_{p,q}$: Incidence angle of light

$\psi_{c,p}$: receiver Field Of View

$R_{(\phi p,q)}$:Generalized Lambertian Radiant Intensity given by,

$R_{\phi q} = ((m+1)\cos^m(\phi q))/2\pi$…….. (2) Where, m is the order of Lambertian emission.

The channel matrix $\mathbf{H}^{DC}_{p,q}$ is highly correlated and real valued when the users are near-by. The receiver collection Area A_p,

$$A_p = \gamma^2 A_{pd,p} / \sin(\varphi_{c,p}) \qquad ……(3)$$

γ : Concentrator refractive index of Photo Diode

At the receiver, the optical signal is directly detected by corresponding Photo Diode, which generates electric signals proportional to the optical power received. Additive White Gaussian noise (shot and thermal noise) with zero mean and variance as,

$$\sigma_p^2 = 2e\rho_p P_p B + 2e\rho_p \chi_{amb} A_p (1 - \cos(\varphi_{cp})) B + i^2_{amp} \qquad (4)$$

e : Electronic charge

χ_{amb}: Ambient light photocurrent

B: Bandwidth of receiver

i_{amp}: Preamplifier noise current density

P_p : Average optical power collected from all LEDs..

A. MU-MIMO-OFDM for VLC SYSTEM

Pre-coding is conducted in time domain and only the DC channel gain is considered. As the distance between transmitter and receiver are different, the variation in temporal delay results in complex channel gain and the phase difference when transformed to frequency domain.

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The time domain channel response is given by,

$$h_{p,q}(t) = h_{p,q}^{DC}\delta(t - \frac{dp,q}{c}) \quad \text{….(5)}$$

Where, δ (.) represent the Dirac delta function and c is velocity of light.

The corresponding frequency-domain channel response is given as,

$$H_{p,q,k} = h_{p,q}^{DC}\exp(-\frac{j2k\pi Bdp,q}{Nc}) \quad \text{…...(6)}$$

Where, B is system Bandwidth, N is size of Fast Fourier Transform.

When temporal delay is considered, the frequency domain channel response is complex-valued, which reduces the channel correlation with phase differences of multiple links. However, to achieve high data rate transmission, wide bandwidth optical components are used and phase in

complex channel gain cannot be neglected anymore. [7] proposed a system which can achieve a higher throughput and higher energy efficiency. The S-BOX is designed by using Advanced Encryption Standard (AES).

Consider a MU-MIMO-OFDM VLC system of bandwidth B, divided into N subcarriers. For the p^{th} user, the information bit stream is firstly mapped onto the complex-valued symbols $D_{p,k}$, where k=0,1,. . . , N -1, according to the chosen constellations, PSK or QAM. Since intensity modulation requires real-valued output, Hermitian symmetry should be imposed on the OFDM subcarriers where we have $D_{p,k} = D^*_{p,N-k}$, k =1,2,. . .N/2 - 1, and the subcarriers $D_{p,0}$ and $D_{p,N/2}$ are set to zero.

At the transmitter of MU-MIMO-OFDM VLC system, precoding is performed on each subcarrier to eliminate multiuser interference. We denote the precoding weights for the k^{th} subcarrier as $\{W_{p,q,k}, 1 \leq p \leq Nr ; 1 \leq q \leq N_t\}$, which can be complex-valued.

The frequency-domain signal obtained by adding all the weighted symbols can be written as

Then, the frequency-domain signals are converted to the time domain by inverse fast Fourier transform (IFFT) as

$$X_{q,n} = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} xq,n \exp(j\frac{2\pi}{N}nk) \qquad n=0,1,\text{………}N-1 \quad \text{…….(8)}$$

which are real-valued since the subcarriers satisfy Hermitian symmetry.

At the beginning of each time-domain OFDM symbol $\mathbf{x}_q = [x_{q,0}, x_{q,1}, \ldots, x_{q,N-1}]^T$, a cyclic prefix (CP) is added to eliminate the inter-symbol interference at the receiver. Since xq,n may be negative in some points, a DC bias PDC,q needs to be added to the qth transmitter to obtain nonnegative signals for emission, which is called DC-biased optical OFDM (DCO-OFDM).

B.PRECODER DESIGN

Frequency-domain symbols are obtained at the receiver by performing FFT is given by

$$R_{p,k} = \sum_{q=1}^{Nr} Hp,q,k\,Xq,k + Z_{p,k}$$

$$R_k = H_k W_k D_k + Z_k \qquad k=0,\text{….}N-1 \quad \text{……(9)}$$

where $H^T_{p,k}$, $W_{p,k}$, and $W_{l,k}$ are N_t x1 vectors of channel gain and precoding weights for the k^{th} subcarrier; and $Z_{p,k}$ denotes the equivalent noise on the k^{th} subcarrier.

The first term denotes the desired signal for the p^{th} user, while the second term is the inter-user interference to the p^{th} user, which should be eliminated by precoding.When all the N_r users are considered, we can rewrite $R_{p,k}$ in the matrix form as,

$$R_k = H_k W_k D_k + Z_k \qquad k=0,1.N-1 \quad \text{……(10)}$$

where $D_k = [D_{1,k}, D_{2,k}, \ldots, D_{Nr,k}]^T$ and $R_k = [R_{1,k}, R_{2,k}, \ldots, R_{Nr,k}]^T$ denote the transmitted and received symbol vectors on the k^{th} subcarrier, $H_k = [H_{1,k}, H_{2,k}, \ldots, H_{Nr,k}]^T$ and $W_k = [W_{1,k}, W_{2,k}, \ldots, W_{Nr,k}]$ represent the corresponding channel and precoding matrices, Z_k is the noise vector on the k^{th} subcarrier.

The two precoding schemes are being used for MU-

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interference by directly forcing the interference terms to be zeros, i.e., the matrix H_kW_k is forced to be diagonal as,

$$H_kW_k=\mathrm{diag}(\lambda_k) \quad .....(11)$$

where all the elements in λ_k are positive, and the precoding matrix can be calculated by

$$W_K=H_k^{+}\,\mathrm{diag}(\lambda_k)=H_k^H(H_kH^H_k)^{-1}\,\mathrm{diag}(\lambda_k) \quad .....(12)$$

However, when the channel matrix is ill-conditioned, zero forcing requires a large normalization factor, which will dramatically reduce the received power. Therefore, when the signal-to-noise ratio (SNR) at the receiver is low, zero forcing cannot achieve a good performance since noise instead of interference is the dominant impairment of the system.

In linear MMSE precoding, however, the interference at the receivers is not identically zero, which achieves a tradeoff between interference and noise based on which one is the dominant part in the signal-to-interference-plus-noise ratio (SINR) at the receiver. The MMSE-based precoding matrix is given by

$$W_K=H_k^H(H_kH^H_k+\mathrm{diag}(\sigma^2_{Zk}))^{-1}\,\mathrm{diag}(\lambda_k) \quad ......(13)$$

Where, σ^2_{Zk} is the variance of Z_k

C. DCO-OFDM-BASED MU-MIMO VLC

Since the generated OFDM time-domain signal $x_{q,n}$ is bipolar, DC bias should be added to each transmitter to obtain non-negative signals for emission, which is denoted as $P_{DC,q}$ for the qth transmitter.

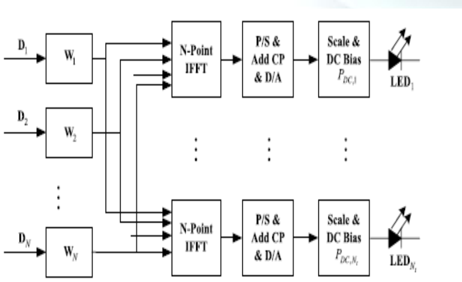

Fig.2 VLC system with Nr users,Nt LED units and N subcarriers.

However, a DC bias can not necessarily guarantee that all the signals become non-negative and part of the signals should be clipped.

The DC bias for the qth transmitter can be written as

$$P_{DC,q}=\eta\sqrt{E\{x^2_{q,n}\}} \quad .....(14)$$

which is usually denoted in the form of $10\log_{10}(\eta^2+1)$, dB since it represents the increase in electric power of original OFDM signals, where η represents the DC bias ratio.

When we use a larger DC bias, there will be less signals clipped, resulting in smaller clipping distortion. However, it is inefficient in terms of power since DC bias does not carry information. There should be a tradeoff between the DC bias and clipping distortion, and we can define a minimum DC bias ratio η_0 to avoid clipping distortion.

When precoding is applied at the transmitter, the electric power of the N_t transmitters is different, which requires different minimum DC bias. If we employ different minimum DC biases for different LED units, we have

$$P_{DC,q}=\eta_0\sqrt{E\{x^2_{q,n}\}} \quad q=0,1N_{t-1} \quad ......(15)$$

which is denoted as the minimum DC bias scheme, and the emitted optical power of the qth LED unit is given by

$$P_{opt,q}=E\{x_{q,n}+P_{DC,q}\}=E\{x_{q,n}\}+P_{DC,q}=P_{dc,q} \quad .....(16)$$

where the equality holds since the expectation of $x_{q,n}$ is zero. When the average optical power of all the LED units is constrained to P for illumination requirement, the biased signal should be scaled and the transmitted signal for the qth LED unit is written as

$$Y_{q,n}=\alpha(x_{q,n}+P_{DC,q}) \quad ....(17)$$

where the scaling factor can be calculated as

$$\alpha=N_tp/\sum_{q=1}^{Nt}P_{dc,q}$$

$$=N_tP/\eta_o\sum_{q=1}^{Nt}P\sqrt{E\{x^2_{q,n}\}} \quad .....(18)$$

Therefore, the actual DC bias for the qth LED unit is given by

$$P_{DC,q}=\alpha P_{DC,q}=\sqrt{E\{x^2_{q,n}\}}N_tP/\sum_{q=1}^{Nt}E\{x^2_{q,n}\} \quad q=0,1N_{t-1}...(19)$$

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Since it can be seen that the emitted optical power for the N_t LED units is different and it will change when the users move on the receiver plane, which will affect the illumination performance of LEDs. In order to provide data transmission and high quality illumination at the same time, we consider a unified DC bias scheme, where all the LED units use the same DC bias as

$$P_{DC,q}=P \quad ....(20)$$

However, in order to avoid clipping distortion at all the N_t transmitters, this DC bias should satisfy requirement of the transmitter with maximum electric power, and the corresponding scaling factor is given by

$$\alpha=P/\eta_o\sqrt{\max(E\{x^2_{q,n}\}} \quad .....(21)$$

Since larger DC biases are utilized for most of the LED units without maximum electric power, the power efficiency of the system is reduced accordingly.

III. SIMULATION RESULT

Two cases of users' location are considered. In case1, the two users are separated far enough, so that they have uncorrelated channel matrix. In case2, the two users are very close and their channel matrix is ill-conditioned. For the above two cases, precoding schemes Zero Forcing and MMSE are performed.

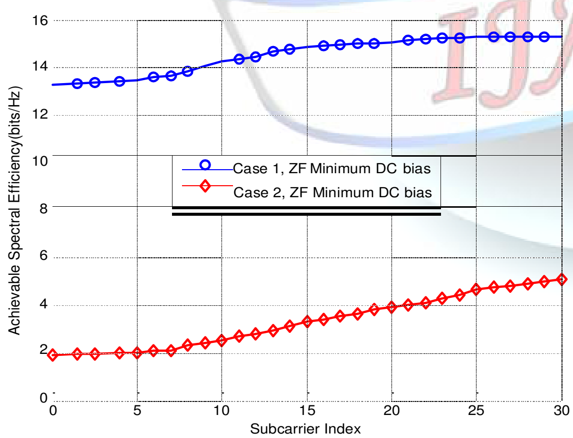

Fig.4.1 Spectral efficiency with minimum DC bias and the average emitted optical power P=0 Db for Zero forcing method.

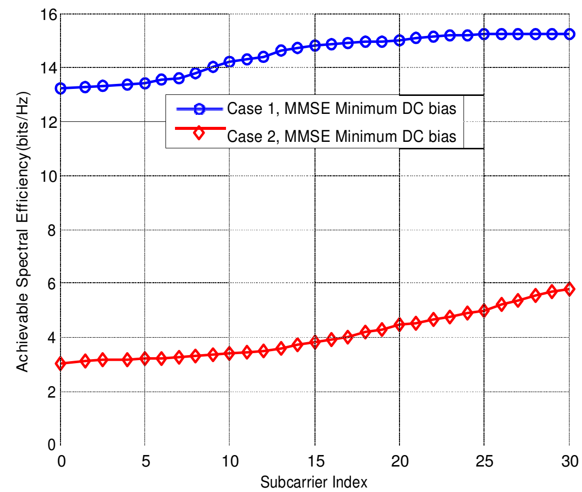

Fig.4.2 Spectral efficiency with minimum DC bias and the average emitted optical power P=0 Db for MMSE method

Fig 4.1,depicts the spectral efficiency of each subcarrier in OFDM with the average emitted optical power P =1 Watt (0 dBW expressed by decibel Watt), where DCO-OFDM is utilized with minimum DC bias for each transmitter with Zero Forcing as the precoding scheme. While Fig 4.2, is for MMSE precoding scheme. Since Hermitian symmetry is applied, only the first to 31th subcarriers carry useful information.

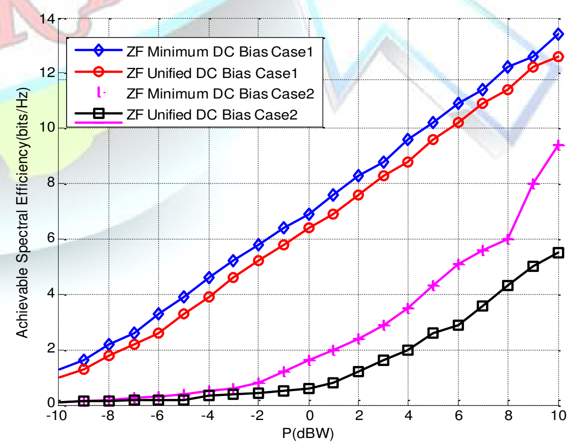

Fig 4.3 Average spectral efficiency with different average emitted optical power and DC bias for Zero Forcing technique.

It is seen that in both the cases, when the subcarrier index increases, the spectral efficiency improves, especially

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the subcarrier with higher index has more phase difference, which makes the channel matrix more uncorrelated.

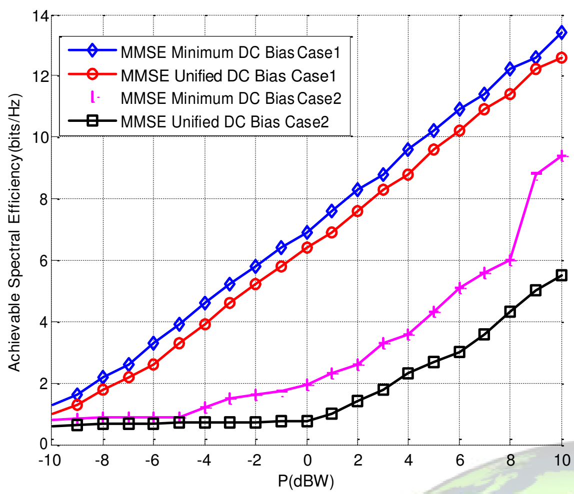

Fig 4.4 Average spectral efficiency with different average emitted optical power and DC bias for MMSE technique

Fig. 4.3 shows the average spectral efficiency with different average emitted optical power, where DCO-OFDM is utilized with minimum DC bias and unified DC bias for both the cases with Zero forcing precoding being used. Whereas, Fig.4.4 is for MMSE precoding technique. It can be seen that MMSE outperforms zero forcing in both cases. MMSE achieves more spectral efficiency when the optical power is low and the noise is the dominant part of interference-plus noise. The performance gain of MMSE becomes larger in Case 2 since its channel matrix is more ill-conditioned. Besides that, the system with minimum DC bias achieves more spectral efficiency than that with unified DC bias, since more power are used for data transmission. However, the system with unified DC bias provides better illumination performance.

IV. CONCLUSION

The subcarrier with higher index achieves more spectral efficiency, especially when the users are highly correlated. Also, MMSE outperforms Zero forcing scheme when the optical power is low and when more performance gain is achieved when the users are closer. Besides that, the system with minimum DC bias achieves more spectral efficiency than that with unified DC bias, since more power are used for data transmission. However, the system with unified DC bias provides better illumination performance.

Alternately, ACO-OFDM (Asymmetricaly Clipped OFDM) which is more power efficient compared with DC bias. In order to avoid DC bias and to further enhance the improvement of spectral efficiency, ACO-OFDM is to be implemented.

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