Transmission Techniques for Multi User MIMO VLC Systems Using Flip-OFDM

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Abstract—Flip Orthogonal Frequency Division Multiplexing (flip-OFDM) is one of the unipolar forms of OFDM used in Visible Light Communication (VLC) systems. This paper analyzed the multi user VLC systems to transfer flip-OFDM based signal using different form of Multiple Input Multiple Output (MIMO) transmission techniques. These transmission techniques are Repetitive Coding (RC), Spatial Modulation (SM), generalized spatial modulation (Generalized SM) and spatial multiplexing (SMP). Multi User Interference (MUI) at the transmitter has been bypassed using precoding process of Block Diagonalization (BD). The performance analysis of proposed system is carried out with the help of simulation. A comparative study for RC, SM, generalized SM and SMP for multi user VLC system is performed with regard to Bit Error Rate (BER) performance. These transmission techniques are compared with and without the use of flip-OFDM. Furthermore, we also analyzed the Peak-to-Average Power Ratio (PAPR) of flip-OFDM signal. Simulation results showed that the generalized SM outperforms RC, SMP, SM approximately by 9dB, 5dB, 2dB Signal-to-Noise Ratio (SNR), respectively without flip-OFDM and, 8.5dB, 7dB, 3.3dB SNR respectively with flip-OFDM to obtain a BER of 10^{-6}. We also analyzed the MIMO transmission techniques with regards to transmission efficiency. It is found that SMP offers better transmission efficiency with lower modulation order. To obtain the spectral efficiency of 8 bits per channel use (bpcu), RC, SM, generalized SM and SMP needs modulation order M = 256, 64, 8 and 4, respectively. Hence SMP is power efficient.

Index Terms—Flip OFDM, visible light communication, MIMO, spatial modulation, generalized spatial modulation, spatial multiplexing, and repetitive coding.

I. Introduction

Optical Wireless Communication (OWC) is an emerging technology which has the potential of number of use cases in the next generation of communication systems [1]. OWC offers multiple advantages over radio frequency (RF) system such as, availability of larger bandwidth, no interference with RF, more secure and so on. Additionally OWC, especially Visible Light Communication (VLC) operates in license free spectrum (380nm – 780nm) and the design is cost effective. It is considered as alternative to RF where RF is not reachable such as underground, mines, subway, and optimal solution for indoor communication [2]. However, the stringent requirement of this technology is Line of Sight (LoS) and because of this, the communication range is less. Furthermore, most of the advanced techniques used in RF system is being analyzed and experimented in VLC. For example, Orthogonal Frequency Division Multiplexing (OFDM) VLC [3], Multiple Input Multiple Output (MIMO) VLC [4]. Of course, some variation of the original forms of these techniques is needed in VLC because of the unipolar characteristic of optical signal. And, it has been seen that for different use cases and scenarios, their performance is enhanced.

In VLC, a transmitter or emitter is group of Light Emitting Diodes (LEDs) and a receiver is group of photodiodes (PDs). The configuration of multiple VLC emitters and PDs is considered as MIMO VLC system. Under LoS, MIMO techniques provides higher gain [5]. Additionally, it allows multiuser access and higher throughput. The different MIMO VLC transmission techniques like Repetition Coding (RC), Spatial Modulation (SM), spatial multiplexing (SMP) and generalized SM have been studied and investigated [5]-[7]. Such MIMO VLC system and its different transmission techniques are also investigated for multiuser [8], [9]. In multiuser system, users can transmit and receive the information in a common bandwidth and high signal-to-noise ratio (SNR) regime. Likewise, variants of OFDM like DC-biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM), asymmetrically clipped DC biased optical OFDM (ADO-OFDM), and flip-OFDM have been discussed [10], [11]. While in DCO-OFDM, unipolar signal is obtained by adding DC to bipolar OFDM signal; in ACO-OFDM, it is obtained by clipping negative portion of bipolar OFDM signal. DCO-OFDM requires more transmitted power or large DC which makes it power inefficient. But, ACO-OFDM is more power efficient than any other OFDM technique due to no DC biasing. However, this technique is inefficient in bandwidth utilization. A combination of DCO and ACO, known as ADO-OFDM improves power and optical efficiency but at the cost of high Bit Error Rate (BER). It is because of clipping noise. In addition, flip-OFDM which is similar to ACO-OFDM is also investigated. In flip-OFDM, positive signal and flipped part of negative signal of bipolar signal is transmitted

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through two different sub-frames. The BER, spectral efficiency and power efficiency performance of flip-OFDM is almost similar to ACO-OFDM, but it uses much lesser hardware. So, design complexity is less and therefore cost effective. Receiver offers enhanced detection compared to ACO-OFDM. Furthermore, unlike ACO-OFDM, the transmitted energy is fully used in flip-OFDM, that is, highly efficient. However, there is further scope of improvement in flip-OFDM. Because double transmission of symbols and associated operations such as Cyclic Prefix (CP), polarity inversion and delay in the symbol is doubled.

Similarly, combined technology of OFDM and MIMO has been investigated in optical domain. In [12], [13], OFDM together with MIMO is implemented for VLC system to improve bandwidth efficiency and data rates. The experimental results are reported in [13] to achieve data rates up to gigabit/s using MIMO OFDM VLC. In this, DC bias is used for Intensity Modulation (IM). To reduce the implementation complexity, positive-negative separation based method is proposed in [14]. MIMO-OFDM analysis for multi-user is discussed in [15]. The DC-biased and ACO-OFDM are used to obtained non-negative signals for IM. The performance evaluation of RC, spatial multiplexing (SMUX) and spatial modulation (SMUD) for MIMO OFDM VLC system is presented in [16] where non-negative real signal is obtained by adding DC bias. MIMO based transmission techniques; generalized LED index modulation optical OFDM (GLIM-OFDM) and extended GLIM-OFDM (e-GLIM-OFDM) is presented in [17] which do not required Hermitian and DC bias. The optical spatial modulation (OSM) and SMP MIMO techniques are studied using ACO-OFDM in [18]. The generalized SM MIMO is compared using flip, DCO & ACO-OFDM in [19] and found that flip-OFDM offers better performance. In previous works, the concept of flip-OFDM is not explored for MIMO based transmission schemes. Also, for the multi-user in the context of MIMO-OFDM VLC systems is not studied. The use of flip-OFDM with MIMO techniques of RC, SM, generalized SM and SMP with comparative analysis in context of VLC is not yet investigated to the best of our knowledge and available literature.

In this paper, we investigated and analyzed flip-OFDM based optical MIMO VLC system for multi user. The use of flip-OFDM with MIMO techniques of RC, SM, generalized SM and SMP is studied and investigated in the context of VLC. Performance analysis of these schemes is carried out and reported. The main contributions in this work are as follows:

- First, we analysed the transmission techniques for multi user VLC without using flip-OFDM and using flip-OFDM. It is found that in both the cases, BER performance of generalized SM transmission technique is better. Furthermore, with flip-OFDM, the BER and SNR performance of VLC system improves as compared to none flip-OFDM.
- Next, spectral efficiency of transmission techniques is investigated, and
- PAPR of flip-OFDM signal is analysed. The simulated result is compared with analytical results.

The remaining part of paper is arranged as follows. The few recent and related works is highlighted in Section II. The proposed system architecture is presented in Section III. In Section IV, mathematical analysis is discussed. The MIMO transmission techniques are discussed in Section V. The simulation results are presented in Section VI while, conclusion is given in Section VII.

II. FEW RECENT AND RELEVANT WORKS

In this section, we have highlighted few very relevant and recent works related to this study. We then summarize their outcomes and research gap.

In [12], authors developed MIMO-OFDM system using an imaging receiver for the high speed indoor optical wireless. The system uses 2 x 9 MIMO configuration. The data rate achieved is 220Mbps at BER of 10^{-3} over 1m of range. In this demonstration OFDM transmission was not optimized. This optimization is presented in [13] where an experimental demonstration of 4 × 9 optimized MIMO system is carried out using 9 channel imaging diversity receiver which enables the VLC transmission at gigabit/s. The DC bias is used to obtain unipolar signal for LEDs in [12, 13]. In [14], positive and negative coefficients separation to satisfy the requirement of non-negative signal transmission is proposed for a MIMO-OFDM VLC system. The minimum mean-square error (MMSE) based receiver is used. The performance of BER and channel capacity are also analyzed. The different MIMO transmission techniques are not addressed either for single user or multiuser system. In [15], MIMO-OFDM is used in VLC system for multi user. DC bias and ACO-OFDM is used to obtain non-negative signal and performance is compared for both, with zero forcing (ZF) and MMSE based receiver. The different MIMO transmission techniques are not investigated in this paper. In [16], three MIMO transmission techniques; RC, SMP and SM are investigated for OFDM VLC system and BER performance is analyzed for single user using DC biased. The generalized SM is not presented and compared with RC, SMP and SM. The RC, SMP and SM are addressed for single user and not for multi user. In [17], GLIM and e-GLIM MIMO techniques are presented using OFDM for VLC system. The positive negative separator is used for non-negativity of the signal. The performance of BER and SNR is analyzed using MMSE based receiver and compared with DCO-OFDM and ACO-OFDM. The analysis is done for single user and not for multi user. The other MIMO techniques; RC, SM and SMP are not presented. In [19], the concept of flip-OFDM is implemented using generalized SM MIMO technique for single user VLC system and found that flip-OFDM offers better performance than other OFDM techniques such as DCO-OFDM and ACO-OFDM. Other MIMO transmission techniques are not presented. The concept of flip-OFDM for MIMO transmission techniques in the context of multiuser VLC has not been investigated and it is done in this paper. In this paper, MIMO transmission techniques; RC, SM, SMP and generalized SM are investigated using flip-OFDM for multi user VLC.

III. Multiuser OFDM MIMO VLC System

The transmitter and receiver part of proposed system architecture is highlighted in Fig. 1 and Fig. 2, respectively.

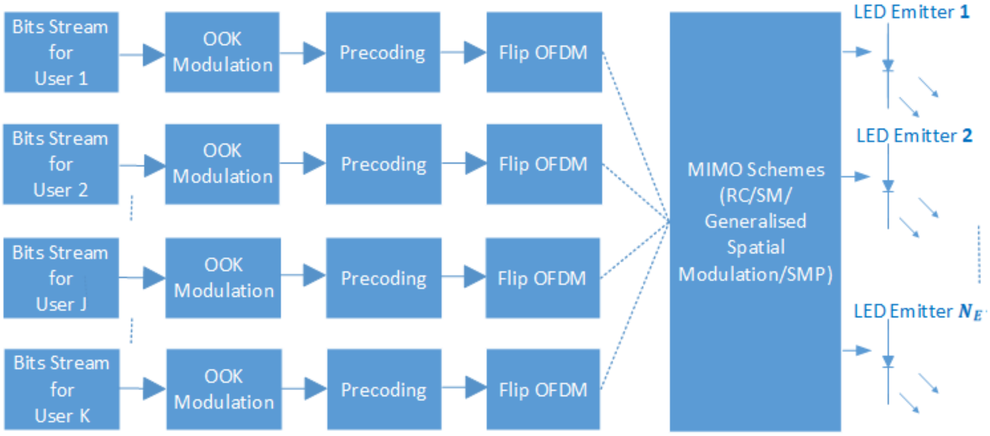

Fig. 1. Multi user OFDM MIMO VLC transmitter

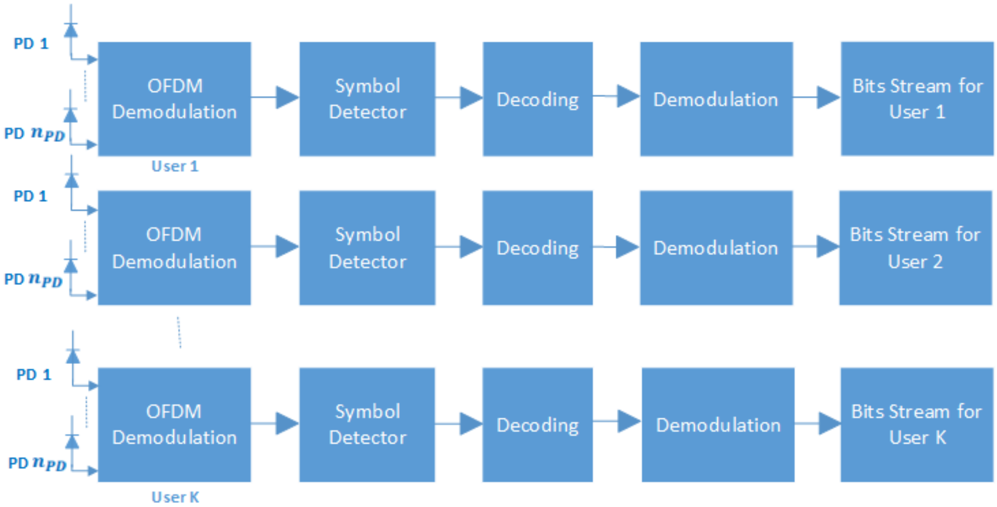

Fig. 2. Multi user OFDM MIMO VLC receiver

We consider the total number of user K. At the transmitter, bit stream for user is modulated by using on-off keying (OOK). The OOK modulated signal is passed through precoding technique to overcome multi user interference (MUI). Block diagonalization (BD) is considered in this system to deal with MUI. We apply the OFDM to attain high transmission rates and combat inter symbol interference (ISI). VLC uses intensity modulation and direct detection (IM/DD) and therefore OFDM signal must be characterized as intensity. Hence, signal must be real and positive. In this work, real and non-negative signal is obtained by using flip-OFDM for LEDs and is explained in detail in Section IV-C. Finally, MIMO techniques are used to achieve high diversity gain. The signal is transmitted through LEDs emitter using RC, SM, generalized SM and SMP to improve the performances such as SNR, BER, transmission efficiency, etc. At the receiver, PDs receive the information through visible light LoS channel and converts light signal into electrical signal. The detailed demodulation process of flip-OFDM is explained in Section IV-C. The maximum likelihood (ML) detection technique is used to estimate the transmitted signals.

In summary, overall system is for multi-user VLC which uses flip-OFDM techniques to obtain unipolar signal from bipolar OFDM signal. This unipolar signal is transmitted using RC, SM, generalized SM and, SMP MIMO techniques. Analysis of the same is presented in this paper.

IV. Mathematical Analysis

The group of LEDs forms an LED array and also called VLC emitter or VLC transmitter. In this paper, the total number of emitters is represented as N_E at the transmitter. LED radiation uniformity reduces with distance. Hence, each LED array is considered as a single point source regardless of spatial distribution of LEDs within each emitter as the spacing between LEDs in the emitter is very small. This reduces the modeling complexity of multiple channel path. At the receiver, each user is equipped with n_{PD}. PDs and total number of PDs is represented as N_{PD}.

A. VLC System Model

In optical channel, the DC gain describes the system channel matrix '*H*'. The DC gain [20], also called channel coefficient, between j^{th} VLC receiver and i^{th} VLC emitter is given as h_{ji}.

$$h_{ji} = \begin{cases} \sum_{l=1}^{LEDs/emitter} \frac{A}{d_{jil}^2} R_O(\emptyset_{jil}) T_s(\psi_{jil}) g(\psi_{jil}) cos(\psi_{jil}), & 0 \le \psi_{jil} \le \psi_c \\ 0, & \psi_{jil} \ge 0 \end{cases} \tag{1}$$

A : Capture area of photo-detector

d_{jil} : Distance between LED to photodetector. l^{th} LED in the i^{th} LED emitter to the j^{th} PD.

$\emptyset_{jil}$: Angle of emergence

$R_O(\emptyset_{jil})$: Lambertian radiant intensity and is given by [20]

$$R_o(\emptyset_{jil}) = \frac{(m+1)}{2\pi} cos^m(\emptyset_{jil}) \tag{2}$$

m: Lambertian order of LED which is given as:

$$m = \frac{-\ln(2)}{\ln(\cos(\varphi_{1/2}))} \tag{3}$$

$\varphi_{1/2}$: Half-power semi angle of LED
ψ_{jil} : Incident angle

$T_s(\psi_{jil})$: Optical filter gain

$g(\psi_{jil})$: Optical concentrator gain

ψ_c : Field-of-view (FOV) of PD

Using Eq.(1), the VLC channel matrix, H is represented as:

$$H = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_E} \\ h_{21} & h_{21} & \cdots & h_{2N_E} \\ & & \vdots & \\ h_{N_{PD}1} & h_{N_{PD}2} & \cdots & h_{N_{PD}N_E} \end{bmatrix} \tag{4}$$

The total received power at j^{th} receiver is given by:

$$P_{rj} = (P_{LOS} + P_{diff}) \times T_s(\psi_{jil}) \times (\psi_{jil}) \tag{5}$$

where, P_{LOS} is total received power in LoS path and P_{diff} is diffused power. PDs receives the signal in form of light emitted from the LED emitters and convert into electrical current. The reflection of light through ceiling, floor and walls are quantitavely very less and so we only considered LoS propagation. The total noise variance, σ_{total}^2, at PDs is sum of shot noise variance, σ_{shot}^2, and thermal noise variance, $\sigma_{thermal}^2$. Hence, the SNR at j^{th} receiver is given by:

$$SNR = \frac{(r \times p_{rj})^2}{\sigma_{total}^2} \tag{6}$$

where, $\sigma_{total}^2 = \sigma_{shot}^2 + \sigma_{thermal}^2$

B. Block Diagonalization Precoding Process

BD precoding technique used to overcome MUI and interference between the PDs of the same user. As a result, noise enhancement in BD is significantly reduced and it improves BER. The interference between the PDs of the same user is eliminated by post-equalization in the receiver. It also offers low complexity implementation at user equipment. The signal to precoding is modulated signal which is represented as $S(t) = (S_1(t), \ldots . S_K(t))^H$. $S_j(t)$ is $(n_{PD} \times 1)$ data vector for j^{th} user terminal. The BD precoding output[21] is expressed as:

$$\begin{aligned} x(t) &= \left(x_1(t), \ldots . x_{N_E}(t)\right)^H \\ &= (X_1, .., X_k)(S_1(t), .. S_K(t))^H \\ &= \textstyle\sum_{j=1}^K X_j\, S_j(t) \end{aligned} \tag{7}$$

$(.)^H$: Hermitian transpose
$S_j(t)$: j^{th} user data symbol
X_j: Matrix corresponding to $S_j(t)$, called precoding matrix.

The user channel matrix is block diagonalized if it satisfies following condition:

$$H_i X_j = 0 \quad for\ all\, i \neq j \quad and\ 1 \le i,\, j \le K \tag{8}$$

H_i : i^{th} user channel matrix.

A channel matrix, $\overline{H_J}$ is created at the receiver to obtain X_j which should also satisfy (8). This matrix is created by including all channel estimate matrices except j^{th} user channel estimate matrix.

$$\overline{H_J} = [\hat{H}_1^H \ldots . \hat{H}_{j-1}^H \hat{H}_{j+1}^H \ldots . \hat{H}_{N_{PD}}^H]^H \tag{9}$$

X_j is defined in the null space of matrix $\overline{H_J}$. It is assumed that the total number of PDs is equal to number of LED emitters. Hence, the singular value decomposition (SVD) of $\overline{H_J}$ is obtained by [20]:

$$\overline{H_J} = \overline{U_J}\,\overline{\Lambda_J}\,[\,\bar{V}_j^{non-zero}\ \ \bar{V}_j^{zero}\,] \tag{10}$$

where, $\bar{V}_j^{non-zero} \in \mathbb{R}$ and $\bar{V}_j^{zero} \in \mathbb{R}$ denotes non-zero and zero singular value respectively. $\overline{U_j} \in \mathbb{R}$ contains left singular vectors. $\overline{\Lambda_j} \in \mathbb{R}$ is derived by arranged singular values of $\overline{H_J}$.

Next, j^{th} user receives the signal only when the emitted signal is along the direction of $\overline{V_j^{zero}}$ and, at that instant of time other receiver does not receive anything.

C. Flip OFDM

The data transmit and receive unit of flip-OFDM is depicted in Fig.3. The parallel divided bit streams are modulated using M-ary quadrature amplitude (M-QAM) technique and transmitted simultaneously over subcarriers. Let us consider $F(n)$ be modulated symbol by n^{th} subcarrier. Assuming N- point IFFT, k^{th} sample output of IFFT operation is given by:

$$f(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} F(n) e^{\frac{j2\pi nk}{N}} \tag{11}$$

Here, the time domain signal $f(k)$ is complex if symbols $F(n)$ is independent in each OFDM subcarriers. To avoid this, property of Hermitian symmetry is imposed by complex conjugate (*). i.e.

$$F(n) = F^*(N-n), \qquad n = 0,1,2, \dots . \frac{N}{2} - 1 \tag{12}$$

The Eq.(11) can be written as:

$$f(k) = \frac{1}{\sqrt{N}} \left[\sum_{n=0}^{\frac{N}{2}-1} F(n) e^{\frac{j2\pi nk}{N}} + F\left(\frac{N}{2}\right) e^{j\pi k} + \sum_{n=\frac{N}{2}+1}^{N-1} F(n) e^{\frac{j2\pi nk}{N}} \right] \tag{13}$$

Applying Hermitian symmetry in (13), we get:

$$f(k) = \frac{1}{\sqrt{N}} \left[\sum_{n=0}^{\frac{N}{2}-1} F(n) e^{\frac{j2\pi nk}{N}} + F\left(\frac{N}{2}\right) e^{j\pi k} + \sum_{n=\frac{N}{2}+1}^{N-1} F^*(N-n) e^{\frac{j2\pi nk}{N}} \right] \tag{14}$$

In order to bypass DC and other complex part in time domain, we set $F(0) = F\left(\frac{N}{2}\right) = 0$. In flip-OFDM, information is carried by 50% of the subcarriers. This makes IFFT output real and bipolar which is represented as:

$$f(k) = f^+(k) + f^-(k) \tag{15}$$

where

$$\left. \begin{aligned} f^+(k) &= \begin{cases} f(k) & if\ f(k) \geq 0 \\ 0 & otherwise \end{cases} \\ &and \\ f^-(k) &= \begin{cases} f(k) & if\ f(k) \leq 0 \\ 0 & otherwise \end{cases} \end{aligned} \right\} \tag{16}$$

and $k = 0,1,2, \dots , N$.

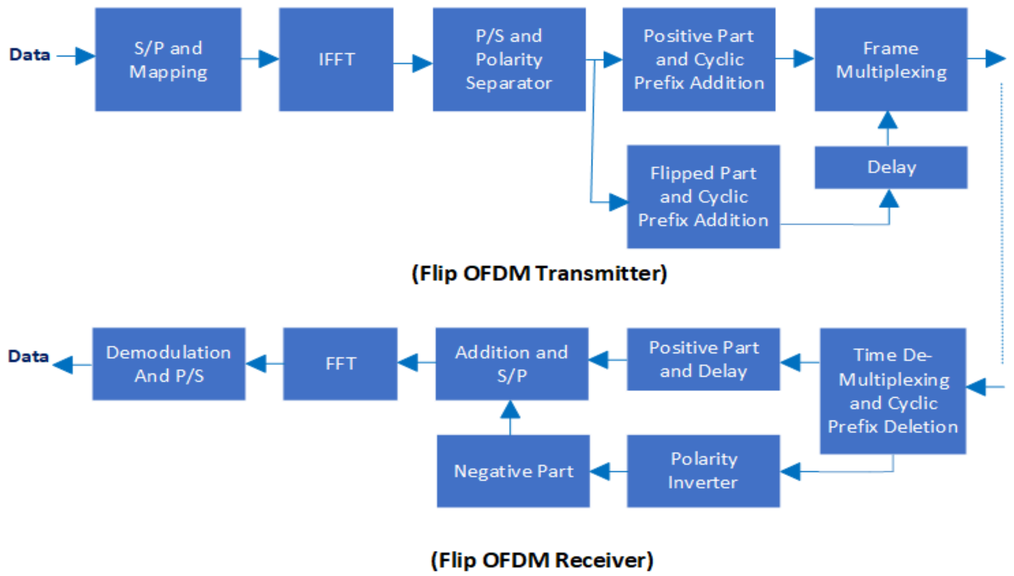

Fig. 3. Transmitter and Receiver block diagram of flip-OFDM

As represented in Fig. 3, positive part $f^+(k)$ is transmitted in one sub-frame and negative part $f^-(k)$ is flipped and transmitted in second sub-frame separately. Cyclic prefix of duration δ is added to both the sub-frames. This makes total OFDM frame length is $(N+\delta)$. Both the sub-frames are time multiplexed but second sub-frame is delayed by $(N+\delta)$ before multiplexing. These two sub-frames are received at the receiver and bipolar OFDM symbol is reconstructed. Cyclic prefixes are removed from time multiplexed frames and subtraction is performed to get original bipolar OFDM symbol. i.e.

$$y(k) = y^+(k) - y^-(k) \tag{17}$$

where $y^+(k)$ represent symbol corresponding to first sub-frame i.e. positive frame and $y^-(k)$ represent symbol corresponding to second sub-frame i.e. flipped frame. The bipolar signal is serial to parallel converted. The complex conjugate signal is obtained by FFT operations. Finally, to detect the desired signal, process of remapping and QAM demodulation operation is performed. We consider constant channel response for both the consecutive sub-frames.

The analytical BER for flip-OFDM in AWGN channel is asymptotically given as [11]:

$$BER \simeq \frac{2}{log_2 M}\left(1-\frac{1}{\sqrt{M}}\right) erfc\left(\sqrt{\frac{3}{2(M-1)}SNR}\right) \quad (18)$$

where, M indicates size of constellation.

In summary, the overall multiuser OFDM MIMO VLC system is presented as

$$y = rP_T Hf + w \quad (19)$$

where, r is the PD's responsivity, P_T is the transmitted power and y is the received signal. H, represents channel matrix, f is the flipped OFDM signal transmitted and w is additive white Gaussian noise.

V. Transmission Techniques for MIMO VLC

We discuss the transmission of flip-OFDM signal by different optical MIMO techniques in this section. We consider the Maximal Likelihood (ML) detection technique to detect the signal with the proper knowledge of channel and synchronization at the receiver.

A. *Repetitive Coding (RC)*

In RC MIMO technique, all LED emitters actively emits the identical information together. The working operation of RC is shown in Fig. 4.

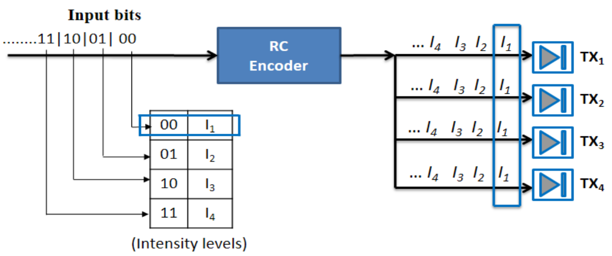

Fig. 4. Representation of RC process with $N_E = 4$ and $M = 4$.

The diversity gains improves due to RC technique and makes the system more robust. It is assumed that individual LED emitter transmits the indistinguishable optical power and at the receiver, optical intensities are added. Hence for RC, signal vectors $f_1 = f_2 =. . . = f_{N_E}$. The RC MIMO technique provides spectral efficiency $R = log_2(M)$ bpcu. The intensity level for RC is given by:

$$I_m^{RC} = \frac{2I}{M-1}m, \text{ for} = 0,1, \ldots, (M-1) \quad (20)$$

where, I is mean optical emitted power.

The BER of RC is expressed as:

$$BER_{RC} \geq \frac{2(M-1)}{M\log_2(M)} Q\left(\frac{1}{M-1}\sqrt{\frac{E_s}{N_0 N_E^2}\sum_{j=1}^{N_{PD}}\left(\sum_{i=1}^{N_E} h_{ji}\right)^2}\right) \quad (21)$$

where, E_s represent mean energy of intensity modulated signals and N_0 is noise power spectral density.

In summary, the RC algorithm can be explained as:

1. The incoming bit streams are divided into sub-streams
2. The number of bits in a sub-stream is $log_2(M)$.
3. All LED emitter transmit the same sub-stream at a time.

B. *Spatial Modulation (SM)*

In SM, only one LED emitter is activated for transmission and remaining emitters are off. The LED emitter indices and M-ary constellation symbol are two units which are responsible for carrying information. The working scenario of SM is represented in Fig. 5. The active emitter is decided by first two bits based on LED activation pattern. The other two bits are used to transmit the intensity level by active emitter. The average BER improves due to elimination of inter channel interference (ICI) in SM as only one LED emitter is active at any instant of time for transmission. At the receiver side, two major tasks are performed. The data symbol detection transmitted by active LED is achieved by joint search over all emitters and symbol using ML detector. In SM, spectral efficiency improves which is given by $R = log_2(N_E) + log_2(M)$ bpcu and M-ary intensity level is:

$$I_m^{SM} = \frac{2I}{M+1}m\,, \;\; for\; m = 0,1, \ldots, M \quad (22)$$

The BER of SM is given by

$$BER_{SM} = \frac{1}{MN_E \log_2(MN_E)}\left(\sum_{j=1}^{M}\sum_{n_E^{(1)}}^{N_E}\sum_{i=1}^{M}\sum_{n_E^{(2)}}^{N_E} d_H \times \left(f_{j\,n_E^{(1)}}, f_{i\,n_E^{(2)}}\right)\{PEP(f_j \to f_i|H)\}\right) \quad (23)$$

The bit assignments $f_{j\,n_E^{(1)}}$ is conveyed by emitter $n_E{}^{(1)}$ and $f_{i\,n_E^{(2)}}$ is the bit assignment transmitted by $n_E{}^{(2)}$. Consequently $d_H\left(f_{j\,n_E^{(1)}}, f_{i\,n_E^{(2)}}\right)$ represent Hamming distance between these two bit assignments. $PEP(f_j \to f_i|H)$ is the pairwise error probability (PEP) that when signal vector f_i is transmitted and receiver takes decision in favor of f_j assuming receiver knows the channel matrix H.

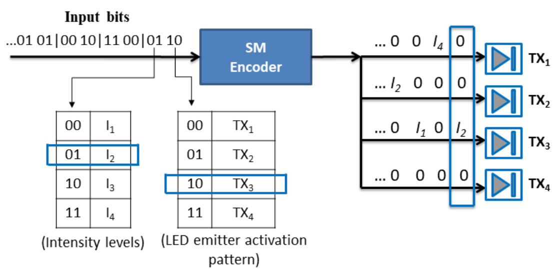

Fig. 5. Representation of SM process with $N_E = 4$ and $M = 4$.

The SM algorithm can be summarized as:

1. The incoming bit streams are divided into blocks. Each block contains $log_2(N_E) + log_2(M)$ bits.
2. From each block, first $log_2(N_E)$ bits decides which LED emitter to be active to transmit the information. The active LED emitter is represented as N_s with $N_s \in \{1,2,..,N_E\}$. While an emitter is transmitting, other LED emitters are inactive.

3. The next $log_2(M)$ bits of a block decides the symbols in the constellation to transmit. Here, f_t is the symbol emitted by LED emitter with $f_t \in \{f_1, f_2, .., f_M\}$.

C. Generalized Spatial Modulation (generalized SM)

Generalized SM is a MIMO technique where more than one LED emitter is activated for transmission while other emitter remains silent. Similar to the SM, in generalized SM, information is conveyed through modulation symbols using LED active pattern and intensity level transmission over active emitters. The operating scenario of generalized SM is represented in Fig. 6. In generalized SM, the active antenna is selected based on $\left\lfloor log_2 \binom{N_E}{N_s} \right\rfloor$ information bits; where N_s is active emitter selected out of N_E. While information is transmitted over N_s emitter, the remaining $(N_E - N_s)$ LED emitters remain silent. The M-ary intensity level of generalized SM is the same as SM as given in Eq. (22) and spectral efficiency is given as:

$$R = \left\lfloor log_2 \binom{N_E}{N_s} \right\rfloor + N_s \lfloor log_2(M) \rfloor \; bpcu \quad (24)$$

The generalized SM performance depends on selection of LED emitter activation pattern as selection affects minimum Euclidean distance. The generalized SM using ML detector decides constellation vector f between any two generalized SM vectors f_i and f_j for channel matrix H.

The BER of generalized SM is given by:

$$BER_{generalized\ SM} = \frac{1}{R|F_{N_E,M}^{N_s}|} \sum_{j=1}^{|F_{N_E,M}^{N_s}|} \sum_{i=1, j\neq i}^{|F_{N_E,M}^{N_s}|} \mathrm{d_H}(f_j, f_i) PEP(f_j \rightarrow f_i|\mathrm{H}) \quad (25)$$

here, $|F_{N_E,M}^{N_s}|$ represents set of all possible signal vector of generalized SM which can be transmitted. The particular activation pattern can be selected for minimum Euclidean distance between two signal vectors f_i and f_j.

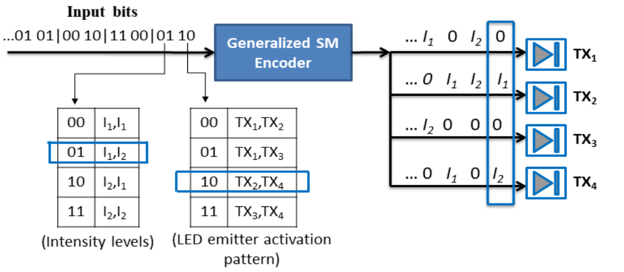

Fig. 6. Representation of generalized SM process with $N_E = 4$, $N_s = 2$ and $M = 2$.

In Summary, the generalized SM algorithm can be explained as:

1. The incoming bit streams are divided into blocks. Each block contains $\left\lfloor log_2 \binom{N_E}{N_s} \right\rfloor + N_s \lfloor log_2(M) \rfloor$ bits.
2. Based on $\left\lfloor log_2 \binom{N_E}{N_s} \right\rfloor$ bits of a block, active LED emitters decided to transmit the information. The N_s LED emitters selected out of N_E. The active LED emitter is represented as N_s with $N_s \in \{1,2, .., N_E\}$. The $(N_E - N_s)$ LED emitters remains inactive.
3. The next $N_s \lfloor log_2(M) \rfloor$ bits of a block decides the symbols in the constellation to transmit. Here, f_t is the symbol emitted by LED emitter with $f_t \in \{f_1, f_2, .., f_M\}$.
4. The constellation vector f chosen such that the Euclidean distance between any two vectors f_i and f_j should be minimum for the channel matrix H.

D. Spatial Multiplexing (SMP)

SMP is a MIMO technique in which independent information is transmitted by all LED emitters simultaneously. In this case, all emitters are active for each channel use. The SMP working scenario is shown in Fig. 7. The signal vector s at any instant has N_E symbols which are modulated and independent. The SMP provides enhanced transmission efficiency $R = N_E log_2(M)$ bpcu. The signal vector in SMP has independent and M-ary modulated N_E symbols.

$$BER_{SMP} = \frac{1}{M^{N_E} log_2(M^{N_E})} \sum_{j=1}^{M^{N_E}} \sum_{i=1}^{M^{N_E}} \mathrm{d_H}(f_j, f_i) PEP(f_j \rightarrow f_i|\mathrm{H}) \quad (26)$$

M^{N_E} is possible combinations of SMP transmitted signal vector.

In summary, the SMP algorithm can be given as:

1. The incoming bit streams are divided into sub-streams and number of sub-streams are equal to number of LED emitters.
2. The number of bits to be transmitted by single LED emitter contained in sub-stream is $N_E log_2(M)$.
3. Each LED emitter transmits the bits contained by sub-stream. The sub-streams are simultaneously transmitted through all existing LED emitters.

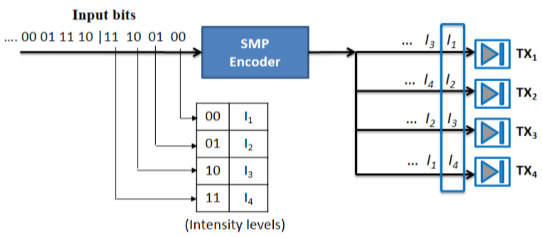

Fig. 7. Representation of SMP process with $N_E = 4$ and $M = 4$.

VI. Results and Discussion

We consider a room geometry of $5m \times 5m \times 3m$ in which 4-LED emitters are fixed on ceiling as shown in Fig. 8. The coordinate of LED emitters are (1.25m, 1.25m, 3.0m), (1.25m, 3.75m, 3.0m), (3.75m, 3.75m, 3.0m), (3.75m, 1.25m, 3.0m) on $x-$, $y-$ and $z-$ axis, respectively. These coordinates are selected to obtain the uniform SNR in the room. Two user terminals are considered at the receiver side and each terminal is equipped with two PDs. The user terminals are at 0.75m above the ground surface and their coordinates are (1.5m, 0.5m, 0.75m) and (3.5m, 3.5m, 0.75m). The whole configuration provides $4 \times [2,2]$ MIMO system for multiuser in VLC. The results are obtained with the help of simulation and important parameters used in simulation are listed in Table I. It is considered that all LED emitters emit same power and field of view (FoV) of PDs is the same. The ML detection method is applied for MIMO transmission schemes.

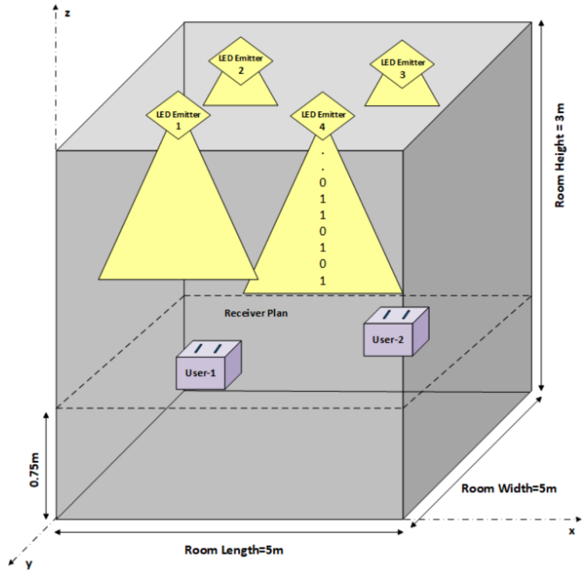

Fig. 8. Geometrical layout of VLC system

TABLE I: SIMULATION PARAMETERS

Parameters	***Values***
Room Dimension	5.0 m × 5.0 × 3.0 m
LED emitters to receiver plane distance	2.25 m
Floor to receiver height	0.75 m
PDs FOV (ψ_c)	70^0
Half power semi angle ($\varphi_{1/2}$)	60^0
PD's Capture area (A)	1 cm^2
Transmission rate	60 Mbps
Single LED power	10 mW
LEDs per emitter	40×40
PD responsivity (*r*)	0.4 Amp/Watt
No. of subcarriers	1024
Length of CP	16
No. of symbols	600

First, we simulated the proposed multi user VLC system for transmission techniques: RC, SM, SMP and generalized SM without using flip-OFDM. The DC bias is used to obtain the non-negative signal for LEDs. The simulated result of BER with regard to SNR is shown in Fig. 9. We find that generalized SM performs better than other transmission techniques.

- RC offers worst performance compared to SMP, SM and generalized SM. RC performs approximately 4dB, 7dB, and 9dB worse compared to SMP, SM, and generalized SM respectively to obtain the same BER 10^{-6}. SM worse about 2 dB compared to generalized SM but it outperforms SMP and RC approximately by 2.5dB and 6.5dB. SMP worse by approximately 2.5dB and 4.5dB compared to SM and generalized SM respectively but outperforms RC by 4dB.
- Generalized SM outperform RC, SMP and SM by approximately 9dB, 5dB and 2dB SNR, respectively to obtain the BER of 10^{-6}.

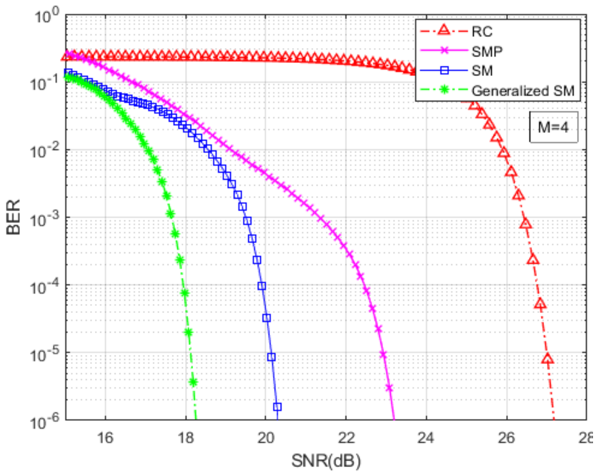

Fig. 9. SNR-BER analysis without flip-OFDM Implementation

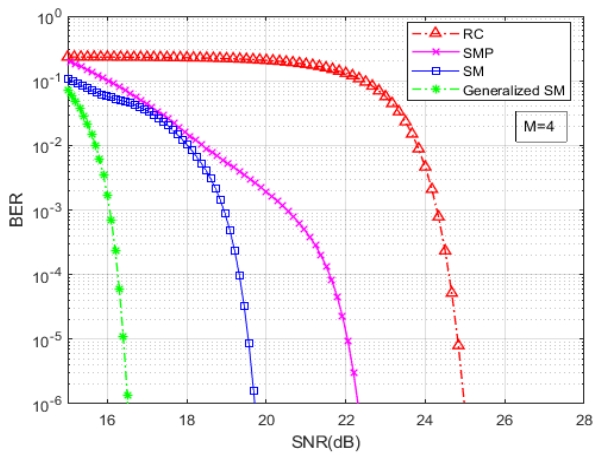

Fig. 10. SNR-BER analysis with flip-OFDM Implementation

Further, we simulated the complete proposed multi user VLC system implementing flip-OFDM. The results of BER with regard to SNR is shown in Fig. 10.

- In this case, the generalized SM outperforms RC, SMP and SM by approximately 8.5dB, 7dB and 3.3 dB SNR respectively to obtain the BER 10^{-6}.
- RC still performs worse than other transmission techniques. SM outperforms SMP and RC. SMP offers worst performance compared to SM and generalized SM.
- We found that the system provides better performance with regard to SNR and BER using flip-OFDM. Generalized SM still offers better performance than RC, SM and SMP.

In summary,

- Due to the effect of spatial interference in SMP, SM and generalized SM gives better SNR-BER performance compared to SMP.
- The generalized SM performance is influenced by channel correlations and channel gain.
- Generalized SM performs better than other transmission techniques due to the spatial interference impact and better hamming distance.

The asymptotical analytical result of BER and SNR for flip-OFDM is shown Fig. 11. According to the results, SNR of 14dB is required to obtain the BER 10^{-6}. Although it is asymptotic behavior, generalized SM performance is closer to this compare to SM, SMP and RC. This could be due to larger value of *N*. *N* is size of IFFT. The FFT operation offers noise whitening for large *N* in frequency domain. Further SNR requirements to achieve same BER increases with increase in constellation size, *M* and use of transmission techniques improves spectral efficiency.

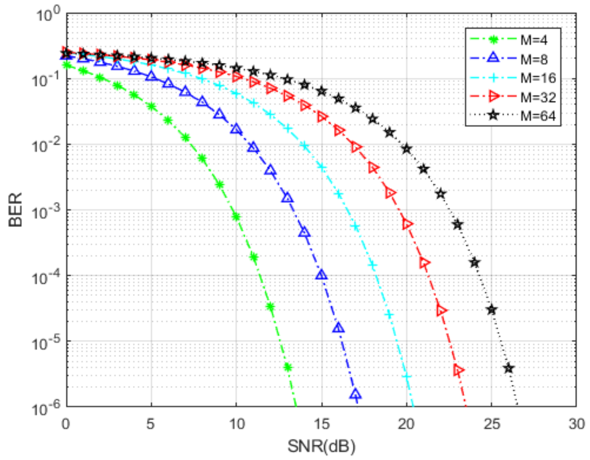

Fig. 11. Theoretical SNR & BER analysis of flip-OFDM

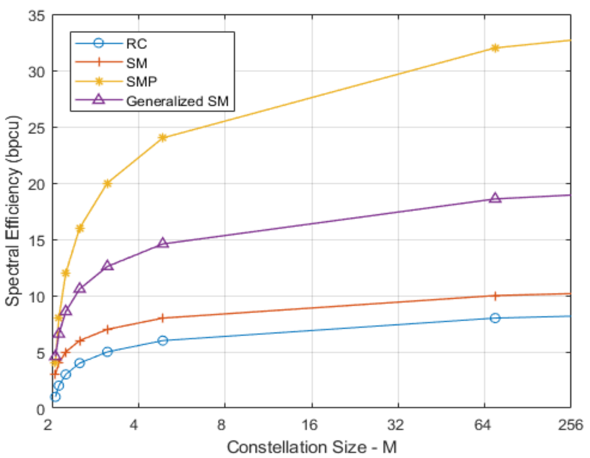

Fig. 12. Spectral efficiency of transmission techniques

Further, analysis is done with regards to transmission efficiency for MIMO transmission techniques. SMP provides better spectral efficiency compared to RC, SM and generalized SM. The simulation result is shown in Fig. 12.

- To obtain the spectral efficiency of 8 bpcu, RC, SM, generalized SM and SMP needs modulation order M = 256, 64, 8 and 4, respectively.
- Similarly for 4 bpcu spectral efficiency, M = 16, 4, 2 and 2 is required by RC, SM, generalized SM and SMP.
- In case of generalized SM transmission efficiency depends on N_t, N_s and M. Generalized SM with $N_E = 4$, $N_s = 2$, $M = 4$ and $N_E = 2$, $N_s = 2$, $M = 8$ gives same spectral efficiency of 6 bpcu.
- The better transmission efficiency can be obtained by SMP with lower modulation order but better SNR-BER performance can be obtained by generalized SM. The power efficiency improves with lower modulation order.
- In SMP, the spectral efficiency increases with number of LED emitters but at the expense of hardware and computational complexity. Hardware complexity due to the fact that receiver has to overcome ICI caused by emitting information simultaneously from all LED emitters. Computational complexity due to number of RF chains equal to number of LED emitters and this leads to power consummation as power requirement will increase with RF chains.
- In SM, only one RF chain is required to transmit which reduces hardware complexity. Furthermore, only one emitter transmits at a time and hence power consumption is independent of number of LED emitters.

Furthermore, we analyzed PAPR of the flip-OFDM signal. The PAPR is illustrated complementary cumulative distribution (CCDF) i.e. probability that PAPR is greater than some certain value. In Fig. 13, we showed the analytical and simulated result for PAPR-CCDF of flip OFDM signal. In proposed flip-OFDM system with 1024 subcarriers and QAM modulation, the PAPR at the output can be as high as 18dB for CCDF of 10^{-5}. This PAPR value is almost the same as offered by any other schemes of OFDM in VLC.

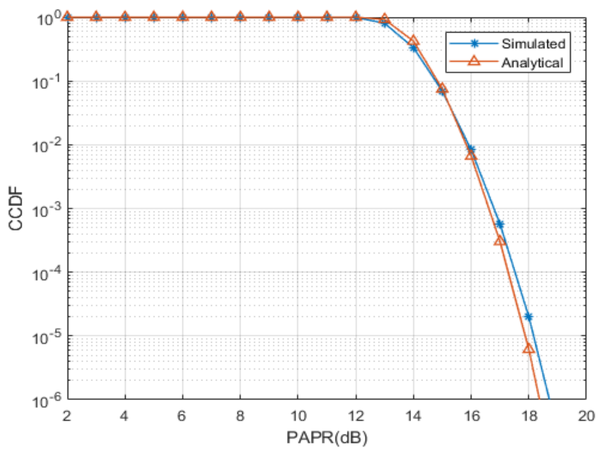

Fig. 13. PAPR CCDF of VLC flip-OFDM signal

VII. Conclusion

The different transmission method using flip-OFDM optical MIMO for multi user VLC system is analyzed. The comparative analysis is performed with and without flip-OFDM. With the help of simulation results, it is found that performance improves using flip-OFDM and generalized SM offers better SNR-BER performance in both the cases. Furthermore, it is analyzed that SMP with lower modulation order provides better transmission efficiency and also they are power efficient. The PAPR CCDF analysis is done and found in same range as offered by other OFDM schemes. The PAPR reduction techniques can be investigated in the context of flip-OFDM VLC which we are carrying out as extension of this work.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mahesh Kumar Jha conducted the research work. Navin Kumar analyzed the data. Navin Kumar and Y V S Lakshmi supervised the work as a supervisor. All authors agreed to this final version of work submission.

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