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Flip-OFDM Optical MIMO Based VLC System Using ML/DL Approach

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Abstract

Flip orthogonal frequency division multiplexing (OFDM) is a variation of OFDM which modifies the bipolar OFDM signal in the unipolar signal by flipping the negative sign of the subcarriers. Flip-OFDM in multiple input multiple output (MIMO) visible light communication (VLC) system improves the orthogonally of the subcarriers and reduces bit error rate, which results in a higher data rate and a more robust communication system. Machine learning (ML) and deep learning (DL) techniques are being used to improve various aspects of VLC systems such as modulation, channel estimation, and MIMO design, which can result in more robust and efficient communication systems. In this paper, deep neural network (DNN), convolution neural network (CNN) and long short-term memory (LSTM) algorithms are used to analyze flip-OFDM optical MIMO VLC system. The MIMO techniques, repetitive coding (RC), spatial modulation (SM), generalized spatial modulation (generalized-SM) and spatial multiplexing (SMP) are analyzed with and without flip-OFDM. Simulation results showed that generalized-SM outperformed SM, SMP and RC with and without flip-OFDM. In both scenarios, CNN improved performance and outperformed LSTM and DNN.

Category: Network and Communications

Keywords: Visible light communication; Flip-OFDM; MIMO techniques; CNN; DNN; LSTM

I. INTRODUCTION

Visible light communication (VLC) is a technology that uses light in the visible spectrum (typically between 400 and 800 nanometers) to transmit data, it has several advantages over the traditional wireless communication systems such as high speed, high security, energy efficiency and it can be integrated with indoor lighting [1]. It can be

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used to provide wireless internet access in places where traditional wireless signals are weak or unavailable, such as airports, hospitals and underground train stations [2]. The advanced techniques of radio frequency (RF) such as orthogonal frequency division multiplexing (OFDM) [3], multiple input multiple output (MIMO) [4] and a combination of MIMO-OFDM [5] are being investigated to get integrated in VLC.

MIMO-OFDM provides several key benefits in VLC systems such as improving the spatial multiplexing (SMP) gain, reducing the interference caused by adjacent subcarriers, increasing the robustness of the system to the movement of the mobile devices, and thus providing a more efficient and robust communication system. In MIMO VLC, multiple light sources and multiple photodetectors are used to transmit and receive multiple data streams simultaneously [6]. Various modes of data transmission in VLC have been investigated. For example, SMP, spatial modulation (SM), generalized-SM and repetition coding (RC) [6-10]. Likewise, to get the real and positive signal for intensity modulation in VLC, different OFDM forms have been investigated. For example, 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 [11, 12]. Flip OFDM is a variation of OFDM which modifies the bipolar OFDM signal in unipolar signal by flipping the negative sign of the subcarriers. In [13], the performance of RC, SM, generalized-SM, and SMP for multi-user VLC systems is studied and compared with and without the use of flip-OFDM.

Machine learning (ML) and deep learning (DL) techniques have been used to improve the performance of VLC systems. VLC systems use light in the visible spectrum to transmit data, and ML/DL techniques can be used to optimize various aspects of the system, such as modulation, coding, and channel estimation [14, 15]. For instance, ML/DL techniques have been applied in the designing of modulation schemes in VLC. ML/DL can be used to optimize the mapping of data symbols to light intensities, which can improve the robustness of the system with resistance to noise and interference. DL techniques have also been used to improve the performance of channel estimation in VLC systems. A channel in a VLC system refers to the propagation of light from the transmitter to the receiver. DL can be used to learn the channel characteristics, such as the path loss and the angular spread of the light, which can improve the accuracy of the channel estimates. ML/DL techniques have been used in the designing of MIMO systems used in VLC. ML/DL can be used to optimize the beam forming and precoding matrices, which can improve the spatial multiplexing gain and reduce inter-symbol interference.

This paper presents an analysis of the Flip-OFDM optical MIMO VLC system using ML/DL. The deep neural network (DNN), convolution neural network (CNN), and long short-term memory (LSTM) algorithms were used as tools. The findings of this work were as follows:

- The RC, SM, SMP and generalized-SM MIMO transmission techniques were implemenetd with and without flip-OFDM. It was concluded that flip-OFDM performance in terms of bit error rate (BER) and signal-to-noise ratio (SNR) was better. Further, generalized-SM outperformed RC, SMP and SM in both cases.
- The VLC system with and without flip-OFDM was analyzed using CNN, LSTM and DNN. MATLAB tool was used to randomly generate data sets for training offline and deploying online. In both cases, the use of ML/DL outperformed the conventional system. In addition, notably, CNN algorithm performance was better than LSTM and DNN.

The other sections of this paper are organized as follows. The flip-OFDM optical MIMO-based VLC system is explained in Section II. Section III describes the ML/DL approach in the VLC system. Section IV summarizes the simulation results and important findings, and Section V is the conclusion.

II. FLIP-OFDM BASED VLC SYSTEM

The transmitter section of multi-user OFDM-MIMO VLC system is shown in Fig. 1. We consider K users to analyze the multiuser VLC system. To avoid interferences due to multiuser, block diagonalization (BD) is applied to the on-off keying (OOK) modulated bit-streams. To combat inter-symbol interference, the OFDM process is applied after precoding. It also assists in high transmission rates. OFDM modulated signal must be real and positive to characterize as intensity and support intensity modulation and direct detection (IM/DD). Here, we use flip-OFDM to obtain real and positive signals from bipolar OFDM signals to transmit through LEDs. Next, MIMO transmission techniques are applied sequentially to transmit the signals from LEDs emitters. We use four different MIMO transmission techniques—RC, SM, generalized-SM, and SMP—to enhance the BER, SNR, transmission efficiency, etc., performance parameters. At the receiver, photodetectors (PDs) are used to receive visible light signals through line-of-sight (LoS) and convert them into electrical signals. The electrical signal is demodulated as per the process shown in Fig. 2. The transmitted signal is estimated by using the maximum likelihood technique. The details of modulation and demodulation process of flip-OFDM are depicted in Fig. 3.

The *M*-ary quadrature amplitude modulation (M-QAM) is applied to modulated parallel divided bit streams to transmit using subcarriers. The k^{th} sample output of *N*-point IFFT process is represented by:

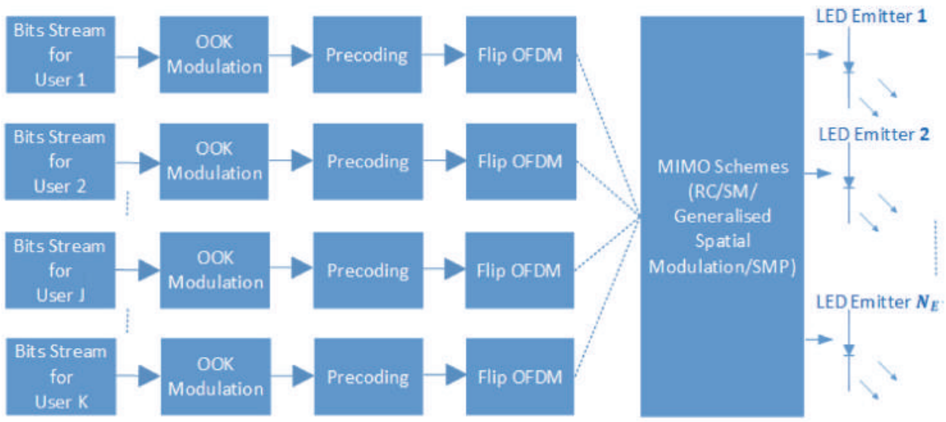

Fig. 1. Transmitter structure for multi-user flip-OFDM optical MIMO VLC.

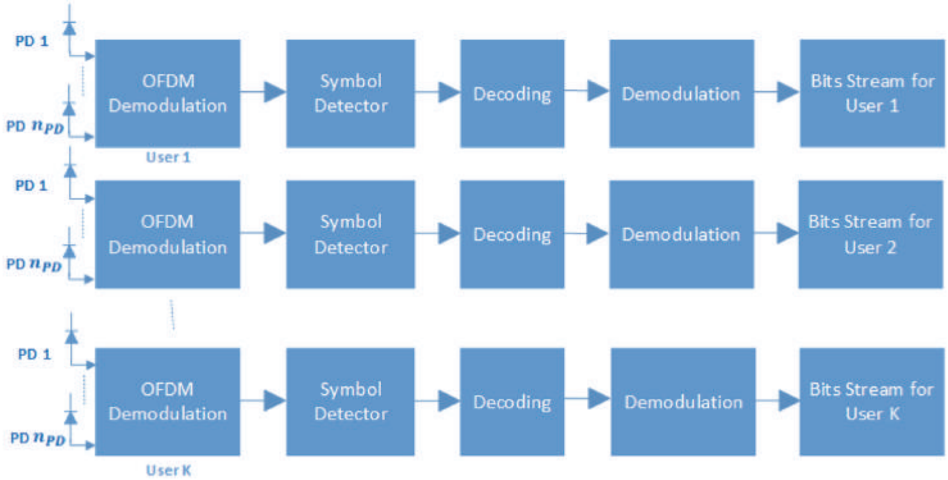

Fig. 2. Receiver structure for multi-user flip-OFDM optical MIMO VLC.

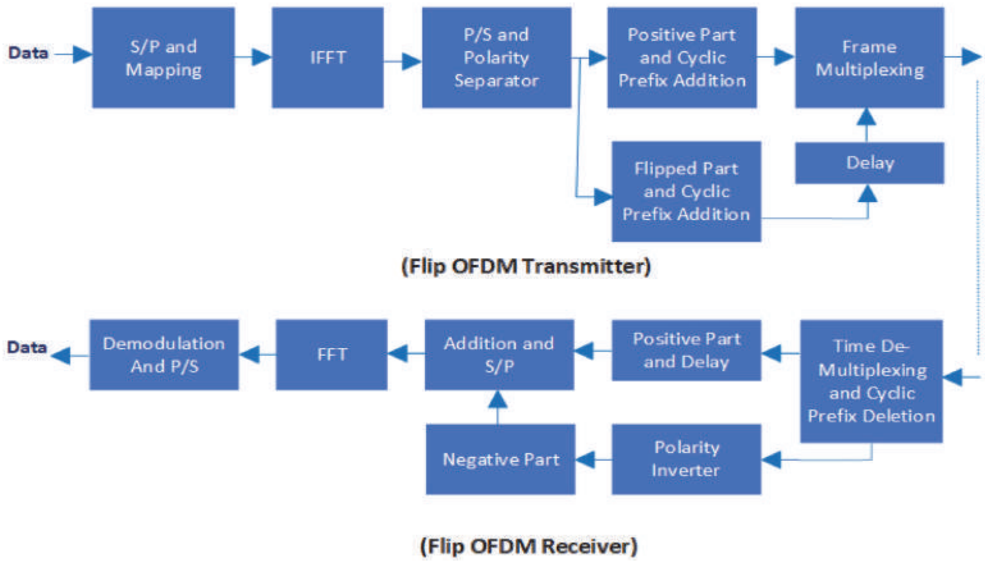

Fig. 3. Block diagram of flip-OFDM.

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

where, $F(n)$ is modulated symbol by n^{th} subcarrier.

To avoid the complex nature of the time domain signal $f(k)$, Hermitian symmetry is imposed, i.e.,

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

Eq. (1) can be written as:

$$f(k)=\frac{1}{\sqrt{N}}\left[\sum_{n=0}^{\frac{N}{2}-1} F(n) e^{\frac{j2\pi nk}{N}} + F\left(\frac{N}{2}\right) e^{j\pi k} + \sum_{n=\frac{N}{2}+1}^{N-1} F(n) e^{\frac{j2\pi nk}{N}}\right] \quad (3)$$

Applying Hermitian symmetry in (3), we get:

$$f(k)=\frac{1}{\sqrt{N}}\left[\sum_{n=0}^{\frac{N}{2}-1} F(n) e^{\frac{j2\pi nk}{N}} + F\left(\frac{N}{2}\right) e^{j\pi k} + \sum_{n=\frac{N}{2}+1}^{N-1} F^*(N-n) e^{\frac{j2\pi nk}{N}}\right] \quad (4)$$

$F(0) = F\left(\frac{N}{2}\right) = 0$ to bypass DC and other complex parts in the time domain. The real and bipolar IFFT output is represented as:

$$f(k) = f^+(k) + f^-(k) \quad (5)$$

where

$$\left.\begin{array}{c} f^+(k) = \begin{cases} f(k) & if\ f(k) \geq 0 \\ 0 & otherwise \end{cases} \\ and \\ f^-(k) = \begin{cases} f(k) & if\ f(k) \leq 0 \\ 0 & otherwise \end{cases} \end{array}\right\} \quad (6)$$

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

As shown in Fig. 3, two different sub-frames are used to transmit the positive ($f^+(k)$), and negative ($f^-(k)$) parts. $f^-(k)$ is flipped before transmission. δ is the duration for cyclic prefix added to the sub- frames, i.e., $(N + \delta)$ is the total length for the OFDM frame. The sub-frames are time multiplexed but the second sub-frame is delayed $(N + \delta)$ before multiplexing.

The OFDM bipolar signal is obtained at the receiver using received two sub-frames. After removing the cyclic prefixes from multiplexed frames, the resultant bipolar OFDM symbol is given as:

$$y(k) = y^+(k) - y^-(k) \quad (7)$$

where $y^+(k)$ and $y^-(k)$ are symbols corresponding to $f^+(k)$ and $f^-(k)$, respectively.

The FFT operation is applied after converting serial to parallel which results in a complex conjugate signal. Finally, QAM demodulation is applied to detect the signal for the users.

III. ML/DL APPROACH FOR FLIP-OFDM BASED VLC SYSTEM

We used three ML/DL algorithms—DNN, CNN, and LSTM—to compare the performance of conventional and flip-OFDM VLC system. In a conventional system presented in Section II, DNN, CNN, and LSTM algorithms are used after DFT operation.

A. DNN

The basic DNN structure is depicted in Fig. 4. We considered N neurons for the input layer. This is decided based on signal reception at PDs and DFT. y_D is input to DNN. L_1 and L_2 are two hidden layers connected to extract the features. To train and optimize the results, rectified linear unit (ReLU) activation function is imposed for hidden layers with b as bias and W as weight. Here, $Z_{L_1}^1$ and $Z_{L_2}^2$ is considered as the output of the first and second hidden layer, respectively, which is given as:

$$Z_{L_1}^1 = f_{ReLU}(W_1\, y_D + b_1) \quad (8)$$

$$Z_{L_2}^2 = f_{ReLU}(W_2 Z_{L_1}^1 + b_2) \quad (9)$$

where $W_1 \in \mathbb{R}^{L_1 \times N}$ & $b_1 \in \mathbb{R}^{L_1}$ represent the first hidden layer and $W_2 \in \mathbb{R}^{L_2 \times L_1}$ & $b_2 \in \mathbb{R}^{L_2}$ for second hidden layer. Also,

$$f_{ReLU}(\tau) = \max(0, \tau) \quad (10)$$

Next, bits estimation is done at the output layer in between (0, 1). To achieve this, the sigmoid function is applied to S neurons.

Hence, after the output layer, the estimated bits are:

$$Z^O = f_{Sigmoid}(W_3 Z_{L_2}^2 + b_o) \quad (11)$$

$$Z^O = \{z_1^O, z_2^O, z_3^O, \ldots \ldots \ldots, z_S^O\}^T \quad (12)$$

Finally, output bits are obtained using a hard decision layer. The threshold operation is imposed to get output bits, b_S.

$$b_s = \begin{cases} 1, & if\ b_s^O \geq 0.5 \\ 0, & if\ b_s^O < 0.5 \end{cases} \quad (13)$$

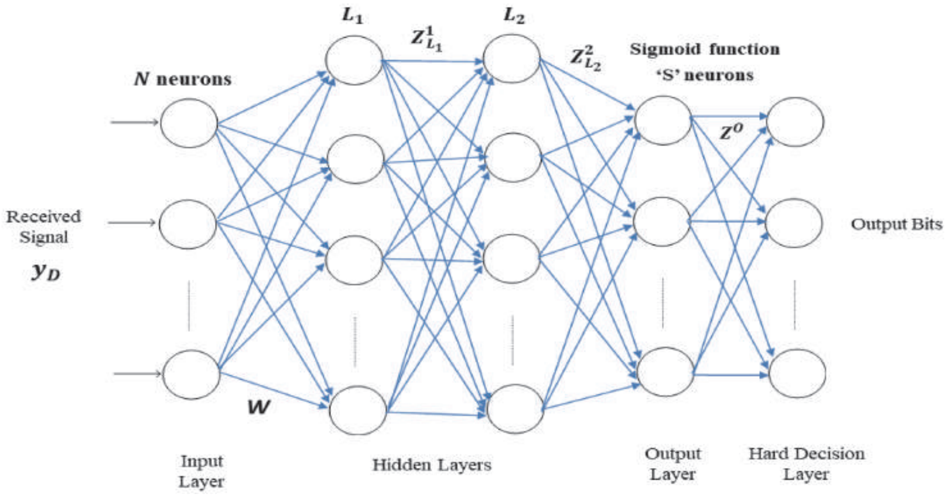

Fig. 4. DNN structure.

The error is found using the loss function, mean square error (MSE), between transmitted and received bits.

B. CNN

Fig. 5 presents the basic structure of CNN. The modulated signal over N subcarriers is input to the first convolution layer. Assuming y_C^R and y_C^I are real and imaginary parts, the input signal is given as $y_c^1 = [y_C^R, y_C^I]$. As per basic CNN operation, convolution is performed between the input and kernel, size M. The output for the first convolution layer is obtained by using the ReLU activation function and is given as:

$$Z_{L_1}^{1,i} = f_{ReLU}(y_c^i) = \max(0, Z_c^{1,i}) \tag{14}$$

where

$$Z_c^{1,i} = y_c^1 * K_1^i + b_1^i \tag{15}$$

$Z_c^{1,i}$ is the output before applying an activation function. K_1^i is i^{th} kernel of thee first convolution layer (i = 1,2,3, ..., M). b_1^i is the bias corresponding to the kernel K_1^i.

Similarly, convolution is performed in between the output of the first convolution layer and kernel with size 2K. Here, to estimate the output bits for the second convolution layer, the sigmoid function is imposed. The output of the second convolution layer is given as:

$$Z_{L_2}^{2,i} = sigmoid(Z_c^{2,i}) \tag{16}$$

where

$$Z_c^{2,i} = y_c^2 * K_2^i + b_2^i \tag{17}$$

y_c^2 is the input to the second convolution layer. $Z_c^{2,i}$ is the output before applying an activation function. K_2^i represent i^{th} kernel for the second convolution layer (i = 1,2,3, ..., $2K$). b_2^i is the bias for the kernel K_2^i. Finally, output bits are obtained using a hard decision layer as per Eq. (13). The MSE is used as a loss function to measure the errors between transmitted and received bits.

C. LSTM

The basic LSTM structure is shown in Fig. 6. The very

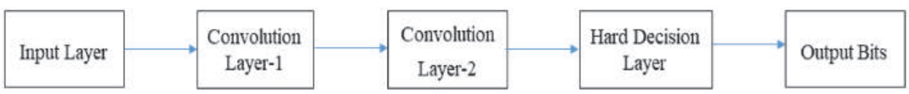

Fig. 5. CNN structure.

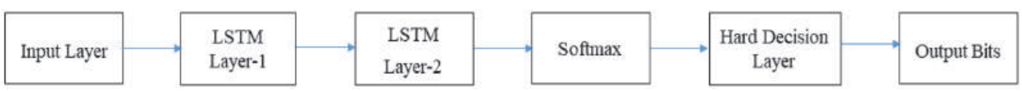

Fig. 6. LSTM structure.

fundamental LSTM process followed as [16]. y with dimension C represents the second LSTM layer output. This output passes through the softmax layer used as the activation function.

$$softmax(y) = \frac{e^{y_i}}{\sum_{j=1}^{C} e^{y_j}} \quad (18)$$

where e^{y_i} and e^{y_j} are the standard exponential function corresponding to the input and output vectors. Finally, output bits are obtained using hard decision layer as per Eq. (13).

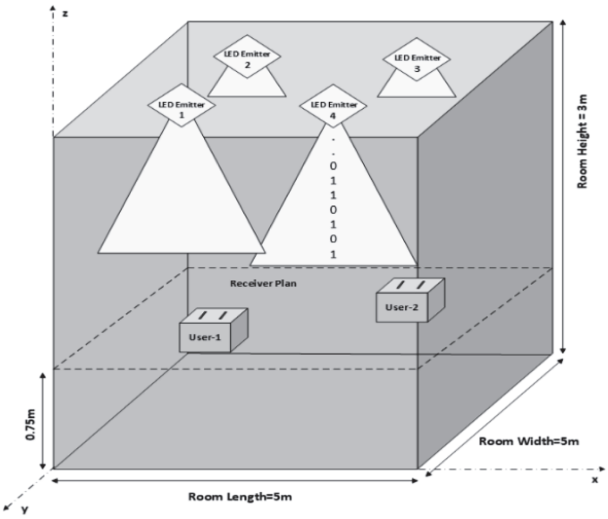

Fig. 7. Geometrical layout of the VLC system.

Table 1. Parameters used in simulation

Parameter	Value
Room layout	5 × 5 × 5 m^3
Coordinates of LEDs emitters	(1.25, 1.25, 3)m (1.25, 3.75, 3)m (3.75, 3.75, 3)m (3.75, 1.25, 3)m
User terminals	$UT1$(1.5, 0.5, 0.75)m $UT2$ (3.5, 3.5, 0.75)m
PDs FOV	70°
Half power semi-angle	60°
PD's capture area	1 cm^2
Bit rate	60 Mbps
Power/LED	10 mW
LEDs/emitter	40×40
Total subcarriers	1024
CP length	16
Total symbols	600

IV. SIMULATION RESULTS AND FINDINGS

Consider a 5 m × 5 m × 3 m room layout in which 4-LED emitters are fixed on the ceiling as shown in Fig. 7. Two user terminals (UTs) each with 2 PDs are considered at the receiver side. The complete configuration is viewed as a 4 × [2,2] multi-user MIMO system in VLC. The simulation results are obtained by MATLAB 2021 software and some simulation parameters are listed in Table 1. The maximum likelihood technique is used for the detection method.

The VLC system explained in Section II is simulated. To analyze the performance of the flip-OFDM based system, we compared it with the VLC system which does not use the flip concept. Instead of flip, DC bias is used to obtain a unipolar signal from a bipolar OFDM signal. The simulation results are shown in Figs. 8 and 9. The

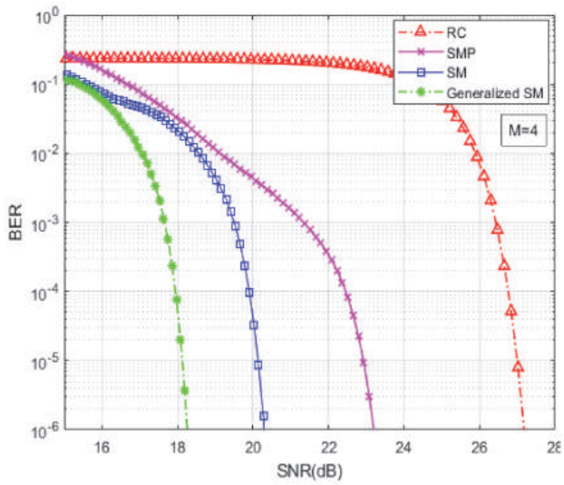

Fig. 8. SNR-BER analysis without flip-OFDM implementation.

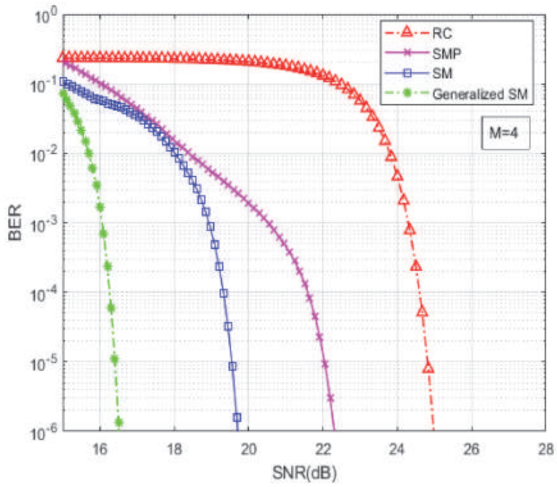

Fig. 9. SNR-BER analysis with flip-OFDM implementation.

Table 2. Performance of flip-OFDM optical MIMO VLC system

MIMO technique	SNR for BER 10^{-6} (dB)	
	Without flip-OFDM	With flip-OFDM
RC	27.1	25
SMP	23.2	22.2
SM	20.2	19.8
Generalized-SM	18.2	16.5

summarized details are presented in Table 2. We find that the generalized-SM outperformed RC, SMP and SM in both cases. Further, flip-OFDM based optical MIMO VLC system performed better with the same BER of 10^{-6}.

In summary,

- Spatial interference affects the SMP by degrading the SNR-BER performance of SMP to a level below that of the generalized-SM and of the SM.
- The channel gain and correlations impact the performance of generalized-SM.
- Out of four MIMO transmission techniques presented, the generalized-SM surpasses other transmission techniques. This is because of better hamming distance and better spatial interference impact.

Next, we analyze both cases, with and without flip-OFDM, using DNN, CNN and LSTM algorithms. MATLAB tool is used to generate the data sets randomly. The 48,000 symbols are generated for training offline and deploying online. The 70% of the data is used for training and the remaining for evaluation. The learning rate was 0.001. Each hidden layer has 16 neurons. The input and the output layer have 4 and 24 neurons, respectively. The performances of BER and SNR using flip-OFDM were obtained using simulation and are shown in Fig. 10. Results are summarized in Table 3. It was observed that CNN, LSTM, and DNN outperformed the convention

Table 3. BER performance using ML/DL approach

Method	SNR for BER 10^{-6} (dB)	
	With flip-OFDM	Without flip-OFDM
RC	25	27.25
LSTM–RC	20.9	22.8
CNN–RC	18.5	20.1
DNN–RC	21.2	23.2
SMP	22.3	23.2
LSTM–SMP	18.5	19.2
CNN–SMP	16.5	17.2
DNN–SMP	19	19.9
SM	19.8	20.2
LSTM–SM	13.5	14
CNN–SM	13	13.5
DNN–SM	14	14.5
Generalized-SM	16.5	18.25
LSTM–generalized-SM	13.5	15.2
CNN–generalized-SM	12.2	13
DNN–generalized-SM	14	15.5

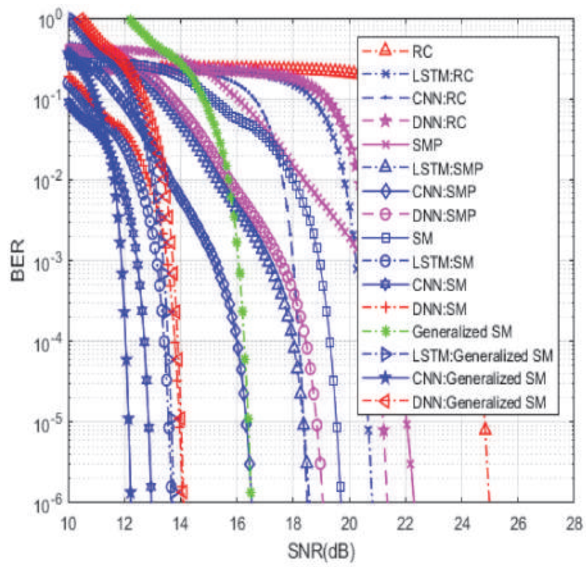

Fig. 10. BER performance using ML/DL approach with flip-OFDM.

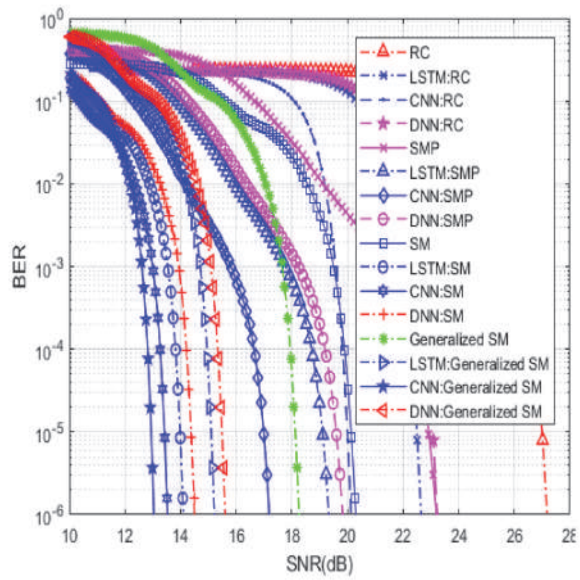

Fig. 11. BER performance using ML/DL approach without flip-OFDM.

OFDM MIMO VLC system. Further, CNN outperformed LSTM and DNN. The BER and SNR performance results without using flip-OFDM were obtained using simulation and are shown in Fig. 11. Results of the same are summarized in Table 3. In addition, in this case, it was observed that CNN, LSTM and DNN outperformed the convention OFDM MIMO VLC system. Further, CNN outperforms LSTM and DNN. Comparing both cases, with and without flip-OFDM using ML/DL approach, it was found that with the flip-OFDM, performance was improved.

V. CONCLUSION

The different MIMO techniques—RC, SM, generalized-SM, and SMP—are compared with and without the use of the flip-OFDM. It was found that the use of flip-OFDM improves the performance. Generalized-SM surpasses other MIMO techniques. CNN, DNN and LSTM algorithms are also used to train and analyze the performance of the VLC system. Simulation results showed that the ML/DL approach at the receiver outperforms the conventional system. Therefore, ML/DL-based receiver is a potential solution to overcome the nonlinearity effects in VLC. The ML/DL applications in VLC are in the early stages of development and it is a promising research area to improve VLC performances and applications.

Conflict of Interest(COI)

The authors have declared that no competing interests exist.

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