Performance Improvement using MIMO-OFDM in Visible Light Communication Systems

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Abstract -- **In the spectrum hungry world of communications, limited data rate of communication is the primary constraint with RF systems. Same applies equally to the other modes of communication systems. Advancements in the world of communications, specially the modulation technique led to manifold increase of data rates and the same can be observed with MIMO-OFDM methods that provide an improvement in reliability by offering spatial diversity as well.**

This paper discusses various aspects of improvements using MIMO-OFDM modulation approach. Reported works done for Visible Light Communication (VLC) towards system performance improvement using MIMO-OFDM methods are discussed. It also describes channel modeling for MIMO, OFDM and MIMO-OFDM systems. The facts and figures are presented with the results of few simulations using traditional BPSK, QPSK and OFDM codes and BER performance has been discussed for SNR levels with respect to BPSK and QPSK modulations.

Keywords: Visible Light Communication, Laser diode, Data rate, Indoor communication, Filtering, Equalization, MIMO, OFDM, MIMO-OFDM

I. INTRODUCTION

COMMUNICATION systems require higher data rates for quick and reliable communication. Same applies to the field of Visible Light Communications (VLC). The visible light covers a spectrum of 380nm - 780nm. Initially the data rate of VLC was not so significant to meet growing needs but with the silicon technology advancements and in-depth researches carried out in material sciences led to a better quality of devices available for various forms of communication.

Talking about optical communications, various studies have shown that LEDs can generate signal spectrum in the band of 380nm - 780nm wavelength band with a quick switching property, that can be simultaneously used for illumination and communication. The idea of parallel illumination and communication via same physical carrier was suggested by Nakagawa *et al*. in 2003 [1- 4]. After the advent of this new revolutionary concept, research gained momentum in the field of VLC across the globe and by 2011, IEEE released visual light wireless communication, a global standard with the name 802.15.7-2011 [5]. LEDs are finding a widespread usage in the areas of visible light communication due to high efficiency, low cost and long life. VLC is becoming highly popular and gaining widespread acceptance for short range wireless optical communication. VLC has various advantages over RF, like immunity to RF and microwave interference, inbuilt security, data network for radio-restricted areas, gigabit data rates, unregulated spectrum and huge bandwidth with available network infrastructure [6 - 8].

Variety of research documentation and literature provide enough evidence that though LEDs offer multiple benefits over conventional light sources yet specifically the phosphor-based white LED has low intrinsic bandwidth limiting data rate to few MHz only. High power white light LEDs are becoming popular these days in various areas of wireless optical communication due to a better modulation bandwidth than other lighting sources such as fluorescent and incandescent lamps. In spite of a few limitations, LEDs are the best optical sources for the VLC systems. Figure 1 shows the basic block diagram of a VLC system.

II. DATA RATE IMPROVEMENT IN VLC SYSTEMS

Methods of data rate improvement are listed in Table 1. Various methods are combined together to provide much better individual results. On a broad scale, a white LED is categorized into three classes

- LEDs using three separate red-green-blue (RGB) emitters
- Blue emitters coated with phosper that emit yellow light
- UV emitters coated with RGB phosper.

Due to higher efficiency and less complexity, blue emitters coated with phospers emitting yellow light (generally called as blue emitters) are found to be more suitable for general illumination and communication. But the biggest challenge is to provide higher data rate with the blue emitters due to their limited modulation bandwidth which is typically between 3-5 MHz. Blue light is the most commonly used wavelength for communication due to enhancement in the modulation bandwidth. Commonly employed method of using blue light is the blue filtering that allows only blue emitted light to enhance the limited modulation bandwidth of white LED

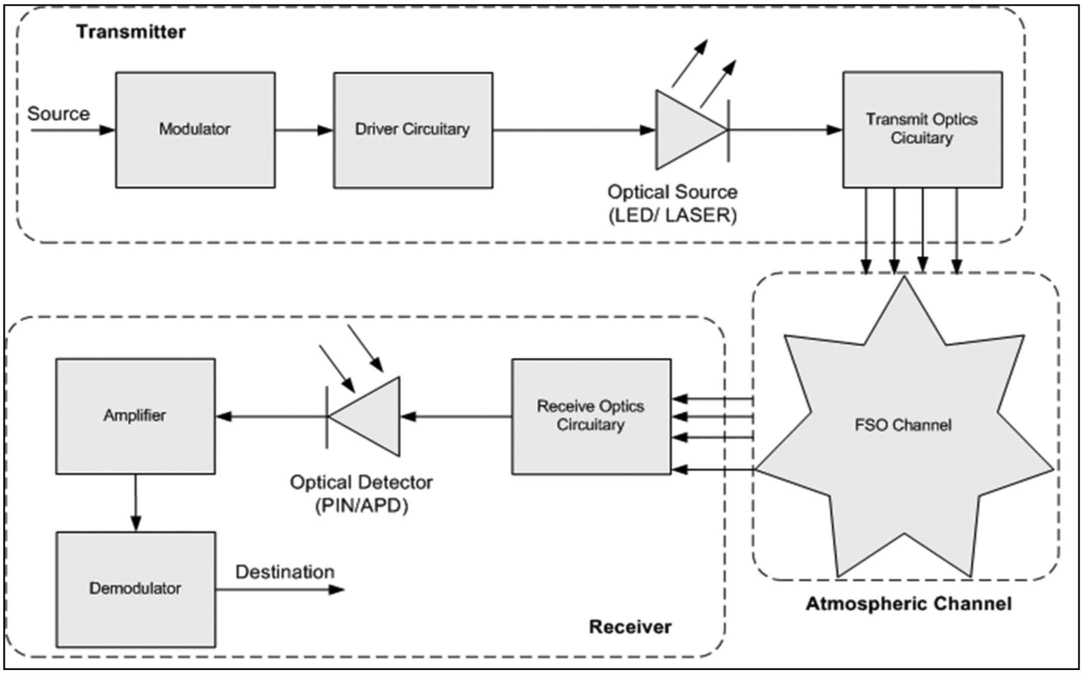

Figure 1. Block diagram of a basic VLC system.

TABLE 1 – METHODS TO IMPROVE DATA RATES

<table>
<tr><td rowspan="6">Blue Filtering</td><td colspan="2">Equalisation</td><td>Modulation</td><td rowspan="6">MIMO</td><td>Hybrid</td></tr>
<tr><td>Hardware</td><td>Software</td><td>OOK</td><td>Filtering & Equalisation</td></tr>
<tr><td>Pre/Post</td><td>Adaptive</td><td>Pulse</td><td>Equalisation & Modulation</td></tr>
<tr><td colspan="2" rowspan="3">Multiple resonance</td><td>OFDM</td><td>Modulation & Multiplexing</td></tr>
<tr><td rowspan="2">CSK</td><td>Equalisation, Modulation & Multiplexing</td></tr>
<tr><td>MIMO & OFDM</td></tr>
</table>

from 3 MHz to 20 MHz with reduced signal strength at the receiver [8]. Deployment of blue filtering at the receiver filters out slow yellow component. Data rate improvement is further achieved using a pre-equalization to the driving circuit and post-equalization of the receiver.

The very first use of blue filter along with OOK was demonstrated practically by Grubor *et al.* [9] at 40-Mbps. This data rate was subsequently improved to 100 Mbps by using multilevel modulation.

Figure 2 shows the impact of blue filtering technique on BER due to higher data rate and increase of distance between the transmitter and receiver in the VLC. In non-usage of blue filtering, background noise causes higher probability of error and unreliable communication due to rise in data rate.

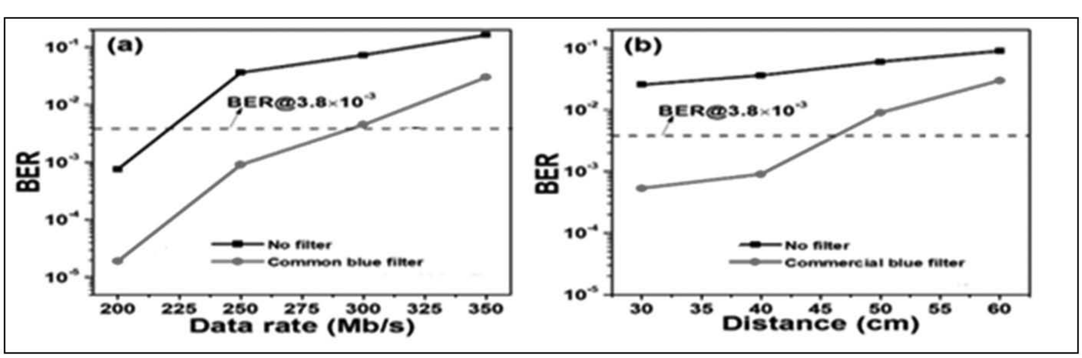

Figure 2. Impact of blue filtering and distance between Tx-Rx on BER.

Howsoever, data rate increase still keeps probability of error to a lower level by 10 dB in case of blue filtering as compared to the non blue filtering.

The other approach to improving data rate in VLC is by use of spectrally efficient modulation techniques like discrete multi-tone modulation technique (DMT), OFDM, MIMO and MIMO-OFDM. Normally, combination of blue filtering, spectrally efficient modulation technique, pre-equalization and post-equalization achieves OOK-NRZ data transmission rate of as high as 340 Mbps.

Zeng *et al.* used equalization, that not only improved data rates but also provided a highly reliable communication channel [10]. Equalization process doubled data rate with the use of non return-to-zero (NRZ)–OOK, and BER was 10^{-6} with respect to non-equalized transmission channel. Based on characteristics of the VLC channel, uneven channel will bring great obstacles to high speed transmission of data. Although OFDM modulation technique can improve system performance to a certain extent, equalization procedure is imperative to further enhance the system capacity. Equalization procedure can be categorized into two types *i.e.* software equalization and hardware equalization. Former mainly involves digital signal processing, while the latter mainly relates to hardware circuit design. Equalization applied at the transmitter (pre-equalization) is an efficient way to increase bandwidth as well as enhance the data rate [1]. Figure 3 shows the architecture and placement of blue filtering techniques and the pre-equalizer and post-equalizer in a VLC system to improve data rate.

Literature shows that hardware pre-equalization technology is proved to be an effective way to improve the bandwidth of the VLC system. But it still suffers from some limitations like analog circuit is susceptible to interference, and its bandwidth is limited. Therefore it does not fit for high-speed signal transmission. On the other hand, software equalization provides more accurate and higher flexibility and is more attractive. Though the limited bandwidth of LED is taken care by using equalization and blue filtering techniques, there exist various issues of flickering and dimming of LED in order to achieve higher data rates.

III. MIMO, OFDM, MIMO-OFDM IN VLC SYSTEMS

Multipath propagation is vital characteristic of data transmission in any wireless communication system. Wireless channel contains different impairment to transmitted signal and channel response. It affects the signal to travel in multipath between transmitter and receiver. Receiver gets the reflection of same symbols in delay versions. Delays or fading occurs due to reflection, refractions, diffractions, shadowing etc. because of buildings, trees, aircrafts, humidity, temperature etc. Delay or fading could be a result of changing phase or magnitude of signals. The multipath effects and delay profile reduce channel efficiency, throughput and cause corrupted information at receiver. In Rayleigh fading, signal travels through different paths and considered to follow independent behavior in every path, phase is uniformly distributed between 0 to 2π and magnitudes vary randomly. While in Rician fading, the line of sight (LOS) exists *i.e.* one of the paths to receiver is much stronger than other one. A signal or symbol of delay version differ in phase with line of sight signal phase. Crust and trough of both these signals cause resultant signal to be high or of attenuated average power. Resultantly, we may get distorted signal at receiver end.

A. MIMO

To cater to multipath propagation and fading effect in wireless communications, the idea of MIMO is employed.
Intelligently multipath effect of propagation is used by MIMO

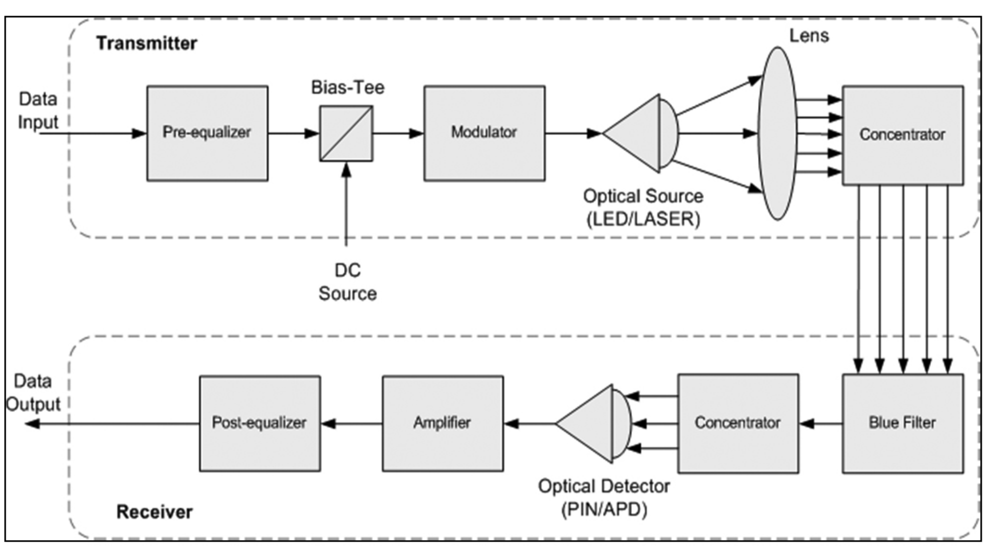

Figure 3. Usage of blue filtering, pre/post equalization in VLC system.

technology to increase capacity of system. For various antenna systems, there are four basic configurations

- Single Input Single Output (SISO)
- Single Input Multiple Output (SIMO)
- Multiple Input Single Output (MISO)
- Multiple Input Multiple Output (MIMO).

Figures 4 to 7 provide a simple block diagram architecture of all the four basic configurations of MIMO systems.

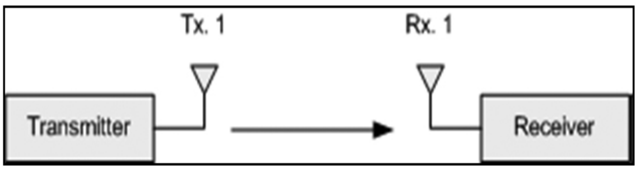

Figure 4. Block diagram of SISO system.

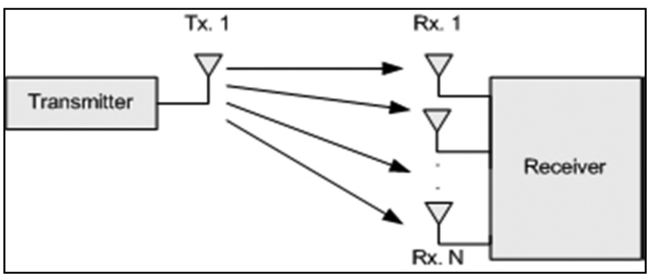

Figure 5. Block diagram of SIMO system.

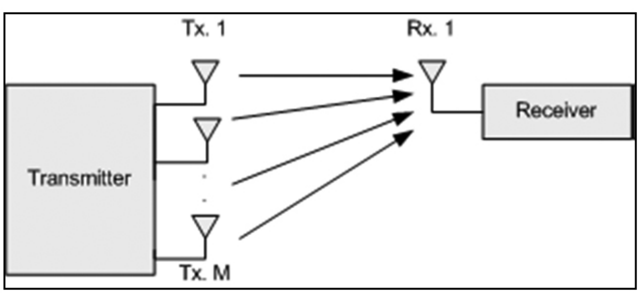

Figure 6. Block diagram of MISO system.

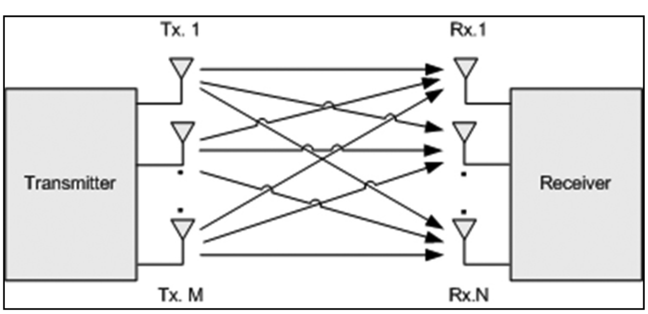

Figure 7. Block diagram of MIMO system.

Multiple-input multiple-output (MIMO) technique provides a linear capacity increment with the increase in the number of transceivers via parallel (multipath) transmissions. In order to utilize the MIMO idea in VLC, more than one optical source is employed. The concept of deployment of multiple transmit sources is quite attractive and popular in VLC systems to provide sufficient and uniform illumination [11]. It works on the principle of different data streams that are transmitted through different antennas and combined at different time intervals using various algorithm at multiple receivers. Various modulation techniques are used with MIMO and researches show that OFDM gives among the fastest rate up to order of 8 GBPS for shorter distances. An more attractive way to enable broadband link is to employ multiple LEDs (which coincides with a typical indoor environment light fixture distribution) with multiple receivers. Parallel transmission offers a linear capacity gain with the number of channels in an ideal crosstalk-free configuration. However, for all practical scenarios, mechanical alignment between transmitter and receiver is hard to achieve; MIMO obviates this alignment condition.

Furthermore, supporting multiple users simultaneously with higher data rates can cause multiple-user or multi-access interference. In addition, MIMO, in this regard, can help not only to limit multi-access interference but also to improve SNR. Zeng *et al.* [13] rigorously analyzed the performance of MIMO (imaging and non imaging) under variety of conditions like multiple receiver positions, imaging receiver diversity, different type of transmitters, and effect of misalignment. In order to model MIMO systems, the following factors are taken in consideration to get maximum required results

- Free space loss and path loss
- Trees, building and other kinds of structures which cause Shadowing
- Doppler shift and Delay spread due to multi-path in mobile environment
- Rician K factor distribution
- Joint Correlation between Tx - Rx antenna.

MIMO techniques have two basic advantages *i.e.* diversity and multiplexing. Spatial dimension can be exploited using MIMO. MIMO achieve high spectral efficiency and data rate, as in 802.11g and 802.11a data rate is 54 Mbps but in MIMO data rate, throughput rises to 108 Mbps. In conventional transmission system SISO, there exist only a single pipe of data but in case of MIMO, there are multiple parallel pipes, which increase the system capacity and supports multimedia applications due to fast speed of transmission and high rate of data. As a whole, the reliability of MIMO system is governed by the spatial diversity and the capacity of the link is governed by the degrees of freedom. In order to model MIMO system, multiple data streams can be spatially multiplexed over M transmitters and N receivers. This spatial multiplexing increases link-capacity due to simultaneous transmission of multiple data streams over the same frequency band.

But the actual geometry of the transmit and receive antenna decides the measure of correlation factors of signals in spatial domain. The antenna diversity merely improves the reliability. The best way to eliminate correlation factor influence in spatial domain, is by employing use of orthogonal signals and polarized antennas. Channel modeling of the MIMO systems is defined by channel matrix (also called as the channel state information - CSI). The CSI determines suitability of MIMO technique in enhancing link-capacity. In contrast to MIMO the CSI of SISO channel does not change and remains constant. In case of the fast fading channels, the MIMO breaks the channel variations to spatial sub-channels. Therefore, knowledge of the CSI (at transmitter or receiver) will open up possibility of design of an intelligent system. Figures 8 and 9 show the analogy of a MIMO system modeling.

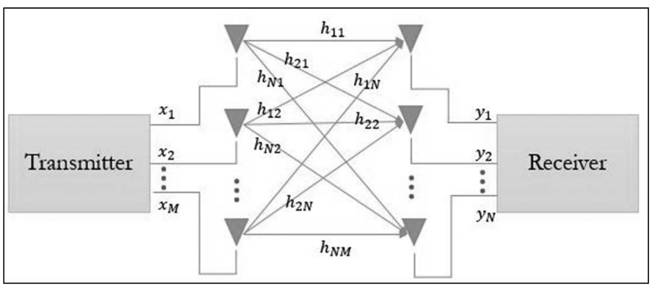

Figure 8. Block diagram of MIMO system architecture.

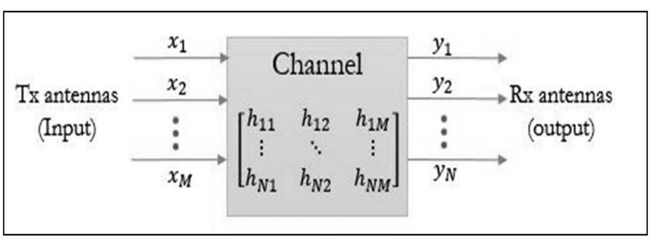

Figure 9. Block diagram of MIMO system model.

In a MIMO modelling configuration, the CSI matrix is formed by transmitting a symbol, say value '1' from each of the transmitting antenna and its response on the multiple receiving antennas are recorded. For example, in a *M* x *N* configuration, at any time instant, the transmit voltage '1' from the *N* antennas (spatially diversified) is recorded with its response on *M* receive antennas. Subsequently, the CSI matrix can be given as

$$A_{m,n} = \begin{pmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m,1} & a_{n,2} & \cdots & a_{m,n} \end{pmatrix} \quad (1)$$

In ideal case, the CSI matrix must have only the real values, but practically they contain the complex values of variations of both amplitude and phase. Based on the knowledge of the CSI with a closed loop diversity scheme, it can be decided to make an efficient use of power of transmission. In terms of mathematical modelling of the MIMO channel, received signal vector **y** can be expressed in terms of channel matrix **H**, input vector **x** and noise vector **n**.

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \quad (2)$$

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} \qquad \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_M \end{bmatrix} \qquad \mathbf{n} = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_M \end{bmatrix} \quad (3)$$

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,n} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ h_{m,1} & h_{m,2} & \cdots & h_{m,n} \end{bmatrix} \quad (4)$$

For a simple 2x2 MIMO model, the MIMO link is expressed as a set of linear equations as,

$$y_1 = h_{11}\mathrm{x}_1 + h_{12}\,\mathrm{x}_2 + n_1 \qquad y_2 = h_{21}x_1 + h_{22}x_2 + n_2 \quad (5)$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \quad (6)$$

The solution to set of linear equations has many challenges. A very small change in the input causes a radical change in the solution. Therefore it is tried to make the solution robust enough that they are least affected by the noise variations. The sensitivity to the solution to small changes in input is measured by a condition number of the CSI. It is an indication to the stability of output to the variation of input.

B. OFDM

The standard BPSK, QPSK etc. are single carrier modulation techniques while the idea of OFDM employs multicarrier modulation technique. Each carrier can employ a different standard modulation scheme. So, based on this concept, it seems to among the efficient and optimal form of modulation scheme. The conventional multi carrier modulation technique utilizes multiple number of the oscillators and filters. On the contrary, usage of the high speed computers and processing capabilities, it has been possible to employ the Fast Fourier Transform (FFT) as a substitute to the deployment of multiple carrier oscillators in the modern digital modulation technique. This supports smart, directional and advance antenna techniques.

The OFDM offers a good response against interferences and multipath fading. The data rate in each subcarrier is inversely proportional to the number of sub channels, which in return increases the time lapse of the symbol. This solves the problem of delayed version of signals in multipath environment. Each sub channel is orthogonal to each other and faces flat fading. Orthogonality depends on carrier spacing. Carrier space is to choose that it must be reciprocal of symbol period. Eventually this is helpful to reduce the ISI and symbol detection at receiver by correlation technique. In VLC, OFDM is a popular modulation technique to achieve higher data rates. Figure 10 shows a simple block diagram of an OFDM technique.

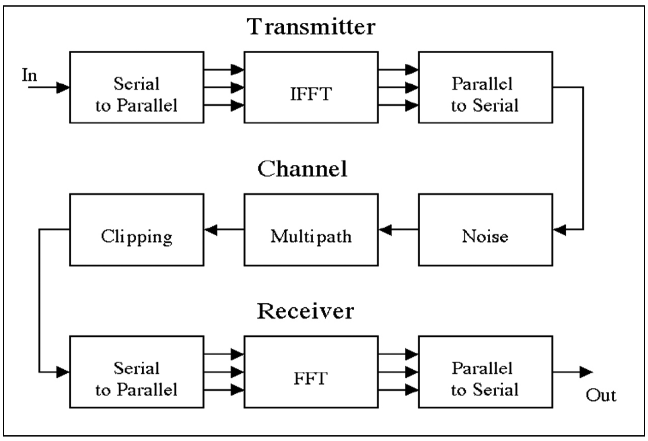

Figure 10. Block diagram of OFDM system modeling.

The OFDM symbols can be generated by taking the inverse fast Fourier transform of a block of symbols from a modulation scheme like BPSK, QPSk or QAM etc. The resulting complex valued bipolar time domain signals can't be used with intensity modulation therefore it can be realized by using Hermitian symbols, and to obtain a unipolar signal, direct current biased optical OFDM and asymmetrically clipped optical OFDM methods are used. In direct current biased optical OFDM, a bias value is added to all samples resulting in unipolar samples. However, the disadvantage of this technique is that the power consumption is increased [13]. In asymmetrically clipped optical OFDM, symmetric time domain signals are achieved by using the properties of fast Fourier transform and OFDM frame structure, and only odd subcarriers are modulated. The advantage of this technique is that no biasing is required [14]. Figure 11 shows the Hermitian symbol based realization of OFDM in a VLC system.

The use of OFDM is not limited to LEDs but has also been extended to be used by Laser Diodes (LD) as well. Moreover, LDs are considered as promising alternative to LEDs for better utilization of the visible light spectrum for communication. Chi *et al.* used a Gallium nitride blue laser diode with 64-quadrature amplitude modulation (QAM) and 32-subcarrier OFDM communication at 9 Gbps over a 5-m free-space link [15]. Various design challenges associated with OFDM scheme are, Useful symbol duration: The size of symbol or length of symbol in respect of time effect the number of carriers and spacing between them. It is helpful in measuring latency etc. Larger symbol duration is helpful in accommodation of delay profile of channel and cause to increment the number of subcarrier, reduces subcarrier spacing and higher the FFT size. There can be an issue of subcarrier offset and instability of OFDM symbol. Subcarrier spacing and number of carriers depend upon application and requirement. In the mobile environment, due to the Doppler shift subcarrier spacing is chosen to be large. Number of subcarriers chosen depends up on channel bandwidth, data rate, through put requirements and territory (ruler, urban etc). If number of carriers is N then it would be reciprocal of duration of symbol in time T, *i.e*.

$$N = 1/T. \tag{7}$$

Selection of number of carrier depends on FFT size supported by FFT module. For higher number of carrier, there would be higher number of complex point processing by FFT. Modulation scheme: This in one of the biggest advantages of OFDM that different modulation scheme can be applied to each sub channel depending on channel condition, data rate, robustness, throughput and channel bandwidth. There could be different modulation scheme applied specified by complex number *i.e.* QPSK, 16 QAM, 64 QAM. Modulation to each sub channel can be made adaptive after getting information and estimation of channel at transmitter.

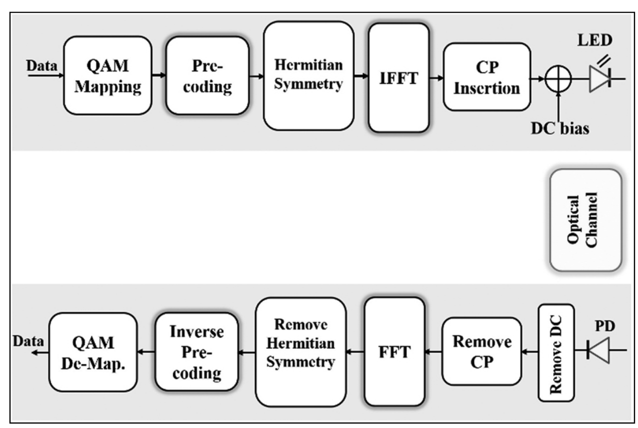

Figure 11. Block diagram of Hermitian symbol based OFDM VLC system.

C. MIMO-OFDM

An experimental work reported by Azhar *et al*. [14] supports Gigabit/s indoor wireless transmission using MIMO-OFDM VLC. The system consists of four MIMO links with each transmitter transmitting at 250 Mbps using OFDM. Utilizing nine-channel imaging diversity receiver, a BER of 10^{-3} was achieved at a range of 1 m. Repetition coding (RC), spatial multiplexing (SMUX) and spatial modulation (SMOD) MIMO techniques were investigated and comparative analysis for OFDM-based MIMO systems was reported in [15]. The performance of MIMO-OFDM VLC system was analyzed in a multi-user setting in [16].

A 100-Gb/s MIMO visible laser light communication system employing vertical-cavity surface-emitting lasers with 16 QAM-OFDM modulating signals is experimentally demonstrated [16]. In advanced broadband communication systems, MIMO-OFDM can combat better against frequency selective and multipath fading (deep fading) and also supports high data rate. MIMO-OFDM reduces the receiver complexities and manipulations as they distribute over multiple sub-carriers the data information and transmits at different frequency levels which are helpful in spectral efficiency and error control transmission. All individual functions of OFDM system such as IDFT/DFT and cyclic prefix codes are applied to individual transmit antennas and receiver antennas (MIMO) and then this makes the combination of MIMO-OFDM. Also for error free transmission it supports Alamouti scheme and with maximum degree of diversity. MIMO-OFDM sends stream of independent data information to increase spatial rate over different antennas and tones[17]. In OFDM, the bandwidth is divided into narrow band flat fading channels and data is transmitted on each channel.

Gregory Raleigh first introduced the MIMO-OFDM scheme. In NLOS, it allows transmission and successful communication. It performs communication on NLOS paths, like base station using MIMO-OFDM utilizes multipath scenario. Consider MIMO-OFDM system having N transmitter antennas and M receiver antennas as in MIMO technique spatial multiplexing is applied. Encoding can be performed collectively or per antenna (PAC). Performance of STBC SM based MIMO has been improved by channel estimation [18]. For N transmit antenna there would be N OFDM transmitter or N parallel branches of OFDM system for N antennas. Raw digital bits are multiplexed in to N braches. For each antenna, there is individual OFDM transmitter performing encoding interleaving, bit mapping (QPSK 16 QAM), IFFT, Guard interval or cycle prefix to each symbol and finally up convert the OFDM symbol to radio frequency then transmit over radio link.

In order to model the MIMO-OFDM system, the basic idea of MIMO and OFDM are combined together. Considering M transmit antennas and N receive antenna with K subcarriers, the frequency domain transmit sequence from the n-th transmit antenna on the k-th OFDM sub-carrier is given by $X_{n,k}$. The received sequence on the m-th receive antenna is given by $Y_{m,k}$ and is expressed mathematically as,

$$Y_{m,k} = \sum_{n=1}^{N} H_{m,n,k} + \xi_{m,k} \tag{8}$$

where $H_{m,n,k}$ is the frequency response of the channel between n-th transmit antenna and m-th receive antenna for k-th subcarrier. $\xi_{m,k}$ is the frequency response of the zero mean AWGN channel with one side power spectral density as η. So in general, the input signal on the k-th subcarrier from N transmit antennas is given by,

$$X_k = [X_{1,k} \quad X_{2,k} \quad \ldots\ldots \; X_{N,k}]^T \tag{9}$$

The CSI matrix is given by,

$$\mathbf{H}_k = \begin{bmatrix} H_{1,1,k} & H_{1,2,k} & \cdots & H_{1,N,k} \\ H_{2,1,k} & H_{2,2,k} & \cdots & H_{2,N,k} \\ \vdots & \vdots & \ddots & \vdots \\ H_{M,1,k} & H_{M,2,k} & \cdots & H_{M,N,k} \end{bmatrix} \tag{10}$$

$$\mathbf{Y}_k = \begin{bmatrix} Y_{1,k} & Y_{2,k} & \cdots & Y_{M,k} \end{bmatrix}^T$$

$$\mathbf{Y}_k = \begin{bmatrix} H_{1,1,k} & H_{1,2,k} & \cdots & H_{1,N,k} \\ H_{2,1,k} & H_{2,2,k} & \cdots & H_{2,N,k} \\ \vdots & \vdots & \ddots & \vdots \\ H_{M,1,k} & H_{M,2,k} & \cdots & H_{M,N,k} \end{bmatrix} \mathbf{X}_k + \begin{bmatrix} \xi_{1,k} \\ \xi_{2,k} \\ \vdots \\ \xi_{M,k} \end{bmatrix}$$

$$\mathbf{Y}_k = \mathbf{H}_k \mathbf{X}_k + \boldsymbol{\xi}_k \tag{11}$$

IV. PERFORMANCE EVALUATION

Performance evaluation for various types of modulations were studied and simulation were carried out for variety of schemes. The first scheme was adopted for standard BPSK modulation. The BPSK mdoulation was simulated in matlab under AWGN channel. A message with data stream of 10^6 bits was generated and the same was modulated using BPSK modulation scheme. The stream was corrupted through a AWGN noisy channel and

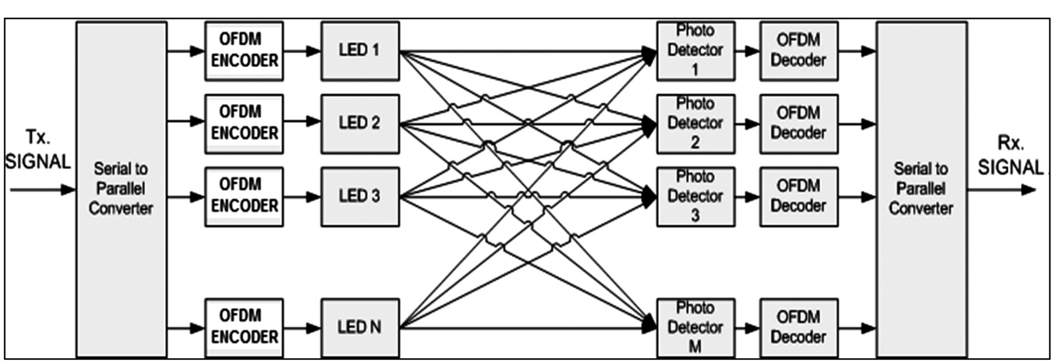

Figure 12. Block diagram of MIMO-OFDM VLC system model.

finally detecetd through a BPSK modulator. The demodulator performance of SNR with the probability of error was plotted to verify the response. The response says that about a BER of 10^{-5} can be achieved in a standard BPSK modulation scheme under AWGN channel with SNR of approximately 9-10 dB. Figure 13 shows the corresponding response.

The following matlab simulation code shows the generation of the data sequence, modulation and the performance evaluation, For signal generation and BER computation

```
nbit = 1000000;
data = randint(1,nbit)
y = awgn(complex(s), SNRdB(k));
error = error/numbit;
```

Futher on a better comparison scale, the modulation scheme was adopted to the QPSK modulation. Figure 14 shows the performance evaluation associated with the standard QPSK scheme. The following matlab functional simulations show performance evaluation of BER vs SNR for standard QPSK modulation scheme under AWGN channel.

For signal generation and BER computation,

```
nbits = 1000000;
si = 2*(round(rand(1,nbits))-0.5);
sq = 2*(round(rand(1,nbits))-0.5);
s = si+j*sq;
w = awgn(s,snrdb,'measured');
si = sign(real(w));
sq = sign(imag(w));
ber = 0.5.*erfc(sqrt(snrlin));
```

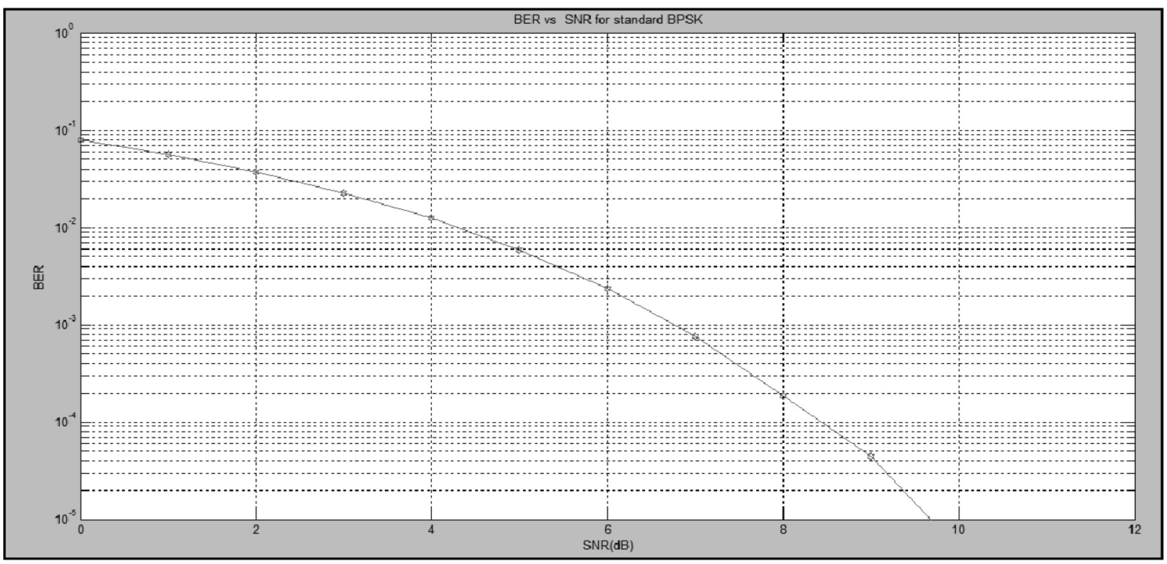

Figure 13. BER vs SNR for BPSK.

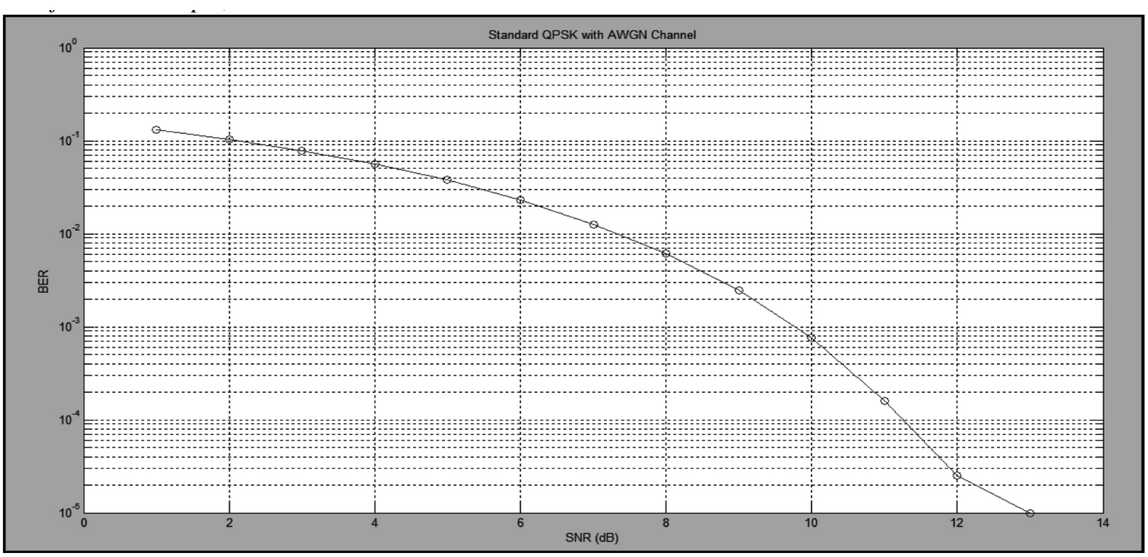

Figure 14. BER vs SNR for QPSK.

Additionally on simulating OFDM approach, using the same kind of data stream with QPSK modulation combined with OFDM technique, provides results better than 10^{-8} for a higher SNR value of 12 dB. Various matlab functions used for simulating the OFDM modulation with QPSK modulation is as,

For signal generation,

```
M = 4;
k = log2(M);
ndatapts = 64;
deltaf = BW/ndatapts;

TFFT = 1/deltaf;
TGI = TFFT/4;
Tsignal = TGI+TFFT ;
Ncp = ndatapts*(TGI/TFFT);
ifftpts = ndatapts;
x1 = randi([0 1],1,64);
```

For modulation of data in NRZ coding scheme with QPSK modulation,

```
dataNRZ = 2*datamod2 - 1;
datasp = reshape(dataNRZ,2,length(x1)/2);
ycomplex = [ycomplex (sign(y1))+(1i*sign(y2))];
```

For Cyclic prefix Coding

```
ifftdataaftercp(:,ireshape)=
vertcat(actualcp(:,ireshape),ifftdatamatrix(:,ireshape));
```

For OFDM signal generation,

```
channel=randn(size(parasertx))+j*randn(size(parsertx));
ofdmsignal=reshape(parasertx,1,ofdmlength);
```

For Channel Modelling of AWGN Channel,

```
awgnnoise = awgn(afterchannel,snr,'measured');
```

Figure 15 shows the results of a BER vs SNR for OFDM simulation with QPSK modulation. Figure 16 shows the results of a MIMO-OFDM simulation for 2x2 configuration.

V. CONCLUSION

Various literature reviews and simulations carried out found that in case of MIMO, increasing the number of both transmit and receive antennas increases the degrees of freedom for communication but simultaneously increases the channel uncertainty. Since the total transmit power is uniformly distributed across the transmitting antennas, increasing the transmitting antennas results in smaller SNR per degree of freedom which leads to finite optimum number of transmit antennas. While in case of increase of receive antenna always leads to increase in the SNR. Therefore increase of receive antennas is always beneficial. Results of simulations, in which BER performance of different schemes is computed shows that MIMO-OFDM with spatial diversity can provide high data rate transmission.

There is no need to increase the transmit power and expansion of bandwidth. In case of how to efficiently use space resources, the MIMO-OFDM technique can solve this problem. The BER of MIMO-OFDM performs the best with BPSK symbols rather the QPSK symbols due to less bits per symbol. The BER performance differs because they exhibit tolerance margin against noise. Thus this lower modulation order reduces BER

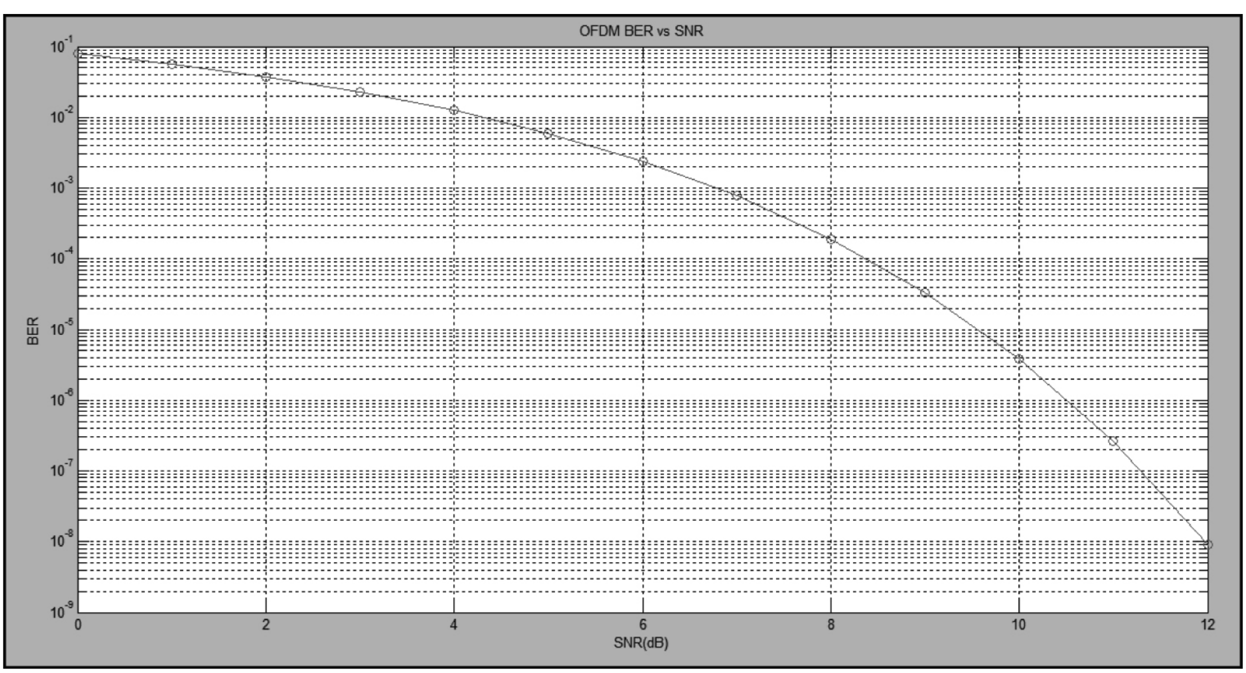

Figure 15. BER vs SNR for OFDM-QPSK.

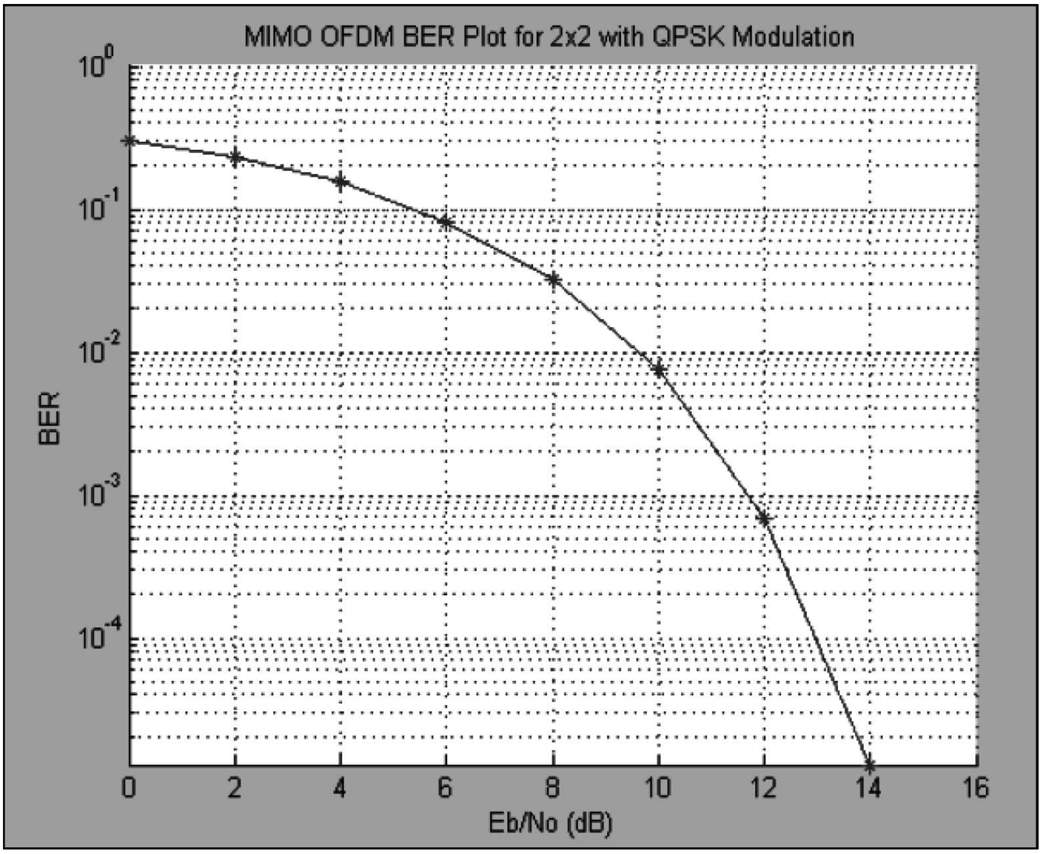

Figure 16. BER vs SNR for MIMO-OFDM-QPSK.

resulting in better and improved performance of OFDM and MIMO systems.

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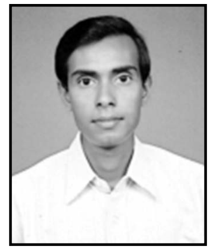

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Journal expresses deep sorrow at the sad demise of author, Satya Prakash after submission of this manuscript. – Editor