SNR Analysis for Visible Light Communication Systems

Aastha Agarwal[1]
Department of Electronics and Communication Engineering,
M.E Student, NITTTR Chandigarh.[1]

Garima Saini[2]
Department of Electronics and Communication Engineering,
Assistant Proffessor,NITTTR,Chandigarh.[2]

Abstract: **White LEDs offers various advantages such as high illuminance, long lifetime and low power consumption. An Indoor optical wireless communication system utilizing white LEDs offers a huge potential to provide high speed data transmission for various indoor applications such as flight entertainment, video transmission and other multimedia services. These systems use white LEDs as the source which can transmit and receive data by flashing light at a speed which is undetectable to the human eyes. In this paper we discuss about the usage of multiple LED arrays i.e. MIMO techniques as compared to single LED array i.e. SISO technique for indoor communication so as to maximize Signal to Noise Ratio (SNR) received.**

I. INTRODUCTION

The demand for wireless broadband communications has been growing steadily for last several years. The congestion and limitations on bandwidths of the radio spectrum have inhibited unrestricted growth of the radio wireless systems. Wireless optical, however, holds the promise of delivering data at much higher rates[1].

The advancements in the Solid state Lightning (SSL) have triggered research in the direction to use Light Emitting diodes for illumination as well as for communication in a cost effective, power efficient way in order to give high data rates for indoor communication. An optical wireless (OW) communication system relies on optical radiations to convey information in free space, with wavelengths ranging from infrared (IR) to ultraviolet (UV) including the visible light spectrum. The transmitter/source converts the electrical signal to an optical signal, and the receiver/detector converts the optical power into electrical current [2].

As the demand for spectrum is rapidly increasing day by day so in order to fulfill this, need of the hour is Optical Wireless Communication (OWC). There are certain advantages of OWC over radio frequency communication which makes it viable option for indoor communication. The OWC utilizes the unregulated, unlicensed part of the electromagnetic spectrum and offers huge bandwidth thus supports very high data rates for a small region [3]. Disorders in immune system and other health issues associated with radio frequency are nonexistent in OWC systems. Also, these systems are highly secure as their signals cannot penetrate through the walls. Moreover these systems have less installation cost and circuitry required as compared to RF systems [3].

This paper is organized as follows. In section II, LED as a source for data transmission is discussed. In section III, the features of proposed system are shown. The effect of number of transmitters on SNR is discussed in section IV and the effect of FOV field of view) on SNR is also discussed. Finally, conclusions are given in section V.

II. LED AS A SOURCE FOR DATA TRANSMISSION

Ideally, a LED source is a Lambertian emitter, i.e., irradiance distribution or illuminance is a cosine function of the viewing angle. A practical approximation of the irradiance distribution following the illustration in Fig.1 is given as

$$\boldsymbol{E}(\boldsymbol{d},\Phi)=\boldsymbol{E_0}(\boldsymbol{d})\boldsymbol{cos^m}(\Phi) \qquad (1)$$

where Φ is the viewing angle and $E_0(d)$ is the irradiance (W/m^2), also given in luminous flux (lm) on the axis at a distance d from the LED. The number n is given by the half power angle, $\varphi_{1/2}$(an angle provided by the manufacturer) defined as the view angle when irradiance is half of the value at 0°. The relation between $\varphi_{1/2}$ and n can be expressed in (2). The LED emitter is modeled using a

$$\boldsymbol{n}=-\frac{\boldsymbol{ln2}}{\boldsymbol{ln}(\boldsymbol{cos\varphi_{1/2}})} \qquad (2)$$

generalized Lambertian radiation pattern Ro(φ). Assuming that P_t is the transmitted power, the radiation intensity is given by:

$$\boldsymbol{Ro}(\Phi)=\left[\frac{(\boldsymbol{n}+\boldsymbol{1})}{\boldsymbol{2\pi}}\right]\boldsymbol{P_t cos^n}(\Phi);\quad \Phi\ \boldsymbol{\varepsilon}\left[-\frac{\boldsymbol{\pi}}{\boldsymbol{2}},\frac{\boldsymbol{\pi}}{\boldsymbol{2}}\right] \quad (3)$$

The power emitted by the LED is PLED, and φ and ψ are the irradiance and incidence angles. The transmitted power is $\boldsymbol{P_{tx} = P_{LED} * Ro(\varphi)}$.

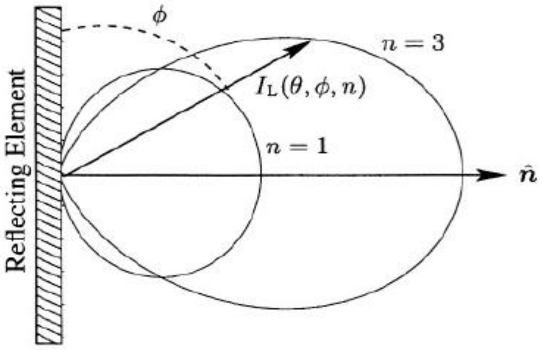


Fig.1 Lambertian emission pattern for mode n. [4].

In this paper we consider an optical wireless MIMO transmission system employing intensity modulation (IM) and direct detection (DD) of the optical carrier using incoherent light sources, e.g. LEDs. The system is equipped with N_t transmitters and N_r photo-detectors at the receiver side. The received signal vector is

$$\mathbf{Y} = \mathbf{Hs} + \mathbf{N} \qquad (4)$$

where N is the sum of ambient shot light noise and thermal noise. It is independent of the transmitted signals and the main noise impairment as commonly assumed in OWC [5].

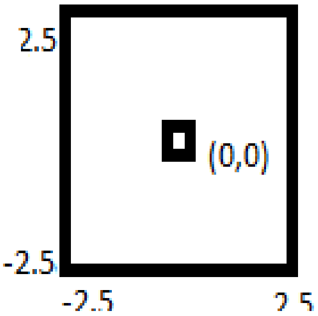
Consequently, N is real valued additive white Gaussian noise (AWGN) with zero mean and a variance $\boldsymbol{\sigma^2 = \sigma^2 shot + \sigma^2\ thermal}$, where σ^2_{shot} is the shot noise variance and σ^2thermal is the thermal noise variance . Thus, the noise power is given by $\boldsymbol{\sigma^2 = N_0 * B}$, where N_0 is the noise power spectral density and B is the bandwidth. [5] .The transmitted signal vector is denoted by $s = [s_1 \ . . . \ s_{Nt}]^T$, with $[\ \cdot\ ]^T$ being the transpose operator. The elements of **s** indicate which signal is emitted by each optical transmitter, i.e. $\mathbf{s_{Nt}}$ denotes the signal emitted by transmitter N_t. The $N_r \times N_t$ channel matrix H is given by

$$\boldsymbol{H} = \begin{bmatrix} \boldsymbol{h_{11}} & \cdots & \boldsymbol{h_{1Nt}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{h_{Nr1}} & \cdots & \boldsymbol{h_{NrNt}} \end{bmatrix} \qquad (5)$$

where h_{NrNt} represents the transfer factor of the wireless link between transmitter N_t and receiver N_r.

III. SYSTEM MODEL

A visible-light indoor optical wireless system utilizing one array, two arrays and four arrays of LED lamps is shown in Fig.2(a), 2(b) and 2(c).



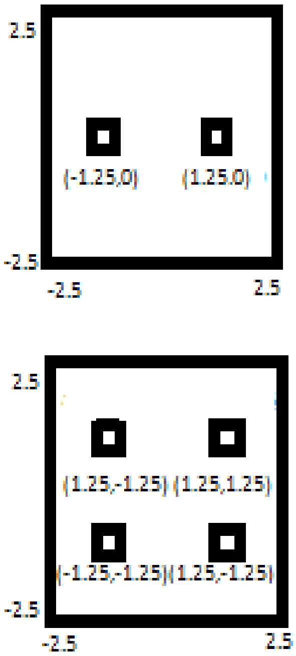


Fig 2. Top view of the position of Transmitters on the ceiling.(a) Single Transmitter,(b) Two Transmitters, (c) Four Transmitters

A room of 5mx5mx3m dimensions is considered for the purpose of analysis. The room contains of a receiver photodiode which is placed on a table of height 0.85m from the floor of the room.

The light signal transmitted from the LED arrays are received by a photodiode. The signals received depend on basic ray optics theory, room geometry, angle of incidence and reflection and field of view of the receiver. The LED emits radiation with intensity $R_0(\Phi)$ at an irradiance angle of Φ. The signal is received by a photo detector of area A_{rx}, at a distance d. The photo detector can receive a signal which lies in its field of view. The radiated signal passes though an optical filter and concentrator to ensure that maximum light falls within the field of view of the receiver. Table 1 shows the various parameters considered for simulations in this paper.

Table1. System Model Parameters

Room size	5m x5m 3m
Desk height from the ceiling	0.85m
Amplifier Bandwidth	50 MHz
Single LED power *PLED*	20mW
Semi-angle at half power	30
No. of LEDs per array	3600
Ceiling reflectivity	0.7
Wall reflectivity	0.8
Detector physical area of PD	1cm^2
Transmission coefficient of optical filter	1
Refractive index of lens at PD	1.5

Photodiode responsivity	0.4
Noise-bandwidth factor	0.562
Absolute temperature	298K
Fixed Capacitance	112pF/cm^2
Transconductance	30mS

In this paper we have analyzed the SNR at three location scenarios as shown in Fig.2. Light beams propagate from the LED to the receiver via two main channels: light of sight (LOS) and diffuse channels.

The LOS Channel transfer function is expressed as

$$H(0)_{LOS} = \begin{cases} \frac{A_{rx}}{d^2} R_0(\varphi)\cos(\psi) & 0 \le \psi \le \psi_c \\ 0 & \psi > \psi_c \end{cases} \qquad (6)$$

where A_{rx} is the detector area, d is the distance between the transmitter and the receiver, $Ro(\varphi)$ is the transmitter radiant intensity and given by (3), ψ is the angle of incidence, ψ_c is the FOV of the photodiode.

The total power of n LEDs in the directed path is

$$P_{rxLOS} = \sum_{n=1}^{LEDs} P_{tx} \; H(0)_{LOS}^{t} \qquad (7)$$

where $H(0)_{LOS}^{t}$ the LED channel DC gain.

In order to calculate the diffuse channel response an integrating sphere model for the optical wireless diffuse signal was introduced in [7] and this is used here. Here, only first reflections from the walls, ceiling and surface are considered. In a room of surface area A_{room} the first diffuse reflection of a wide-beam optical source emits a intensity I_1 and is given by

$$I_1 = \rho 1 \frac{P_{totalLED}}{A_{room}} \qquad (8)$$

where ρ_1 is the reflectivity of the surface and $P_{totalLED}$ is the total power transmitted by all the LEDs .

The average reflectivity ρ inside the room is defined as

$$\rho = \frac{1}{A_{room}} \sum_i A_i \rho_i \qquad (9)$$

where the individual reflectivities ρ of walls, ceiling, floor and other objects in the room are weighted by their individual areas Ai. Therefore, the total intensity is

$$I = I_1 \sum_{j=1}^{\infty} \rho^{j-1} \frac{I1}{1-\rho} \qquad (10)$$

where the index j is the number of reflections.

The received diffused power P_{diff} with the receiving area A_{rx} is $P_{diff} = A_{rx}*I.$

At the receiver, light passes through the optical filter and concentrator, so the received power is

$$P_{rx} = \left(P_{LOS} + P_{diff}\right) * T_f(\psi) * g(\psi) \qquad (12)$$

where $T_f\ (\psi)$ is the transmission coefficient of the optical filter, and $g(\psi)$ is the concentrator gain.

The photodiode is used to convert the received optical power into the electrical current, and the output current is:

$$i = P_{rx} * R \qquad (13)$$

where R is the photodiode responsivity (A/W).

The SNR is given by:

$$SNR = \frac{(RP_{rx})^2}{\sigma_{total}^2} \qquad (14)$$

where σ^2_{total} is total noise variance and it is given by:

$$\sigma_{total}^2 = \sigma_{thermal}^2 + \sigma_{shot}^2 + \sigma_{amplifier}^2 \qquad (15)$$

where the shot-noise variance σ^2shot is given by $\sigma^2_{shot} = 2*q*R\ (P_{rx} + P_n)\ *B_n$ (16)

where $B_n = I_2 R_b$, where R_b is data rate and I_2 is the noise-bandwidth factor [6].

The amplifier noise variance is given by:

$$\sigma^2_{amplifier} = i^2_{amplifier} B_a \qquad (17)$$

where B_a is the amplifier bandwidth.

The thermal noise variance is given by

$$\sigma_{thermal}^2 = \frac{8\pi k T_k A R_b I_2 B^2}{G} + \frac{16\pi^2 K T_k \Gamma {R_b}^2 A^2 I_3 B^3}{g_m} \qquad (18)$$

where the two terms represent feedback resistor noise, and channel noise respectively. Here K is the Boltzmann’s constant G is the open loop voltage gain, T_k is the absolute temperature, n is the capacitance of photo detector per unit area, g_m is the transconductance [8].

IV SNR PERFORMANCE

An SNR can express the quality of communication. The analysis of signal to noise ratio is done in the absence of multipath fading effects. In our channel model, the information carrier is a light wave whose dimensions are in the order of thousands of wavelengths, leading to spatial diversity, which prevents multipath fading. For the above reasons multipath fading can be neglected[8]. The modulation technique used is OOK . The noise added due to the transmission through the channel is shot noise and thermal noise and during detection of signal an additional amplifier noise is also added. Here the analysis is done for one transmitter, 2 transmitters and four transmitters located at positions as shown in Fig 2.

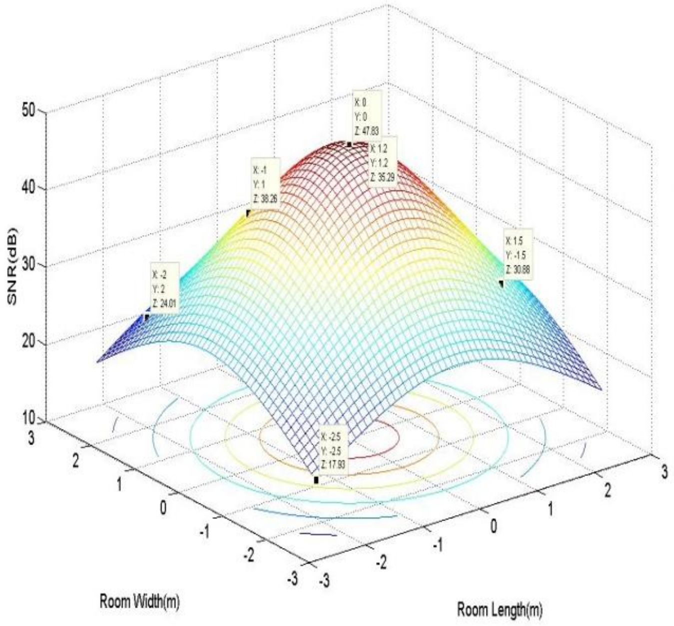


Fig. 3 SNR distributions for single transmitter inside a room.

Fig 3 shows the SNR obtained is case of single transmitter. The maximum value of SNR is 47.8dB with a minimum of 17.9dB and average of 32.6dB. The simulations are done at a data rate of 1Mbps. Fig.4 shows the simulation for SNR in the presence of two transmitting arrays. It is observed that the maximum SNR obtained is 48.62dB with a minimum of 25.975dB and an average of 39.0514dB. Further, Fig.5 shows the SNR distribution for four transmitters. The maximum value is 49.59dB, minimum is 36.40dB and an average of 45.73dB is achieved.

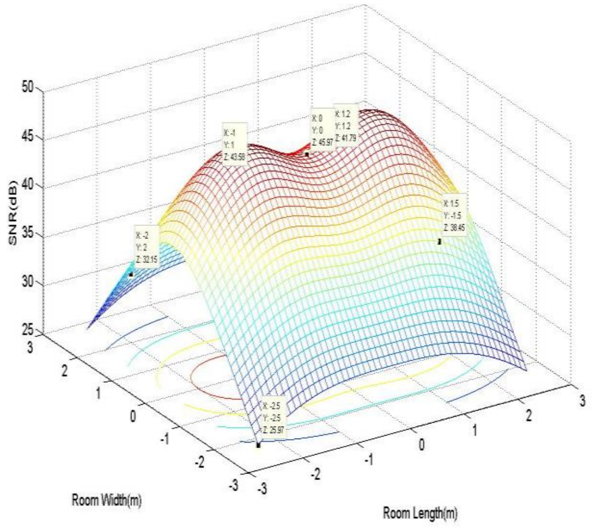


Fig 4 SNR distributions for two transmitters inside a room.

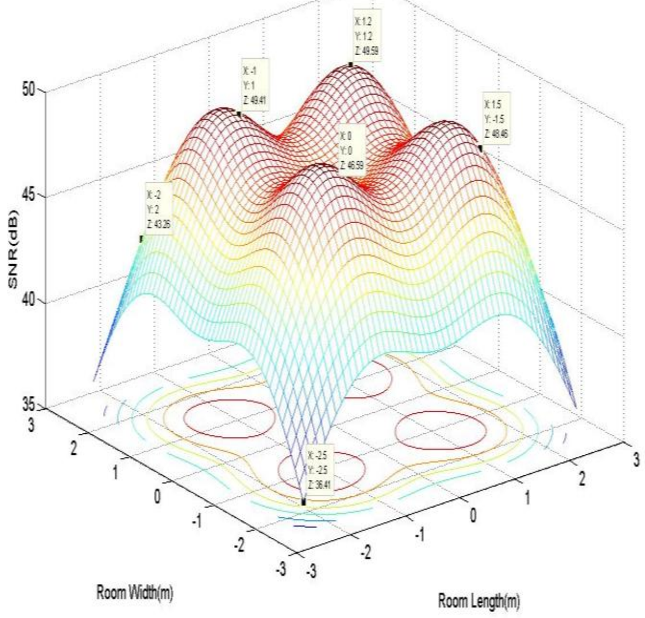


Figure 5 SNR distributions for four transmitters inside a room.

Table 2 shows the comparison of average SNR at different data rates for the above three configurations. It is seen that the best SNR performance is given by 4x4 system which can be used to transmit data up to 1Gbps.

Table2 SNR for SISO, 2x2 MIMO and 4x4 MIMO.

Data rate	**SNR (1 Tx)**	**SNR(2 Tx)**	**SNR(4 Tx)**
10bps	33.54dB	39.92dB	46.60dB
1kbps	33.54dB	29.92dB	46.60dB
100kbps	33.45dB	39.83dB	46.51dB
10Mbps	27.27dB	33.65dB	40.33dB
1Gbps	-7.03dB	-0.650dB	6.033dB
100Gbps	-46.95dB	-40.56dB	-33.88dB

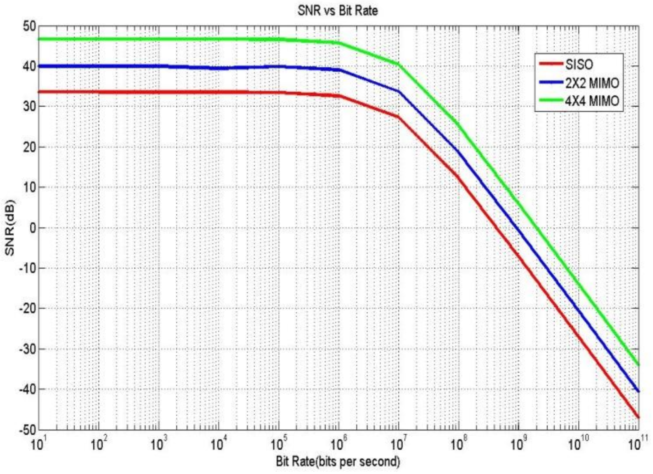


Fig 6 Average SNR vs. BER for SISO, 2x2 MIMO and 4x4 MIMO systems.

Fig 6 shows the graph for comparison of average SNR for various bit rates. The value for SNR decreases as bit rate increases. Thus, using visible light communication a data rate transfer up to 1Gbps can be done. It is seen from the table that SNR is negative for bit rate above 1Gbps for all the three systems.

The negative value of SNR represents that the signal power is less than the noise power, i.e. noise signal is the dominating signal, such region is known as blind region.

In visible light communication the inter symbol interference depends on the FOV of the receiver and the transmitted data rate. Fig 7 shows the dependence of SNR on the field of view of the signal and data rate for a four transmitter system. It is seen that as field of view increases the SNR decreases continuously. Also, for each angle the performance of 4x4 MIMO is better than 2x2 MIMO which is further better than SISO systems. Fig 7 shows the dependence of SNR on FOV at a bit rate of 10Mbps.

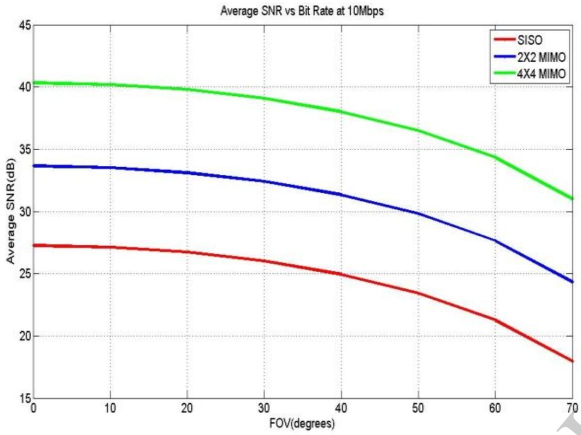


Fig 7 Average SNR vs. FOV at bit rate of 10Mbps.

V CONCLUSION

In this paper we proposed the use of multiple input multiple output system for indoor optical wireless communication systems as compared to single input single output systems. The simulations are done for SISO, 2x2 MIMO and 4x4 MIMO systems. It is seen that 4x4 MIMO gives better results as compared to the other two systems at higher data rates and large field of view angles. The 4x4 system also provides better illuminance as compared to the other two systems.

REFERENCES

[1] Ahmed Mahdy and Jitender S. Deogun, “Wireless Optical Communications: A Survey”, IEEE Conference on Wireless Communications and Networking Conference, Pages: 2399-2404, 2004.

[2] Harald Haas, Hany Elgala, Jacobs Raed Mesleh, “Indoor Optical Wireless Communication: Potential and State-Of-the-Art”, IEEE Communications Magazine, Pages : 56-62, Sept 2011.

[3] M. Saadi, L. Wattisuttikulkij, Y. Zhao, P. Sangwongngam4 , “Visible Light Communication: Opportunities, Challenges and Channel Models”, International Journal of Electronics & Informatics, Vol. , No. 1, Page(s): 1 – 11, July 2013.

[4] Hoa Le Minh, Zabih Ghassemlooy, Dominic O’Brien, Grahame Faulkner, “Indoor Gigabit Optical Wireless Communications: Challenges and Possibilities”, IEEE 12th International Conference on Transparent Optical Networks (ICTON), Page(s): 1 – 6, July 2010.

[5] Thilo Fath and Harald Haas., “Performance Comparison of MIMO Techniques for Optical Wireless Communications in Indoor Environments”, IEEE Transactions On Communications, Vol. 61, No. 2, Page(s): 733-742 , Feb 2013.

[6] Dominic O' Brien, Hao Le Minh, Lubin Zeng et.al."Improvement of Data Rate by using equalization in an indoor visible light communication system", 4th IEEE International Conference on Circuits and Systems for Communications(ICCSC), Page(s):678-682,May 2008.

[7] V.Jungnickel, V.Pohl, S.Nonning and C.Von Helmolt, ”A Physical Model of the Wireless Infrared Communication Channel,” IEEE Journal on Selected Areas in Communications, Vol. 20, No.3, 2002.

[8] Toshihiko Komine, Massao Nakagawa, "Fundamental analysis for visible light communication system using led lights", IEEE Transactions on Consumer Electronics,Vol.50, No.1,Feb 2004.

[9] Kwonhyung Lee, John. Barry, “Indoor Channel Characteristics for Visible Light Communications”, IEEE Communications Letters, 2011.

[10] Mohsen Kavehrad, “Sustainable Energy-Efficient Wireless Applications Using Light”, IEEE Communications Magazine, 2010.

[11] Y. A. Chau and S.-H. Yu, “Space modulation on wireless fading channels,” IEEE Vehicular Technology Conference, Vol. 3, pp. 1668–1671,2001.

[12] Daniel W. Bliss, Keith W. Forsythe, and Amanda M. Chan, “MIMO Wireless Communication”, Lincoln Laboratory Journal, Vol.15, No.1,Page(s): 90 – 126, 2005.

[13] Ahmad Helmi Azhar, Tuan-Anh Tran, and Dominic O’Brien, “A Gigabit/s Indoor Wireless Transmission Using MIMO-OFDM Visible-Light Communications”, IEEE Photonics Technology Letters, Vol. 25, No. 2, , Page(s): 171-174, JAN 2013.

[14] Haigh, P. A., Le Minh, H., and Ghassemlooy, Z., "Transmitter Distribution for MIMO Visible Light Communication Systems", 12th Annual Post Graduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting (PGNet2011), Page(s): 190-193, 2011.

[15] Irina Stefan, Harald Burchardt, Harald Haas, “Area Spectral Efficiency Performance Comparison between VLC and RF Femtocell Networks ”, IEEE International Conference on Optical Networks and Systems , Page(s): 3825– 3829, 2013.

[16] Wasiu O. Popool, Enrique Poves, Harald Haas, “Error Performance of Generalized Space Shift Keying for Indoor Visible Light Communications”, IEEE Transactions On Communications, Vol. 61, No. 5, Page(s): 1968-1976,2013.

[17] Kaiyun Cui, Gang Chen, Zhengyuan Xu, and Richard D. Roberts., “Line-of-sight Visible Light Communication System Design and Demonstration”, IEEE Conference on Communication Systems Networks and Digital Signal Processing (CSNDSP), , Page(s): 621 - 625, 2010.

[18] Ning Hao Minglun Zhang, “An OOK Based Visible Light Communication System for Short Distance”, IEEE International Conference On Communications and Networking, Page(s): 306-307, 2012.

[19] Soo-Yong Jung, Swook Hann, and Chang-Soo Park, “TDOA-Based Optical Wireless Indoor Localization Using LED Ceiling Lamps”, IEEE Transactions on Consumer Electronics, Vol. 57, No. 4, Page(s): 1592 – 1597, 2011.

[20] Dong-Fang Zhang, Yi-Jun Zhu, Yan-Yu Zhang, “Multi-LED Phase-Shifted OOK Modulation Based Visible Light Communication Systems”, IEEE Photonics Technology Letters, Vol. 25, No. 23, Page(s): 2251 – 2254,2012.