

Performance of Channel Estimation for Multiuser VLC System Using DCO-OFDM and ACO-OFDM

Jayashree Pradhan
*Department of Electronics
and Communication*

*National Institute of
Technology Rourkela*
Rourkela, India
jayashreepradhan12@gmail.com

Vinod Kiran Kappala
*School of Electronics
Engineering (SENSE)*

VIT-AP University
Amaravati, India
vinodkiran427@gmail.com

Santos Kumar Das
*Department of Electronics
and Communication*

*National Institute of
Technology Rourkela*
Rourkela, India
dassk@nitrkl.ac.in

Abstract—Visible light communication (VLC) is secured and high-speed communication for a specified area location. This provides a green-fuzzy technology for optical wireless communication system design. The VLC channel included different parameters, where the variation of the parameter can be analyzed from different channel estimation techniques. The VLC channel is affected by both static and mobile environments. Previously most of the research is on static VLC channels but recently mobile VLC communication is in trend and has more applications in the real world. Thermal noise, ambient noise, shot noise, the distance of the transceiver, and the position of the receiver are some parameters, which has caused a major effect on the VLC Channel estimation system. So many estimation techniques for VLC channels are available to estimate the performance of communication links. In this paper, a detailed comparative analysis is given for both DC-biased optical orthogonal frequency division multiplexing (DCO OFDM) and asymmetrically clipped orthogonal frequency division multiplexing (ACO OFDM). Here, a novel VLC channel estimation technique for multiple-input-multiple-output (MIMO) ACO OFDM is designed, where the performance of linear minimum mean square error (LMMSE) channel estimation technique can be concluded with the bit error rate (BER) response. The paper considers least square (LS) and LMMSE channel estimation techniques to compare the proposed work with the verified work.

Index Terms—BER, DCO OFDM, ACO OFDM, Photodiode, VLC.

I. INTRODUCTION

VLC is a high-speed secured communication, for which it has gained valuable research interest in today's world communication. VLC communication is having freely (unlicensed) available spectrum with a wide range of bandwidth i.e. 355–755, highly secured and low installation cost. Nowadays advanced research is going on in the area of underwater communication, indoor aircraft, and indoor hospital application though it is free from radio frequency, and outdoor vehicle communication [1], [2]. There are so many advantages of VLC communication, but the communication performance is bounded due to non-linearity, bandwidth constraint, and noise introduced from the light sources [3], [4], [5].

It is challenging to accomplish a faithful communication system in a VLC system. The stochastic and unpredictable behavior of the VLC channel response is constructed by a monotonic distribution function. Thus estimating the receiver's channel state information (CSI) before data transmission is a very well-known method of resolving this problem [6], [7]. A low-cost visible light communication system was created using

the duo-binary modulation method. The use of wavelength division multiplexing increases the capacity. Over a dispersed link of 1.3 m, polarisation multiplexing was used as well [8]. Different techniques have been proposed for static and mobile VLC channel estimation for both O-OFDM (Optical OFDM) systems. In [9] the authors proposed a minimum mean square error (MMSE) error by using the adaptive statistical Bayesian technique for static users. However, the unconditional nature of the VLC channel is very tough to design a transceiver and its channel characterization, the author involves the LS channel estimation only [10]. In [11] the author designs a single input single output (SISO) VLC communication system for LS estimator for static users with lower estimation accuracy. A MIMO-OFDM VLC system is designed to increase the data rate and mitigate the constraint associated with the bandwidth. Different environmental conditions are not considered to design the system model. A DCO OFDM MIMO VLC system is designed to estimate the downlink (DL) VLC channel. In the mobile scenario, the VLC channel performance is not discussed [12]. Most of the authors considered static channel estimation for VLC communication. But in real-time scenarios, the VLC channel is mobile in nature, where all environmental conditions included variations of different channel parameters. In [13] the authors explain the variation of different modulations under time-varying VLC channels. In [14], the authors developed some algorithms for the estimation of the VLC channel which reduces the effect of intersymbol interference (ISI). Optical-based OFDM system was designed for VLC channel estimation of SISO user scenarios [15]. In [16] the authors explain to mitigate the LED non-linearity for time-varying VLC channels using the minimum symbol error rate (MSER) technique. A Ray tracing VLC channel is used to post estimated the line of sight (LoS) communication with a post-equalization technique to mitigate the effect of mobility [17], [18].

Different visible light sources can cause a major interference in light communication. Various mechanisms are adapted to mitigate the effect of different noises [19]. A better channel state information (CSI) included at the transmitter with sufficient addition of pilots can make the system more appropriate for real-time implementation under massive MIMO systems including feedback strategy systems [20]. In [21], the authors explained a massive MIMO VLC channel matrix to estimate problems using convolutional neural networks, and they used

the MMSE method as a benchmark to assess the suggested estimate performance. However, they don't go into detail on the impact of downlink pilot overhead or the CSI feedback. In [22], [23] the authors derived closed-form equations and intricate MMSE computations in the ideal power allocation strategy for finite-alphabet inputs. A suboptimal power allocation system based on the suggested lower bound in order to maximize spectral efficiency while also adhering to the average optical power and total transmit power constraints. For ACO OFDM VLC in the 5th generation, which is explained as compressive sensing (CS) method for channel estimation method. The authors presented a self-aware step size sparsity adaptive matching pursuit (SS-SAMP) algorithm with limited estimator analysis [24].

In this paper,

- Both LoS and non-line-of-sight (NLoS) channels are included to estimate the channel under the presence of different background noise and interference. The estimation performance is analyzed for both O-OFDM systems.
- A MIMO ACO OFDM VLC system is designed and its channel is estimated with an LMMSE channel estimator for multiuser environments with bit error rate analysis. The remaining part is structured as mentioned below: Section II, discusses the proposed system model adopted. Section III, presents the mathematical framework of the statistical channel estimation. Section IV derives the expression for the proposed LMMSE estimation for the MIMO ACO OFDM. Section V analyses the results, Section VI includes the research work.

II. SYSTEM MODEL

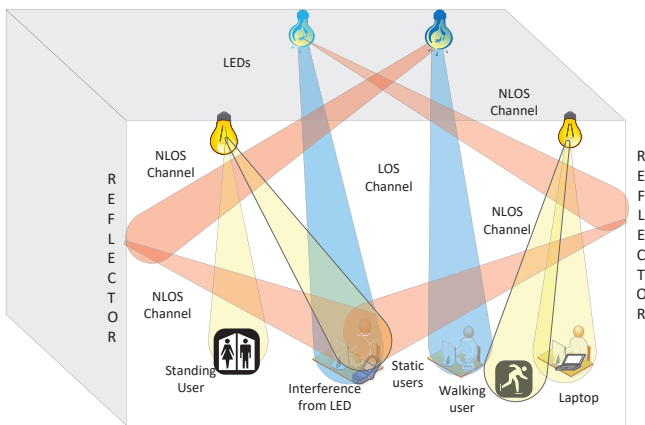


Fig. 1. A multiuser indoor VLC system

Fig. 1 represents a VLC system model for indoor communication, consisting of direct and reflected communication links. The indoor system model includes light sources other than the transmitter light emitting diode (LED), treated as noise. In this model, LED is treated as the transmission of light, and different receivers are connected, which formed a single input multi-output (SIMO) [25]. In the SIMO system model, both LoS and NLoS are considered for VLC communication. The interferences are ambient noise, sunlight, and LED light (used for lighting only, not for communication). A time-varying VLC channel can be estimated for a multiuser environment. In this

paper, we explained LS and LMMSE channel estimation using both sitting and fast-walking users. The system model Fig. 1 is designed for mobile and static scenarios.

A. ACO OFDM System

Fig. 2 designs an O-OFDM system model that includes an ACO OFDM system when odd subcarriers are allocated for transmitter data. The data are mapped with QAM and fed to Hermitian symmetry for real data. The parallel real data are now processed to inverse fast Fourier transform (IFFT) and cyclic prefix (CP) is added. CP is used to reduce the impact of inter-symbol interference (ISI). The clipper gives a real and positive signal. Here, the real and positive signal drives the LED, where the output signal is received at the photo-diode through the VLC channel. The VLC channel will estimate using LMMSE and LS estimators. The transmitted signal is written as

$$S = \left[0, S_1, 0, S_3, \dots, S_{\frac{N}{4}-1}, 0, \dots, S_{\frac{N}{2}-1}, 0, \dots, S_{\frac{N}{4}-1}^*, 0, \dots, S_{\frac{N}{2}-1}^*, \dots, S_1^* \right], \quad (1)$$

where S_m complex values symbol with $m = 0, 1, 2, \dots, N-1$. The received data after IFFT is expressed as

$$s = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} S_m \exp\left(j \frac{2\pi}{N} nm\right). \quad (2)$$

In this method, $\frac{1}{4}$ th subcarriers are carried for data transmission and estimation, which can cause a lower data rate but the optical power and spectral efficiency is more [23]. The time domain signal is clipped with a clipper, where only the negative signal is clipped to zero. After the clipper, the received signal is a positive signal.

B. DCO OFDM System

Fig. 2 stands for the DCO OFDM model when both odd and even sub-carriers are used for data transmission. The pilot-added signal is sent to Hermitian symmetry resulting in real data at the output [26]. The real parallel data are processed to IFFT with added CP. A real and positive signal can be possible with the addition of DC bias, which drives the LED. The optical signal can be processed through LED and received at the photo-detector. The source signal is written as

$$S = \left[S_0, S_1, \dots, S_{\frac{N}{2}-1}, S_{\frac{N}{2}-1}^*, \dots, S_0^* \right], \quad (3)$$

$$S_m = S_{N-m}^* \text{ for } 0 < m < \frac{N}{2} \quad (4)$$

where due to Hermitian symmetry $\frac{N}{2}$ symbols are transformed to complex conjugate of the original data symbol. The output of IFFT is expressed as the same as the ACO OFDM with $\frac{N}{2}$ th data. Here an extra DC bias is used to get the positive signal, which requires more optical power than the ACO OFDM. Here, $\frac{N}{2}$ th subcarriers are meant for original data and further onwards that is used for estimation. The further processes are the same as ACO OFDM with an extra addition of a DC bias circuit, which introduces some interferences.

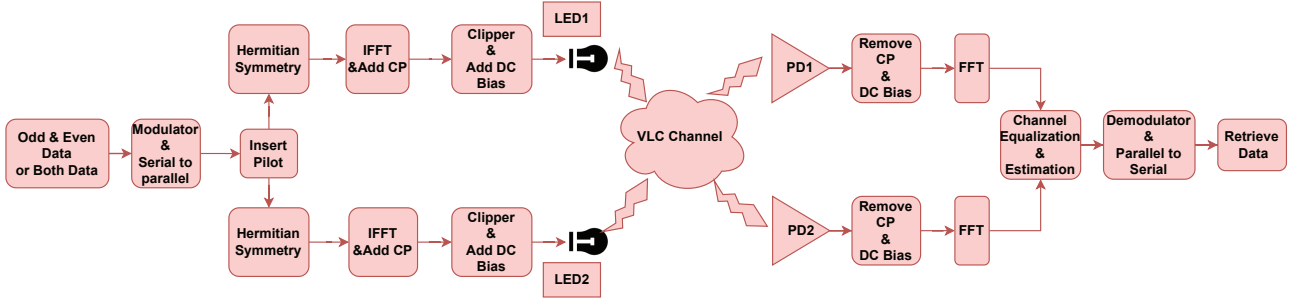


Fig. 2. System Diagram of Dual MIMO O-OFDM System.

C. Time-varying VLC Channel

The indoor VLC time-varying channel consists of two paths, (i) NLoS channel and (ii) LoS channel [27]. The gain of the above channel can be expressed in the 5 and 6. The channel gain can be derived for VLC LoS as

$$H_{LoS(0)} = \frac{A_r(p+1)}{2\pi d^2} \cos^p(\psi) T_s(\varphi) g(\varphi) \cos(\varphi), \quad (5)$$

where φ is varies from $0 \leq \varphi \leq FOV$, A_r is defined as detector area and p stands for Lambertian order. The NLoS VLC channel gain can be expressed as

$$H_{NLoS(0)} = \frac{A_r(p+1)}{2\pi} \frac{\rho_j dA_{wall}}{d_j^2} \cos^p(\psi) T_s(\varphi) g(\varphi) \cos(\varphi), \quad (6)$$

where d_j is the distance of transceiver with j th reflections. The real-time channel of VLC communication is a time-varying nature but so many authors considered it a static channel to overcome the interferences. The received signal from the photodetector is fed to a fast Fourier transform (FFT), where the received signal from the detector is converted to a frequency domain signal.

III. VLC DATA ANALYSIS

Fig. 2 explains the proposed dual block diagram of the comparative system model, which includes both MIMO ACO OFDM and MIMO DCO OFDM modulation. A 2×2 MIMO system is presented in the block diagram. The input data are processed to 16 QAM mapper and Hermitian symmetry for real data. The DCO OFDM includes all data with an extra DC bias circuit and the ACO OFDM system includes only odd subcarriers with a clipper circuit. Most of the papers are concentrated on pilot-based channel estimation for both techniques. From the received pilot data the VLC channel is estimated and analyzed its BER performance. Pilot symbols having sequence N_p are placed with the data symbols for data transmission at the transmitter section. The received symbol vector Y has been obtained as the product of input data and the channel's additive noise vectors S and W respectively. The received signal for all sub-carrier is defined as

$$Y = SH + W, \quad (7)$$

where the element of W are zero mean, $\sigma^2 I$ variance and h is the transceiver distance.

A. LS Channel Estimator

where the minimum function is expressed as $\|Y - SH\|^2$. The least-square solution is given as

$$\begin{aligned} H_{LS} &= (S^H S)^{-1} S^H Y \\ &= (S^H)^{-1} X^{-1} S^H Y \\ &= S^{-1} Y \end{aligned} \quad (8)$$

B. LMMSE Channel Estimator

The LMMSE estimator for the channel H can be expressed as

$$\begin{aligned} H_L \hat{M}MSE &= R_{HY} R_{YY}^{-1} Y, \\ &= R \sigma_h^2 S^T (R \sigma_h^2 S S^T + R \sigma^2 I)^{-1} Y, \\ &= \sigma_h^2 S^T (\sigma_h^2 S S^T + \sigma^2 I)^{-1} Y, \end{aligned} \quad (9)$$

where R_{HY} (cross-covariance) = $R \sigma_h^2 S^T$ and R_{YY} (covariance of Y) = $R \sigma_h^2 S S^T + R \sigma^2 I$.

IV. PROPOSED CHANNEL ESTIMATION SYSTEM

The proposed system consists of a detailed mathematical analysis of LMMSE channel estimation for the ACO OFDM system. The MIMO ACO OFDM LMMSE VLC channel estimation aims to estimate the channel matrix H based on the received signal Y , the transmit signal S and statistical information about the channel and noise. Let's consider a MIMO system with N_r receive antennas and N_t transmit antennas. The signal received from the output of FFT can be represented as

$$Y_r = H S_t + W \quad (10)$$

Let us estimate S_t using the matrix R , then $\hat{S} = RY$. The factor $E \left[\left\| \hat{S}_t - S_t \right\|^2 \right]$ can be minimized with $\arg \min E \left[\left\| \hat{R}^H \hat{S}_t - S_t \right\|^2 \right]$ is known as LMMSE estimator. The estimated vector \hat{S}_t can be derived as

$$\hat{S}_t = C_{S_t Y_r} C_{Y_r Y_r}^{-1} Y_r, \quad (11)$$

where $C_{S_t Y_r}$ is the cross covariance, C_{SS} is the transmit covariance and $C_{Y_r Y_r}$ defines the receiver co-variance. ACO OFDM VLC channel can be estimated from the co-variance of both receiver and transmitter as follows

$$\begin{aligned} C_{Y_r Y_r} &= E \left[\bar{Y}_r \bar{Y}_r^H \right] \\ &= E \left[(\bar{H} \bar{S}_t + \bar{W})(\bar{H} \bar{S}_t + \bar{W})^H \right] \end{aligned} \quad (12)$$

$$= E [\mathbf{H}\mathbf{R}_{S_t S_t} \mathbf{H}^H + \sigma^2 \mathbf{I}]$$

where $C_{S_t S_t} = \mathbb{P}_d \mathbf{I}_t$ and that can be derived as follows

$$C_{S_t S_t} = E[\bar{\mathbf{S}}\bar{\mathbf{S}}^H]$$

$$= E \left[\begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_t \end{bmatrix} \begin{bmatrix} S_1^* & S_2^* & \cdots & S_t^* \end{bmatrix} \right]$$

$$= E \begin{bmatrix} |S_1|^2 & S_1 S_2^* & \cdots & S_1 S_t^* \\ S_2 S_1^* & |S_2|^2 & \cdots & S_2 S_t^* \\ \vdots & & \ddots & \vdots \\ S_t S_1^* & \cdots & & |S_t|^2 \end{bmatrix} = \begin{bmatrix} \mathbb{P}_d & 0 & \cdots & 0 \\ 0 & \mathbb{P}_d & \cdots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbb{P}_d \end{bmatrix} \quad (13)$$

So the total output for transmitting covariance can be derived as $C_{S_t S_t} = \mathbb{P}_d \mathbf{I}$. Now same procedure can be adopted to derive the cross-covariance for other parameters.

$$C_{Y_r S_t} = E [\bar{\mathbf{Y}}_r \bar{\mathbf{S}}_t^H]$$

$$= E [(\mathbf{H}\bar{\mathbf{S}}_t + \mathbf{W})\bar{\mathbf{S}}_t^H]$$

$$= E [\mathbf{H}\bar{\mathbf{S}}_t \bar{\mathbf{S}}_t^H]$$

$$C_{Y_r S_t} = \mathbf{H}\mathbb{P}_d \quad (14)$$

From the equation(11), the LMMSE estimator of the ACO OFDM MIMO system can be derived as

$$\bar{\mathbf{R}} = (\mathbb{P}_d \mathbf{H}\mathbf{H}^H + \sigma^2 \mathbf{I})^{-1} \mathbb{P}_d \mathbf{H}. \quad (15)$$

the LMMSE estimator for the MIMO ACO OFDM system is very useful at low SNR. It is convenient to design an estimator with less number of pilot sub-carriers, which also reduces the overall inter-symbol interference (ISI) of the communication system. In the result section it can be explained more elaborately using BER performance of the system.

V. RESULT AND DISCUSSION

TABLE I
PARAMETER FOR SIMULATION

Sl. No	Indoor Parameters	LoS and NLoS Values
1	Dimensions of the Hall	$4m \times 4m \times 3m$
2	VLC Transmitter angle	60, 60
3	Indoor Irradiance Angle (Psi)	20, 20
4	Indoor Incidence Angle (varphi)	20, 20
5	Physical gain of Concentrator	1, 1
6	Transceiver distance(h)	4 m, 3 m
7	Design Responsivity	0.95 A/W
8	Field of View	70, 60
9	Sub-carrier assigned	64, 64
10	Order of Lambertian (m)	1, 1
11	Area of PD (A)	$1cm^2, 1cm^2$
12	Constellation Order	16 QAM

A dual O-OFDM VLC system is designed for indoor VLC systems with all environmental conditions. The designed system also undergoes different channel estimation techniques

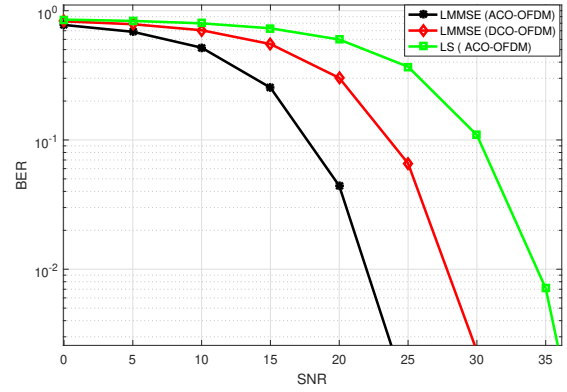


Fig. 3. BER performance of LoS VLC channel

to estimate the VLC channel. FoV, transceiver distance, and ambient noise parameters are considered to design an indoor VLC system, where required parameters are presented in Table I. A big room of size $4m \times 4m \times 3m$ is specified for simulation. The transceiver distance is 4 m for both modulations.

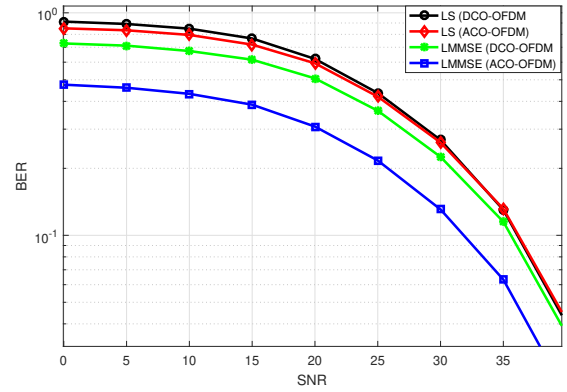


Fig. 4. BER analysis for NLoS channel

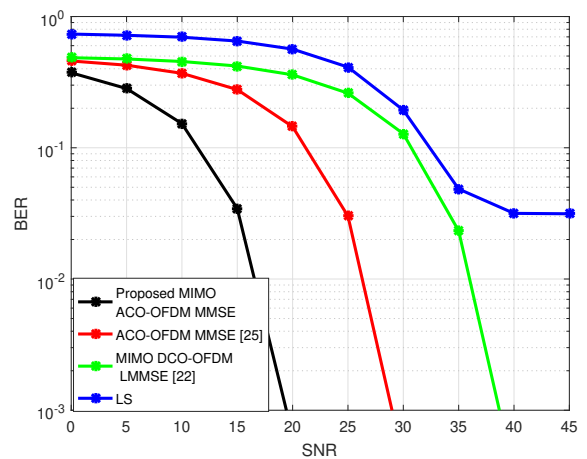


Fig. 5. Channel Estimation Performance under Different Modulation for VLC Channel

For simulation, $N = 64$ OFDM subcarriers are assumed, and $B = 5MHz$ is the baseband equivalent channel bandwidth. It has a subcarrier interval of $\Delta f = \frac{5}{64}$ MHz. The anal-

ogous channel's delay spread is believed to be less than 230 ns. The diffuse VLC channel can be designed and simulated in MATLAB. The FoV effect with distance has an impact on the output signal at the receiver. So here FoV is kept at 80 degrees. The BER response is used to monitor the communication link's performance.

The VLC channel includes DCO OFDM and ACO OFDM systems that are designed for motile users. Fig. 3 consists of three plots for LS and LMMSE estimators. The comparison can be analyzed by both the system model. Though the LS estimator is a robust estimator it degrades its performance for the mobile user. From Fig. 3, it can be observed that the LMMSE performance of ACO OFDM is better than the DCO OFDM with 5dB SNR gap at the same BER.

Fig. 4 explains the NLoS VLC channel estimation performance using LS and LMMSE estimators, where at 25 dB of SNR the error rate is less for the ACO OFDM technique. The NLoS channel is more prone to interferences but that can be mitigated by the MIMO ACO OFDM technique at the lower constellation. This concludes that the proposed technique gives better BER performance than the other [28].

Fig. 5 explains the LMMSE system achievement for the proposed system model and a detailed comparison is explained with enduring techniques. The model is designed for time-varying channel estimation, which can be designed by a linear estimator. The proposed MIMO ACO OFDM VLC channel is estimated by the LMMSE estimator and compared with ACO OFDM [22] and MIMO DCO OFDM [29]. Here 16-QAM is considered for all cases with 64 subcarriers. MIMO ACO OFDM has better BER performance at 20dB SNR, which performs the LMMSE estimation for the system. From Fig. 5 it is observed that though the LS estimator is common and easy to implement, the LMMSE system performance is far better than the LS estimator. For the MIMO VLC case, the effect of ambient noise increased, which drastically affected on LS estimator.

VI. CONCLUSION

The paper includes a comparative structure of VLC channel estimation for dual O-OFDM systems. At low SNR the channel estimation for ACO OFDM is having better BER performance than the DCO OFDM system for a given constellation. MIMO VLC system is having better performance than the single-user performance. The estimation performance can be verified from both LS and LMMSE estimators. The LMMSE estimator performs better than the LS estimator for all systems. Though the design of the LMMSE estimator is more complex than the LS estimator, the error probability of the LMMSE estimator is less, which justifies the level of performance of the system model. VLC system includes both NLoS and LoS communication. Here for the same distance of transceiver LoS channel performance is better than NLoS channel. The performance of channel estimation can be enhanced by adopting an intelligent reflecting surface (IRS) technique, which can be treated as future work. In this work, a comparative BER performance analysis of channel estimation is given for both modulation techniques.

REFERENCES

[1] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?" *Journal of Lightwave Technology*, vol. 34, no. 6, pp. 1533–1544, 2015.

- [2] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE communications surveys & tutorials*, vol. 17, no. 4, pp. 2047–2077, 2015.
- [3] T. Wang, F. Yang, J. Song, and Z. Han, "Dimming techniques of visible light communications for human-centric illumination networks: State-of-the-art, challenges, and trends," *IEEE Wireless Communications*, vol. 27, no. 4, pp. 88–95, 2020.
- [4] L. E. M. Matheus, A. B. Vieira, L. F. Vieira, M. A. Vieira, and O. Gnawali, "Visible light communication: concepts, applications and challenges," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 4, pp. 3204–3237, 2019.
- [5] S. Chaudhary, A. Sharma, and V. Singh, "Optimization of high speed and long haul inter-satellite communication link by incorporating differential phase shift key and orthogonal frequency division multiplexing scheme," *Optik*, vol. 176, pp. 185–190, 2019.
- [6] L. Yin, W. O. Popoola, X. Wu, and H. Haas, "Performance evaluation of non-orthogonal multiple access in visible light communication," *IEEE Transactions on Communications*, vol. 64, no. 12, pp. 5162–5175, 2016.
- [7] M. Jani, P. Garg, and A. Gupta, "Performance analysis of a mixed cooperative plc-vlc system for indoor communication systems," *IEEE Systems Journal*, vol. 14, no. 1, pp. 469–476, 2019.
- [8] L. Li and A. Sharma, "High speed rgb-based duobinary-encoded visible light communication system under the impact of turbulences," *Frontiers in Physics*, p. 602, 2022.
- [9] X. Chen and M. Jiang, "Adaptive statistical bayesian MMSE channel estimation for visible light communication," *IEEE Transactions on Signal Processing*, vol. 65, no. 5, pp. 1287–1299, 2016.
- [10] R. K. Pal, S. P. Dash, S. Joshi, and D. Ghose, "Channel estimation and performance analysis of a Wide-FOV visible light communication system with random receiver orientation and location," *IEEE Transactions on Wireless Communications*, 2022.
- [11] S. Mohapatra, G. Satapathy, S. P. Dash, and P. R. Sahu, "Performance analysis of visible light communication system with imperfect csi," *IEEE Communications Letters*, vol. 24, no. 12, pp. 2844–2848, 2020.
- [12] O. Narmanlioglu and M. Uysal, "Multi-user massive mimo visible light communications with limited pilot transmission," *IEEE Transactions on Wireless Communications*, vol. 21, no. 6, pp. 4197–4211, 2021.
- [13] A. Costanzo, V. Loscri, and M. Biagi, "Adaptive modulation control for visible light communication systems," *Journal of Lightwave Technology*, vol. 39, no. 9, pp. 2780–2789, 2021.
- [14] T. Foggi, G. Colavolpe, E. Forestieri, and G. Prati, "Channel estimation algorithms for mlcd in optical communication systems," *IEEE Photonics Technology Letters*, vol. 18, no. 19, pp. 1984–1986, 2006.
- [15] T. Zhang, S. Guo, H. Chen, F. Zhong, and C. Ma, "Enhancing the bit error rate of indoor visible light communication systems using adaptive channel estimation algorithm," *Iet Communications*, vol. 9, no. 4, pp. 501–507, 2015.
- [16] R. Mitra, F. Miramirkhani, V. Bhatia, and M. Uysal, "Mixture-kernel based post-distortion in rkh for time-varying vlc channels," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 2, pp. 1564–1577, 2018.
- [17] C. W. Chow, C. Yeh, Y. Liu, and P. Huang, "Background optical noises circumvention in LED optical wireless systems using OFDM," *IEEE photonics Journal*, vol. 5, no. 2, pp. 7900709–7900709, 2013.
- [18] C. Chi Wai, C. Yeh, Y. Liu, and P. Huang, "Mitigation of optical background noise in light-emitting diode (LED) optical wireless communication systems," *IEEE Photonics Journal*, vol. 5, no. 1, pp. 7900307–7900307, 2013.
- [19] C.-C. Chang, Y.-J. Su, U. Kurokawa, and B. I. Choi, "Interference rejection using filter-based sensor array in VLC systems," *IEEE Sensors Journal*, vol. 12, no. 5, pp. 1025–1032, 2011.
- [20] S. Jain, R. Mitra, and V. Bhatia, "Adaptive precoding-based detection algorithm for massive mimo visible light communication," *IEEE Communications Letters*, vol. 22, no. 9, pp. 1842–1845, 2018.
- [21] Z. Gao, Y. Wang, X. Liu, F. Zhou, and K.-K. Wong, "Ffdnet-based channel estimation for massive mimo visible light communication systems," *IEEE Wireless Communications Letters*, vol. 9, no. 3, pp. 340–343, 2019.
- [22] X. Qian, H. Deng, and H. He, "Joint synchronization and channel estimation of aco-ofdm systems with simplified transceiver," *IEEE Photonics Technology Letters*, vol. 30, no. 4, pp. 383–386, 2018.
- [23] S. Ma, R. Yang, X. Deng, X. Ling, X. Zhang, F. Zhou, S. Li, and D. W. K. Ng, "Spectral and energy efficiency of ACO-OFDM in visible light communication systems," *IEEE Transactions on Wireless Communications*, vol. 21, no. 4, pp. 2147–2161, 2021.
- [24] M. T. Niaz, F. Imdad, W. Ejaz, and H. S. Kim, "Compressed sensing-based channel estimation for aco-ofdm visible light communications in 5g systems," *EURASIP Journal on Wireless Communications and Networking*, vol. 2016, pp. 1–14, 2016.

- [25] R. Otte, L. P. De Jong, and A. H. Van Roermund, "Wireless optical PPM telemetry and the influence of lighting flicker," *IEEE Transactions on Instrumentation and Measurement*, vol. 47, no. 1, pp. 51–55, 1998.
- [26] R. Mitra and V. Bhatia, "Precoding technique for ill-conditioned massive mimo-vlc system," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*. IEEE, 2018, pp. 1–5.
- [27] S. Jain, R. Mitra, and V. Bhatia, "Hybrid adaptive precoder and post-distorter for massive-mimo vlc," *IEEE Communications Letters*, vol. 24, no. 1, pp. 150–154, 2019.
- [28] S. D. Dissanayake and J. Armstrong, "Comparison of aco-ofdm, dco-ofdm and ado-ofdm in im/dd systems," *Journal of lightwave technology*, vol. 31, no. 7, pp. 1063–1072, 2013.
- [29] K. R. Sekhar and R. Mitra, "Performance analysis of dco-ofdm over precoded massive mimo vlc channel," in *2018 IEEE international conference on advanced networks and telecommunications systems (ANTS)*. IEEE, 2018, pp. 1–6.