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Performance Evaluation of NRZ-OOK and Carrier-Less Amplitude Phase Modulation in Li-Fi Environment

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Abstract. Light Fidelity (Li-Fi) is a wireless technology that utilizes light emitting diodes to convey data. Li-Fi has emerged as a promising alternative to radio frequency communication technology in recent years. This paper examines the performance characterisation between NRZ-OOK and carrier-less amplitude-phase modulation (CAP-2, CAP-4 and CAP-8), within a simulated Li-Fi environment. For the parameters of interest, the eye pattern, bit error rate (BER) and constellation diagram are reported. As no distance is specified in the simulation, the BER for CAP is zero, allowing an ideal transmission to be emulated. The scatter diagram increases as the number of CAP modulations increases. For the eye pattern, CAP modulation provides a better visual representation of how noise might affect system performance compared to OOK modulation.

1. Introduction

Light Fidelity (Li-Fi) is a subset of optical wireless communication(OWC) technology, was introduced in order to accommodate the increasing need for capacity and bandwidth at high-speed access driven by the rising number of wireless applications and users. Through the illumination of Light-Emitting Diodes (LEDs) lamp, it sends information wirelessly using the visible light spectrum as opposed to the radio spectrum. Li-Fi, which is free unlicensed spectrum unlike RF spectrum, guarantees efficiency, availability, security, safety, and cost-effectiveness. Furthermore, the transceiver circuitry is simple and there is no multipath fading [1]-[6].

Extensive research has been carried on the LED-based wireless system as LEDs lamp gradually replacing conventional fluorescent light as illumination sources due to their high quality, excellent energy efficiency, and longer lifespan [7]-[9]. Moreover, by superimposing a modulated driving signal on the direct current (DC) bias, it is possible to regulate the luminance that is produced, enabling simultaneous data transmission (the AC component) and illumination (the DC component). LEDs are therefore a perfect choice for data transmission in indoor environments. Thus, LEDs are a suitable component for the Li-Fi system as data transmitters for the indoor environment [10]-[14].

However, studies reveal that the LEDs system's LEDs' have weak modulation bandwidths, which limit the amount of data that can be sent. There have been reports of new advanced multilevel modulation formats, demonstrating that the next optical communication system can be solved in a variety of ways. But it does seem that, practically, all of these advanced modulation forms require complex and expensive transmission methods. Advanced modulation formats that lower the system complexity while simultaneously attaining better bit rates and spectrum efficiency with fewer optoelectronic components will make the optical transmission system more viable and efficient [15]-[22].

Single Carrier Modulation (SCM) has emerged as one of the intriguing OWC modulation schemes. On-Off Keying (OOK), Pulse Amplitude Modulation (PAM), and Pulse Position Modulation (PPM) are examples of SCM that are appropriate for visible light communication (VLC) systems [23][24]. In OOK scheme, the incoming binary data stream is used to control the intensity of the LED by turning it ON to represent a binary one or turning it OFF to represent a binary zero. The OOK signal amplitude must be positive because the intensity modulation and direct detection (IM/DD) approach must be utilised, which is implemented as uni-polar non-return-to-zero (NRZ) signalling. Each transmission symbol corresponds to a bit, and therefore the symbol rate corresponds to the bit rate. Due to its relative simplicity, OOK was widely adopted for OWC [10][11][25]-[28]. The LEDs must be turned ON and OFF at faster rates to achieve higher data rates. An ideal OOK modulated signal has pulse shapes with fast rise and fall times. The modulation bandwidth is determined by the lifetime of the minority carriers in the active area of the LEDs. The rise time is relatively constant, whereas the fall time depends on the voltage applied across the LED. Dependence of rising and fall times on the internal parasitic capacitances (diffusion and junction capacitance) and their voltage dependence limits the modulation bandwidth and thereby OOK performance. Techniques such as carrier flush out [28] to remove the remaining carriers during the OFF phase and the resultant faster fall times have caused an improvement in modulation bandwidth. However, due to the spectral inefficiency of the OOK scheme, it is not suited for high data rate systems.

Carrier-less amplitude phase (CAP) modulation has been extensively studied for OWC system. This is owing to a unique mix of excellent spectral efficiency and ease of implementation. Due to its unique qualities that contribute to implementation benefits in OWC. CAP, being a single carrier modulation, offers a lower peak-to-average power ratio (PAPR) compared with discrete multi-tone (DMT), which one of the significant difficulties is high PAPR [30]. Due to the significant optical power constraints imposed by eye safety standards and design considerations on the transmitter front-end, the low PAPR factor of CAP modulation is ideally matched to OWC. Thus, the carrier-less amplitude phase (CAP) modulation scheme could be a good alternative for developing a flexible, simple, and affordable optical access as well as in network communications network. In addition, this modulation scheme is suitable for Li-Fi systems because of its low peak-to-average power ratio (PAPR) and simple transceiver design. CAP modulation is a multidimensional and multilevel modulation that mimics quadrature amplitude modulation (QAM) at the phase in which it transmits two input data streams concurrently. As the working concept of CAP modulation is comparable to QAM, it does not require local oscillators (LOs), RF mixers, or phase-locked loops in this circuits. In contrast, instead of using a carrier, CAP employs transversal filters with an orthogonal impulse response to produce in-phase and quadrature filters to segregate the data streams.

Furthermore, considering LEDs are incoherent light sources, designing an effective, coherent receiver is difficult. OWC incorporates the intensity modulation and direct detection (IM/DD) technology as a possible transceiver option [11]. Since the optical emitter's intensity is modulated in OWC, the data-carrying signal has to be real-valued, unipolar, and non-negative. Consequently, the CAP signal is real-valued, obviating the need for additional processing techniques like DMT's Hermitian symmetry [30]. In contrast to the quadrature amplitude modulation (QAM) equivalent, the CAP transceiver is comparatively easy to design since it utilises a digital finite impulse response (FIR) filter and bypasses the requirement for carrier modulation and recovery [13][32][33].

In this article, the signal transmission quality and the performance of NRZ-OOK and CAP (CAP-2, CAP4 and CAP8) modulations is evaluated within LI-Fi environment.

2. Methodology

This paper discussed a Li-Fi system comprised of a single transmitter (with a single LED) and a receiver. The simulated parameters are considered based on [1]-[3]. **Table 1** summarises the critical factors for a typical room setting that are utilised in Li-Fi system modelling, to analyse system performance, the parameter of a room, transmitter, receiver and noise.

Table 1. Li-Fi simulation parameters

Type	Parameter	Value
Transmitter	Number of Transmitters (LED)	1
	Power Radiated by LED	1 W
	Angle of Irradiance	70^o
	Field of View (FOV)	70^o
	LED location in the room	[2,2,2]
	Number of LEDs per array	60*60
	Center Luminous Intensity	0.73 cd
Room & Other	Size of Room [W x L x H]	[4 x 4 x 2] m
	Noise Current	0.562 A
	Amplifier Bandwidth Factor	50×10^6
	Ambient Light Power	5×10^{-12} A
	Data Rate	1×10^6 b/s
	Distance Between Tx and Rx	1 m
	Filter Coefficient	1
	Electron Charge	1.6×10^{-19} C
Receiver	Photodetector Area	1×10^{-4} cm^2
	Angle of Irradiance	70^o
	Field of View (FOV)	90^o
	Responsivity	1 A/W
	Photodetector Concentrator Refractive Index	1.46

The standard CAP-2 scheme in **Figure 1** was developed using Simulink's rectangular quadrature amplitude modulation module. As a result, generate CAP-2. The QAM is identical to the CAP in that it allows for multiple levels and modulation in several dimensions. Nevertheless, CAP does not generate two orthogonal components with a sinusoidal carrier. As a result, the ratio of sample-to-symbol is proportional to the dimension count in a linear way. Additionally, it also explains how the orthogonal waveform is generated using the CAP.

Both the transmitter and receiver use digital technology. The procedure is referred to as encoding in the transmitter section. The transmitter will decompose the data stream into blocks of binary data. A single pair is used to encode each data block. Two orthogonal signals are formed after encoding, which are then merged before transmission. For that implementation, the incoming sequences are up-sampled to match the implementation sampling rate, and hence the rate of this procedure. The Additive white Gaussian noise (AWGN) channel with the 10 dB signal-to-noise-ratio (SNR) level is set for modelling noise in this block. This process is referred to as decoding at the receiver end, and it is responsible for decoding the data symbol in order to recover the block binary digits. The receiver's output is down-sampled to the original symbol rate. Separation of the two orthogonal summed modulated signals is possible.

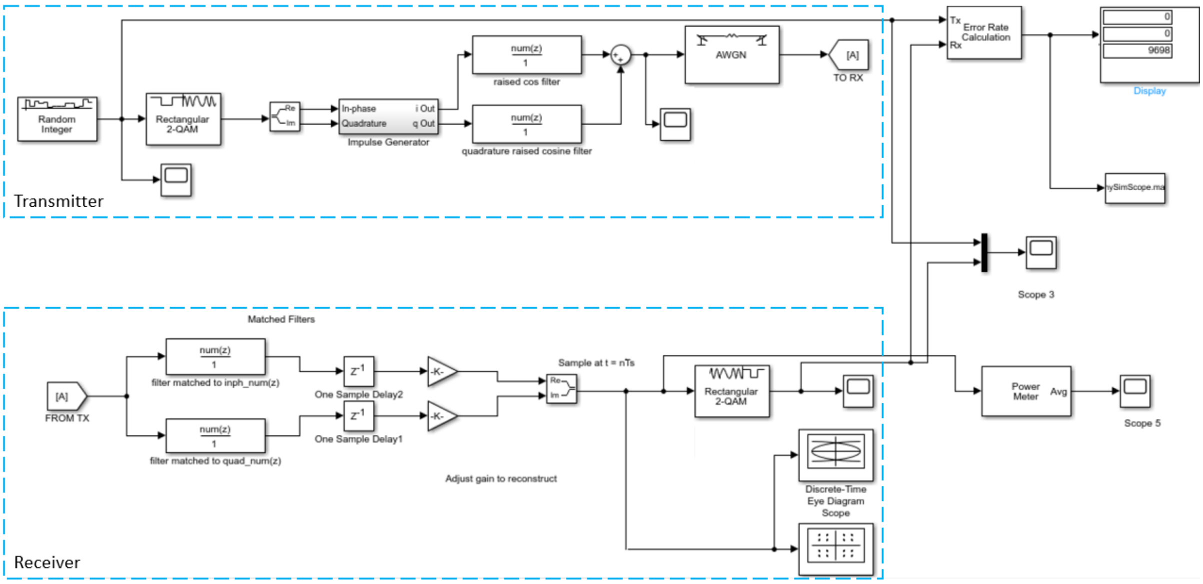


Figure 1. CAP-2 scheme

3. Results

3.1. Li-Fi Simulation Results

Transmitted and Received pulses is shown as in **Figure 2**. The pattern of illumination for a single LED transmitter with a semi-angle, half-power of 70° is shown in **Figure 3**, assuming no extra light is reflected from the surrounding walls. ISO defines sufficient illuminance as being between 3000 and 1500 lx. It was observed that the illuminance is greatest in the centre and diminishes toward the margins. The maximum luminous flux value is 652 lx in the centre of the room, while the minimum value is 250 lx at the periphery. As a result, the LED bulbs with the specifications employed in this simulation can provide an adequate illumination level.

SNR can be utilised to indicate the quality of a communication link in OWC. SNR is used to determine the VLC link's capacity. The optical signal-to-noise ratio (SNR) can be defined as the ratio of the average signal power received to the ambient noise. **Figure 4** shows the SNR distribution in 4m x 4m x 2m room. The maximum SNR is observed close to the centre of the room. The maximum SNR 29.2 dB is observed at the centre, while a minimum of -6.7dB is observed at the edges.

The power distribution seems to be symmetrical due to the symmetry of the room and the location of the transmitters. The high received power is generated at the central spots, collecting the most energy as shown in **Figure 5**. The greatest power received is -51dBm. With a received power of -60dBm, the received power drops as the photodiode (PD) location moves further away.

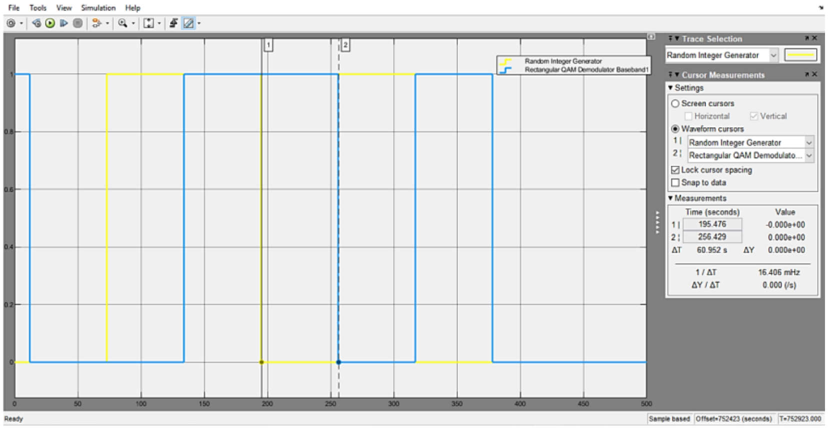


Figure 2. Transmitter and receiver pulses

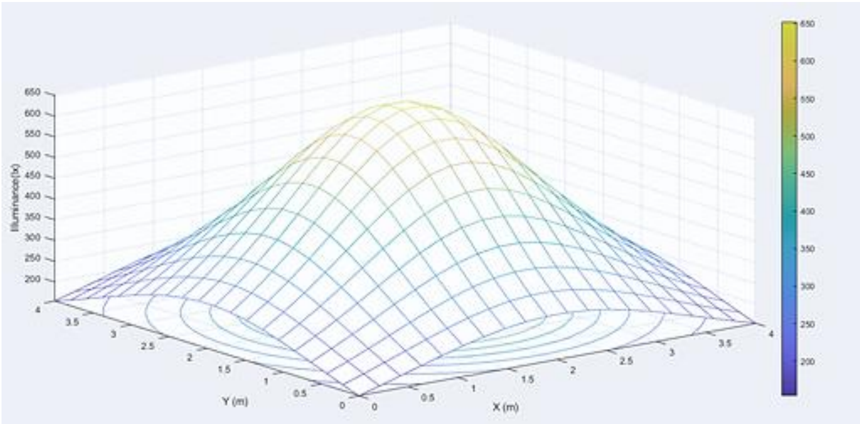


Figure 3. Distribution of single LED illumination pattern

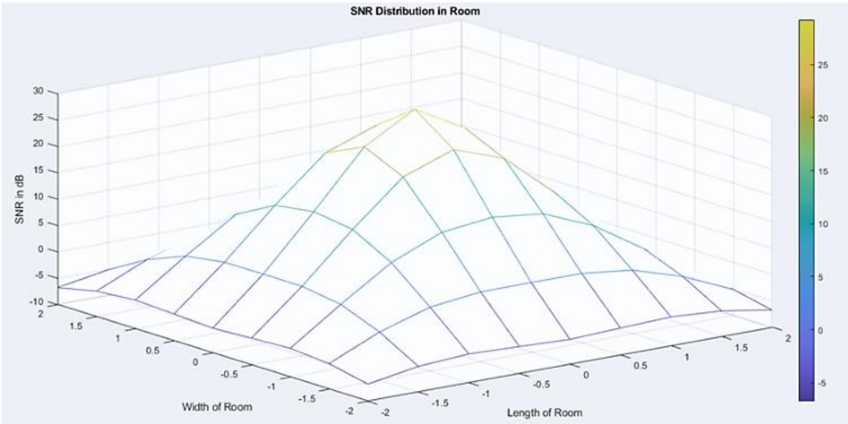


Figure 4. Distribution of SNR

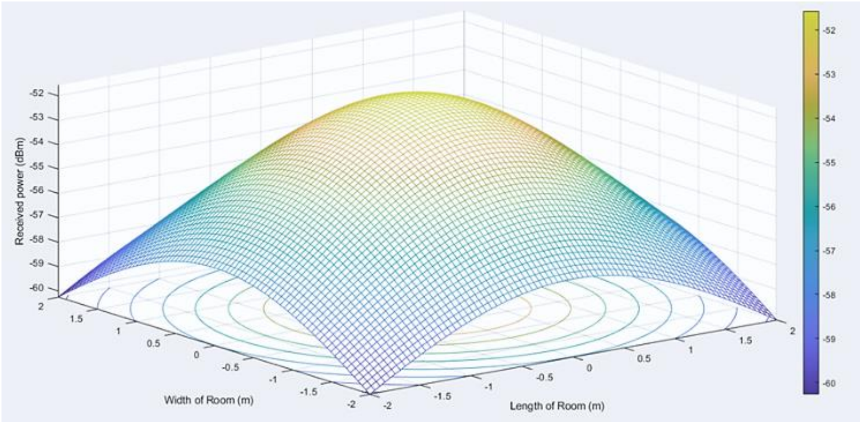


Figure 5. Distribution of received power

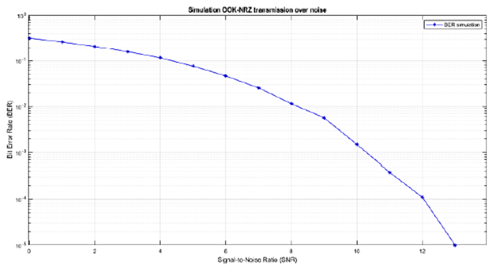
3.2. Performance Analysis

3.2.1. *Bit Error Rate.* BER is a commonly used indicator of system performance in wireless communications. BER is the number of bits collected from the data stream of the communication channel that compensate for noise errors. The BER of NRZ-OOK as a function of SNR is given as (1) [16].

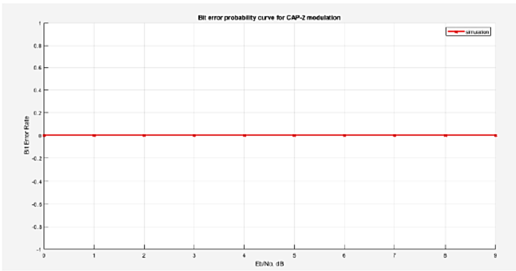
$$\mathrm{BER}_{\text{NRZ-OOK}} = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{S/_N}\right) \quad (1)$$

The BER curve can also be used to illustrate a digital communication system's performance. The energy-per-bit-to-noise-power-spectral-density (EbNO) ratio is proportional to the SNR, taking the bit rates of the various constellations into consideration. EbNO ratio is also known as normalized SNR measured or SNR per bit.

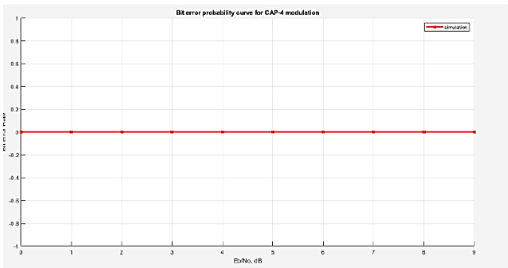
From **Figure 6**, the BER illustrates that as more bit signals are sent out for OOK modulation, the bit error rate increases. Yet, there is no bit error rate for CAP modulation as there is no distance set in simulation. Therefore, perfect transmission is simulated.



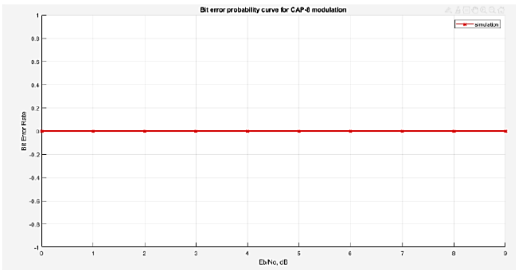
OOK Modulation



CAP- 2 Modulation



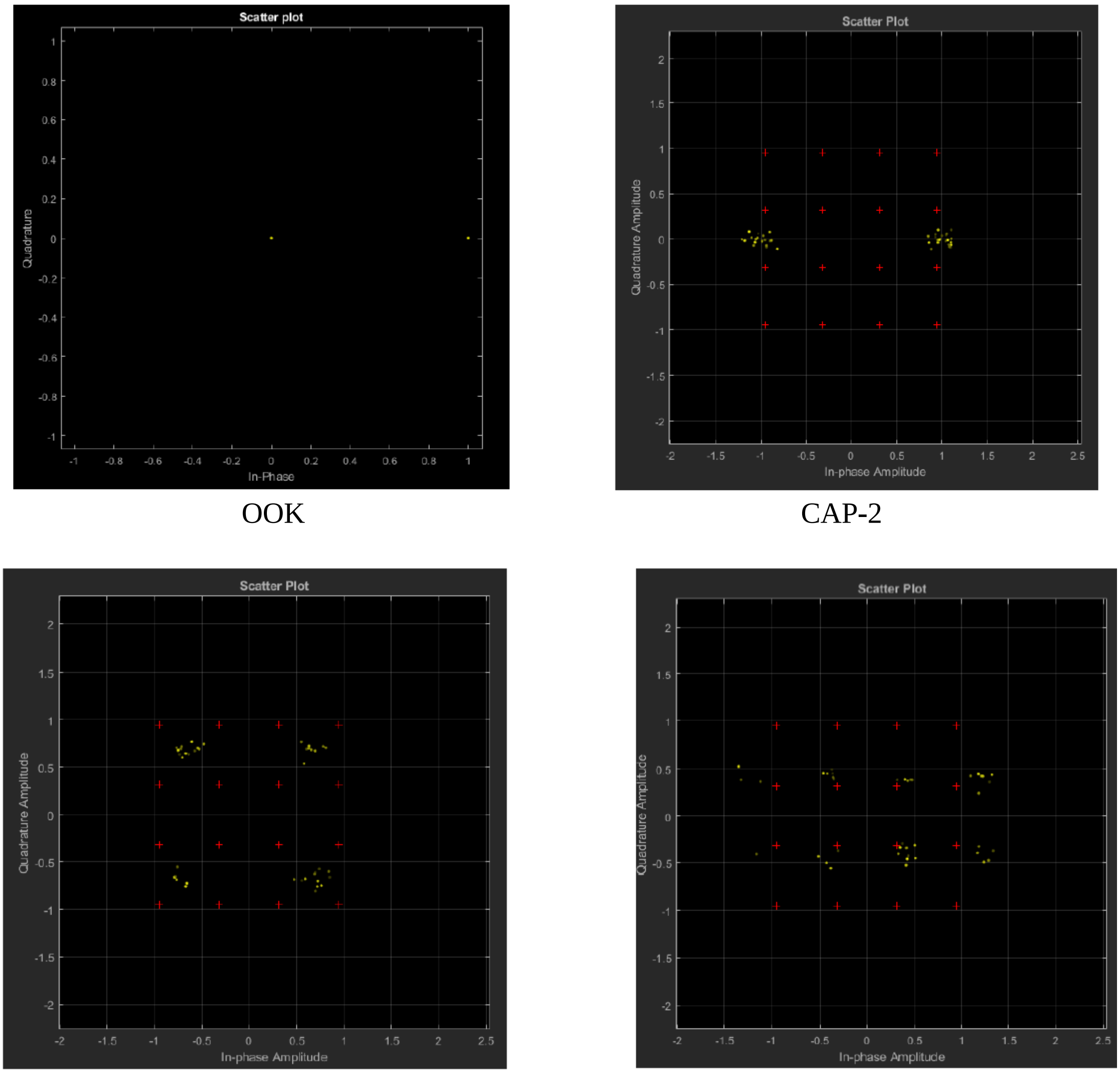
CAP- 4 Modulation



CAP- 8 Modulation

Figure 6. BER plot for OOK, CAP-2, CAP-4 and CAP-8

3.2.2. Constellation diagram analysis. A scatter plot or constellation diagram is employed to view the constellation of a digitally modulated signal. In terms of constellation diagrams in **Figure 7**, it can be observed that as the modulation number increases, the constellation diagram also increases. In OOK modulation, logic zero is denoted by lower amplitude, while logic one is denoted by a greater amplitude. In OOK modulation, there is no carrier involved during the transmission of logic zero. Rather than that, the carrier is transmitted during logic one transmission.



OOK CAP-2

CAP-4 CAP-8

Figure 7. Constellation diagram for OOK, CAP-2, CAP-4 and CAP-8

The OOK modulation transmitter enters the IDLE state during logic "zero" transmission. Therefore, it is plotted at point 0,0, while logic one is plotted at 1,0. The constellation points in QAM for CAP modulation are typically placed in a square grid with uniform vertical and horizontal spacing. Upgrading to a higher-order constellation permits the transmission of additional bits per symbol. Nonetheless, in attempt to conduct a fair assessment, the constellation's mean energy must remain constant. As a result, points will be closer together and hence more prone to noise and other forms of contamination, as we see in the eyes diagram of CAP-8 compared to CAP-2 or 4. The constellation diagram can be used to determine the signal's quality parameters, such as modulation error ratio (MER) and error vector magnitude (EVM). The EVM would be used to determine the performance of a digital signal transmitted by the transmitter and received by the receiver, as well as the distance between the points from their desired locations.

Every constellation point pointing in the desired direction will be displayed in the received signal. While the MER is used to determine the performance of a digital radio transmitter or receiver employing digital modulation such as QAM, the power received is utilised to determine the loss measures and the power from a source or present at a receiver. The QAM is similar to the CAP in that it allows for multiple levels and modulation in several dimensions. In contrast to QAM, the CAP does not require the creation of sinusoidal signals at both ends, at the transmitter and receiver. Additionally, CAP can be used to modulate in more than two dimensions if orthogonal pulse forms can be discovered.

Based on the constellation diagram, it can be observed that the EVM of CAP-4 is the best while the EVM of CAP-8 measures the worse of a digital signal of the transmitter and receiver. This says that CAP-8 has the least ideal constellation diagram location than CAP-2 and CAP-4. In terms of MER, CAP-4 has the best reading value compared to CAP-2 and CAP-8. However, CAP-8 records the least reading for MER. In terms of power received, CAP-8 has the highest reading of 12.42dBW compared to other CAP modulation. From **Table 2**, it can be concluded that CAP-4 record the best reading value overall compared to other CAP modulation.

Table 2. Comparison of the Modulation scheme for EVM, MER and Output Power

Modulation	EVM (dB)	MER (dB)	Average power (dBW)
OOK	Unable to be retrieved	Unable to be retrieved	Unable to be retrieved
CAP-2	-10.900	10.900	0.132
CAP-4	-9.600	11.300	5.450
CAP-8	-11.900	9.800	12.420

3.2.3. Eye Diagram analysis. An eye diagram illustrates the effect of noise on system performance. The eye diagram OOK modulation in **Figure 8** is significantly distorted due to many input bits. In terms of the eye diagram, it was noted that CAP modulation offers a better visual representation of how noise could affect system performance than OOK modulation. However, CAP-4 offers a better eye diagram because the quality of the in-phase signal and quadrature signal is better than CAP-2 and CAP-8.

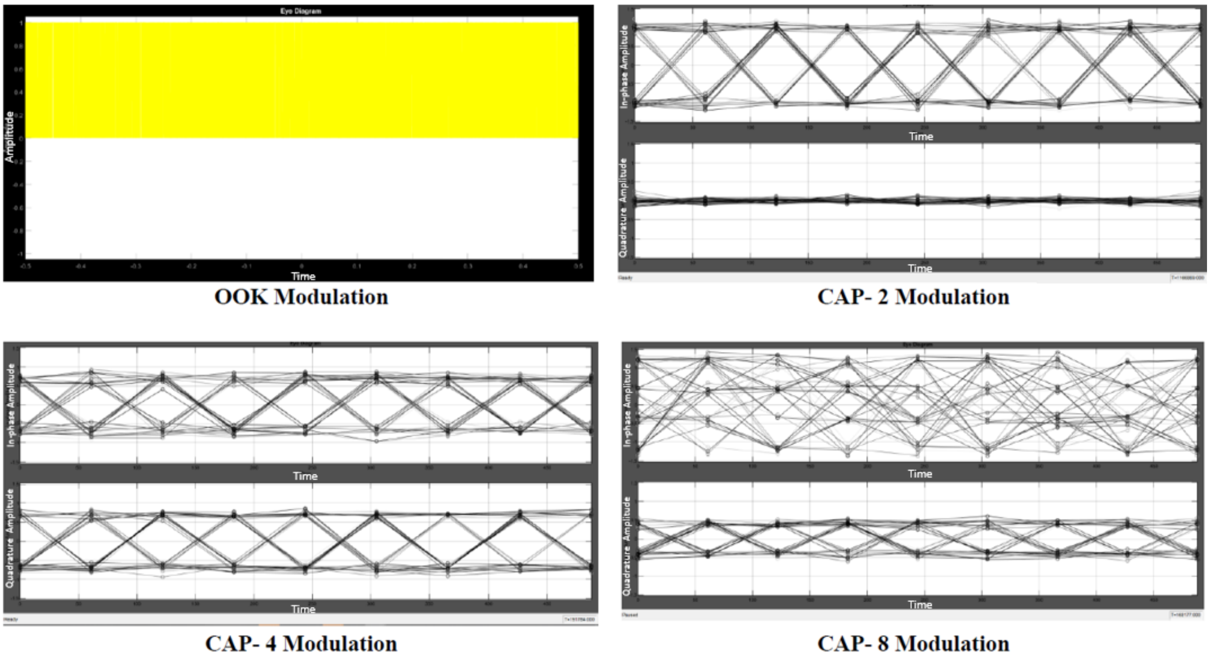


Figure 8. Eye diagram for OOK, CAP-2, CAP-4 and CAP-8

4. Discussion

From the result above, a comparison between CAP modulation and OOK modulation can be made for the VLC system. In BER analysis, CAP modulation records a better result than OOK modulation. This is because, as the input bit rate increases in OOK modulation, the output bit error also increases. However, for CAP modulation, perfect transmission is simulated with zero error.

For constellation diagram analysis, OOK modulation only has two states that allow for the transmission of either a 0 or a 1. However, numerous alternative points can be used with QAM, each with its defined phase and amplitude values. QAM, which doubles the number of states to four, results in a symbol with two bits. The number of bits per symbol can be raised further by increasing the constellation's size. This is what is referred to as a constellation diagram. Different values are assigned to the various places, allowing a single signal to transport data at a considerably greater rate. The number of bits per symbol is equal to the log base 2 of the number of constellation points. **Table 3** tabulated that OOK and CAP-2 carry the least bits per symbol, which is 1 while CAP-8 carry the highest bit per symbol of 3. Therefore, from the constellation diagram it can be said that CAP-8 is the best as it can contain more bits of data per symbol compared to OOK and CAP-2 and CAP-4 modulation. It is also worth noting that increasing the data rate of a link by using a higher-level CAP format is possible.

Table 3. Bit per Symbol comparison

Modulation	Bits per Symbol
OOK	1
CAP-2	1
CAP-4	2
CAP-8	3

EVM and MER can also be determined from a constellation diagram. Unfortunately, EVM and MER for OOK modulation cannot be retrieved. This is because due to limitation in MATLAB coding or MATLAB functions for figure plotted out with coding. But for CAP modulation, EVM of CAP-4 is the best while the EVM of CAP-8 measures the worse of a digital signal which may be due to rectangular, rather than the square shape of the constellation that affects the performance of signal transmitted. For MER, CAP-4 still records the highest reading compared to other CAP while CAP-8 records the least MER reading. This can be said that CAP-8 has the least favourite performance of a digital transmitter or receiver employing digital modulation. However, CAP-8 records the highest power received, meaning it has the most negligible power loss of signal at the receiver. In conclusion, the performance of transmitter and receiver in terms of EVM and MER, CAP-4 will be recommended even though CAP-8 has better output power.

For the eyes diagram, with a large input bit, OOK modulation recorded a very distorted signal which CAP modulation provides a better eyes diagram. This also proves that OOK modulation is not very good with large input data compared to CAP modulation. However, CAP-4 provides a superior eye diagram due to the superior quality of the in-phase and quadrature signals compared to CAP-2 and CAP-8. In conclusion, CAP modulation is better compared to OOK modulation.

5. Conclusion

The future of visible-light communication technology is exceptionally bright. This invention addressed the issue of incorporating visible-light communication technology into existing infrastructure without requiring significant alterations. It is a fast-growing part of the communication industry, and it is simply implemented at a low cost.

It is proven that by using CAP modulation, LED's bandwidth limitation can be overcome in the VLC system. In BER analysis, CAP modulation records a better result than OOK modulation. This is because, as the input bit rate increases in OOK modulation, the output bit error also increases. For the constellation diagram the EVM of CAP-4 (-9.6dB) is the best while the EVM of CAP-8 (-11.9dB) measures the worse of a digital signal of the transmitter and receiver. This says that CAP-8 has the least ideal constellation diagram location than CAP-2 and CAP-4. In terms of MER, CAP-4 (11.3dB) has the best reading value compared to CAP-2 (10.9dB) and CAP-8 (9.8dB). However, CAP-8 records the least reading for MER. In terms of power received, CAP-8 has the highest reading of 12.42dBW compared to other CAP modulation. Therefore, it can be concluded that CAP-4 record the best reading value overall compared to other CAP modulation. For bit per symbol, it can be concluded that OOK and CAP-2 carry the least bits per symbol, which is 1 while CAP-8 carries the highest bit per symbol of 3. Therefore, from the constellation diagram it can be said that CAP-8 is the best as it can contain more bits of data per symbol compared to OOK and CAP-2 and CAP-4 modulation. For the eyes diagram, with a large input bit, OOK modulation recorded a very distorted signal which CAP modulation provides a better eyes diagram. This also proves that OOK modulation is not very good with large input data compared to CAP modulation. However, CAP-4 provides a superior eye diagram due to the superior quality of the in-phase and quadrature signals compared to CAP-2 and CAP-8.

Taking everything into account, CAP modulation is suitable for indoor VLC system which use LED as an optical source.

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References

[1] Alfattani, S., 2021. Review of LiFi technology and its future applications. *Journal of Optical Communications*, *42*(1), pp.121-132.

[2] Jukaria, M., Singh, B.K. and Kumar, A., 2018. Review of Li Fi technology: scope of next generation communication system for home area network. *International Journal of Engineering, Science and Mathematics*, *7*(3), pp.265-275.

[3] Demirkol, I., Camps-Mur, D., Paradells, J., Combalia, M., Popoola, W. and Haas, H., 2019. Powering the Internet of Things through light communication. *IEEE Communications Magazine*, *57*(6), pp.107-113.
[4] Merah, M.M., 2019. Conception and realization of an indoor multi-user Light-Fidelity link (Doctoral dissertation, Université Paris-Saclay).
[5] Bober, K.L., Jungnickel, V., Emmelmann, M., Riegel, M., Tangdiongga, E., Koonen, A.M.J., Linnartz, J.P., Behnke, D., Müller, M., Bök, P.B. and Colonques, S.V., 2020, July. A flexible system concept for LiFi in the Internet of Things. In *2020 22nd International Conference on Transparent Optical Networks (ICTON)* (pp. 1-4). IEEE.
[6] Chen, C., Bian, R. and Haas, H., 2018, May. Omnidirectional transmitter and receiver design for wireless infrared uplink transmission in LiFi. In *2018 IEEE International Conference on Communications Workshops (ICC Workshops)* (pp. 1-6). IEEE.
[7] Wu, S., Wang, H. and Youn, C.H., 2014. Visible light communications for 5G wireless networking systems: from fixed to mobile communications. *Ieee Network*, *28*(6), pp.41-45.
[8] Kitano, S., Haruyama, S. and Nakagawa, M., 2003, October. LED road illumination communications system. In *2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No. 03CH37484)* (Vol. 5, pp. 3346-3350). IEEE.
[9] Karunatilaka, D., Zafar, F., Kalavally, V. and Parthiban, R., 2015. LED based indoor visible light communications: State of the art. *IEEE communications surveys & tutorials*, *17*(3), pp.1649-1678.
[10] Di Mauro, S. and Raciti, A., 2014, September. Analysis and comparison of CFLs and LED lamps. In *2014 AEIT Annual Conference-From Research to Industry: The Need for a More Effective Technology Transfer (AEIT)* (pp. 1-6). IEEE.
[11] Tanaka, Y., Komine, T., Haruyama, S. and Nakagawa, M., 2001, October. Indoor visible communication utilizing plural white LEDs as lighting. In *12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications. PIMRC 2001. Proceedings (Cat. No. 01TH8598)* (Vol. 2, pp. F-F). IEEE.
[12] Fujimoto, N. and Yamamoto, S., 2014, September. The fastest visible light transmissions of 662 Mb/s by a blue LED, 600 Mb/s by a red LED, and 520 Mb/s by a green LED based on simple OOK-NRZ modulation of a commercially available RGB-type white LED using pre-emphasis and post-equalizing techniques. In *2014 The European Conference on Optical Communication (ECOC)* (pp. 1-3). IEEE.
[13] Merah, M.M., 2019. Conception and realization of an indoor multi-user Light-Fidelity link (Doctoral dissertation, Université Paris-Saclay).
[14] Singh, L., Rout, M., Bishal, J.S. and Ratnam, J., 2022. Data Transfer Using Light Fidelity (Li-Fi) Technology—A Methodological Comparative Study. In Biologically Inspired Techniques in Many Criteria Decision Making (pp. 315-321). Springer, Singapore.
[15] Zaiton, A.M., Rahim, H.R.A., Jasman, F. and Yong, C.K., 2020, January. Performance characterization of phase shift keying modulation techniques for indoor visible light communication system. In AIP Conference Proceedings (Vol. 2203, No. 1, p. 020023). AIP Publishing LLC.
[16] Islim, M.S. and Haas, H., 2019. Modulation techniques for Li-Fi. ZTE communications, 14(2), pp.29-40.
[17] Mutalip, Z.B.A., 2010, March. Frequency chirp characteristics on WDM direct modulation. In 2010 Second International Conference on Computer Engineering and Applications (Vol. 1, pp. 125-128). IEEE.
[18] Yesilkaya, A., Bian, R., Tavakkolnia, I. and Haas, H., 2019. OFDM-based optical spatial modulation. IEEE Journal of Selected Topics in Signal Processing, 13(6), pp.1433-1444.
[19] Guzatov, D.V., Gaponenko, S.V. and Demir, H.V., 2018. Possible plasmonic acceleration of LED modulation for Li-Fi applications. Plasmonics, 13(6), pp.2133-2140.
[20] Swami, K.T. and Moghe, A.A., 2020, December. A Review of LiFi Technology. In 2020 5th IEEE International Conference on Recent Advances and Innovations in Engineering (ICRAIE) (pp. 1-5). IEEE.

[21] Pikasis, E. and Popoola, W.O., 2018. Understanding LiFi Effect on LED Light Quality. In 2018 IEEE Photonics Conference (IPC) (pp. 1-2). IEEE.

[22] Karthik, N., Palanisamy, B., Karthikeyan, T., Chandrakumar, K. and Thirunavukkarasu, K., 2019. Light Fidelity (LIFI) Data Exchange Using Secure Attribute Based Encryption Implementation. Journal of Computational and Theoretical Nanoscience, 16(5-6), pp.2317-2320.

[23] Higgins, M., Rihawi, Z., Mutalip, Z.A., Green, R. and Leeson, M.S., 2013. Optical Wireless Communications in Vehicular Systems. *Communication in Transportation Systems*, pp.209-222.

[24] Zaiton, A.M., Eng, C.H. and Jasman, F., 2020, March. Pulse position modulation characterization for indoor visible light communication system. In Journal of Physics: Conference Series (Vol. 1502, No. 1, p. 012005). IOP Publishing.

[25] Jasman, F., Zaiton, A.M., Ahmad, Z. and Rihawi, Z., 2018. Scattering regimes for underwater optical wireless communications using Monte Carlo simulation. Int. J. Elect. Comput. Eng, 8, pp.2571-2577.

[26] Zaiton, A.M., Muhammad, H.R. and Jasman, F., 2020, March. Solar panel receiver characterisation for indoor visible light communication system. In Journal of Physics: Conference Series (Vol. 1502, No. 1, p. 012016). IOP Publishing.

[27] Rihawi, Z.S., Mutalip, Z.A., Green, R.J., Higgins, M.D. and Leeson, M.S., 2016. Free-space optical communications in vehicular networks using rectangular guiding models. IEEE Photonics Technology Letters, 28(13), pp.1430-1433.

[28] Vučić, J., Kottke, C., Nerreter, S., Habel, K., Büttner, A., Langer, K.D. and Walewski, J.W., 2010, March. 230 Mbit/s via a wireless visible-light link based on OOK modulation of phosphorescent white LEDs. In *2010 Conference on Optical Fiber Communication (OFC/NFOEC), collocated National Fiber Optic Engineers Conference* (pp. 1-3). IEEE.

[29] Kishi, T., Tanaka, H. and Umeda, Y., 2011, December. A high speed LED driver for visible light communications with drawing out remaining carriers by a CMOS inverter. In *Asia-Pacific Microwave Conference 2011* (pp. 1234-1237). IEEE.

[30] Popoola, W.O., Ghassemlooy, Z. and Stewart, B.G., 2014. Pilot-assisted PAPR reduction technique for optical OFDM communication systems. *Journal of Lightwave Technology*, *32*(7), pp.1374-1382.

[31] Stepniak, G. and Siuzdak, J., 2014. Experimental investigation of PAM, CAP and DMT modulations efficiency over a double-step-index polymer optical fiber. *Optical Fiber Technology*, *20*(4), pp.369-373.

[32] Schubert, E.F., 2018. *Light-emitting diodes*. E. Fred Schubert.

[33] Akande, K.O., 2019. Enhanced carrierless amplitude and phase modulation for optical communication systems.