

Performance evaluation of carrier-less amplitude phase modulation scheme for indoor visible light communication system

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In the field of visible light communication (VLC) systems, carrier-less amplitude and phase modulation have lately been explored as an alternative to various modulation techniques, especially optical orthogonal-frequency-division-multiplexing. This study simulates the performance of carrier-less amplitude phase (CAP) modulation compared to basic On-Off Keying in terms of bit-error-rate, constellation diagram and eye diagram. The performance of CAP-2, CAP -4 and CAP-8 was considered in this study due to low computational complexity. Based on various modulation orders of CAP signals, CAP-4 has the lowest EVM (-10.90 dB) and highest MER (11.30 dB) which indicates better performance, supported by good eye-diagram representation. Non-square constellation diagram limits the performance of CAP-8 scheme.

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1. Introduction

The demand for a data communication network which can supply higher bandwidth at high-speed access grew day by day as the communication industry evolved. The solution could be a visible light communication (VLC) system, which can provide high-speed wireless communications with various advantages [1, 2].

Visible Light Communication (VLC) is a revolutionary innovation integrating data transfer and light-emitting diode (LED) illumination [2]. VLC systems can provide high-speed wireless communications while also offering numerous advantages, including a large license-free bandwidth, low-cost components, strong encryption, and resilience to electromagnetic disturbance [3, 4]. Visible light communications (VLC) are used for high-speed, cable-free communication. Visible-light communication does not interfere with RF communications is a huge advantage. This allowed hospitals and space stations to use visible-light communication. Visible-light communication is becoming more popular for various applications due to its security, ease of implementation, and license-free band features [5, 6].

As intensive research has been done regarding the LED-based wireless VLC system, because of their excellent quality, excellent energy efficiency, and longer lifetime, light-emitting diodes (LEDs) are progressively taking over conventional fluorescent light as illumination sources [7-11]. Furthermore, a modulated driving signal can be superimposed on the direct current (DC) bias, and

the intensity of their generated light can be controlled, allowing for data transfer (AC component) and illumination (DC component) at the same time. As a result, LEDs offer an ideal solution for data transmission in interior contexts [12, 13]. LEDs are a suitable component for the VLC system as data transmitters for the indoor environment. Nonetheless, the study shows that the LEDs employed in the system have poor modulation bandwidths, restricting the data rate achieved. 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 [5], [14]. However, it appears that almost 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. As a result, the carrier-less amplitude phase (CAP) modulation scheme is a promising candidate for constructing a versatile, less complex, and cost-effective optical access communications network. Aside from that, due to their low peak-to-average power ratio (PAPR) and straightforward transceiver design, this technology is appropriate for VLC systems [15-17]. CAP modulation is a multidimensional and multilevel modulation system that mimics quadrature amplitude modulation (QAM) at the phase in which it transmits two input data streams simultaneously. Because the working concept of CAP modulation is similar to that of QAM, it does not need local oscillators (LOs), RF mixers, or phase-

locked loops, which unnecessarily complicate the electronic circuits. On the other hand, instead of using the carrier, CAP employs transversal filters with an orthogonal impulse response to produce in-phase and quadrature filters to segregate the data streams.

Along with the increased usage of smartphones and the rise of the Internet of Things (IoT), the ever-increasing traffic on wireless networks has created a huge requirement for dependable high-speed data connections. Cisco predicts that by 2021, data traffic demand would have surpassed the 49 EB/month barrier, implying a 47% annual increase from 2016, a sevenfold increase over 2016 (web, data and voice over IP 24%, video 54%, audio 37%, file sharing 49%) [18]. Only cellular traffic is included in this projection, which eliminates traffic offloaded upon Wi-Fi and tiny cells from dual-mode devices. Readers, handheld gaming consoles, and other portable gadgets with inbuilt cellular connectivity fall into the "other portable devices" category. The "M2M" category includes wearables [18].

OOK is a digital modulation method that is relatively basic that is used in VLC systems. The LED is turned ON to represent a binary one or turned OFF to indicate a binary zero in this technique, which uses the incoming binary data stream to regulate the intensity of the LED. The OOK signal amplitude must be positive because the intensity modulation and direct detection (IM/DD) approach must be utilised, which is implemented as unipolar non-return-to-zero (NRZ) signaling. Since each transmission symbol represents a single bit, the symbol rate and bit rate are equal. Due to its relative simplicity, OOK was adopted for optical wireless communication (OWC) early [19] in its modern history and widely [5], [20-23]. To obtain larger data rates, the LEDs must be turned ON and OFF more quickly. The ideal pulse form for an OOK-modulated signal has a fast rise and fall time. The modulation bandwidth is determined by the lifetime of the minority carriers in the active area of the LEDs. While the fall time is mostly dependent on the voltage put across the LED, the rising time is often constant [17]. The modulation bandwidth and, consequently, OOK performance are constrained by the dependency of rising and falling times on internal parasitic capacitances (diffusion and junction capacitance) and their voltage dependence. Techniques such as carrier flush out [25] are used to remove the remaining carriers during the OFF phase and the resultant faster fall times have caused an improvement in modulation bandwidth. However, the OOK technique is not appropriate for large data rate systems due to its spectral inefficiency.

The CAP modulation technique has been extensively studied for VLC applications. This is owing to a unique mix of excellent spectral efficiency and ease of implementation [26-28]. Due to its unique qualities that contribute to implementation benefits in optical wireless communication (OWC), CAP modulation is currently frequently employed in VLC. CAP, being a single carrier modulation, offers a lower peak-to-average power ratio (PAPR) compared with discrete multitone (DMT), which one of the significant difficulties is high PAPR [29]. 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 [20].

Furthermore, considering LEDs are incoherent light sources, designing an effective, coherent receiver is difficult. VLC incorporates intensity modulation and direct detection (IM/DD) technology as a possible transceiver option [21]. Since the optical emitter's intensity is modulated in VLC, the data-carrying signal must 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 [15]. 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 [24, 30, 31].

The purpose of this article is to compare the performance of On-Off Keying (OOK) modulation and Carrier-less Amplitude Phase (CAP) modulation for visible light communication.

2. Methodology

This paper discussed an indoor VLC system comprised of a single transmitter and receiver. The project is considering a single LED. These parameters are considered based on [1-3]. To analyse VLC system performance, the parameter of a room, LED, receiver and noise are set. Table 1 summarises the critical parameters for a typical room setting that are utilised in VLC system modelling.

Table 1. Simulation parameters

VLC Ideal Parameter		
Type	Parameter	Value
Transmitter	Number of Transmitters (LED)	1
	Power Radiated by LED	1 W
	Angle of Irradiance	70^0
	Field of View (FOV)	70^0
	LED location in the room	[2,2,2]
	Number of LEDs per array	60^*60
	Center Luminous Intensity	0.73
Room & Other	Size of Room [W x L x H]	$[4 \times 4 \times 2]$ 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
Receiver	Electron Charge	1.6×10^{-19}
	Photodetector Area	1×10^{-4} cm ²
	Angle of Irradiance	70^0
	Field of View (FOV)	90^0
	Responsivity	1 A/W
Photodetector Concentrator	1.46	
Refractive Index		

The standard CAP-2 scheme, depicted in Fig. 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. 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.

Both the digital transmitter and receiver are used. 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 is then merged before transmission. The input sequences are up-sampled for that implementation to match the implementation sampling rate and, consequently, the rate of this method. The AWGN channel with the 10 dB SNR level is set for modelling noise in this block.

In the meantime, the process is referred to as decoding at the receiver end, and it is responsible for decoding the data symbol 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.

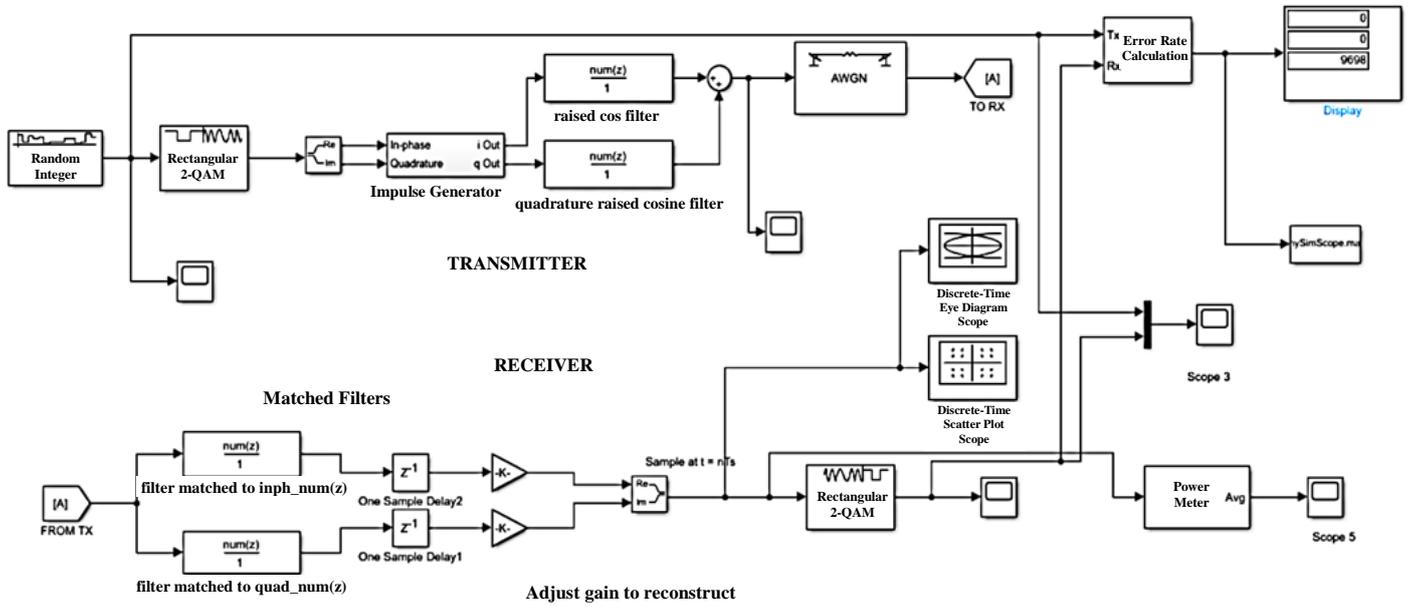


Fig. 1. CAP-2 scheme

The scatter plot is 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. EVM (dB) is calculated by using Equation (1)

$$EVM(dB) = 10 \log_{10} \left(\frac{P_{error}}{P_{reference}} \right) \quad (1)$$

where P_{error} is the measured/error symbol vector, and $P_{reference}$ is the ideal/reference symbol vector power.

$$MER(dB) = 10 \log_{10} \left(\frac{P_{signal}}{P_{error}} \right) \quad (2)$$

The MER as Equation (2) is used to determine the performance of a digital radio transceiver 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 where it allows for multiple levels of 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.

Scatter plot analysis for OOK modulation only allow two states 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. From Table 2, it can be observed 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 scatter plot 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 2. Bit per symbol comparison

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

3. Result

3.1. VLC simulation result

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. Fig. 2 shows the SNR distribution in a $4\text{m} \times 4\text{m} \times 2\text{m}$ room. The maximum SNR is observed close to the centre of the room. The maximum SNR of 29.2 dB is observed at the centre, while a minimum of -6.7 dB is observed at the corners.

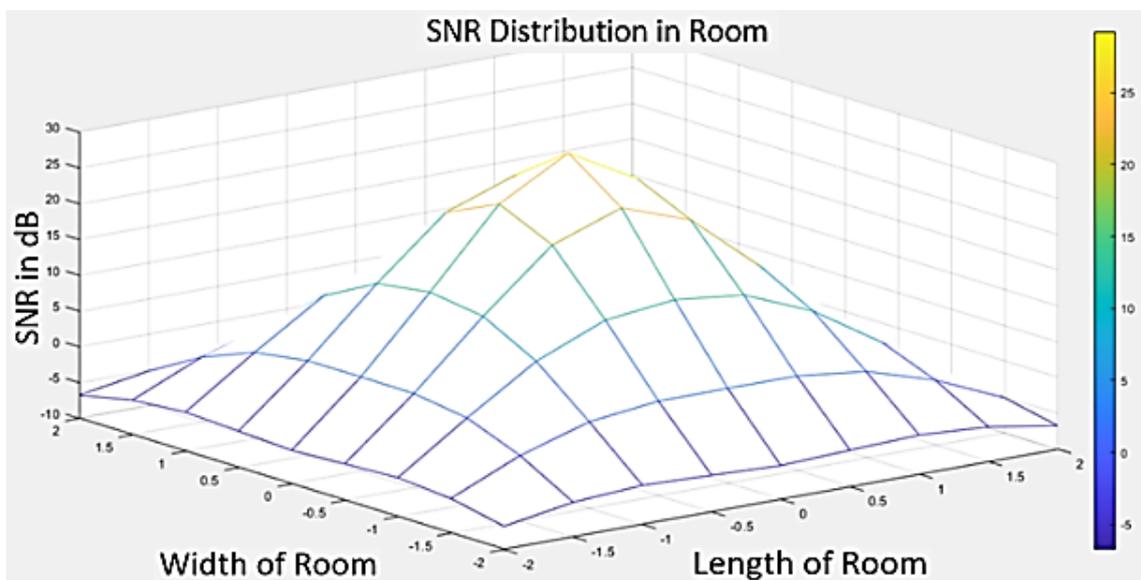


Fig. 2. SNR Distribution in the room (color online)

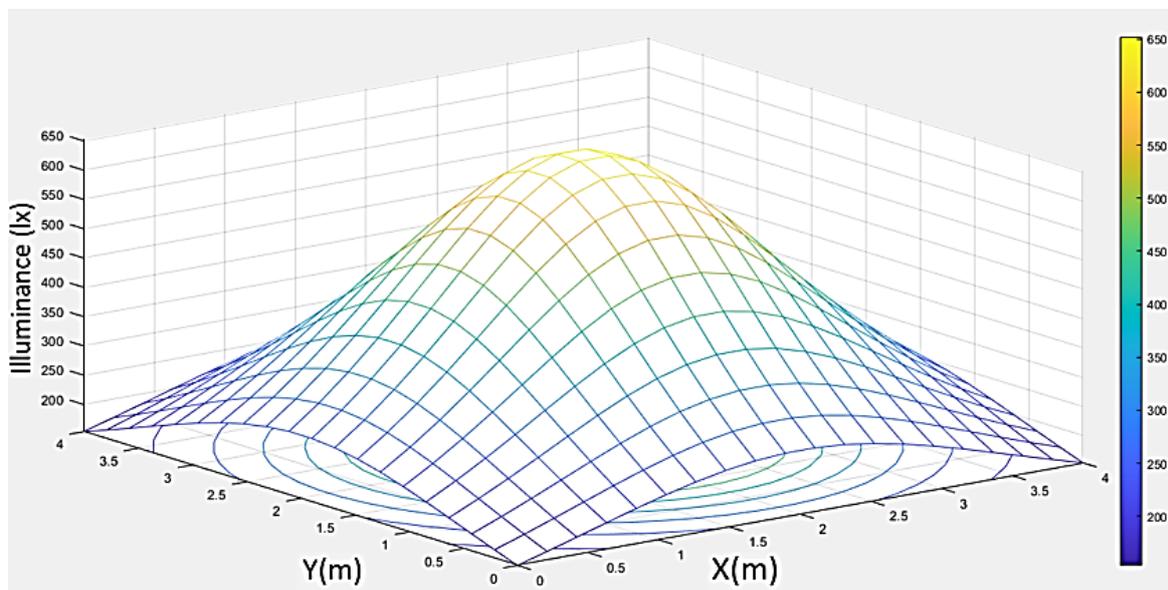


Fig. 3. The pattern of illumination for a single LED transmitter (color online)

The pattern of illumination for a single LED transmitter with a semi-angle, half-power of 70° is shown in Fig. 3, assuming no extra light is reflected from the surrounding walls. 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. ISO defines sufficient illuminance as being between 3000 and 1500 lx. Therefore, the LED bulbs with the specifications employed in this simulation could not provide sufficient illumination levels for the room. More

LED lights must be installed, however, for this study purpose, we only consider one light at the centre of the room.

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 Fig. 4. The greatest power received is -51 dBm. With a received power of -60 dBm, the received power drops as the PD location moves further away.

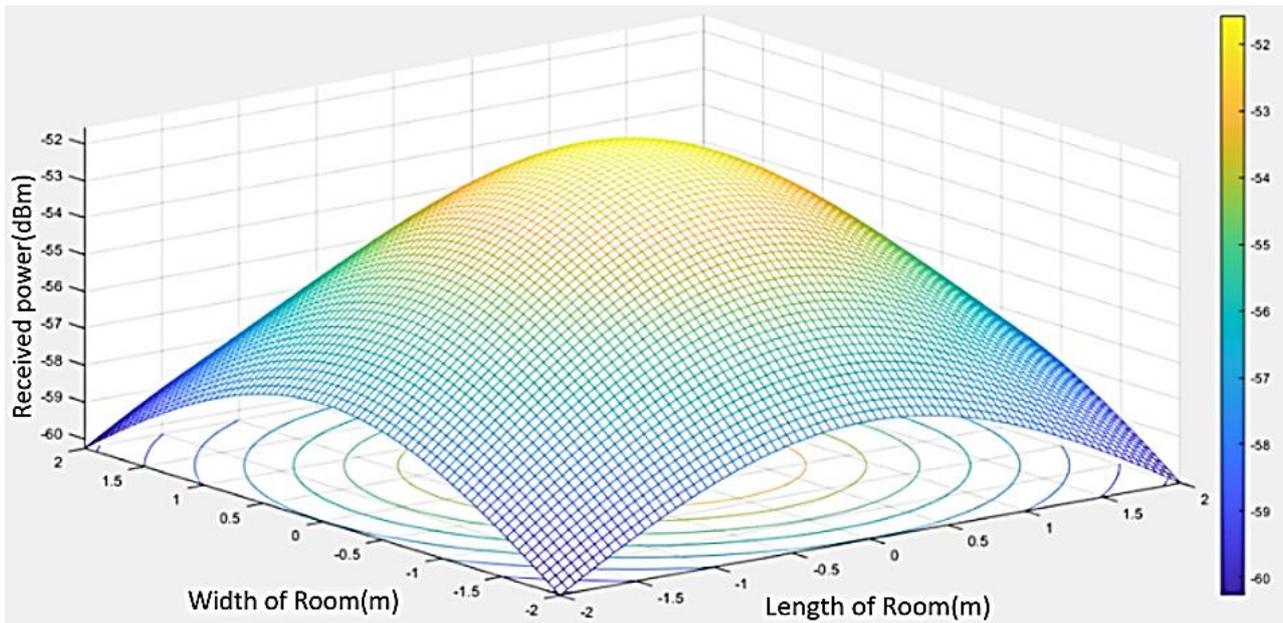


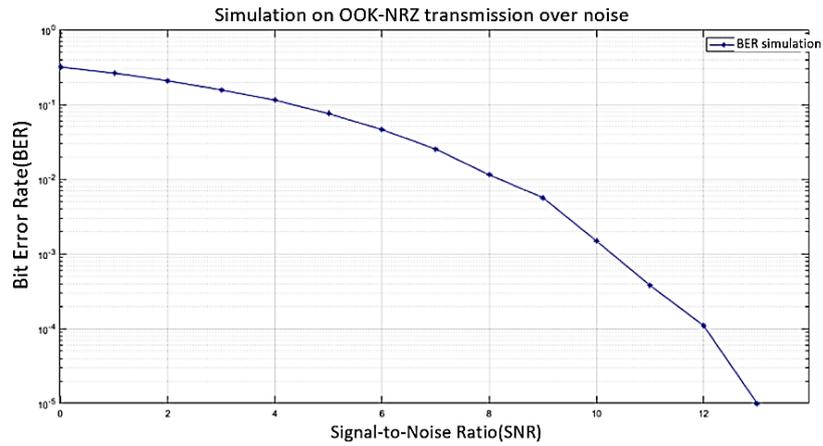
Fig. 4. Received power distribution (color online)

3.2. Performance evaluation

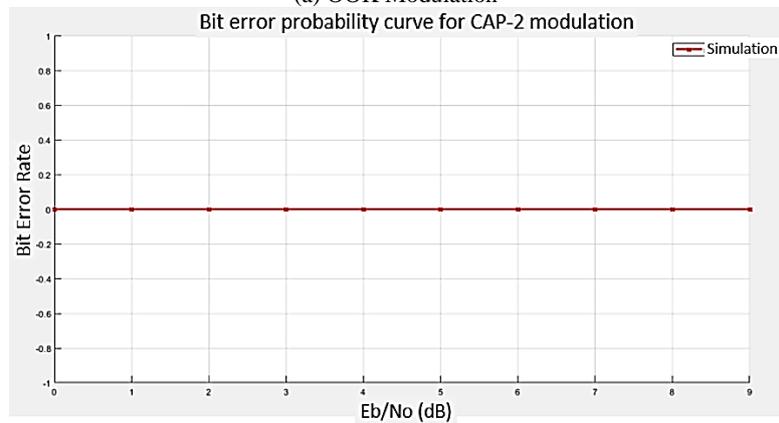
3.2.1. BER analysis

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. Thus, the BER curve can be used to illustrate a digital communication system's performance. The E_b/N_0 ratio is proportional to the SNR, taking the bit rates of the various constellations into consideration.

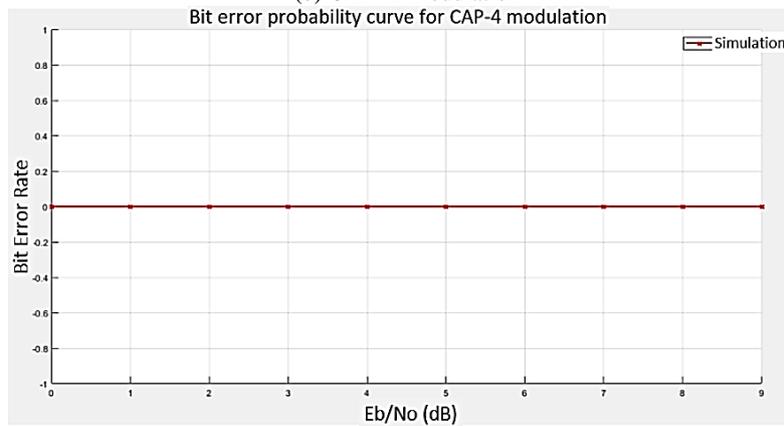
From Fig. 5 (a), the bit error rate graph observed that as more bit signals are sent out for OOK modulation, the bit error rate increases. The decreasing trend starts at 10 dB. Fig. 5 (b) – (d) represents the bit error rate graph for CAP-2, -4 and -8 using the same plot scale. The plot shows similar trend in which a linear line is obtained between 0 – 9 dB E_b/N_0 axis. These curves show the best performance that can be achieved across the link with 1 W transmitted power.



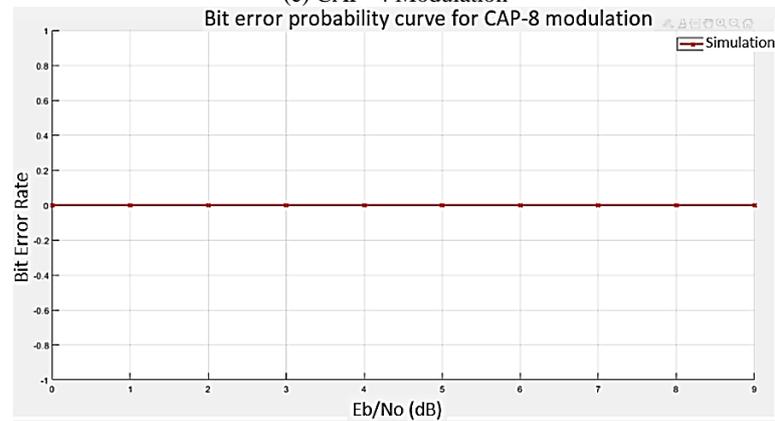
(a) OOK Modulation



(b) CAP- 2 Modulation



(c) CAP- 4 Modulation



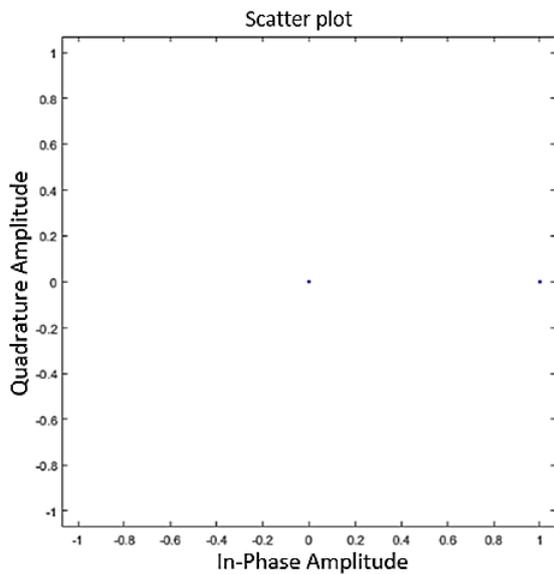
(d) CAP- 8 Modulation

Fig. 5. BER graph for (a) OOK, (b) CAP-2, (c) CAP-4, (d) CAP-8

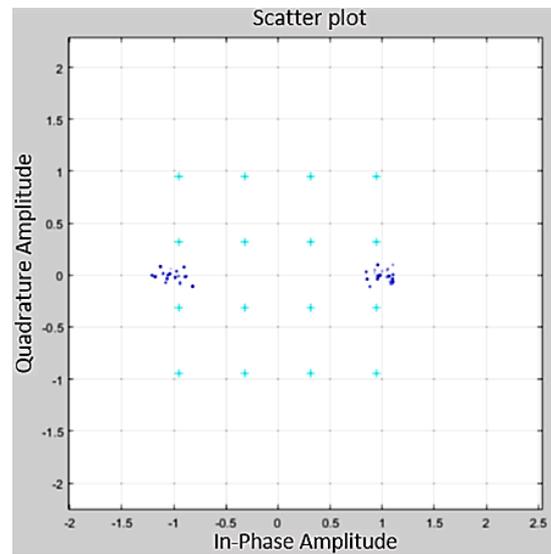
3.2.2. Scatter Plot analysis

A scatter plot or constellation diagram is employed to view the constellation of a digitally modulated signal. This is important to indicate the quality of the chosen

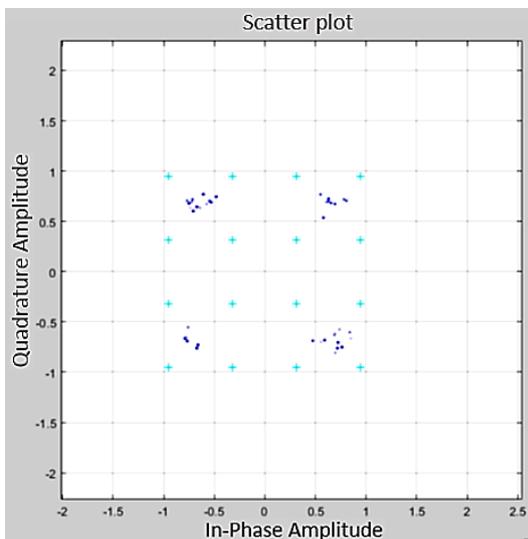
modulation format. Errors are easily indicated in symbols due to the closely located symbols. Each symbol is obtaining excess power, which causes the symbol to spread further and diminishes its effective power.



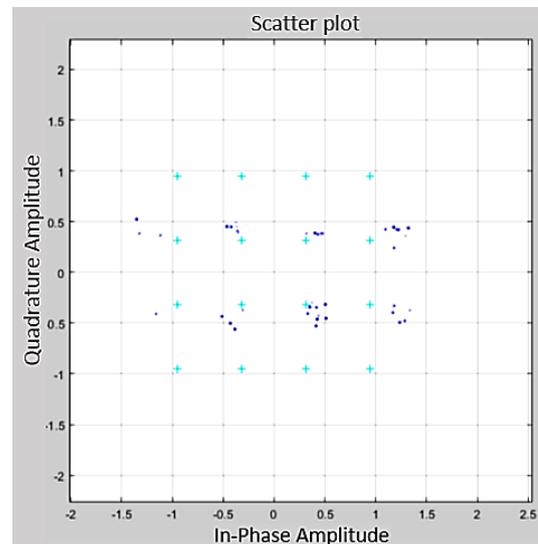
(a) OOK Modulation



(b) CAP- 2 Modulation



(c) CAP- 4 Modulation



(d) CAP- 8 Modulation

Fig. 6. Scatter Plot for (a) OOK, (b) CAP-2, (c) CAP-4, (d) CAP-8

In OOK modulation, logic zero is denoted by a lower amplitude, while logic one is denoted by a greater amplitude, and there is no carrier involved during the transmission of logic zero. The carrier is transmitted during logic one transmission. As a result, 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 as in Fig. 6 (a).

The constellation points in QAM for CAP modulation are typically placed in a square grid with uniform vertical and horizontal spacing. Fig. 6 (b) – (d) represents the constellation diagram for CAP-2, 4 and 8 respectively. CAP-2 and Cap-4 signify square balanced two symbols and four symbols' phases CAP. This square constellation is preferred due to the simplicity of its modulation and demodulation algorithms. While CAP-8 in Fig. 6 (d) has a non-square (rectangular) constellation diagram. Through

visual inspection of Fig. 6 (b) – (d), it can be seen that the points are far off the reference point, thus data in Table 3 is used to draw further information.

Table 3. 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	-10.90	10.90	0.13
CAP-4	-9.60	11.30	5.45
CAP-8	-11.90	9.80	12.42

Larger values of EVM indicate the greater distance between measured and ideal points. The reading for EVM is -9.60 dB for CAP-4, -10.90 dB for CAP-2 and -11.90 dB for CAP-8 in ascending orders. A lower the EVM value indicates better performance. CAP-4 represent the shortest gap between measured and ideal points, while CAP-2 and CAP-8 have higher probability of bit errors.

MER measure the closeness of the bits to the ideal point. A lower MER value indicates a high error. The values of MER in descending order are 11.30 dB for CAP-2, 10.90 dB for CAP-2 and 9.80 dB for CAP-8.

In terms of average power received, CAP-8 has the highest reading of 12.42 dBW compared to CAP-4 (5.45 dBW) and CAP-2 (0.13 dBW).

3.2.3. Eye diagram analysis

In digital communications, an eye diagram illustrates the effect of noise on system performance. The generated eye diagram for this study is as in Fig. 7.

OOK signal is displaying an ideal eye diagram as based on the scatter plot, the distance and phase between each constellation point are the furthest as only 1 bit at a time is transferred. The eye crossing is at 50%.

As for CAP modulation, CAP-4 offers a better eye diagram as the quality of the in-phase signal and quadrature signal is wide and clear compared to CAP-2 and CAP-8. The eye-crossing of CAP-2 and CAP-4 is at 50%. Further, CAP-8 shows a very poor SNR level. This also satisfies the EVM and MER in the constellation diagram.

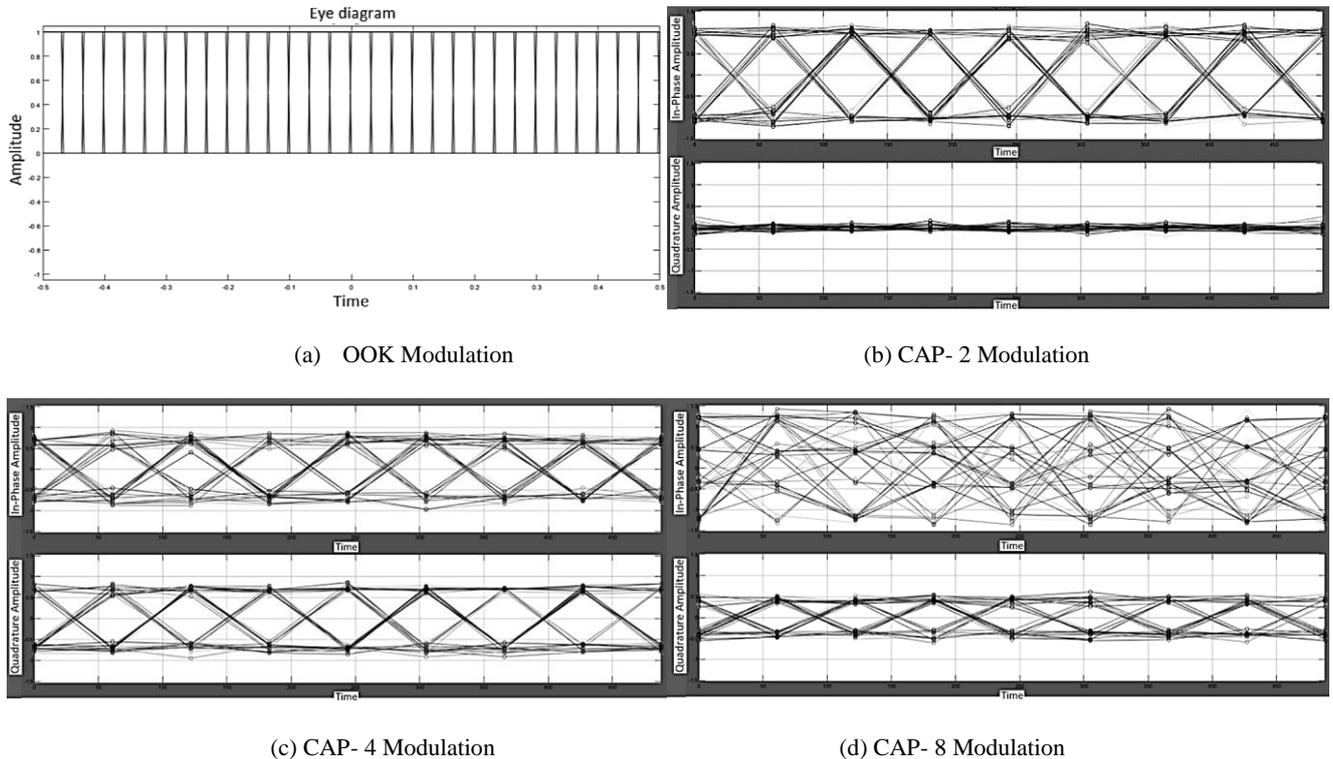


Fig. 7. Eye diagram for (a) OOK, (b) CAP-2, (c) CAP-4, (d) CAP-8

4. Discussion

From Section 3, a comparison between OOK modulation and CAP modulation can be made for the VLC system. Based on BER analysis, if we took 10^{-1} as a reasonable BER at 1W transmitted power within a $4 \times 4 \times$

2 m room size, OOK shows a decreasing trend at 4 dB, while CAP is still in linear line after 9 dB. As the input bit rate increases in OOK modulation, the output bit error also increases. While the error rate for CAP modulation is still linear at zero scales, thus CAP modulation records a better result than OOK modulation.

Table 4. Performance of m-CAP based on EVM, MER and Output Power

Performance Ranking	EVM (dB)	MER (dB)	Average power (dBW)
1	CAP-4	CAP-4	CAP-8
2	CAP-2	CAP-2	CAP-4
3	CAP-8	CAP-8	CAP-2

Due to limitations in MATLAB coding knowledge or MATLAB functions for scatter plots without a coding, the EVM and MER for OOK modulation cannot be retrieved in this study.

Table 4 outlines the performance of CAP modulation in ascending order based on EVM, MER and average received power. Theoretically, higher-order modulation should have better (lower) EVM values. Unfortunately, for this study CAP-8 does not comply with the theory due to an unexpected rectangular/non-square constellation diagram.

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 scatter plot 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.

Observation on the eye-diagram shows that OOK modulation provides a better eyes diagram due to only 1 bit being transferred at a time, and the distance and phase between each constellation point are the furthest compared to CAP. CAP-4 provides a greater eye diagram due to the best quality in terms of in-phase and quadrature signals compared to CAP-2 and CAP-8.

5. Conclusion

In this paper, we investigated the performance of OOK, CAP-2, CAP-4 and CAP-8 modulation in the context of VLC. Using MATLAB simulations, we showed that OOK modulation displays the best result in terms of scatter plot, the distance and phase between each constellation point are the furthest compared to CAP as only 1 bit at a time is transferred for OOK. Theoretically, higher-order modulation should have better (lower) EVM values. Unfortunately, by comparing mCAP scheme, CAP-4 shows better performance compared to CAP-8 due to an unexpected rectangular/non-square constellation diagram. This leads to further studies on the performance of higher-order CAP modulation for indoor applications. To emphasis CAP's benefits and disadvantages, a more thorough comparison with other emerging technologies should be made.

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