Advanced signal transformation techniques to improve spectral efficiency in visible light communication systems

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ABSTRACT

Visible light communication (VLC) offers high-speed wireless communication using the visible light spectrum. Achieving high spectral efficiency while maintaining a low bit error rate (BER) remains a challenge. This paper explores the use of quadrature amplitude modulation (QAM) combined with orthogonal frequency division multiplexing (OFDM) to address these challenges. Matrix laboratory (MATLAB) simulations show that QAM-OFDM achieves a BER of 0.001 at comparable signal-to-noise ratios (SNR), outperforming traditional hermitian symmetry (HS), complex signal mapping (CSM), and quad-light emitting diode (LED) complex modulation (QCM) techniques. Unlike CSM, and QCM, which increase complexity, and BER, QAM-OFDM efficiently utilizes available bandwidth, reducing errors, and enhancing spectral efficiency. The study concludes, that QAM-OFDM happens to be the optimal solution for the future VLC systems, offering better performance within both efficiency, and reliability.

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1. INTRODUCTION

Visible light communication (VLC) has emerged as a potential technique, that employs the visible light spectrum (400–700 nm) in favor of high-speed wireless communication. VLC systems depend upon regulating the intensity of light emitting diodes (LEDs) to convey data to photodetectors (PDs), providing both lighting, and data transmission capabilities. VLC presents a compelling alternative to conventional radio frequency (RF) communication, particularly within settings where RF signals encounter interference or limitations [1]. A key issue within VLC systems happens to be attaining high spectral efficiency, defined as the quantity regarding information conveyed per unit regarding bandwidth. Spectral efficiency happens to be essential for satisfying the increasing, and also need within favor regarding expedited, and also more dependable wireless communication. Conventional techniques, such as hermitian symmetry (HS), have been extensively employed within VLC systems, to guarantee real-valued signal delivery. Nevertheless, HS necessitates double the bandwidth, and also introduces considerable complexity to make, the signal processing pipeline, hence constraining the data flow, and also elevating the bit error flow [2].

To tackle thoes issues, researchers have suggested alternative signal transformation methods, such like complex signal mapping (CSM), and quad-LED complex modulation (QCM), which seek to enhance spectral efficiency, through circumventing the bandwidth overhead associated alongside HS [3], [4]. CSM converts intricate signals into tangible, and also positive numbers, minimizing the necessity for the bandwidth duplication yet, it adds complexity, and may lead to an increased bit error rate (BER) due to noise during signal conversion [5]. Likewise, QCM employs four LEDs to individually convey the real, and also the imaginary components of the complicated signals nevertheless, the intricacy regarding signal distribution among many LEDs may result in an elevated BER [6].

This work proposes the utilization of the quadrature amplitude modulation (QAM) within conjunction alongside, orthogonal frequency division multiplexing (OFDM) towards address the limitations regarding both CSM, and also QCM. QAM, combined with the OFDM facilitates efficient frequency, usage through allocating data among several subcarriers, resulting within substantial decreases within BER, even amidst elevated noise levels [7]. Our matrix laboratory (MATLAB) simulations indicate, that the QAM-OFDM methodology attains a BER of 0.001 at the similar signal-to-noise ratios (SNR), surpassing for both CSM, and also QCM, while concurrently streamlining the signal processing demands.

2. METHOD

The VLC system was designed within an indoor space of 3×4×5 meters (length × width × height) as shown in Figure 1. This room size is suitable for small and medium-sized indoor environments, including offices and schools, where VLC systems are likely to be used. Taking into account any obstacles or reflective surfaces that might affect signal quality, the system design ensures uniform coverage and efficient communications throughout the space as shown in Figure 2 [8], [9].

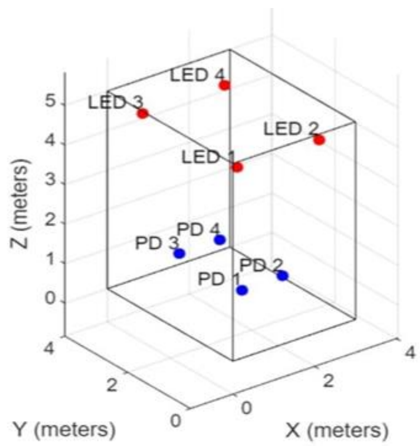

Figure 1. Geometric arrangement of the indoor VLC system

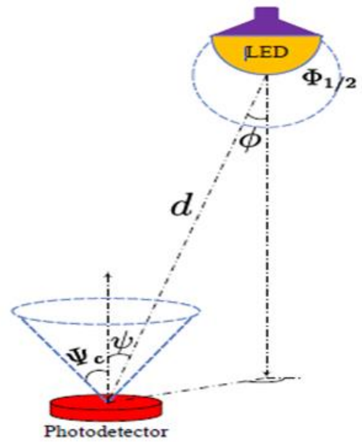

Figure 2. Geometrical representation of a LOS VLC channel model

The DC channel gain can be expressed as shown in Figure 1:

$$h(\emptyset) = \begin{cases} \frac{Ad(K+1)}{2\pi\mathcal{D}2} cos^k(\emptyset)\mathcal{T}_S(\psi)g(\psi)\cos(\psi) & ,0 \le \psi \le \psi_c \\ 0 & elsewhere \end{cases} \quad (1)$$

where:

K = index lambert
$\emptyset$ = irradiance angle
ψ = incidence angle
ψ_c = field of view
$\mathcal{T}_S(\psi)$ = optical band-pass filter
$g(\psi)$ = non-imaging concentrator
Ad = area of photodiode

We must specify the location regarding the components (LEDs and PDs) within the room, and explain how these components turn out towards be placed, and interact inside the environment within order towards establish a geometric configuration regarding the regarded indoor VLC system within favor regarding our model. The intended indoor VLC system's geometric arrangement happens towards being thoroughly shown as following.

2.1. System configuration and engineering parameters

The VLC system was designed within a mosaic room measuring 3 meters long, 4 meters wide, and 5 square meters. All system components operate within this 3×4×5 cubic meter space. Four LED ceiling lights were installed at a height of 4.5 meters (i.e., 0.5 meters from the ceiling), arranged in a rectangular grid to provide both illumination and signaling within the room. The light positions are located at coordinates (0.5, 0.5, 4.5), (2.5, 0.5, 4.5), (0.5, 3.5, 4.5), and (3.5, 3.5, 4.5) meters, respectively. This central position provides the most effective illumination across the entire area.

The PDs were distributed within the same geometric framework to receive the LEDs. Four receivers were installed at coordinates (1, 1, 1), (2, 1, 1), (1, 3, 1), and (1, 2, 3) meters. These receivers were positioned one meter above the ground, the approximate height for receiving electronic signal devices. They were arranged in a coordinate grid to match the lamp arrangement, enabling comprehensive signal coverage and ensuring direct line-of-sight (LOS) communication between the transmitter and receiver.

The system is based on a three-dimensional coordinate system where the origin is at point (0, 0, 0) in the room's operating corner, the X-axis runs the length of the room, the Y-axis is its width, and the Z-axis is vertical from the ground towards the receiver. The signal is transmitted loudly from the LEDs directly to the receiver via the direct LOS. The intersecting geometric arrangement of the lamps contributes to overlapping illumination between their zones, thus defining the signal area and ensuring consistent and stable reception intensity within the room.

In the X-Y plane, the light sources and receivers are distributed at the intersections of a virtual grid, with lights near the ceiling (Z=4.5 m) and receivers near the ground (Z=1 m). In the balcony view (X-Z or Y-Z plane), the lights appear near the ceiling and the receivers near the ground. Generally, a high-intensity LED lighting system is used as both the light source and the data carrier, since it rapidly modulates sunlight to transmit information. The PDs capture multiple light signals and convert them into electrical signals for subsequent processing. We employed advanced algorithms for decoding and signal correction, including stabilization of indoor environments even in complex environments.

3. SIGNAL TRANSFORMTIONAL METHOD

This study examines two sophisticated signal transformation techniques designed towards improve spectral efficiency, and also minimize BER, within VLC systems, QAM, within conjunction alongside the OFDM, and also alternative methods such as CSM, and also QCM. QAM alongside OFDM employs subcarrier signal dispersion, enhancing frequency utilization, and also markedly decreasing BER, especially within high noise environments. The integration of the QAM, and also OFDM enhances spectrum efficiency through alleviating, the constraints of the conventional HS methods [10], [11].

CSM converts complex signals into real, and also positive values without dependence upon HS, hence eliminating bandwidth doubling. Nevertheless, the conversion process adds complexity, leading towards elevated noise levels, and also an increased BER [12]. Despite enhancing spectral efficiency, the implementation of the CSM happens to be constrained through these limitations [13].

QCM allocates the real, and also imaginary components regarding complex signals across four LEDs. This approach obviates the requirement, for the HS nonetheless, its intricate signal distribution results, in a higher BER relative to QAM-OFDM. Although QCM demonstrates potential within enhancing spectral efficiency, the complexity regarding signal processing continues to pose a considerable problem [14]. In comparison, QAM alongside OFDM happens to be the most efficient technique, providing an optimal balance, between spectral efficiency, and also low BER, especially within high SNR settings [15].

4. MATHEMATICAL MODELING

4.1. CSM mathematical model

In the VLC system, the transmitted optical signal is represented by the mathematical model for modulating the composite signal (CSM). A more precise examination of the transmitted waveform and its properties is made possible by this model, which describes the signal in the carrier frequency range through its real and imaginary components. The following is a mathematical expression for the transmitted signal:

$$s(t) = \mathrm{Re}\{x(t)\} \cdot \cos(2\pi f_c t) - \mathrm{Im}\{x(t)\} \cdot \sin(2\pi f_c t) \tag{2}$$

Re and Im respectively represent the real, and imaginary components regarding the signal; where $s(t)$ happens towards being the sent signal, $x(t)$ is the complex signal towards be communicated, f_c happens towards be the carrier frequency. Appropriate for the intensity modulation within VLC [16]. This approach guarantees, that the sent signal happens to be genuine, and positive.

4.2. QCM mathematical model

Every LED within the QCM system happens towards be allocated within this model towards generate light matching a certain quadrant regarding the complicated signal. Towards maximized spectrum efficiency, the four LEDs cooperate towards communicating the whole complex signal without the need within favor regarding HS [17].

$$x_{\mathrm{QCM}} = \begin{cases} \mathrm{LED}_1; & \mathrm{Re}(s) \geq 0 \\ \mathrm{LED}_2; & \mathrm{Re}(s) < 0 \\ \mathrm{LED}_3; & \mathrm{Im}(s) \geq 0 \\ \mathrm{LED}_4; & \mathrm{Im}(s) < 0 \end{cases} \tag{3}$$

4.3. QAM-OFDM mathematical model

The suggested system integrates QAM alongside OFDM towards facilitate efficient signal transmission within a VLC system. QAM facilitates the transmission, of the symbols by modifying the amplitude and also the phase of the carrier signal. OFDM segments, the signal into several subcarriers, hence enhancing bandwidth efficiency, and also reducing the BER. The mathematical model in favor of QAM, alongside OFDM, happens to to be delineated as (4).

$$s(t) = \sum_{k=1}^{N} \; [I_k \cos(2\pi f_k t) - Q_k \, \sin(2\pi \, f_k t)] \tag{4}$$

where I_k, and also Q_k turn out to be the in-phase and also quadrature components, and also f_k represents the carrier frequency for each subcarrier. The implementation of this model works to improve the spectral efficiency, by utilizing the available bandwidth efficiently through the use of the subcarriers, as demonstrated within [7], [18].

5. CONFIGURATION FOR THE SIMULATION

5.1. MATLAB simulation environment an explanation

A detailed simulation used to to be conducted using MATLAB to assess the performance. Regarding several modulation strategies within a VLC system. The simulation aims towards replicating a standard indoor setting, factoring within room size, the arrangement regarding LEDs, PDs, and also the signal modulation methods employed within VLC systems.

5.2. Room and system setup

The simulation occurs within, a room measuring 5 meters in length, 4 meters within breadth, and also 3 meters within height, exemplifying standard interior situations, like offices or schools. Four LED transmitters, and also four PDs turn out to be strategically placed, within the room at the designated heights to simulate authentic communication settings [19]. The arrangement guarantees, that signals turn out to be delivered, and also received beneath realistic conditions.

The LED transmitters turn out to be situated at a height of 2.5 meters, whereas the PDs turn out to be located at a height of 0.75 meters. The field regarding view (FOV), for each PD happens to be established at 48.5 degrees, a standard configuration within favor, regarding VLC systems towards guarantee comprehensive coverage within the room [20]. This configuration happens to be selected, to replicate authentic communication settings, considering possible signal reflections, and also environmental obstructions.

5.3. Modulation techniques and parameters

To increase spectrum efficiency and reduce BER, the simulation makes use of QAM in combination with OFDM. In this instance, the data is modulated using 16-QAM, but the OFDM technique distributes the data across 64 subcarriers and adds a cyclic prefix length of about 16 to reduce inter-symbol interference [21], [22]. The key parameters used within the simulation include:

– SNR range: 0 dB towards 30 dB (in steps regarding 2 dB)
– Modulation order (M): 16 (for 16-QAM)
– Number regarding bits: 1 million
– Number regarding subcarriers: 64
– Cyclic prefix length: 16

6. SIMULATION WORKFLOW

Simulation assesses the performance of the proposed VLC system at the physical layer, focusing on data transmission efficiency and signal quality in a realistic digital environment. The model encompasses data generation, multi-level modulation, and OFDM processing, allowing examination of factors like code interference, SNR and BER for an accurate performance evaluation prior to real-world application. Detailed simulation processes are discussed.

– The system initiates the generation of 1 million random bits, furthermore modulating them using 16-QAM. This guarantees efficient data transmission within the VLC system.
– OFDM modulation: the modulated symbols turn out towards be allocated among various subcarriers utilizing OFDM. The inverse fast fourier transform (IFFT) to be utilized to transfer signals coming from the frequency domain towards the time domain, subsequently incorporating a cyclic prefix towards mitigate inter-symbol interference [23].
– Signal transmission, and noise addition: the OFDM-modulated signal happens to be sent, and additive white gaussian noise (AWGN) happens to be introduced toward replicating real-world channel circumstances. The simulation evaluates the system’s performance across a spectrum regarding SNR levels, coming from 0 dB towards 30 dB.
– Reception and demodulation: upon receiving the noisy signal, the system eliminates the cyclic prefix, executes the FFT towards reverting the symbols to the frequency domain, furthermore demodulates the symbols alongside 16-QAM [24].
– BER calculation: the BER happens to be determined through analyzing the transmitted, and received bits for each SNR level. The simulation findings indicate, that the integration regarding QAM alongside OFDM markedly decreases BER like SNR rises, validating the efficacy regarding the modulation strategy within favor regarding VLC systems [25].

The MATLAB simulation results indicate, that the proposed QAM-OFDM method significantly reduces BER relative to alternative modulation approaches, especially alongside increasing SNR. This confirms the efficacy, of QAM-OFDM for enhancing the performance, of the VLC systems within indoor settings. A comprehensive comparison alongside alternative modulation techniques, including CSM, and also QCM, reinforces the superiority of this method, for the spectral efficiency, and also error reduction.

7. RESULTS AND DISCUSSIONS

This section examines the outcomes derived, coming from MATLAB simulations, regarding various modulation schemes employed within a VLC system. Specifically emphasizing QAM alongside OFDM, CSM, and also QCM. The primary performance indicator assessed to the BER as a function of the SNR measured in decibels (dB).

7.1. QCM-OFDM results

The first simulation was assessed the performance of QCM with the OFDM. The BER vs SNR graph Figure 2 shows a fluctuating trend, indicating, that QCM introduces more complexity into the VLC system. The error rate happens to be consistently high, remaining above 0.499 within most cases. This indicates, that while QCM avoids the need for the HS, the additional complexity regarding distributing signals across multiple LEDs results within a higher error rate, particularly within indoor environments alongside noise interference.

7.2. CSM-OFDM results

The second simulation assessed CSM within conjunction alongside OFDM, and the outcomes turn out towards be illustrated within Figure 3. The BER versus SNR graph indicates, that CSM has marginally superior performance compared towards QCM. Nevertheless, CSM continues to experience moderate error rates, ranging coming from 0.35 towards 0.5 across the majority regarding SNR levels. This indicates, that although CSM enhances spectral efficiency through circumventing HS, the conversion regarding complex signals into real, and positive values elevates the error rate owing towards noise during signal transformation [1].

7.3. OFDM-QAM results

The third simulation assessed the efficacy of 16-QAM within conjunction with OFDM. As illustrated in Figure 4, this combination significantly enhances system performance. The BER against the SNR curve exhibits a pronounced fall, alongside the BER markedly decreasing as the SNR rises. The BER begins at 0.28806 at 0 dB, and progressively declines towards 0 at 22 dB, and higher. Our verifies, that OFDM-QAM significantly diminishes errors alongside enhanced signal intensity, establishing it as the most economical modulation system within our analysisas shown in Figure 5. The detailed results regarding SNR vs BER within favor regarding OFDM-QAM turn out to be provided within the Table 1.

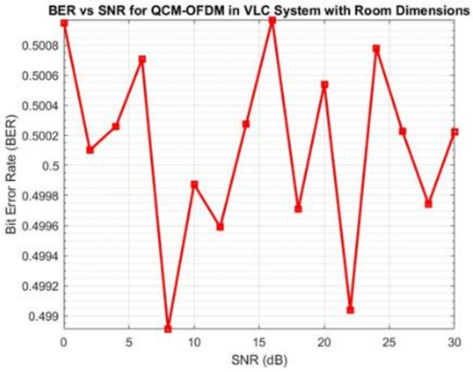

Figure 3. BER vs SNR for QCM-OFDM in VLC

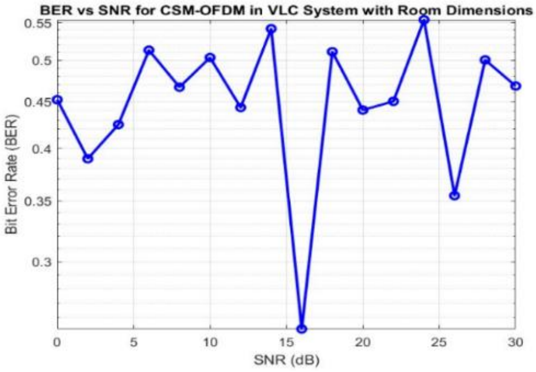

Figure 4. BER vs SNR for CSM-OFDM in VLC

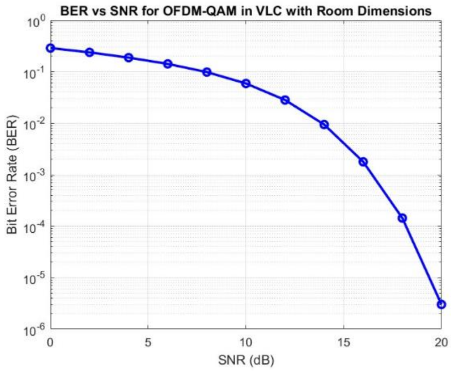

Figure 5. BER vs SNR for OFDM-QAM in VLC

Table 1. BER performance across various SNR levels

Technique	BER at low SNR (0-10 dB)	BER at high SNR (>20 dB)	Spectral efficiency	Complexity
QAM alongside OFDM	Low (~0.28806 at 0 dB)	Zero (0 at 22 dB, and above)	High	Moderate
CSM alongside OFDM	Medium (~0.45 at 0 dB)	High (~0.3 30 dB)	Medium	High
QCM alongside OFDM	High (~0.5 at 0 dB)	High (~0.5 at 30 dB)	Medium	Very high

8. CONCLUSION

This research assessed three distinct signal transformation, and modulation approaches QAM alongside OFDM, CSM, and QCM within the framework regarding VLC systems. The main emphasis used to be upon evaluating the BER performance regarding each method in the relation to the SNR, simulating indoor settings alongside MATLAB. The principal conclusions regarding this study turn out to be like QAM alongside OFDM exhibited optimal performance, alongside a BER regarding 0 at SNR levels regarding 22 dB, and above. The implementation of OFDM alongside subcarrier modulation demonstrated efficacy in minimizing mistakes, hence enhancing the system’s resilience towards noise. This finding aligns with the literature. Which validated the advantages of OFDM-QAM regarding error reduction, and spectrum efficiency within VLC systems. And CSM exhibited moderate performance, alongside the BER varying between 0.35, and 0.5, contingent upon the SNR values. The conversion regarding complex signals into real, and positive values elevates the BER due towards noise during signal translation. QCM, although providing a means of circumventing HS, exhibited the greatest BER within all simulations. That QCM adds complexity through dispersing signals among numerous LEDs, resulting in an elevated BER due to signal misalignment, and interference within indoor settings. The results demonstrate, that QAM alongside OFDM happens to be the most effective modulation strategy for attaining low error rates, and good spectral efficiency within VLC systems, particularly within noisy situations. Enhancing system efficiency via elevated modulation orders, adaptive systems, and hybrid technologies to satisfy the increasing demand in favor of the high-speed, dependable wireless communication within indoor settings.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Sameh Najeh	✓	✓		✓	✓	✓			✓	✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper.

DATA AVAILABILITY

The data that support the findings of this study were generated through MATLAB-based simulations. These data are available from the corresponding author upon reasonable request. No external datasets were used or analyzed in this research.

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