

Quad-LED Complex Modulation (QCM) for Visible Light Wireless Communication

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Abstract—In this paper, we propose a simple and novel complex modulation scheme for multiple-LED wireless communication, termed as *quad-LED complex modulation (QCM)*. The proposed QCM scheme uses four LEDs (hence the name ‘quad-LED’), one LED each to map positive real, negative real, positive imaginary, and negative imaginary parts of complex modulation symbols like QAM symbols. The QCM scheme does not need Hermitian symmetry operation to generate LED compatible positive real transmit signals. Instead it exploits spatial indexing of LEDs to convey sign information. The proposed QCM module can serve as a basic building block to bring in the benefits of complex modulation to VLC. For example, QCM with phase rotation (QAM-PR) where the complex modulation symbols are rotated in phase before mapping the signals to the LEDs achieves improved bit error performance. We also find that the proposed QCM when used along with OFDM, termed as QCM-OFDM, achieves very good performance.

Keywords – Visible light communication, quad-LED complex modulation (QCM), QCM with phase rotation, QCM-OFDM.

I. INTRODUCTION

Wireless communication using visible light wavelengths (400 to 700 nm) in indoor local area network environments is emerging as a promising area of research [1]. Visible light communication (VLC) is evolving as an appealing complementary technology to radio frequency (RF) communication technology [2]. In VLC, simple and inexpensive light emitting diodes (LED) and photo diodes (PD) act as signal transmitters and receptors, respectively, replacing more complex and expensive transmit/receive RF hardware and antennas in RF wireless communication systems. Other favorable features in VLC include availability of abundant visible light spectrum at no cost, no licensing/RF radiation issues, and inherent security in closed-room applications. The possibility of using the same LEDs to simultaneously provide both energy-efficient lighting as well as high-speed short-range communication is another attractive feature.

The potential to use multiple LEDs and PDs in multiple-input multiple-output (MIMO) array configurations has enthused MIMO wireless researchers to take special interest in VLC [3]-[9]. Signaling schemes considered in multiple-LED VLC include space shift keying (SSK) and its generalization (GSSK), where the ON/OFF status of the LEDs and the indices of the LEDs which are ON convey information bits [6],[7]. Other multiple-LED signaling schemes considered in the literature include spatial multiplexing (SMP), spatial modulation (SM), and generalized spatial modulation (GSM) [4],[8],[9],[10]. These works have considered real signal sets like M -ary pulse amplitude modulation (PAM) with positive-valued signal points in line with the need for the transmit

signal in VLC to be positive and real-valued to intensity modulate the LEDs.

The VLC channel between an LED and a photo detector in indoor environments can be a multipath channel. The multipath effects can be mitigated by using orthogonal frequency division multiplexing (OFDM). The use of complex signal sets like M -ary quadrature amplitude modulation (QAM) along with OFDM in VLC is studied extensively in the literature [11]-[21]. Techniques reported in these works include DC-biased optical (DCO) OFDM [12], asymmetrically clipped optical (ACO) OFDM [16]-[17], flip OFDM [18],[19], and non-DC biased (NDC) OFDM [21]. A key constraint in these techniques, however, is that they perform Hermitian symmetry operation on the QAM symbol vector at the IFFT input so that the IFFT output would be positive and real-valued. A consequence of this, for example, is that N channel uses are needed to send $N/2$ symbols.

Our new contribution in this paper is that we propose a simple and novel complex modulation scheme for multiple-LED VLC, which does not need Hermitian symmetry operation. Instead, in the proposed scheme, LEDs are simultaneously intensity modulated by the magnitudes of the real and imaginary parts of a complex symbol, and the sign information is conveyed through spatial indexing of additional LEDs. We call the proposed scheme as *quad-LED complex modulation (QCM)* scheme. The QCM scheme uses four LEDs (hence the name ‘quad-LED’), one LED each to map positive real, negative real, positive imaginary, and negative imaginary parts of complex modulation symbols like QAM symbols. Simulation results show that the proposed QCM scheme achieves good bit error rate (BER) performance. Also, using the proposed QCM module as a basic building block in VLC, techniques which are applied to complex modulation schemes to improve performance in RF wireless fading channels can be applied to VLC as well. For example, we find that QCM with phase rotation (QCM-PR) of the complex modulation symbols before mapping the signals to the LEDs achieves improved BER performance. We also find that the proposed QCM when used along with OFDM, termed as QCM-OFDM, achieves very good performance.

The rest of this paper is organized as follows. The indoor VLC system model is presented in Section II. The proposed QCM scheme and its performance are presented in Section III. The QCM-PR scheme and its performance are presented in Section IV. Section V presents the QCM-OFDM scheme and its performance. Conclusions are presented in Section VI.

II. INDOOR VLC SYSTEM MODEL

Consider an indoor VLC system with N_t LEDs (transmitter) and N_r photo detectors (receiver). Assume that the

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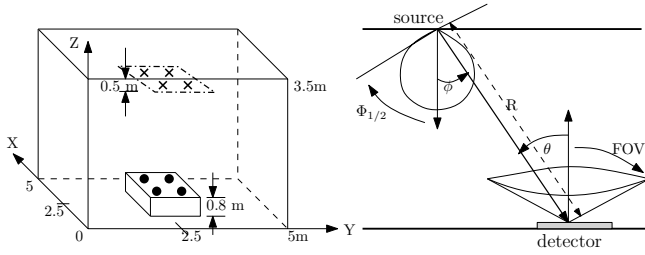


Fig. 1. Geometric set-up of the considered indoor VLC system. A dot represents a photo detector and a cross represents an LED.

LEDs have a Lambertian radiation pattern [22],[23]. In a given channel use, each LED is either OFF or emits light with some intensity which is the magnitude of either the real part or imaginary part of a complex modulation symbol. An LED which is OFF implies a light intensity of zero. Let $\mathbf{x} = [x_1 \ x_2 \ \dots \ x_{N_t}]^T$ denote the $N_t \times 1$ transmit signal vector, where x_i is the light intensity emitted by the i th LED. Let \mathbf{H} denote the $N_r \times N_t$ MIMO VLC channel matrix:

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & \dots & h_{1N_t} \\ h_{21} & h_{22} & h_{23} & \dots & h_{2N_t} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & h_{N_r3} & \dots & h_{N_rN_t} \end{bmatrix}, \quad (1)$$

where h_{ij} is the channel gain between j th LED and i th photo detector, $j = 1, 2, \dots, N_t$ and $i = 1, 2, \dots, N_r$. As in [4], we consider only the line-of-sight (LOS) paths between the LEDs and the photo detectors. From [22], the LOS channel gain h_{ij} is calculated as (see Fig. 1 for the definition of various angles in the model)

$$h_{ij} = \frac{n+1}{2\pi} \cos^n \phi_{ij} \cos \theta_{ij} \frac{A}{R_{ij}^2} \text{rect}\left(\frac{\theta_{ij}}{\text{FOV}}\right), \quad (2)$$

where ϕ_{ij} is the angle of emergence with respect to the j th source (LED) and the normal at the source, n is the mode number of the radiating lobe given by $n = \frac{-\ln(2)}{\ln \cos \Phi_{\frac{1}{2}}}$, $\Phi_{\frac{1}{2}}$ is the half-power semiangle of the LED [23], θ_{ij} is the angle of incidence at the i th photo detector, A is the area of the detector, R_{ij} is the distance between the j th source and the i th detector, FOV is the field of view of the detector, and $\text{rect}(x) = 1$, if $|x| \leq 1$, and $\text{rect}(x) = 0$, if $|x| > 1$.

The LEDs and the photo detectors are placed in a room of size $5\text{m} \times 5\text{m} \times 3.5\text{m}$ as shown in Fig. 1. The LEDs are placed at a height of 0.5m below the ceiling and the photo detectors are placed on a table of height 0.8m. Let d_{tx} denote the distance between the LEDs and d_{rx} denote the distance between the photo detectors.

Assuming perfect synchronization, the $N_r \times 1$ received signal vector at the receiver is given by

$$\mathbf{y} = r\mathbf{H}\mathbf{x} + \mathbf{n}, \quad (3)$$

where r is the responsivity of the detector [24] and \mathbf{n} is the noise vector of dimension $N_r \times 1$. Each element in the noise vector \mathbf{n} is the sum of received thermal noise and ambient shot light noise, which can be modeled as i.i.d. real AWGN with zero mean and variance σ^2 [25]. The average received signal-to-noise ratio (SNR) is given by $\bar{\gamma} = \frac{r^2 P_r^2}{\sigma^2}$, where $P_r^2 = \frac{1}{N_r} \sum_{i=1}^{N_r} \mathbb{E}[|\mathbf{H}_i \mathbf{x}|^2]$, and \mathbf{H}_i is the i th row of \mathbf{H} .

Real part s_I	Status of LEDs	Imag. part s_Q	Status of LEDs
≥ 0	LED1 emits $ s_I $ LED2 is OFF	≥ 0	LED3 emits $ s_Q $ LED4 is OFF
< 0	LED1 is OFF LED2 emits $ s_I $	< 0	LED3 is OFF LED4 emits $ s_Q $

TABLE I
MAPPING OF COMPLEX SYMBOL s (WITH REAL PART s_I AND IMAGINARY PART s_Q) TO LEDs ACTIVITY IN QCM.

III. PROPOSED QCM SCHEME

A. QCM transmitter

The proposed QCM scheme uses four LEDs at the transmitter. Figure 2 shows the block diagram of a QCM transmitter. Let \mathbb{A} denote the complex modulation alphabet used (e.g., QAM). In each channel use, one complex symbol from \mathbb{A} (chosen based on $\log_2 |\mathbb{A}|$ information bits) is signaled by the four LEDs as described below.

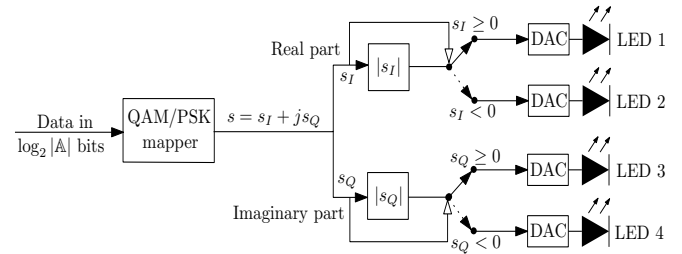


Fig. 2. QCM transmitter.

Each complex modulation symbol can have a positive or negative real part, and a positive or negative imaginary part. For example, the signal set for 16-QAM is $\{\pm 1 \pm j1, \pm 1 \pm j3, \pm 3 \pm j1, \pm 3 \pm j3\}$. Let $s \in \mathbb{A}$ be the complex symbol to be signaled in a given channel use. Let

$$s = s_I + js_Q,$$

where s_I and s_Q are the real and imaginary parts of s , respectively. Two LEDs (say, LED1 and LED2) are used to convey the magnitude and sign of s_I as follows. LED1 will emit with intensity $|s_I|$ if s_I is positive (≥ 0), whereas LED2 will emit with the same intensity $|s_I|$ if s_I is negative (< 0). Note that, since s_I is either ≥ 0 or < 0 , only any one of LED1 and LED2 will be ON in a given channel use and the other will be OFF. In a similar way, the remaining two LEDs (i.e., LED3 and LED4) will convey the magnitude and sign of s_Q in such a way that LED3 will emit intensity $|s_Q|$ if s_Q is ≥ 0 , whereas LED4 will emit with the same intensity $|s_Q|$ if s_Q is < 0 . Therefore, QCM sends one complex symbol in one channel use. The mapping of the magnitudes and signs of s_I and s_Q to the activity of LEDs in a given channel use is summarized in Table I.

Examples: If $s = -3 + j1$, then the LEDs will be activated as follows: LED1: OFF; LED2: emits 3; LED3: emits 1; LED4: OFF. The $N_t \times 1$ (i.e., 4×1) QCM transmit vector in this example is $\mathbf{x} = [0 \ 3 \ 1 \ 0]^T$. Likewise, if $s = 1 - j3$, then activation of LEDs will be as follows: LED1: emits 1; LED2: OFF; LED3: OFF; LED4: emits 3. The corresponding QCM transmit vector is $\mathbf{x} = [1 \ 0 \ 0 \ 3]^T$.

Remark 1: Because of the proposed mapping, in any given channel use, two LEDs (one among LED1 and LED2, and

another one among LED3 and LED4) will be ON simultaneously and the remaining two LEDs will be OFF.

Remark 2: The complex symbol conveyed in a channel use can be detected from the received QCM signal using the knowledge of the QCM map (Table I) at the receiver.

B. QCM signal detection

Figure 3 shows the block diagram of a QCM receiver with $N_r = 4$ PDs. Following the system model in Sec. II, the $N_r \times 1$ received signal vector at the output of the PDs is given by (3). Assuming perfect channel knowledge at the receiver, the maximum likelihood (ML) estimate of the transmit vector \mathbf{x} is obtained as

$$\hat{\mathbf{x}}_{ML} = \underset{\mathbf{x} \in \mathbb{S}_Q}{\operatorname{argmin}} \|\mathbf{y} - r\mathbf{H}\mathbf{x}\|^2, \quad (4)$$

where \mathbb{S}_Q denotes the QCM signal set (consisting of all possible \mathbf{x} vectors). The detected vector $\hat{\mathbf{x}}_{ML}$ is demapped to the corresponding complex symbol \hat{s}_{ML} , which is then demapped to get the corresponding information bits.

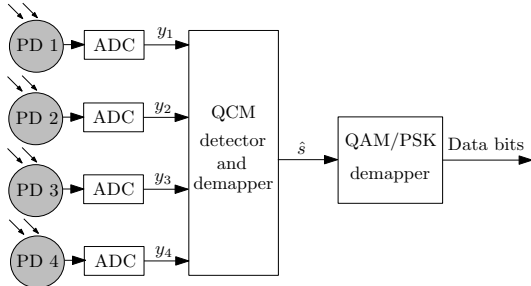


Fig. 3. QCM receiver.

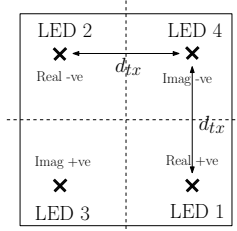


Fig. 4. Placement of LEDs and signal mapping to LEDs.

C. BER performance of QCM

We evaluated the BER performance of QCM through simulations. The various system parameters used in the simulation are listed in Table II. The placement of LEDs and the signal mapping to these LEDs used in the simulations are shown Fig. 4. We evaluate the performance of QCM for various modulation alphabets including BPSK, 4-, 16-, and 64-QAM.

In Fig. 5, we plot the simulated BER of QCM with $d_{tx} = 1\text{m}$ and ML detection for BPSK of 1 bit per channel use (bpcu), 4-QAM (2 bpcu), 16-QAM (4 bpcu), and 64-QAM (6 bpcu). From Fig. 5, We observe that QCM achieves 10^{-4} BER at an E_b/N_0 of about 37 dB for BPSK, 40 dB for 4-QAM, 42.5 dB for 16-QAM, and 46.5 dB for 64-QAM. This observed increase in the required E_b/N_0 for increased QAM size is because of the reduced minimum distance for larger QAM size, and it is in line with what happens in conventional RF modulation. In addition, we observe crossovers which

Room	Length (X)	5m
	Width (Y)	5m
	Height (Z)	3.5m
Transmitter	No. of LEDs (N_t)	4
	Height from the floor	3m
	Elevation	-90°
	Azimuth	0°
	$\Phi_{1/2}$	60°
	Mode number, n	1
	d_{tx}	0.2m to 4.8m
Receiver	No. of PDs (N_r)	4
	Height from the floor	0.8m
	Elevation	90°
	Azimuth	0°
	Responsivity, r	1 Ampere/Watt
	FOV	85°
	d_{rx}	0.1m

TABLE II
SYSTEM PARAMETERS IN THE CONSIDERED INDOOR VLC SYSTEM.

show better performance for larger-sized QAM at low SNRs (e.g., crossover between the performance of 4-QAM and 16-QAM at around 4×10^{-2} BER). This crossover occurs due to the degrading effect of an equal-power interferer² on the one hand, and the benefit of a strong interferer in multiuser detection³ on the other hand. This can be further explained with the following example. The signal received at the i th PD is $y_i = h_l|s_I| + h_k|s_Q| + n_i$, where h_l and h_k are the channel gains corresponding to the LEDs chosen to transmit $|s_I|$ and $|s_Q|$, respectively. For 4-QAM, the transmit signals from both the active LEDs will be 1 (i.e., both $|s_I|$ and $|s_Q|$ will be 1). Whereas for 16-QAM, the transmit signal from each active LED can be 1 or 3 (i.e., $|s_I|$ can be 1 or 3, and so is $|s_Q|$). Therefore, the received signal for 4-QAM is $y_i = h_l + h_k + n_i$. Also, h_l and h_k can be nearly equal because of high channel correlation, making 4-QAM detection unreliable at low SNRs. Whereas, since $|s_I|, |s_Q| \in \{1, 3\}$ in 16-QAM, the effect of channel correlation between h_l and h_k in 16-QAM detection is reduced. That is, $\mathbb{E}(|h_l|s_I| - h_k|s_Q|)$ is larger for 16-QAM compared to that for 4-QAM.

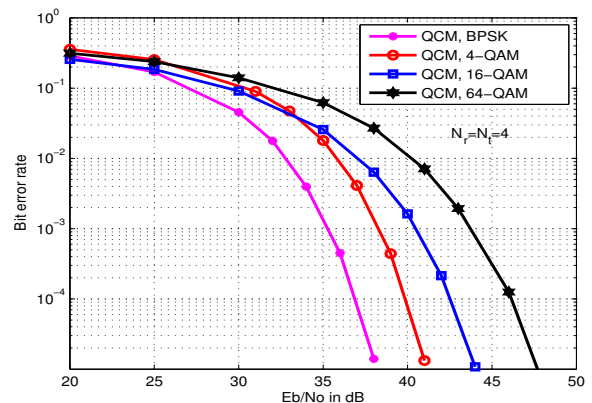


Fig. 5. BER performance of QCM with BPSK, 4-QAM, 16-QAM, and 64-QAM at $d_{tx} = 1\text{m}$.

Effect of varying d_{tx} : Figure 6 shows the effect of varying the spacing between the LEDs (d_{tx} varied in the range 0.2m to 4.8m) on the BER performance of QCM with 4-QAM and 16-QAM at $E_b/N_0 = 35\text{ dB}$. From Fig. 6, we see that there

²Signals from two active LEDs interfere with each other at the receiver.

³A strong interferer can be effectively canceled in a multiuser detector [26].

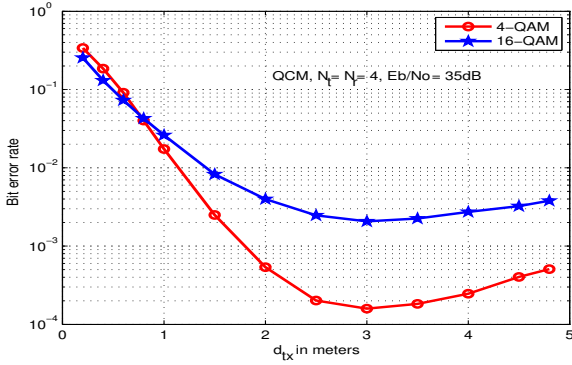


Fig. 6. BER performance of QCM as a function of d_{tx} for 4-QAM and 16-QAM at $E_b/N_0 = 35$ dB and fixed $d_{rx}=0.1$ m.

is an optimum d_{tx} (around 3m) which gives the best BER performance. If d_{tx} is increased above and decreased below this optimum spacing, the BER worsens. The reason for this optimum can be explained as follows. On the one hand, the channel gains get weaker as d_{tx} is increased. This reduces the received signal level, which is a source of BER degradation. On the other hand, the channel correlation also gets weaker as d_{tx} is increased. This reduced channel correlation is a source of BER improvement. These opposing effects of weak channel gains and weak channel correlations for increasing d_{tx} results in an optimum spacing. Also, as observed and explained in Fig. 5, in Fig. 6 also we see that QCM with 16-QAM can perform a little better than QCM with 4-QAM when d_{tx} is small and channel correlation is high.

IV. QCM WITH PHASE ROTATION

Rotation of complex modulation symbols is known to improve BER performance in RF communications [27]. Motivated by this and the fact that QCM allows the use of complex modulation alphabets in VLC, in this section we explore the possibility of improving the performance of QCM through rotation of the complex modulation symbols.

A. QCM-PR transmitter

In QCM with phase rotation, a complex symbol from a modulation alphabet \mathbb{A} is rotated by a phase angle of θ before being transmitted by the quad-LED setup. Let $s \in \mathbb{A}$ be the complex symbol chosen based on the input information bits. Instead of sending the symbol s as such in QCM, the QCM-PR transmitter sends the rotated complex symbol s' given by

$$s' = e^{j\theta} s \quad (5)$$

through the quad-LED setup as described before. Therefore,

$$\begin{aligned} s'_I &= s_I \cos \theta - s_Q \sin \theta, \\ s'_Q &= s_I \sin \theta + s_Q \cos \theta. \end{aligned} \quad (6)$$

Let \mathbf{x}' be the QCM transmit vector constructed using s'_I and s'_Q . Now, \mathbf{x}' is the transmitted vector corresponding to the complex signal s rotated by a phase angle θ .

B. QCM-PR signal detection

We assume that the angle of rotation θ is known both at the transmitter and receiver. The ML estimate of the transmitted symbol s is then given by

$$\hat{\mathbf{x}}'_{ML} = \underset{\mathbf{x}' \in \mathbb{S}_{QP}}{\operatorname{argmin}} \|\mathbf{y} - r\mathbf{H}\mathbf{x}'\|^2. \quad (7)$$

where \mathbb{S}_{QP} denotes the QCM-PR signal set. The detected vector $\hat{\mathbf{x}}'_{ML}$ is demapped to the corresponding complex symbol \hat{s}'_{ML} , which is then demapped to get the corresponding information bits.

C. BER performance of QCM-PR

We evaluated the BER performance of QCM-PR scheme. The simulation parameter settings, LEDs placement, and signal mapping to LEDs are same as those used in Sec. III-C.

BER as a function of rotation angle θ : In Fig. 7, we plot the BER of QCM-PR scheme as a function of the rotation angle θ (in degrees) at $d_{tx} = 1$ m. BER plots for 4-QAM with $E_b/N_0 = 37$ dB and 16-QAM with $E_b/N_0 = 40$ dB are shown. We limit the range of θ value in the x-axis from 0° to 90° as the pattern of the plots repeat after 90° due to symmetry. Note that $\theta = 0$ corresponds to the basic QCM without rotation. The following interesting observations can be made from Fig. 7. First, for both 4-QAM and 16-QAM, the BER plots are symmetrical with respect to 45° , which can be expected. Second, for 4-QAM, $\theta = 45^\circ$ happens to be the optimum rotation which gives the best BER⁴. Note that there is more than an order improvement in BER at this optimum rotation compared to basic QCM without rotation (see BERs at $\theta = 0^\circ$ and $\theta = 45^\circ$). Third, for 16-QAM, there are two optimum angles around 45° because of symmetry; $\theta = 43^\circ$ is one of them.

Figure 8 shows a comparison between the BER performance of QCM-PR (with optimum rotation angles) and QCM (no rotation) at $d_{tx} = 1$ m. BER plots for 4-QAM and 16-QAM are shown. It can be seen that optimum phase rotation improves the BER performance by about 2 to 3 dB.

QCM-PR vs QCM for different d_{tx} : Figure 9 shows how varying d_{tx} affects the BER performance of QCM-PR and QCM at $E_b/N_0 = 35$ dB. As observed for QCM in Fig. 6, we see that there is an optimum spacing in QCM-PR as well, which is due to the opposing effects of weak channel gains and weak channel correlation for increasing d_{tx} values. QCM-PR achieves better performance compared to QCM. For example, at $d_{tx} = 3$ m, there is about 3 orders of BER improvement for 4-QAM. This reinforces the benefit of phase rotation.

V. QCM-OFDM

Since QCM allows the transmission of complex symbols using the quad-LED setup, OFDM signaling can be carried out using QCM. In this section, we present the QCM-OFDM scheme, its detection and performance.

A. QCM-OFDM transmitter

In the QCM-OFDM transmitter, N complex symbols from \mathbb{A} (chosen based on $N \log_2 |\mathbb{A}|$ information bits) will be transmitted by the four LEDs in N channel uses, where

⁴It is interesting to note that QCM-PR with 4-QAM and $\theta = 45^\circ$ rotation specializes to SSK with $N_t = 4$. That is, the 4-QAM signal set when rotated by 45° becomes $\{1 + j0, 0 + j1, -1 + j0, 0 - j1\}$. When mapped to the LEDs as per QCM, the resulting QCM signal set becomes $\{[1000]^T, [0010]^T, [0100]^T, [0001]^T\}$, which is the same as the SSK signal set with $N_t = 4$. Because of this, only one LED will be ON at a time in QCM-PR with $\theta = 45^\circ$ and therefore there will be no interference.

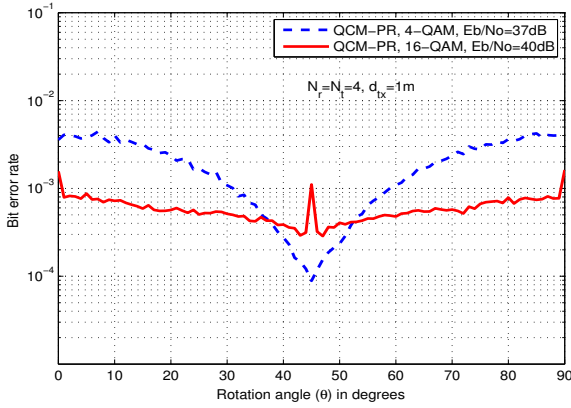


Fig. 7. BER performance of QCM-PR as a function of rotation angle θ for 4-QAM, $E_b/N_0 = 37$ dB and 16-QAM, $E_b/N_0 = 40$ dB at $d_{tx} = 1$ m.

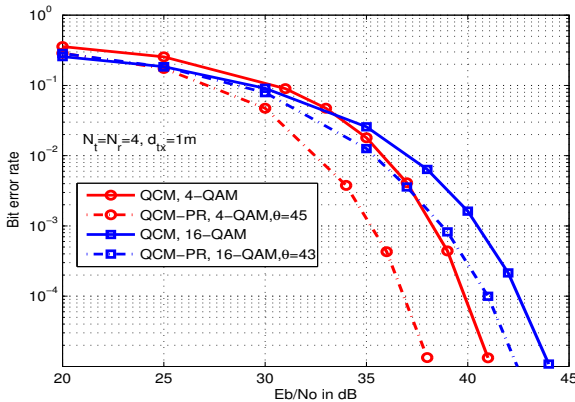


Fig. 8. BER versus E_b/N_0 characteristics of QCM and QCM-PR for 4-QAM and 16-QAM at $d_{tx} = 1$ m.

N is the number of subcarriers. The N complex symbols $\mathbf{v} = [v_1, v_2, \dots, v_N]^T \in \mathbb{A}^N$ are transformed using inverse Fourier transform (IFFT) to obtain the complex transmit symbols $\mathbf{s} = [s_1, s_2, \dots, s_N]^T = \mathbf{F}^H \mathbf{v}$, where \mathbf{F} is the Fourier transform matrix. The N output symbols from the IFFT block are then transmitted one by one in N channel uses by the quad-LED setup in the QCM transmitter. Thus, effectively N complex modulation symbols are sent in N channel uses. Let \mathbf{x}_n denote the $N_t \times 1$ (i.e., 4×1) transmit vector corresponding to s_n , $n = 1, 2, \dots, N$.

B. QCM-OFDM signal detection

Let $\mathbf{Y} = [\mathbf{y}_1, \mathbf{y}_2, \dots, \mathbf{y}_N]$ be the matrix of received vectors corresponding to the matrix of transmit vectors $\mathbf{X} = [\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_N]$, i.e., corresponding to the signal vector $\mathbf{s} = [s_1, s_2, \dots, s_N]^T$. Before performing Fourier transform (FFT) operation, we need to detect the transmitted symbols $s_i \in [0, \infty)$. This detection involves two stages, namely, (i) active LEDs identification, and (ii) complex symbol reconstruction.

1) *Active LEDs identification:* To discern the two active LEDs in the quad-LED setup, we compute

$$z_{i,j} = (\mathbf{h}_j^T \mathbf{h}_j)^{-1} \mathbf{h}_j^T \mathbf{y}_i, \quad j = 1, 2, 3, 4, \quad i = 1, \dots, N, \quad (8)$$

where \mathbf{h}_j is the j th column of the channel matrix \mathbf{H} . For the i th channel use, the LEDs corresponding to the two largest

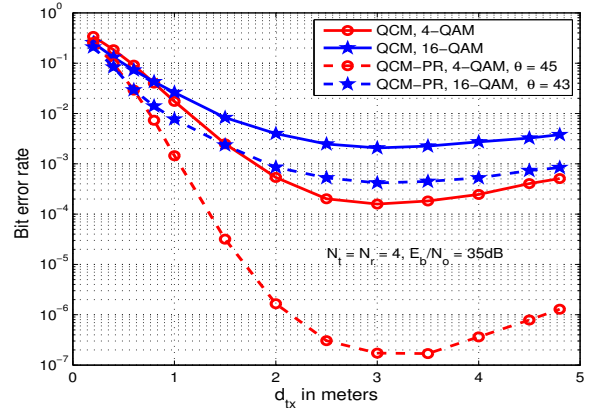


Fig. 9. BER versus LED spacing (d_{tx}) characteristics of QCM and QCM-PR for 4-QAM and 16-QAM at $E_b/N_0 = 35$ dB.

values of $|z_{i,j}|$ are detected to be active. That is, if i_1 and i_2 are the indices of the active LEDs in the i th channel use, then

$$\hat{i}_1 = \underset{j \in \{1,2,3,4\}}{\operatorname{argmax}} |z_{i,j}| \quad i_1 \in \{1, 2, 3, 4\}$$

$$\hat{i}_2 = \underset{j \in \{1,2,3,4\} \setminus i_1}{\operatorname{argmax}} |z_{i,j}| \quad i_2 \in \{1, 2, 3, 4\} \setminus i_1.$$

2) *Complex symbol reconstruction:* After identifying the active LEDs, we need to detect s_I and s_Q . This can be achieved through a zero-forcing (ZF) type detector. Let $\mathbf{s}_i = [s_I^i, s_Q^i]^T$ be the transmitted signal values corresponding to the complex signal s_i . Form \mathbf{H}_{ZF} matrix using the i_1 th and i_2 th columns of \mathbf{H} as $\mathbf{H}_{ZF} = [\mathbf{h}_{i_1} \ \mathbf{h}_{i_2}]$. Now, the ZF detector output is given by

$$\hat{\mathbf{s}}_i = (\mathbf{H}_{ZF}^T \mathbf{H}_{ZF})^{-1} \mathbf{H}_{ZF}^T \mathbf{y}_i. \quad (9)$$

Finally, an estimate of the transmitted complex symbol is obtained as $\hat{s}_i = \hat{s}_I^i + j\hat{s}_Q^i$. Now, $\hat{\mathbf{v}} = \mathbf{F}\hat{\mathbf{s}}$. The $N \log_2 |\mathbb{A}|$ information bits are demapped from $\hat{\mathbf{v}}$.

C. Minimum distance detector

The above zero forcing detector is a sub-optimal detector. Therefore, to further improve the performance of QCM-OFDM, we use a minimum distance (MD) detector. This detector is described as follows. Let \mathbb{S}_F be the set of all possible values the vector \mathbf{s} can take, i.e., $\mathbf{s} \in \mathbb{S}_F$ and $|\mathbb{S}_F| = |\mathbb{A}^N|$. \mathbf{x}_n is the QCM transmit vector in the n th channel use, $n = 1, 2, \dots, N$, and $\mathbf{X} = [\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_N]$ is the matrix of QCM transmit vectors for one QCM-OFDM symbol. Let \mathbb{S}_{QO} be the set of all possible values of the matrix \mathbf{X} , i.e., $\mathbf{X} \in \mathbb{S}_{QO}$ and $|\mathbb{S}_{QO}| = |\mathbb{A}^N|$. Therefore, for every $\mathbf{v} \in \mathbb{A}$ there exists a corresponding matrix $\mathbf{X} \in \mathbb{S}_{QO}$ and vice versa. The estimate of \mathbf{v} in the MD detector is obtained as

$$\hat{\mathbf{v}} = \underset{\mathbf{X} \in \mathbb{S}_{QO}}{\operatorname{argmin}} \|\mathbf{Y} - r\mathbf{H}\mathbf{X}\|. \quad (10)$$

The $N \log_2 |\mathbb{A}|$ information bits are demapped from $\hat{\mathbf{v}}$.

D. BER performance of QCM-OFDM

We evaluated the BER performance of QCM-OFDM scheme through simulations. The simulation parameter settings, LEDs placement, and signal mapping to LEDs are same as those used in Sec. III-C. Figure 10 shows the BER

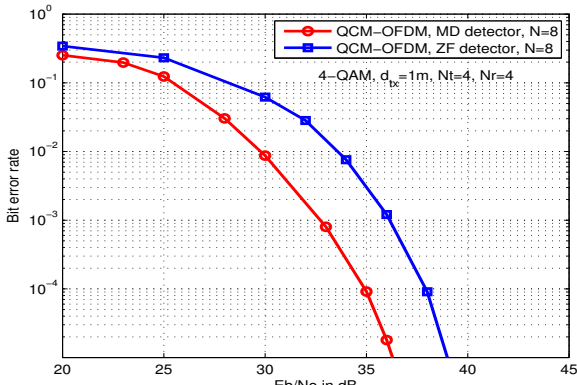


Fig. 10. BER performance of QCM-OFDM with ZF detection and MD detection for $N = 8$, 4-QAM, $d_{tx} = 1m$.

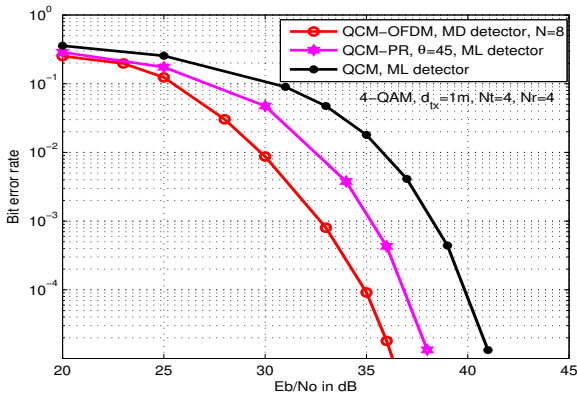


Fig. 11. BER performance comparison between QCM, QCM-PR, and QCM-OFDM for 4-QAM at $d_{tx} = 1m$.

performance of QCM-OFDM with $N = 8$ and 4-QAM at $d_{tx} = 1m$. The performance achieved by ZF detection and MD detection (presented in the previous subsection) are plotted. It can be seen that the MD detector achieves better performance by 2.5 dB to 3.5 dB compared to the ZF detector. In Fig. 11, we compare the performance of QCM, QCM-PR with optimum rotation $\theta = 45^\circ$, and QCM-OFDM with 4-QAM and $d_{tx} = 1m$. It can be seen that QCM-OFDM with MD detection achieves better performance compared to both QAM and QCM-PR. For example, at a BER of 10^{-4} , QCM-OFDM performs better than QCM-PR and QCM by about 2 dB and 5 dB, respectively.

VI. CONCLUSIONS

We introduced a simple and novel complex modulation scheme suited for multiple-LED VLC. The scheme is termed as QCM (Quad-LED Complex Modulation). It uses four LEDs, one LED each to map positive real, negative real, positive imaginary, and negative imaginary parts of complex modulation symbols like QAM symbols. QCM does not have to perform Hermitian symmetry operation to generate LED compatible positive real signals. Instead, it exploits spatial indexing of LEDs to convey the sign information. Simulation results showed that the proposed QCM scheme can achieve good BER performance in indoor VLC systems. It was also shown that the performance of QCM can be further improved by phase rotation (QCM-PR) of the complex modulation symbols prior to mapping the complex signals to the LEDs. We further showed that QCM when used along with

OFDM (QCM-OFDM) can achieve very good performance. The QCM scheme can therefore serve a basic building block to bring in the benefits of complex modulation to VLC.

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