2 Gbit/s VLC Scheme Using Time-Frequency Color-Clustered MIMO Based on BCYR LEDs

Phyu Phyu Han, Atul Sewaiwar, and Yeon-Ho Chung*
Department of Information and Communication, Pukyong National University, Busan 608-737, Korea

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A 2 Gbit/s visible-light communication (VLC) scheme using time-frequency color-clustered (TFCC) multiple-input multiple-output (MIMO) based on blue, cyan, yellow, and red (BCYR) light-emitting diodes (LEDs) is presented. In the proposed scheme, BCYR LEDs are employed to form four different color clusters. Data transmission using the four color clusters is performed in MIMO, so that the scheme achieves a very high speed of data transmission. Moreover, the scheme employs the TFCC strategy to yield high performance in terms of bit error rate (BER). TFCC operates in such a way that the original data and the two delayed versions of the data are multiplied by orthogonal frequencies and then transmitted using a specific color of the BCYR LED. In the receiver, color filters are employed to detect the data transmitted from the desired cluster. Selection combining (SC) is also performed to yield a diversity effect within each color cluster, to further improve the performance. Performance evaluation demonstrates that the proposed TFCC MIMO VLC offers a data rate of 2 Gbit/s and a bit error rate of $4 \times 10^{-5}$, at an $E_b/N_0$ value of merely 3 dB.

Keywords: Light emitting diodes, Optical MIMO, Color cluster, Time-frequency diversity

OCIS codes: (200.2605) Free-space optical communication; (230.3670) Light-emitting diodes; (150.2950) Illumination; (060.4230) Multiplexing

I. INTRODUCTION

Visible light communication (VLC) systems rely upon visible radiation from light emitting diodes (LEDs) to convey information in a wireless environment. The main feature of VLC lies in data transmission ability via lighting units typically installed to provide illumination indoors. VLC can be considered a strong contender for future indoor wireless communications with high data rate and high performance [1].

Multiple-input multiple-output (MIMO) transmission has become attractive because it can enhance the capacity of a VLC system without requiring any increase in transmission bandwidth or power. Researchers have demonstrated optical MIMO techniques based on nonimaging and imaging approaches to achieve high data rates [2, 3]. A 4×4 MIMO VLC scheme with a commercial charge-coupled device (CCD) as an image sensor receiver was demonstrated in [4]. An experimental 4×4 MIMO VLC achieved a data rate of 10 Gbit/s using a vertical cavity surface emitter laser (VCSEL) [5]. MIMO techniques coupled with OFDM and equalization [6], spatial modulation [7], and spatial multiplexing [8] have been proposed in the literature. In the MIMO VLC, phosphor-coated white LEDs are predominantly employed for transmission [2-4, 6-8], because these LEDs are popular, cheap, and easy to manufacture. Unlike these studies, a color-clustered MIMO technique using RGB LEDs was also proposed [9]. The color-clustered scheme for multuser data transmission using RGB LEDs was first proposed in [10], while the study in [11] enhanced this strategy for a color-clustered bidirectional multuser scheme, based on an efficient frame structure.

Although the aforementioned MIMO techniques present efficient schemes to achieve high data rates, the high performance in terms of BER was achieved at the expense of signal to noise ratio (SNR). These MIMO techniques can be strengthened by incorporating diversity benefits in the...
transmitter, thus achieving high performance at relatively low SNR values. In a diversity technique, multiple copies of the original data stream are transmitted via separate transmission paths. To achieve the diversity benefit, it is known that these multiple transmissions must undergo independent fading in the context of time and/or frequency. In this paper, we consider a combined time and frequency diversity scheme based on the color-clustering method. In particular, we investigate an efficient time-frequency high-speed and high-performance color-clustered MIMO VLC based on blue, cyan, yellow, and red (BCYR) LEDs, for a high-performance and high-speed MIMO VLC system. The use of the BCYR LEDs was first reported for a four-color CSK modulation scheme in [12]. The CSK scheme utilized a complex maximum likelihood (ML) detection technique, and a BER of $10^{-5}$ was achieved at an $E_b/N_0$ value of approximately 9 dB, with a data rate of only 48 Mbps using 4-CSK. This data rate, however, was increased to 144 Mbps using a high modulation format of 64-CSK, at the expense of increased complexity and diminishing performance gain. Therefore, there is a need for a comprehensive study of the viability of a BCYR LED for a high-speed and high-performance VLC.

To achieve high-speed data transmission, LEDs with a high 3 dB modulation bandwidth [13] can be utilized, which can also fulfill the illumination requirements. The 3 dB modulation bandwidth of an LED can be defined as the range of frequencies used to modulate the drive current for which the detected optical power drops by 3 dB, with respect to the optical power emitted with DC drive current. It is found that LEDs can theoretically have a 3 dB bandwidth of up to 2 GHz [13, 14]. Additionally, an LED with an optical modulation bandwidth of 1.7 GHz has also been proposed [15].

While achieving high-speed data transmission, we consider the time-frequency color-cluster (TFCC) scheme, to significantly improve the performance of the proposed VLC. In TFCC, the original data and two delayed versions of the data are multiplied by orthogonal frequencies, then transmitted using a specific color of the BCYR LED. It is important to note that the orthogonal frequency employed provides a significant performance improvement in the form of frequency multiplexing. This phenomenon is called the diversity effect [16]. Therefore, the composite signal of the time-frequency-modulated data streams is transmitted using one specific color of the BCYR LEDs present in the specific color cluster. An array of photodiodes (PDs) is installed at the receiver, each equipped with an individual color filter. Each color filter filters out the modulated data for the desired data stream from the specified color cluster, thereby limiting the interference from the data transmitted using different colors. We also employ selection combining (SC) at the receiving end, where most probable bits are detected to produce improved performance. Simulation results verify that the proposed scheme can achieve a data rate of 2 Gbit/s with a BER value of $4 \times 10^{-5}$, showing its superiority over conventional transmission schemes reported in the literature [9, 12].

The proposed scheme is focused on addressing two of the most fundamental issues in VLCs: high data speed and high performance. Although the BCYR LEDs and diversity schemes have already been introduced in the literature, these techniques have been unable to deliver a high-speed, high-performance VLC system. Based on the BCYR LEDs and the unique double diversity techniques, however, the proposed scheme demonstrates that it can offer a data rate of 2 Gbit/s and a bit error rate of $4 \times 10^{-5}$ at an $E_b/N_0$ value of merely 3 dB.

The remainder of the paper is organized as follows: Section 2 describes the proposed scheme, while the discussion of the theoretical analysis is presented in Section 3, and simulation results are shown in Section 4. Conclusions are drawn in Section 5.

II. PROPOSED MODEL

2.1. BCYR LED-Based VLC

A typical indoor environment for the proposed scheme, with room dimensions of 5 m × 5 m × 3 m (length × width × height), is shown in Fig. 1(a). The proposed scheme consists of four different color clusters in blue, cyan, yellow,
and red colors, exploiting commercially available BCYR LEDs. Recognizing the fact that VLC systems in an indoor environment should fulfill illumination functionality besides providing wireless data communication, we placed 25 BCYR LEDs in each color cluster, to ensure the proper brightness level defined by ISO [17]. In other words, a total of 100 BCYR LEDs are installed in the ceiling. Figure 1(b) shows the four BCYR LED color clusters. To mitigate intersymbol interference (ISI) between LEDs, the LEDs are suitably separated. It is important to note that since multi-color LEDs are employed in the present study can be considered by mixing colors in a quadrilateral constellation shape of CIE 1931 [12].

The detailed description of the scheme, in terms of the functionalities of transmitter and receiver, is provided below.

2.2. Transmitter

Figure 2(a) depicts the transmitter structure, composed of the modulators and the BCYR LEDs. At the transmitter, an input binary sequence is first divided into four parallel streams \( d_n(t) \), \( \forall n \in \{b, c, y, r\} \), i.e. one for each color cluster. Each data stream and its two delayed versions are then modulated by multiplying with orthogonal frequencies. This modulation process is depicted in Fig. 2(b). All three modulated signals are then added and provided with DC bias, to obtain a composite signal for transmission. The resultant composite signal is transmitted from each color cluster.

It is important to note that the amount of delay in the delayed paths needs to be determined in such a way that the paths undergo independent transmission over the optical channel, to exploit the diversity effect for improved performance. In a typical indoor environment, the signal transmitted along the direct path and also that from the first reflection reach the receiver within 2 ns [17]. As a result, we set the value of the delay \( \tau \) to 2 ns. Also, with the two delayed data paths employed, the symbol duration \( T_s \) is set to 2 ns. Thus, it is apparent that each cluster achieves a data rate of 500 Mbit/s. The composite signal from each cluster is given by

\[
m_s(t) = \sum_{l=1}^{3} d_n(t-(l-1)\tau)\cos(2\pi f_l t) \forall n \in \{b, c, y, r\}
\]

where \( d_n(t) \in [0, 1] \) and \( \tau \) represents the path delay shown in Fig. 2(b). \( f_l \) represents an orthogonal frequency separated by \( \Delta f \) for \( l \in \{1, 2, 3\} \). In the present simulation, the value of base frequency \( f_1 \) is fixed at 0.5 GHz \( (1/T_s) \), and \( \Delta f \) is fixed at 0.5 GHz, i.e. the respective values of \( f_1, f_2, \) and \( f_3 \) are 0.5, 1.0, and 1.5 GHz. This is because the frequency separation must satisfy the orthogonality condition, \( \Delta f = N/T_s, \forall N \in Z \). It is also worth noting that the frequency selection is dependent upon the 3 dB bandwidth of an LED. The reported maximum modulation bandwidth of an LED is 1.7 GHz [15]; hence the selected frequencies of \( f_1, f_2, \) and \( f_3 \) are justified.

2.3. Receiver

The receiver structure for the proposed scheme is shown in Fig. 3. The four receivers installed at the receiving end consist of three PDs, each receiver equipped with a color filter to filter out the data transmitted from other clusters. The signal \( y_{nj} \), received after passing through the color filter \( n(n \in \{b, c, y, r\}) \) on the \( j \)th receiver, can be written as [2]

\[
y_{nj} = \mathcal{P}_{\text{LED}} \sum_{i=1}^{N_T} h_{ij} t_i + \sqrt{i_{n}^2}
\]

where \( \gamma \) is the detector responsivity, \( \overline{v^2_{nj}} \) is the mean square noise current at the input to the \( j \)th receiver, \( \mathcal{P}_{\text{LED}} \) is the total power of the LED, and \( t_i \) is the convolution of the \( j \)th parallel binary data stream with the LED impulse response. The DC channel gain \( h_{ij} \) between transmitter \( i \) and receiver \( j \) can be estimated by summing all the power reaching the \( j \)th receiver from the \( K \) LEDs in transmitter \( i \) as [2]

\[
h_{ij} = \begin{cases} \sum_{k=1}^{K} \frac{A_{jk}^j}{d_{ijk}^2} R_v(\theta_{ijk}) \cos(\Phi_{ijk}), & 0 \leq \Phi_{ijk} \leq \Phi_c \\ 0, & \Phi_{ijk} > \Phi_c \end{cases}
\]
where $A_r$ is the receiver collection area for the $j$th receiver, $d_{ijk}$ is the distance between the $k$th LED in the $i$th transmitter and the $j$th receiver, $\theta_{ijk}$ is the emission angle, $\Phi_{ijk}$ is the angle of incidence of the light at the receiver, and $\Phi_c$ is the receiver FOV. $R_o(\theta_{ijk})$ represents the Lambertian radiant intensity of the LED, measured in W/sr, and is given by

$$R_o(\theta_{ijk}) = I_0 \cos^{m_l} \theta_{ijk}$$  \hspace{1cm} (4)$$

where $m_l$ is the order of Lambertian emission related to the LED’s semi-angle at half power, $\psi_{1/2}$, and is defined as $m_l = -\ln 2 / \ln(\cos(\psi_{1/2}))$.

The received signal from each PD is passed through the coherent demodulator as shown in Fig. 3(b). It can be observed from Fig. 3(b) that $y_n(t)$ is the received signal in color $n(n \in \{b, c, y, r\})$ at the $j$th receiver (PD). The demodulator extracts the reference carrier needed to downconvert the received signal. The sum of all three paths after downconversion is then fed into the decision circuit, which performs an estimation based on the composite signal. The filtered and downconverted received signal in each cluster is then compared to the data received from the other PDs of the same cluster to perform the SC for detection of the most probable bit among the three candidates [9]. This SC process further provides the performance improvement of the proposed system. The demodulated signals from the four clusters are finally multiplexed to recover the original data stream. The use of color filters over the PDs would eventually increase the cost of implementing the proposed system but this increased cost is readily compensated by the significant benefits of using these color filters.

### III. THEORETICAL ANALYSIS

#### 3.1. Illumination

The luminance expresses the brightness of an illuminated surface. It is assumed that the light intensity emitted from the source has a cosine dependence on the angle of emission with respect to the normal surface [17]. The luminous intensity at angle $\phi$ is given by

$$I(\phi) = I(0) \cos^{m_l} \phi$$  \hspace{1cm} (5)$$

A horizontal illuminance $E_{hor}$ at a point $(x, y)$ is given by

$$E_{hor} = I(0) \cos^{m_l} \phi D_d^2 \cos(\Phi)$$  \hspace{1cm} (6)$$

where $I(0)$ is the center luminance intensity of the LED, $\phi$ is the angle of irradiance, $\Phi$ is the angle of incidence, and $D_d$ is the distance between the LED and the detector's surface.

#### 3.2. Optical Wireless Channel

The optical wireless channel is modeled as additive white Gaussian noise (AWGN) and is expressed as

$$Y(t) = N(t) \otimes h(t) + X(t)$$  \hspace{1cm} (7)$$

where $Y(t)$ represents the received signal, $\gamma$ is the detector responsivity, $X(t)$ represents the transmitted optical pulse, $h(t)$ is the channel impulse response, $N(t)$ represents AWGN, and the symbol $\otimes$ denotes convolution.

#### 3.3. Bit Error Rate and Maximum Achievable Data Rate

The bit error rate $P_e$ can be obtained by comparing the transmitted data $d(t)$ and the estimated data $\hat{d}(t)$.

$$P_e = \frac{N_e[\hat{d}(t) \neq d(t)]}{N_T}$$  \hspace{1cm} (8)$$

where $N_e[\hat{d}(t) \neq d(t)]$ represents the number of bits in error between $d(t)$ and $\hat{d}(t)$, and $N_T$ represents the number of transmitted bits.

For a given error rate $P_e$, the maximum achievable data
where $R_{\text{max}}$ represents the maximum data rate for the system concerned, and $BER_m$ denotes the maximum tolerable bit error rate. It can be observed from Eq. (9) that the system can achieve the maximum data transmission rate in the case of error-free transmission, i.e. when $P_e$ is equal to 0. Since it is not possible to achieve an error-free transmission, the maximum tolerable BER, $BER_m$, can be defined for an application. For example, the value of $BER_m$ could be set to $10^3$ for voice transmission and $10^6$ for multimedia transmission.

### IV. SIMULATION RESULTS

To evaluate the effectiveness of the proposed scheme, performance evaluation via computer simulations is performed using the parameters listed in Table 1.

Figure 4 shows the illumination distribution results obtained from Eq. (6). According to the ISO standard [17], it can be said that the room is sufficiently illuminated at nearly all positions, with illuminance of 250 to 900 lx, except for the far corners of the room.

Simulation is performed under AWGN using Eq. (7). Figure 5 describes the bit error rate (BER) performance comparison of the proposed scheme to conventional transmission schemes reported in the VLC literature: the RGB MIMO scheme, BCYR LED (or RGB LED)-based 4-CSK, and OOK. For the MIMO schemes, we considered the SC combining technology. For a fair comparison to existing

| TABLE 1. System simulation parameters | Values |
|--------------------------------------|--------|
| Dimension of room | $5 \times 5 \times 3 \text{ m}$ |
| Transmitter position | $[2.5, 2.5, 3]$ |
| Height of receiver plane | 0.85 m above ground |
| Transmitted optical power / LED | 3 W |
| Number of LEDs | 100 (4×25) |
| LED half angle | 60° |
| LED interval | 1 cm |
| Effective area of each PD | 1 cm$^2$ |
| Field of Vision (FOV) of a PD | 60° |
| First frequency component ($f_1$) | 0.5 GHz |
| Frequency separation ($\Delta f$) | 0.5 GHz |
schemes, the simulations were performed while keeping the data rates for all schemes constant at 2 Gbps. In other words, the bit duration for each of the schemes is determined to limit the data rate to 2 Gbps. It can be observed from Fig. 5 that a BER of $4 \times 10^{-5}$ is achieved at an $E_b/N_0$ value of 4 dB with the proposed TFCC. Also, an additional 1 dB gain is observed with selection combining. Over both conventional OOK and RGB LED-based 4-CSK [12], the proposed scheme yields approximately 9.3 dB gain in terms of $E_b/N_0$ at the reference BER of $4 \times 10^{-5}$. Furthermore, the proposed scheme shows its superiority over advanced transmission schemes such as RGB LED MIMO [9] and BCYR LED-based 4-CSK [12] by gains of approximately 4 and 6 dB, respectively. Hence, the time-frequency color-clustered MIMO scheme coupled with the SC offers superior performance, even at very low $E_b/N_0$ values. Clearly, this is due to the proposed TFCC transmission strategy that exploits the diversity effect at its maximum in the time and frequency domains. In more concrete terms, a single bit is transmitted over the three branches in the modulator and is then received via the three PDs, thereby facilitating the SC.

In addition to the BER performance analysis, it is worth investigating estimated data rates over the entire room in the assumed indoor environment (see Fig. 1(a)). Figure 6(a) shows the data rate distribution for the proposed scheme, at the reference BER value of $10^{-3}$. It was found that a data rate of 2 Gbit/s was achieved with the proposed scheme over most locations in the indoor environment, except for the far corners.

We have further analyzed the achievable data rates relative to the $E_b/N_0$ values. According to the achievable data rate of Eq. (9), we obtained the simulation results. Figure 6(b) shows the data rate comparison to conventional transmission schemes. The maximum data rate of 2 Gbit/s for the proposed scheme was achieved at an $E_b/N_0$ value of 3 dB. This data rate is the highest achievable rate among the considered schemes. Viewing Figs. 5 and 6(b) together, it can be found that the proposed scheme offers a BER value of $4 \times 10^{-5}$ and a data rate of 2 Gbit/s, all at an $E_b/N_0$ value of 3 dB.

V. CONCLUSION

A 2 Gbit/s VLC scheme using a novel time-frequency color-clustered MIMO based on BCYR LEDs is presented. The proposed scheme achieves a high-speed and high-performance VLC by exploiting the diversity gain (for high performance) and color-clustered multiplexing (for high speed) in the TFCC MIMO based on the BCYR LEDs. When compared to the most recent transmission schemes such as RGB MIMO VLC and 4-CSK (BCYR LEDs), it achieves gains of approximately 4 and 6 dB, respectively. In addition, the data rate comparison reveals that the proposed scheme attains the highest achievable rate among all other considered schemes. Therefore, the proposed high-speed and high-performance MIMO VLC can be considered a candidate for an efficient indoor VLC link.

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