Adaptive M-PAM for Multiuser MISO Indoor VLC Systems

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Abstract—In multiuser multiple input single output (MISO) visible light communication (VLC) systems using LEDs with limited rise-times, it is essential to find effective M-ary modulation schemes to increase the bit rate. In this paper, we propose an adaptive M-ary pulse amplitude modulation (M-PAM) algorithm to support multiple users. The proposed algorithm can adjust the modulation constellation size for each user to maximize the bit rate under different channel environments such as shadowing, light dimming, and the impact of multiple access interference. In our MISO approach, multiple LED lamps coordinate to provide users with maximum data rates. We compare optical code division multiplexing access (OCDMA) using our adaptive M-PAM with time division multiplexing access (TDMA). The OCDMA technique can offer a higher bit rate when the number of users is larger than the length of the OCDMA code.

Index Terms—Visible light communications, adaptive modulation, pulse-amplitude modulation, multiuser MISO, shadowing, CDMA, TDMA.

I. INTRODUCTION

Visible light communications (VLC) has attracted much attention in recent research due to its many advantages over radio-frequency (RF) communications. It is immune to RF interference, has low power consumption, low impact on human health, can offer higher security, and can provide potentially high data-rate connectivity. Moreover, VLC systems can be applied in environments that disallow RF, such as airplanes, military facilities, and hospitals [1], [2].

For VLC to compete with RF millimeter-wave technology, it needs to deliver reliable high-speed wireless internet access. To improve the transmission data rate, a fast rise-time light emitting diodes (LED), named μLED, could be used [3], at the expense of lower transmit powers. Furthermore, faster symbol rates can lead to multi-path effects due to the dispersive nature of the channel, which impact the system performance by introducing intersymbol interference (ISI). It is therefore desirable to find an efficient modulation for VLC systems to increase the data rate without increasing the signal bandwidth. Since light emitted from LEDs is non-coherent, an M-ary intensity modulation that has a high bandwidth efficiency such as M-ary pulse amplitude modulation (M-PAM) is a good choice [4]. In this paper we propose a robust and high-rate multiuser system design based on M-PAM.

To support multiple users, multiple input single output (MISO) processing and optical code division multiple access (OCDMA) can be applied [5]–[8]. Multiple LED lamps transmit CDMA coded signals in a coordinated manner to support multiple users, making the system robust against channel shadowing. In addition, to diminish the multiple access interference (MAI) and improve the signal to interference plus noise ratio (SINR), the transmitted power from each LED can be optimally allocated to users and optimally detected using a minimum mean square error (MMSE) filter at the receivers, as proposed in our previous work [9]. In this paper we adopt an adaptive M-PAM modulation scheme instead of the on-off keying (OOK) previously used. The adaptive M-PAM modulation algorithm selects a different constellation size for each user to optimize the transmitted data rate in a fair manner. Users with better channel downlink quality can benefit from a larger modulation constellation size and/or be allocated a lower portion of the total LED power so that all users can maintain a preset communication performance level. We show that CDMA is able to provide higher data rates than time division multiplexing access (TDMA) for the same performance when the number of users is larger than the code length.

Recently, some significant research has been directed towards designing modulation schemes for VLC systems [4]. M-PAM was explored in [10] to yield a \((\log_2 M)\)-fold increase in the data rate compared with OOK. Instead, orthogonal frequency division multiplexing (OFDM) can be used to increase the data rate and efficiently combat ISI [11], [12]. Furthermore, researchers have proposed adaptive modulation schemes for VLC based on OFDM [13]. The drawback of OFDM is that it has a relative high peak to average power ratio (PAPR), making it more sensitive to the nonlinear distortion of the LEDs than pulsed techniques such as PAM. An M-ary variable period modulation (MVPM) scheme for VLC was proposed in [14]; MVPM has been proven capable of reducing the slot duration to increase the data transfer rate in VLC system. However, it is difficult to keep all the users synchronized. In addition, the narrow time slot may introduce ISI from multipath in the indoor channel. A MIMO-PPM technology was proposed in [15] to improve the data rates without reducing the reliability of the link. However, the multiuser case was not considered in [15]. Furthermore, PPM is bandwidth inefficient and very sensitive to external interference that may cause a complete data corruption. To alleviate these drawbacks, we propose a MISO CDMA VLC system using an adaptive M-PAM modulation scheme with synchronized symbol rate across users and LED
lamps. Channel state information at the transmitter is assumed known perfectly so that when the downlink channel conditions change due to motion or shadowing, the proposed algorithm can adjust the modulation constellation size to optimize the bit rate adaptively.

The remainder of the paper is organized as follows. The system model is described in Section II. In Section III, we derive the adaptive M-PAM algorithm. In Section IV, TDMA and OCDMA techniques having the same bandwidth are compared. Numerical results are discussed in Section V. The paper is concluded in Section VI.

II. SYSTEM DESCRIPTION

Typical indoor VLC systems use white LED lamps as transmitters. Unlike RF communication systems, the most viable modulation/demodulation technique for VLC systems is intensity modulation/direct-detection (IM/DD) because of the noncoherent nature of the transmitted signal. In this paper, M-PAM is used as the modulation scheme and OCDMA is used as the multiple access scheme. The transmitter model we use is a lamp that contains multiple LEDs with different orientations [16] that are power-controlled as one.

Studies on the impulse response of an indoor optical channel show that the received optical pulse can be classified into a line of sight (LOS) and a diffuse component [17]. For computational complexity reasons, in this paper we assume the channel gain only contains the LOS part. We suppose there are \( K \) users in an access area within the indoor environment and \( Q \) LEDs serve them, and denote them by \( k = 1, \ldots, K \) and \( q = 1, \ldots, Q \), respectively. The general formula for the channel gain between the \( q \)th LED and the \( k \)th user's photodetector (PD) can be written as [9]

\[
 h_{qk} = \frac{R_e A_r \cos(r_{qk})}{2\pi d_{qk}^2} \left( m + 1 \right) \cos^m(r_{qk}) \equiv r_{qk} (1) 
\]

where \( A_r \) is the area of the photodetector, \( R_e \) is its responsivity, and \( d_{qk} \) is the distance between the \( q \)th LED and user \( k \), \( r_{qk} \) is the unit vector pointing from the LED towards the user, \( n_k \) is the \( k \)th receiver’s normal unit vector, and \( \hat{l}_q \) represents the radiation unit direction vector for the \( q \)th LED. In (1), the notation \( \langle x, y \rangle \) represents the angle between vectors \( x \) and \( y \). Fig. 1 illustrates this notation. In addition, \( m \) is the Lambertian mode of the light source, which is related to the LED’s semielongitude \( \Phi_{1/2} \) by \( m = \frac{\ln 2}{\ln(\cos(\Phi_{1/2}))} \).

Define \( h_k = (h_{1k}, h_{2k}, \ldots, h_{Qk})^T \).

III. ADAPTIVE M-PAM

We assume all LED lamps are synchronized with each other and all contribute to the data transmission for all users in the access area of interest. The VLC channel between LED \( q \) and user \( k \) is completely characterized by \( h_{qk} \) using (1) and known at the transmitters. Using M-PAM modulation, we assume the amplitude of the transmitted symbol for user \( k \) is \( a_k \in \{0, \frac{1}{M_k-1}, \frac{2}{M_k-1}, \ldots, 1\} \), and each symbol carries \( \log_2 M_k \) bits, where \( M_k \) is the modulation constellation size for user \( k \). Since we assume the binary data is equally likely, the \( a_k \) are uniformly distributed. Thus, the transmitted signal for the \( q \)th LED can be represented as

\[
 s_q(t) = \sum_{k=1}^{K} p_{qk} a_k c_k(t), \tag{2}
\]

where \( p_{qk} \) is the power allocated to the \( q \)th LED for user \( k \) and \( c_k(t) \) is the OCDMA codeword for user \( k \). Since our previous paper [18], the received signal for user \( k \) after MMSE filtering can be represented as

\[
y_k = a^TB_k Cw_k + n_k^T w_k, \tag{3}
\]

where \( a = (a_1, a_2, \ldots, a_K)^T \) is the transmitted symbol vector; the MMSE filter for user \( k \) is defined as \( w_k \); \( C \) represents the CDMA code matrix, which can be represented as \( C = (c_1, c_2, \ldots, c_K)^T \), where \( c_k \) is the CDMA code for user \( k \); \( n_k \) is the noise at the user \( k \), which can be modeled as Gaussian distributed noise with variance \( \sigma^2 \). To facilitate the formulation, we define the matrix \( B_k = \text{diag}(h_k^T \cdot P) \), where

\[
P = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1K} \\ p_{21} & p_{22} & \cdots & p_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ p_{Q1} & p_{Q2} & \cdots & p_{QQ} \end{pmatrix} \tag{4}
\]

represents the power allocation matrix. After some calculations, the MMSE filter for user \( k \) can be represented as

\[
w_k = \left( C^T B_k \Sigma_a B_k C + \sigma^2 I \right)^{-1} C^T B_k q_k \tag{5}
\]

where \( I \) is the identity matrix of the same size as the OCDMA code matrix \( C \), and \( \Sigma_a \) is the correlation matrix for the transmitted symbol, which can be calculated as

\[
\Sigma_a = \begin{pmatrix} E\{a_1 \cdot a_1\} & E\{a_1 \cdot a_2\} & \cdots & E\{a_1 \cdot a_K\} \\ E\{a_2 \cdot a_1\} & E\{a_2 \cdot a_2\} & \cdots & E\{a_2 \cdot a_K\} \\ \vdots & \vdots & \ddots & \vdots \\ E\{a_K \cdot a_1\} & E\{a_K \cdot a_2\} & \cdots & E\{a_K \cdot a_K\} \end{pmatrix}, \tag{6}
\]

and

\[
q_k = (E\{a_k \cdot a_1\}, E\{a_k \cdot a_2\}, \ldots, E\{a_k \cdot a_K\})^T \tag{7}
\]
where $E\{a_k \cdot a_v\}$ can be calculated as
\[
E\{a_k \cdot a_v\} = \begin{cases} 
\frac{2M_k - 1}{6(M_k - 1)} & k = v \\
\frac{1}{4} & k \neq v
\end{cases}.
\] (8)

The SINR for user $k$ can be represented as [16]\(^1\)
\[
\text{SINR}^{(k)} = \frac{w_k^T C_k^T B_k \tilde{E}_k \Sigma_n \tilde{E}_k B_k^T C_k w_k}{w_k^T C_k^T B_k \tilde{A}_k \Sigma_n \tilde{A}_k B_k^T C_k w_k + \sigma^2 w_k^T w_k},
\] (9)
where the matrix $\tilde{E}_k$ is defined as a matrix with a ‘1’ in its $(k,k)$th element and zeros in all other places, and $\tilde{A}_k = I - \tilde{E}_k$.

From (6)-(9), we conclude that the SINR for user $k$ depends on the power allocation scheme and the M-ary modulation constellation size of all users. Therefore, the SINR is a function of $M = (M_1, M_2, \cdots, M_K)^T$ and the power allocation matrix $P$.

The bit error rate (BER) for user $k$ when using M-PAM can be represented approximately as [19]
\[
\text{BER}_k = \frac{M_k - 1}{M_k \log_2 M_k} \text{erfc} \left( \sqrt{\frac{\text{SINR}^{(k)}}{(M_k - 1)^2}} \right),
\] (10)
where $\text{erfc}(\cdot)$ is the complementary error function, which is defined as
\[
\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-u^2} du.
\] (11)

In this paper, our adaptive M-PAM scheme can adjust the modulation constellation size for different users, i.e., choose the optimal constellation size to optimize the throughput for all users. The bit rate for user $k$ can be represented as
\[
R_b^{(k)} = R_s \cdot \log_2 M_k,
\] (12)
where $R_s$ is the symbol rate, assumed to be the same for all users. To optimize the throughput fairly, the optimization cost function we use is given by
\[
[P^*, M^*] = \arg\max_{P,M} \min_k R_b^{(k)},
\] (13)
where $P^*$ and $M^*$ are the optimal solutions for power allocation and modulation constellation size, respectively. When doing the optimization, a peak transmitted power constraint must be considered. To satisfy the communication quality, a constraint on the BER should also be taken into account. Thus, the optimization constraints can be represented as
\[
\sum_{k=1}^{K} p_{qk} \leq P_o \quad \text{and} \quad p_{qk} \geq 0 \quad \forall q_k, \quad \text{and} \quad \text{BER}_k \leq b_c,
\] (14)
where $P_o$ is the peak transmitted power. $b_c$ is the desired BER for each user, which guarantees the communication quality.

\(^1\)For all SINR expressions, the responsivity of the receiver is ignored. It is nonetheless accounted for in the simulation results.

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**IV. OCDMA vs TDMA USING M-PAM**

Since the OCDMA codes are not perfectly orthogonal, it is not evident a priori whether OCDMA is a more efficient method to support multiple users in indoor VLC systems than an orthogonal multiple-access scheme, such as TDMA [21].
In this section, we analyze the throughput achievable with our optimized adaptive M-PAM algorithm using OCDMA vs. TDMA. We compare the SINR, modulation constellation size and the bit rate achievable using OCDMA and TDMA. To keep the comparison fair, we assume the OCDMA and TDMA options use the same bandwidth, i.e., the pulse width, $T_c$, for both OCDMA and TDMA is the same, as shown in Fig. 3. For TDMA, if the number of users increases, the symbol rate for each user decreases, since each time slot can only be used by one user at a time. For OCDMA, the symbol rate for each user only depends on the length of the codeword $L$. Thus, we can write the symbol rate $\tilde{R}_s$ and $\bar{R}_s$ using TDMA and OCDMA, respectively, as

$$\tilde{R}_s = \frac{1}{K \cdot T_c}, \quad \bar{R}_s = \frac{1}{L \cdot T_c}.$$  \hspace{1cm} (15)

Therefore, the bit rate for user $k$ using TDMA and OCDMA can be expressed as

$$\tilde{R}_b^{(k)} = \frac{\log_2 \tilde{M}_k}{K \cdot T_c}, \quad \bar{R}_b^{(k)} = \frac{\log_2 \tilde{M}_k}{L \cdot T_c},$$  \hspace{1cm} (16)

where $\tilde{M}_k$ and $\tilde{M}_k$ are the modulation constellation sizes for user $k$ using TDMA and OCDMA, respectively.

To compare the SINR for TDMA and OCDMA, in the following analysis we assume the average transmitted power is $P$, and the channel gain $h$ from the lamp to all users is the same. Then, we can roughly represent the SINR for each user using TDMA as

$$\tilde{\text{SINR}} = \frac{h^2 P^2}{\sigma^2}. $$  \hspace{1cm} (17)

Similarly, the SINR for each user using OCDMA can be roughly represented as

$$\bar{\text{SINR}} = \frac{h^2 P^2 \omega}{(K-1)h^2 P^2 \lambda + \sigma^2 K^2 L}. $$  \hspace{1cm} (18)

where $\lambda$ is the upper-bound on the cross-correlation value for OCDMA codes used, and $\omega$ is the code weight. Note that this expression is a worst case since the MMSE filter would remove much of the MAI.

From (17) and (18), we obtain

$$\frac{\tilde{\text{SINR}}}{\text{SINR}} = \frac{\sigma^2}{(K-1)h^2 P^2 \lambda + \sigma^2 K^2 L}. $$  \hspace{1cm} (19)

Since $K \geq 1$ and $\omega < L$, we conclude $\tilde{\text{SINR}} < \text{SINR}$. In other words, the modulation constellation size for TDMA is greater than or equal to that of OCDMA.

From (16), we see that the bit rate is related to the number of users $K$ and the length of the code $L$ for TDMA and OCDMA, respectively. Comparing the bit rate, we get

$$\frac{\tilde{R}_b}{\bar{R}_b} = \frac{K}{L} \frac{\log_2 \tilde{M}_k}{\log_2 \tilde{M}_k}. $$  \hspace{1cm} (20)

and thus

$$K \geq \frac{\xi \cdot L}{\tilde{M}_k},$$  \hspace{1cm} (21)

Since for both $\tilde{M}_k$ and $\tilde{M}_k$ can be chosen from small values such as $\{2, 4, 8, 16\}$, we can safely assume that $\xi \approx 1$. Therefore, we can conclude that, when the number of users is larger than the length of OCDMA code, the OCDMA technique can offer a higher bit rate than using TDMA. The highest data rate is achieved when the minimum length code needed to support the number of users is chosen.

### V. Numerical Results

In this section, the performance of the proposed adaptive M-PAM algorithm is shown using simulation. To test the applicability of the algorithm in different scenarios, we show results for different users cases in a large indoor environment, i.e., an empty and unfurnished room. Unless otherwise noted, the parameters used to obtain the numerical results are shown in Table I. The OCDMA system uses optical orthogonal codes (OOC) [22]. We assume the users are randomly dispersed in the room. The geometric position of the lamps and users ($K = 40$ case) is shown in Fig. 4.

The shadowing effects are also taken into account in this paper, since it is common for objects such as furniture and pedestrians to partially block the light from an LED lamp. We model the shadowing effect as an optical power loss from the lamp to all users is the same. Therefore, we can conclude that, when the number of users is larger than the length of OCDMA code, the OCDMA technique can offer a higher bit rate than using TDMA. The highest data rate is achieved when the minimum length code needed to support the number of users is chosen.

### TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of room</td>
<td>$12.5 \text{ m} \times 12.5 \text{ m} \times 3 \text{ m}$</td>
</tr>
<tr>
<td>Semiangle of LEDs</td>
<td>$60^\circ$</td>
</tr>
<tr>
<td>Responsivity</td>
<td>$0.5 \text{ A/W}$</td>
</tr>
<tr>
<td>Area of PD</td>
<td>$1 \text{ cm}^2$</td>
</tr>
<tr>
<td>Peak optical power per lamp</td>
<td>$300 \text{ mW}$</td>
</tr>
<tr>
<td>Noise variance</td>
<td>$\sigma^2 = 2 \mu\text{W}$</td>
</tr>
<tr>
<td>Modulation constellation sizes</td>
<td>$2, 4, 8, 16$</td>
</tr>
<tr>
<td>Chip rate</td>
<td>$70 \text{ M-pulses/s}$</td>
</tr>
<tr>
<td>$b_k$</td>
<td>$\leq 10^{-3}$</td>
</tr>
<tr>
<td>OOC code index</td>
<td>$L = 25: {1, 2, 7} {1, 3, 10}$</td>
</tr>
<tr>
<td></td>
<td>${1, 4, 12} {1, 5, 14}$</td>
</tr>
<tr>
<td></td>
<td>$L = 19: {1, 2, 6} {1, 3, 9}$</td>
</tr>
<tr>
<td></td>
<td>${1, 4, 11}$</td>
</tr>
<tr>
<td></td>
<td>$L = 13: {1, 2, 5} {1, 3, 8}$</td>
</tr>
</tbody>
</table>

From (20), we see that the bit rate is related to the number of users $K$ and the length of the code $L$ for TDMA and OCDMA, respectively. Comparing the bit rate, we get

$$\frac{\tilde{R}_b}{\bar{R}_b} = \frac{K}{L} \frac{\log_2 \tilde{M}_k}{\log_2 \tilde{M}_k}.$$  \hspace{1cm} (20)
loss assuming one quarter of all users are suffering from the shadowing effect. The average modulation constellation size for TDMA is uniformly higher than using OCDMA, as expected due to the lower SINR of OCDMA because of the MAI it experiences.

For higher quality communications, a lower desired BER can be used, inevitably leading to a smaller modulation constellation size, as evident from (10). Simulation results in Fig. 6 show the performance for various values of $b_e$. As expected, the algorithm must sacrifice data rate to obtain a better BER performance.

Although Fig. 7 shows that TDMA has a larger modulation constellation size than OCDMA, the throughput also depends on the relation between the bit rate and the symbol rate, given in (12). Numerical results showing the average bit rate using OCDMA and TDMA are given in Fig. 8, and prove that we can obtain a higher bit rate using OCDMA if we choose the best OCDMA code. In this paper, we use OOC codes with length 13, 19 or 25 to support multiple users. These OOC codes can support up to 26, 57 and 100 users, respectively [22]. The results show that the average bit rate for OCDMA is higher than TDMA when the number of users is larger than 15, 20, and 28 when using the length 13, 19 and 25 OOC codes, respectively. We can get a higher bit rate using OCDMA than TDMA by choosing the right OCDMA codes. The highest throughput obtainable for this scenario is labeled ‘OCDMA,
In this work, we use OOC codes as the family of OCDMA spreading sequences. For our algorithm, the optimal codes in the OOC family can be selected to offer the highest bit rate. In practice, other code families can be applied instead.

VI. CONCLUSION

In this paper, we propose an adaptive M-PAM algorithm using OCDMA and MISO techniques to support multiple users. Depending on the SINR at the receivers, the proposed algorithm can choose the optimal power allocation and M-PAM constellation size for the users to optimize the bit rate fairly. It is able to adapt to different shadowing effects and desired BERs. Compared with the same algorithm using TDMA, the proposed algorithm using OCDMA can offer a higher bit rate when the number of users is larger than the length of the OCMDA code.

REFERENCES