Channel Ranking Based Spreading Factor Optimization for Multiuser Visible Light Communication OFDM-IDMA with Parallel Interference Cancellation

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Abstract This paper proposes a channel ranking based spreading factor optimization for orthogonal frequency division multiple interleave division multiple access (OFDM-IDMA) on visible light communication (VLC) systems. VLC is under the global spotlight, since light emitting diode (LED) has recently become a part of building infrastructure and its functionality is quite easy by implementing communication components to LED lighting. To enhance the VLC capability, OFDM-IDMA was previously proposed as a multiple access method. It also employs a spectrum spreading, in which the symbol is orthogonally spread to a specified number of subcarriers. Here, an interleave pattern specific to the transmission signal of each user can improve the separation capacity of the source signal and therefore multiple access becomes possible in VLC-OFDM-IDMA. However, it requires a lower rate error correction code and a large spread factor to limit the throughput performance. To resolve this problem, we introduce a new channel ranking and allocate an appropriate spreading factor to each user according to their channel state. Overall, BER performance and throughput performance can be enhanced by optimising the spread code.

Keywords: visible light communication, OFDM, OVSF code, parallel interference cancellation

1. Introduction

With the recent development of wireless communication technology and the spread of wireless communication devices such as smartphones and tablets, the demand for high-speed and large-capacity communication is growing. However, the current spectrum used for wireless communication is limited and there is an impediment to the development of communication technology. A promising solution is visible light communication (VLC) [1], which is expected to be a new medium of communication. As a specific emitting element, light-emitting diodes (LED) [2] have become a possible candidate because they are widely used as lighting equipment. The use of LEDs is considered an economical and omnipresent communication device. Furthermore, LEDs are safe for the human body and secure because the light cannot penetrate the wall, whereas radio waves do the wall made of wood and gypsum board, etc [3]. Therefore, it can be considered as an advantageous communication technology. In VLC, intensity modulation and direct detection (IM/DD) [4] are used as a method for generating the transmission signal. The intensity of the LED light is modulated by the encoder, and the received signal is converted from optical to electrical signal by the photodiode. In VLC, optical signals transmitted by multiple users are mixed on the receiver side. In order to separate these mixed signals, an appropriate multiple access scheme is required. Typical multiple access methods are time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA) [5][6].

Due to demand for high bandwidth efficiency, orthogonal frequency division multiplex (OFDM) based on interleaved multiple access division (IDMA) [7][8] has been previously proposed. IDMA can help to identify user data even in the field of signal amplitude, like VLC [18] by bit rearrangement models dedicated to each user. The joint application of OFDM and IDMA enables broadband communication [9][10] in VLC; its effectiveness has been clarified [11]. Since signal streams are spatially multiplexed in OFDM-IDMA, it has a limit in the number of capable users. To enhance system capability, parallel interference cancellation (PIC) is also essential [12]. Orthogonal spreading code is auxiliary applied to detect each user’s signal more accurately. It spreads a mapped symbol to a certain number of subcarriers with specified sequence which are orthogonal for every user. We previously disclosed that bit error rate (BER) performance of OFDM-IDMA can be improved in proportion to the increase of the spreading factor whereas the throughput performance
is reduced.

Orthogonal variable spread factor (OVSF) codes are capable of various code lengths with maintained orthogonality. By focusing on this property of OVSF codes, it is possible to improve the throughput of the system by optimizing the spread factor by maintaining the BER features. In order to achieve the above objective, this paper newly proposes a channel ranking based spreading factor optimization for VLC-OFDM-IDMA incorporating PIC [13]. The short spread factor is given to users in a good channel gain. Conversely, a large one is assigned to them in a weak channel gain. This paper expands the content of the conference paper [13] by examining a wider variety of propagation factors and we find that system throughput and BER performance can be improved. Interference cancellation based CDMA for multiuser detection with OVSF codes and channel ranking concepts were widely investigated in wireless and optical communication fields [14][15][16]. IM/DD merely deals with the amplitude of a signal. Phase and IQ modulations cannot be applied to the VLC unlike traditional wireless communication. It limits the application of spatial multiplexing approaches such as multiple output multiple entries (MIMO). Therefore, in IM/DD, signal multiplexing in the power domain is the possible approach to enhance the capability of the system under the limited spectral resource; CDMA is considered the promising solution [17]. To further improve interference mitigation performance (user separation), we used nonorthogonal techniques like IDMA and PIC. This paper discloses the unprecedented impact of incorporating the above technologies into VLC.

The rest of this paper is organized as follows. Section II describes the system model of VLC with LEDs, OFDM, IDMA, and interference cancellation, respectively. The proposed scheme is explained in Section III. Section IV presents the simulation results. Section V provides the conclusion of this paper.

2. System Model

2.1 Transmitter

The transmitter structure of the multiuser VLC-OFDM-IDMA system is shown in Fig. 1. Interleaving is performed after the forward error correction (FEC) code. Different interleaving patterns are applied per user to attain the signal separation for IDMA. After interleaving, OFDM modulation is performed using a quadrature phase shift keying (QPSK) symbol mapping. In VLC, since the propagation medium of information between the transmitter and the receiver is a visible light, the transceiver needs to make the signals only in the amplitude domain. After that, the transmit signal is generated by applying a bias current before LED input. The symbol of the \( u \)-th user \( X_u(k) \) \((k \in [0, 1, \cdots, N_c - 1], N_c \) is the number of subcarriers) generated by the QPSK mapping is converted to the time-domain signal sequence via inverse fast Fourier transform (IFFT) through a parallel-to-serial (P/S) conversion. Here, frequency-domain symbol sequence is rearranged according to the following conditions (also, see Fig. 2) to obtain the real-valued time-domain signals for intensity modulation (IM) as,

\[
X_u(2N_c - k) = X_u(k) \\
X_u(0) = X_u(N_c) = 0
\]

The output signal after IFFT is expressed by

\[
s_u(t) = \sum_{k=0}^{2N_c-1} X_u(k)e^{j2\pi(kt)/2N_c}
\]

where \( s_u(t) \) is a time-domain OFDM symbol which has only real values suitable for IM. The guard interval is inserted to the head of the OFDM symbol to prevent inter-symbol interference (ISI).

Figure 3 shows the circuit to drive the LED. The signal after OFDM modulation is converted to the current and the bias current is added in the electronic circuit. The generated current is used as a drive current of the LED. LEDs have the nonlinear characteristics. Details are explained in the next subsection.

2.2 Electric-optical domain interface

LEDs have a nonlinearity between input current and output power. The input current to the output power is defined as,

\[
P_{out}(t) = c_0 + c_1I_m(t) + c_2I_m^2(t)
\]

where \( c_0 = \beta, c_1 = 1, c_2 = -4\beta + 2 \), and \( \beta \) are parameters representing nonlinearity depending on various LEDs.
as shown in Table 1 [2]. The red LED has the strongest nonlinear characteristic while the white LED exhibits an almost linear one.

### 2.3 Receiver

The receiver structure is shown in Fig. 4. At the receiver, the optical signal is converted to current values by the photodetector. The OFDM demodulator removes the guard interval from the time-domain received signal to remove the ISI impact. FFT is then performed and channel estimation for each user is performed. This paper assumes the perfect knowledge of channel state information (CSI). After the channel estimation, expanded frames in the frequency-domain are converted to the original ones and (P/S) conversion is performed. The received symbol \( R(k) \) at the \( k \)-th subcarrier is given by,

\[
R(k) = \sum_{\ell=1}^{U} H_{\ell}(k) X_{\ell}(k) + n(k) \tag{5}
\]

where \( U \) is the number of users, \( H_{\ell}(k) \) is the channel coefficient of the \( k \)-th subcarrier and the \( \ell \)-th user. \( n(k) \) represents an additive white Gaussian noise (AWGN). Focusing on the \( u \)-th user, (5) can be rewritten as,

\[
R(k) = H_u(k)X_u(k) + \sum_{\ell \neq u} H_{\ell}(k)X_{\ell}(k) + n(k)
\]

\[
= H_u(k)X_u(k) + \zeta(k) \tag{6}
\]

where \( \zeta(k) \) represents an interference component called multiple access interference (MAI). MAI should be removed by the interference cancellation.

\[
\hat{X}_u(k) = \frac{R(k)}{H_u(k)} = X_u(k) + \frac{\zeta(k)}{H_u(k)}
\]

\[
= X_u(k) + \hat{\zeta}_u(k) \tag{7}
\]

Through the QPSK demapping, deinterleaving and decoding, transmitted bit sequence of the \( u \)-th user is recovered. However, (7) still contains MAI components. Symbol estimation accuracy can be improved by an iterative operation of PIC. The RGU is replica signal generation unit. Through re-encoding, interleaving and QPSK mapping, replica symbols \( \hat{X}(k) \) are regenerated by the RGU. After multiplying CSI, the interference replica signal can be obtained by superposing that for interfering users.

\[
\tilde{R}(k) = \sum_{\ell=1}^{U} H_{\ell}(k)\hat{X}_\ell(k) = H_u(k)\hat{X}_u(k) + \hat{\zeta}(k) \tag{8}
\]

Figure 5 depicts a schematic flow of the PIC to suppress MAI [19]. First, the received signal is individually equalized by CSI of each user. The obtained signal for the \( u \)-th user can be expressed as follows,
Symbol estimation is performed again by using CSI of each user as,

\[
\hat{X}_u = \frac{\hat{R}(k)}{\hat{H}_u(k)} = \hat{X}_u(k) + \frac{\hat{z}_u(k)}{\hat{H}_u(k)} = \hat{X}_u(k) + \tilde{\zeta}_u(k) \tag{9}
\]

Given the estimated symbol as \(\hat{X}_u(k)\), the difference between the two symbols can be calculated by

\[
\Delta X_u(k) = \hat{X}_u(k) - \tilde{X}_u(k) \tag{10}
\]

Received symbol is updated by using this difference component for the subsequent PIC step as,

\[
X_u(k) = \Delta X_u(k) + \hat{X}_u(k) \tag{11}
\]

Through the above series of processes, the detection accuracy of received signal can be gradually improved. As the number of users increases, the effect of the MAI term increases. FEC and orthogonal spreading code can improve the symbol estimation accuracy. However, these methods degrade the throughput performance due to their nonnegligible overheads. This study focuses on the spreading factor of the orthogonal codes and examines its optimization with observing the channel gain.

3. Proposed Scheme

3.1 Orthogonal variable spreading code

In the conventional scheme, the spreading code length was fixed to 8 [12]. The proposed scheme newly introduces the spreading factor of 4 and 16 to improve the system throughput performance as well as maintaining the BER performance. The generation diagram of OVSF codes is shown in Fig. 6 [20][21]. OVSF codes have a tree structure in which \(c(i, j)\) represents the \(j\)-th code of the \(i\)-th layer. OVSF codes are orthogonal to each other even with different spreading factors [22][23]. Let the number of information data bits and the spreading factor denote \(N_b\) and \(f\), respectively. The number of transmission bit length \(N_b\) is \(C = N_b \times f\). If \(f\) is halved, \(N_b\) becomes \(R \times f/2\); the information data bits can be increased to \(2N_b\) when transmitting the same frame length. We can increase the number of data bits by shortening the spreading factor. In contrast, the number of data bits is decreased when \(N\) is doubled, but the BER performance can be improved thanks to improved signal detection capability. Orthogonality is ensured only if the code assigned to each user is not on the path of the same route. Fig. 7 exemplifies a case in which codes \(c(3, 2), c(4, 1),\) and \(c(4, 7)\) are assigned. The codes \(c(2, 1), c(2, 2), c(3, 1),\) and \(c(3, 4)\) cannot be assigned to other users. In contrast, the codes \(c(3, 3), c(4, 2),\) and \(c(4, 8)\), etc. can be assigned. Priority can be given when the code length is shortened. However, the number of users is limited. Use of the large spreading factor reduces user restrictions [24][25]. The application of OVSF facilitates multiplexed signal separation because the cross-correlation between the symbols for different users is sufficiently low; the desired signal can be extracted without MAI [26][27]. However, CSI estimation error and the Doppler shift break its orthogonality and cause residual MAI components which should be eliminated by PIC.

3.2 Channel ranking

Orthogonal spreading codes can reduce the influence of MAI as the spreading factor becomes large, but there exists a trade-off between the MAI suppression capability and the achievable throughput performance [28]. This paper additionally introduces a channel ranking to prevent BER characteristics degradation from the use of shortened spreading factor, in order to enhance the system throughput performance. Its concept is drawn in Fig. 8. The key feature of our proposal is to shorten the spreading factor of users who experienced the larger channel gain, i.e. the less impact of MAI. On the other hand, enlarge the spreading factor of users who experienced the smaller channel
gain, i.e. strongly affected by MAI. Based on estimated CSI, these path gains are calculated and sorted in descending order. Here, we allocate short spreading factor (4 in this study) to the user having the larger channel gain, and large spreading factors (16) are allocated to the user having the smaller channel gain. The achievable throughput value of the better user can be doubled and thus overall throughput performance is expected to be enhanced. BER performance of the worst user can be improved. Therefore, overall system performance can be optimized.

4. Computer Simulation

4.1 Simulation parameters

Simulation parameters are shown in Table 2. This evaluation assumes the ideally linear characteristic of LED. The proposed method compares by assigning the different spreading factors as 4, 8 and 16, as described above. The number of terminal bits for the convolutional code is 64, hence the numbers of input data bits become 124, 376, and 880 for spreading factors of 16, 8, 4, respectively. The interleaver type is random and the simulation deploys 5 users. Static 3 path Rayleigh fading channel is assumed and is spatially uncorrelated among users [18]. Such multipath channel can be consistent even in the VLC systems assuming indoor scenario [29][30][31]. Perfect knowledge of channel state at the receiver is also assumed. Evaluations metrics are BER and throughput. As for the throughput calculation, 64 data symbols are regarded as one packet.

4.2 Simulation results

First, effectiveness of the channel ranking is disclosed. Figures 9, 10, and 11 show per user BER, average BER, and throughput performances, respectively. Figure 9 plots the BER performances of each user with ranking and that of average for all 5 users. Figure 10 shows comparison of average BER performances with and without channel ranking. In the proposed scheme, the spreading factor of 4 is assigned to one of the users who has the largest channel gain and 8 for remaining users. Even by shortening the spreading factor, BER performance of the best channel gain user is the best. Then BER characteristics of other users tend to deteriorate according to the order of ranking. Assigning a large spreading factor can compensate for the worst channel gain user. It will be presented in detail in the following evaluation. From Fig. 10, the proposed scheme achieves the best average BER performance. It can outperform the case where the long spreading factor $f = 8$ is used for all 5 users. As for the sum-throughput performance as shown in Fig. 11, it can be confirmed that higher throughput performance can be attained at a lower region of energy per bit to noise power spectral density ratio ($E_b/N_0$). As seen by the per-user-performance, its improvement is remarkable with the channel ranking. Following evaluation focuses on the average BER and sum-throughput performances, respectively.

Figures 12 and 13 present the comparison of average BER and sum-throughput performances to verify the effectiveness of the proposed scheme by optimizing spreading factors. In the conventional scheme, the spreading factor is fixed to 8 for all 5 users.

Here we examined five cases for channel ranking based spreading factor allocation in addition to the following case A [13];

A) $f = 4$ for the best channel gain user, $f = 8$ for remaining 4 users

B) $f = 4$ for the best channel gain user, $f = 8$ for 3 users, and $f = 16$ for the worst channel gain user

C) $f = 4$ for the best channel gain user, $f = 8$ for 2 users, and $f = 16$ for the worst channel gain 2 users

| Table 2 | Simulation parameters |
|---------|-----------------------|
| Transmission scheme | VLC-OFDM |
| Modulation | QPSK |
| Transmission bandwidth | 20 MHz |
| Number of subcarriers | 128 |
| FFT size | 128 |
| Guard Interval | 16 |
| Number of pilot symbols | 2 |
| Number of data symbols | 64 |
| Number of multipaths | 3 |
| Number of users | 5 |
| Number of PIC iterations | 2 |
| Error correction code | Convolutional code, rate 1/2 |
| Spreading factor | 4, 8, 16 |
| Input data bits | 880, 376, 124 |
| Interleaver type | Random |
Fig. 9 BER performances per user and 5 users averaged

Fig. 10 BER performances averaged

Fig. 11 Throughput performances per user and 5 users total

Fig. 12 Average BER performances with various spreading factor assignment cases for A, B and C

D) \( f = 4 \) for the best channel gain 2 users, \( f = 8 \) for 1 user, and \( f = 16 \) for the worst channel gain 2 users

E) \( f = 4 \) for the best channel gain 2 users, \( f = 16 \) for remaining 3 users

From Fig. 12, the BER performance of the case A has deteriorated by about 1.5 dB at the BER\(= 10^{-4} \), compared to the conventional scheme. Shortening the spreading factor is more susceptible to MAI than conventional one. It degrades the signal detection accuracy for the best channel gain user and is affected to overall BER performance. With the cases for B and C, which introduced spreading factor of 16 for the worst channel gain, can compensate such impact and improve BER performances by about 1.2 dB and 1.9 dB, respectively.

Observing Fig. 13, the case A can achieve the highest system throughput performance and it is 30% higher than the conventional case. It is because the combination of spreading factors is smallest in the case A. It should be noted that the improvement of the throughput is more than theoretical due to the terminal bit insertion. Halved
spreading factor surely contributed to raising the overall throughput value.

In case B, introducing the spreading factor of 16 reduces the system throughput performance but it is still better than the conventional case than 15%. Further, as described above, the case B is advantageous in terms of BER performance. When increasing the 16 spreading factor users to 2 (the case C), the maximum system throughput performance is equivalent to the conventional case. This case also provides good BER performance and hence the higher throughput can be obtained at lower Eb/No region. Figures 14 and 15 plot the results to compare the cases D and E, i.e. the spreading factor of 4 is assigned to 2 users according to the proposed channel ranking. The result for BER performance is equivalent (the Case D) or slightly improved by 1.0 dB (the Case E) compared to the conventional case. It is dependent on the number of users with a spreading factor of 16. As for the total system throughput performance shown in Fig. 15, the case D can achieve the highest value as same as the case A. Moreover, increase of the throughput value with Eb/No can be improved better than the Case A. In the Case E, sum-throughput can also be improved by about 15% and its increase is more rapid than the conventional case. Introducing large spreading factor such as \( f = 16 \) is more robust to detect the received signal in an accurate manner. It contributes to ensure good BER performance even in increasing shortened spreading factor users.

Although the respective throughput performance is distributed among users, overall system performance can be optimized by using the proposed approach. In VLC, the channel gain through which each user passes is considered to have a large impact on its ranking and spreading factor assignment. Since the channel environment in this evaluation has a Rayleigh distribution, there is a difference of about 10 dB gains depending on the situation. From Figs 12 to 15, cases D and E in the proposed scheme can be improved in terms of both BER and throughput characteristics compared to the conventional one. This results indicates that the effectiveness of applying variable spreading factors in a relative manner. Furthermore, the finding obtained in this study is that the combination of spreading factors that maximizes sum-throughput can be determined depending on Eb/No conditions. We can conclude that overall multiple access schemes including our proposal, i.e. OFDM-IDMA with channel ranking based spreading factor determination on PIC, could be one of the most effective solutions for spectrally efficient VLC.
means. Meanwhile, the combination of spreading factor is fixed in this paper. If the optimal spreading factor can be dynamically allocated according to the respective channel gain of individual users, further performance improvement can be expected. It should be investigated as our future work.

5. Conclusion

This paper proposed the channel ranking based orthogonal spreading factor optimization for VLC-OFDM-IDMA system with PIC, in order to improve the system throughput performance while maintaining the BER performance. Small spreading factor is assigned to the user who experienced the larger channel gain and vice versa. The proposed approach can realize balanced signal detection accuracy for PIC with minimizing overall spreading factors. Computer simulation verified that the proposed scheme improved throughput and BER performances compared to the case where a fixed spreading factor is assigned to all users. Future work includes to enhance our scheme such that dynamic spreading factor assignment according to the fluctuation of channel and more flexible adaptive modulation and coding.

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