Journal of Engineering and Applied Sciences 13 (Special Issue 6): 5258-5265, 2018
ISSN: 1816-949X

Multi-Rate Optical CDMA System Using OVSF Codes for Visible Light Communication in Diffuse Channel

[1]Kyuntak Kim, [2]Kyujin Lee and [1]Kyesan Lee
[1]Department of Electronic and Radio Engineering, Kyung Hee University,
1732 Deogyeong-daero Giheung-gu, Yongin-si, 17104 Gyeonggi-do, Korea
[2]Department of Electronic Engineering, Semyung University,
65 Semyung-ro, Jecheon, 27136 Chungbuk, Korea

Abstract: This study proposes a multi-rate Optical Code Division Multiple Access (OCDMA) downlink system in Visible Light Communication (VLC) based on Orthogonal Variable Spreading Factor (OVSF) codes in indoor diffuse channel. In a realistic indoor environment, there are many reflected light waves due to walls or obstacles, and that is cause by Inter-Symbol Interference (ISI) owing to multipath dispersion. This channel model is referred to as diffuse channel. Impulse responses of the diffuse channel depend on Root Mean Square (RMS) delay spread values, so, the adaptive multi-rate transmission systems are required according to channel states. OCDMA system is an attracting attention as one of the promising multiple access technologies in VLC because entire asynchronous optical channel can be shared simultaneously between multiple users. Furthermore, transmission capacity can be improved by using the specific orthogonal spread codes assigned to each user. Based on these characteristics in order to support a variety of transmission data rates in accordance with the RMS delay spread values, the OVSF codes are adopted to an OCDMA system. A mainly feature of the OVSF codes are able to ensure orthogonality between different lengths of spreading code sets. Therefore, the orthogonal codes which have different Spreading Factor (SF), (i.e., length of spread codes) can be allocated to users according to channel states. Our proposed system can improve the total through put of the downlink VLC system by allocating the spreading codes with appropriate length according to the RMS delay spread values.

Key words: Optical code division multiple access, downlink visible light communication, white LED lighting, orthogonal variable spreading factor, throughput, direct-sequence spread spectrum

INTRODUCTION

Recently, devices using wireless communication are increasing rapidly as IoT service is activated in various social fields. As a result of that, the exhaustion of frequency resource caused by rapidly growing data traffic is discussed on a major issue. In order to solve such a problem, it is expected that a variety of different communication systems will be combined into one network in the next generation wireless communication (Lee *et al*., 2016).

Among various candidate technologies, VLC using white LED is an attracting attention from industry and academia to provide a personal area wireless communication service in indoor environment. VLC can provide both communication services and lighting functions simultaneously. Furthermore, optical signals of VLC are not subject to electromagnetic interference, because the optical spectrum is not overlapped with the radio frequency spectrum (Kim and Lee, 2016; Karunatilaka *et al*., 2015). Therefore, the VLC systems are free from radio frequency regulations because it do not use the radio frequency resources.

Nevertheless, more research is needed on several challenge problems for practical implement of VLC systems. Among them, one of challenge problems is a study on effective multiple access techniques because future wireless optical communication networks will be expected to require broadband access technology in order to simultaneously provide various information services to a large number of users. OCDMA is attracting attention as one of the influential multiple access technologies in VLC (Salehi, 2007; Stok and Sargent, 2002) because entire asynchronous optical channel can be shared simultaneously between multiple users. In other words, OCDMA can achieve a low transmission delay because

---

Corresponding Author: Kyujin Lee, Department of Electronic Engineering, Semyung University,
65 Semyungro, Jecheon, 27136, Chungbuk, Korea

there is no waiting time for data transmission. Furthermore, transmission capacity can be improved by using the specific orthogonal spread codes assigned to each user. These OCDMA systems are referred to as incoherent OCDMA systems. The incoherent OCDMA techniques can be mainly classified into 3 types which are 2-D coding, spectral-amplitude coding and time spreading (Prucnal, 2005; Shah, 2003). Among these techniques, time spread OCDMA systems using Direct Sequence Spread Spectrum (DSSS) scheme are widely used in VLC because those systems can be simply implemented based on Intensity Modulation (IM). For these reasons this study will be only considered about time spread OCDMA system.

Meanwhile, in a realistic indoor environment, there are many reflected light waves due to walls or obstacles and that leads to Inter-Symbol Interference (ISI) caused by multipath dispersion (Saadi *et al*., 2013). Multipath dispersion means the effect of ISI due to time delay between received optical signals which are reflected through different paths and these transmission environment is referred to as diffuse channels. Achievable Bit Error Rate (BER) and throughput performance in the diffuse channels is a much reduced compared with an LOS channel. Fortunately, the multipath dispersion effect can be significantly mitigated using the DSSS scheme of the OCDMA system. By Yi *et al*. (2013), Shi and Ghafouri-Shiraz (2016), the BER performance of OCDMA was evaluated according to several spread code types. However, these earlier studies did not consider techniques to support a variety of transmission data rates depending on traffic requirements or channel state conditions. Also, impulse response of the diffuse channel depends on Root Mean Square (RMS) delay spread values so, it is essential to study on technique for supporting the multi-rate transmission systems according to channel states.

In order to support a variety of transmission data rates, this study proposes a multi-rate OCDMA system applying OVSF codes. A mainly feature of the OVSF codes are able to ensure orthogonality between different lengths of spreading code sets (Liu and Adachi, 2006). Therefore, the orthogonal codes with the different Spreading Factor (SF) (i.e., length of spread codes) can be assigned to users in accordance with the required throughput levels when OVSF codes are applied to the OCDMA system. We analyze effects according to the RMS delay spread values in the diffuse channel and then the throughput performance of the proposed system which is allocated by orthogonal codes with different spreading factor according to various RMS delay spread values. The simulation results substantiate that the throughput of our proposed system can be enhanced compared with the conventional OCDMA systems with the equal SF codes applied.

MATERIALS AND METHODS

Design of multi-rate OCDMA system

Conventional OCDMA system architecture: Figure 1 and 2 illustrate the block diagrams of the OCDMA transmitter and receiver architectures and our proposed system is applied to a white LED lighting composed of red, green and blue three sub-LED devices. First, at the transmitter, the binary input data of each user are de-multiplexed and entered in to each sub-LED device. In each of the three sub-LED device, the binary input data are modulated by Binary Phase Shift Keying (BPSK) because the modulated signal in the optical systems should be expressed as the real-values. For this reason, the BPSK modulation among several M-PSK modulation schemes is applied to the proposed system. Then, the modulated symbols of each user are spread in the time domain by DSSS where to design the multi-rate systems with DSSS, more details will be described in next sub-section. The spreading chip sequences of each user are combined by summation and then the signal normalization process is conducted. Finally, to remove the negative values of the combined signals, DC offset with a certain level is added to them, and the optical signals after performing intensity modulation are emitted to the receivers.

At the receiver of user 1, the received optical signals in each wavelength are changed into the electrical signals by a PhotoDiode (PD) and then the DC offset added at the transmitter is eliminated. Then, the de-spreading process is performed by the cross correlation operation which is multiplying total received signal by the orthogonal spreading codes of user 1. Through, this de-spreading process, the time domain chip sequences are converted into symbols. Finally, those symbols can detect binary information data by the demodulation process.

Proposed multi-rate OCDMA system: In order to design a multi-rate OCDMA system, the OVSF codes are adopted to our proposed system as mentioned earlier. The OVSF code sets are able to be represented by a code tree and since, the creation method of the OVSF code tree has already been introduced in many literatures such as (Tseng and Chao, 2002; Hasegawa *et al*., 2007), this study omits the details of that. One of the main characteristics when the OVSF code sets were created is that there is a parent-child relationship between the code sets in the same branch and the orthogonality between the OVSF code sets with a parent-child relationship at the same

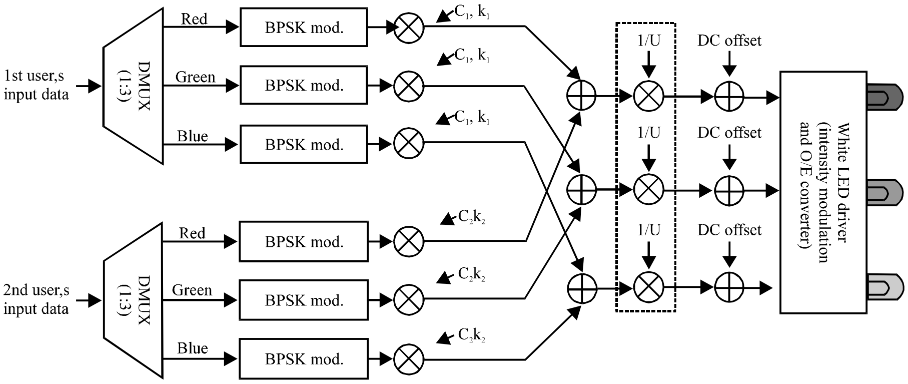

Fig. 1: OCDMA transmitter structure of two users based on white LED lighting

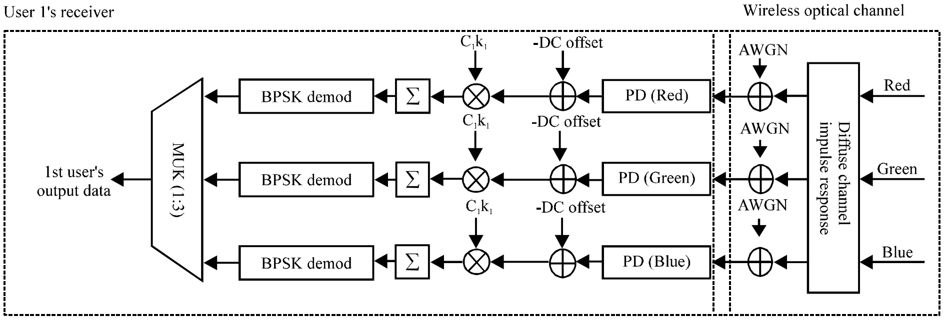

Fig. 2: OCDMA receiver structure of user 1

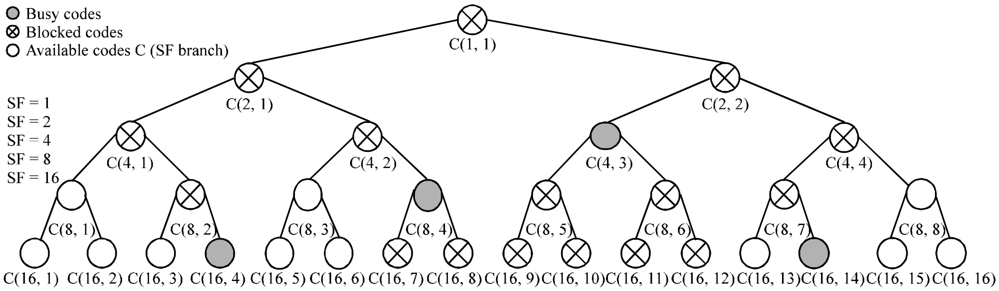

Fig. 3: An example of OVSF code allocation scenario for four users

branch cannot be guaranteed. Therefore, the OVSF code sets of different branch should be assigned to users. Figure 3 illustrates an example of code assignment scenario in the OVSF code tree. Through, these characteristics of the OVSF codes, we can design the multi-rate OCDMA system. Figure 4 illustrates the pulse waveforms modulated by OOK of the chips in which the BPSK symbols of 1 and -1 are spread according to the OVSF code sets selected in Fig. 3.

In Fig. 4 T_c and T_b denote a chip duration and a bit duration, respectively. As shown in Fig. 4, the multi-rate of our proposed system can be determined in accordance with the length of the spreading codes assigned to each user because the chip rate is equal to each other in order to ensure the orthogonality between the OVSF codes assigned to each user.

As mentioned earlier, the transmission symbols of spread chip data in each sub-LED device can be recovered via. the cross correlation operation which is represented as follows:

$$\tilde{S}_{w,u,n_u} = \left\langle \vec{r}_{w,u,nu} \vec{C}_u \right\rangle \quad (1)$$

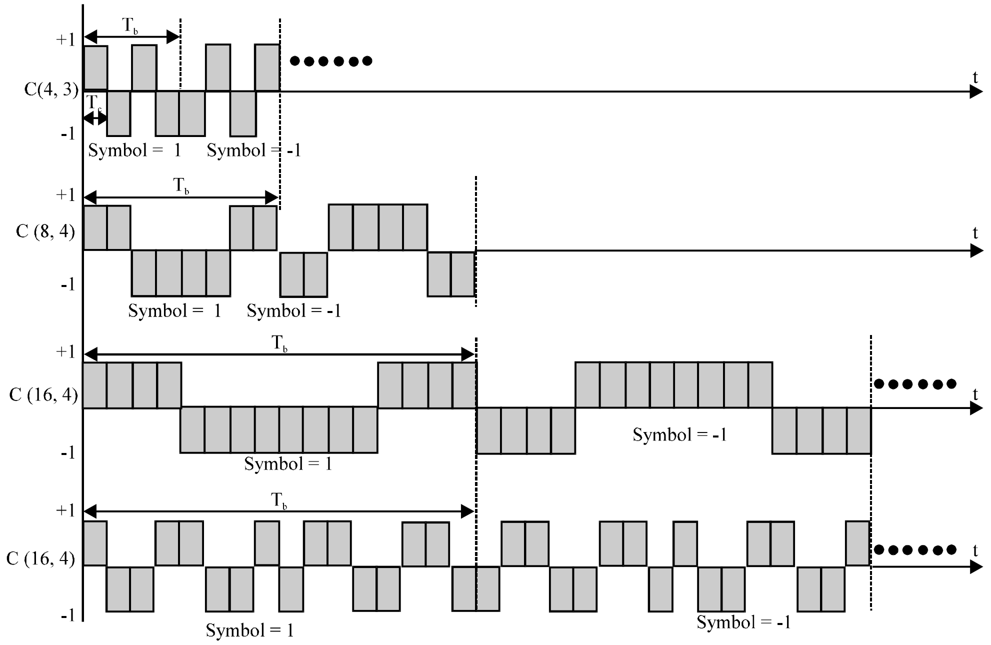

Fig. 4: An example of the spread chip pulse waveforms modulated by OOK according to the OVSF code sets selected in Fig. 3

Where, (.) is the inner-product operation. $S_{w,u,nu}$ is the recovered n-th transmission symbol of the u-th user. w means the sub-LED devices of red, green and blue wavelength. $\vec{r}_{w,u,nu}$ means the n-th received symbol of the u-th user which is consisted of spread chips and denoted by:

$$\vec{r}_{w,\,u,\,n_u} = [r_{w,\,u,\,n_u},1, r_{w,\,u,\,n_u},\ 2,\ldots, r_{w,\,u,\,n_u} SF_u] \tag{2}$$

Where, Sf_u denotes the length of spreading codes allocated to the u-th user. The kth received chip of the u-th user's nth symbol, $r_{w,\,u,\,nu,\,ku}$ can be derived as follows:

$$\begin{aligned} r_{w,\,u,\,n_u,\,k_u} &= y_{w,\,u,\,n_u,\,k_u} + V_{w,\,u,\,n_u,\,k_u} \\ &= y_w X_{w,\,n_u,\,k_u} \otimes h_{e,\,u}(n_u, k_u, \tau) + V_{w,\,u,\,n_u,\,k_u} S \end{aligned} \tag{3}$$

Where, yw and ⊗ mean the O/E (Optical to Electrical) conversion efficiency of each sub-LED device and the convolution operation, respectively. The multiple access transmission signal can be obtained by combining the spreading data of all users and the k-th chip of the η-th symbol on the basis of the u -th user about that can be denoted by X_{w}, n_u, k_u. Also, $h_{e,u}$ (n_u, $k_u\tau$) and $V_{w,u,nu}$, k_u are the diffuse channel impulse responses and adaptive white Gaussian noise of the u-th user where the details of the diffuse channel impulse responses will be discussed in the next section. In Eq. 1 $\vec{c}u$ is the OVSF codes of the u-th user and it can be denoted by:

$$\vec{C}u = [cu_1, c_{u,\,2}, \ldots, c_u, SF_u] \tag{4}$$

Through Eq. of 2-4, Eq. 1 can be rewritten as follows:

$$\tilde{S}_{w,u,n_u} = \left\langle \vec{r}_{w,u,n_u} \right\rangle = \sum_{k_u=1}^{SF_u} C_u, k_u y_{w,u,n_u,k_u} + \sum_{k=1}^{SF_u} C_u, k_u V_{w,u,n_u,k_u} \tag{5}$$

The aim of the proposed system is to improve the throughput of the entire networks by allocating spreading codes with different lengths according to the channel conditions of each user. In a realistic indoor environment, there are many reflected optical rays due to walls or obstacles and these optical rays lead to the multipath dispersion. This channel is generally referred to as a diffuse channel and the details about characteristics of that and impact on throughput performance will be described with numerical analysis in the next study.

Analysis of diffuse channel: Figure 5 illustrates a simple example of a diffuse channel model that can be generated in an indoor environment.

As shown in Fig. 5, there are the multipath transmission links including Line of Sight (LOS) and Non-Line of Sight (NLOS) links between the transmitter

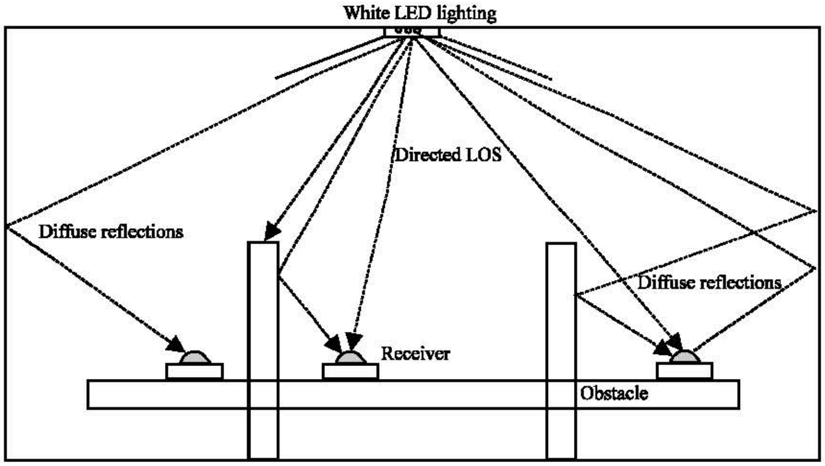

Fig. 5: An example of the diffuse channel model in the indoor environment

and the receivers. At the receiver, the incident optical signals can be divided according to the number of reflection order by surfaces of walls or obstacles and this causes the multipath dispersion in time domain (Pakravan and Kavehrad, 2011). In general, the received power of the incident optical signals is reduced when the number of bounces were increased. This is because the reflectance of each surface is smaller than one (Barry *et al*., 1993). In addition, the reflected optical signals via the multipath transmission links have different arrival times compared to the optical signal which is transmitted via. a LOS transmission link. Based on those characteristics, amplitudes of the diffuse channel impulse responses can be expressed as delta function sequences of geometrically decay. In the proposed VLC-OCDMA system, these sequences of the u-th user can be measured by the exponential decay model (Carruthers and Kahn, 1997) which is expressed as follows:

$$h_{e,u}(n_u k_u, \tau) = \frac{1}{\tau}\exp\left(\frac{-n_u k_u}{\tau}\right) \tag{5}$$

$$u(n_u k_u),\ \text{for } n_u k_u = 1, 2, ..., L_{u,p}$$

In Eq. 6 $L_{u,v}$ is the lengths of the u-th user's packet, and it is able to be define as $_{Lu,v} = L_{u,s} \times SF_u$ where $I_{u,s}$ is the symbol lengths of the u-th user. Also τ is a decay constant which is derived by:

$$\pi = \frac{2\tau_{RMS}}{T} \tag{7}$$

where, T denotes a sampling period. In our proposed system, white LED composed of 3 LED devices (i.e., red, green and blue LED devices) is applied, so, the chip rate in each LED device is $R_c/3$ where R_c denotes the total chip rate. Also, when the number of samples per chip denotes M_b, T can be defined as follows:

$$T = \frac{3}{R_c M_c} \tag{8}$$

In Eq. 7 the RMS delay spread, τ_{RMS}, can be expressed as follows 17:

$$\tau_{RMS} = \sqrt{\frac{1}{P_T}\sum_{i=0}^{Mp} P_i \tau_i^2 - \tau_0^2} \tag{9}$$

Where:

P_T = The total received optical power
P_i = The received optical power from i-th transmission path
τ_i = The delay time of i-th path's received optical signal compared to the first arriving optical signal
τ_0 = The average delay time which is given as follows:

$$\tau_0 = \frac{1}{P_T}\sum_{i=0}^{M_p} P_i \tau_i \tag{10}$$

From Eq. 6-10 we can demonstrate that the amplitude sequences of diffuse channel impulse responses are reduced when the RMS delay spread values were increased. Therefore, the throughput can be degraded because the channel DC gain which is defined as is reduced:

$$G_u = \sum_{n_u k_u} h_{e,u}(n_u k_u, \tau)$$

In the proposed system, the achievable throughput of the u-th user can be defined as and can be expressed by:

$$R_u = \sum_w R_{u,w}$$

$$R_{u,w} = B_w \log_2\left(1+\frac{y_w{}^2 P K_w G_u{}^2}{\wedge_{u,w}+N_{0,w}B_w}\right) \qquad (11)$$

Where:

B_w, K_w and $N_{0,w}$ = The transmission bandwidth, the mixture ratios and the noise power spectral density of each color wavelength, respectively

P = The average transmitted power

$\wedge_{u,w}$ = Multiple Access Interference (MAI) of each color wavelength from u-th user

RESULTS AND DISCUSSION

We use computer simulations to appraise the throughput performance of our proposed system. Four types of specifications regarding the mixture ratios and O/E conversion efficiencies on each sub-LED chip of a white LED lighting were proposed (Yuichi *et al*., 2004). Among them, the second type is adopted to our simulations because the difference of the mixture ratios between sub-LED chips is the smallest and this characteristic makes it possible to achieve the BEST performance in terms of BER. Also, the spread chip rate is 800Mcps and the range of SF can be variably selected from 0-32. The main simulation parameters are summarized in Table 1.

The results of Fig. 6 and 7 show the impulse response and DC gain of the diffuse channel according to the several RMS delay spread values. From these results, we can demonstrate that the channel DC gain is reduced, when the RMS delay spread was increased. Therefore, an adaptive multi-rate transmission system according to the RMS delay spread values is required in the down link VLC systems.

The results from Fig. 8 and 9 show the BER performance of the entire down link network, when the number of users was set to 3 and 4, respectively. Then, Fig. 10 shows the throughput performance of the proposed systems and the conventional systems. In those simulation results, the RMS delay spread conditions for users are assumed to be 1-4 nsec, respectively. Correspondingly for those conditions, the SF conditions of user 1-4 are set to 4, 8, 16 and 32. Also, the conventional system means that the spreading codes with the same SF are allocated to users regardless of the channel conditions. The BER of our proposed systems is degraded compared with the conventional system with the maximum SF conditions (i.e., SF = 16 and 32) as shown in Fig. 8 and 9. However, the throughput of the proposed systems can be improved as compared with the

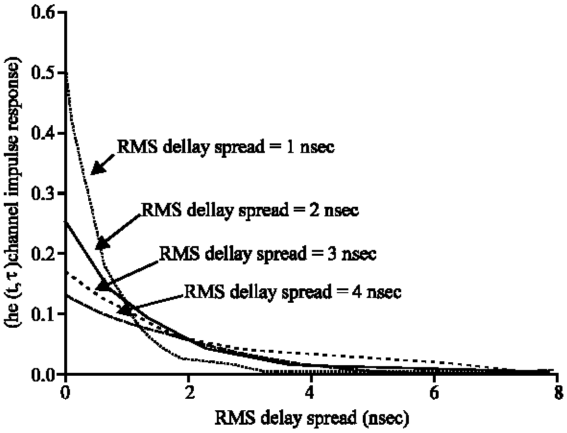

Fig. 6: Impulse responses of the diffuse channel according to the several RMS delay spread conditions

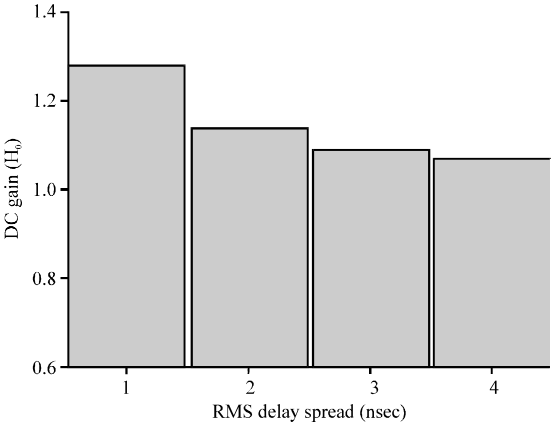

Fig. 7: The diffuse channel DC gains according to the several RMS delay spread conditions

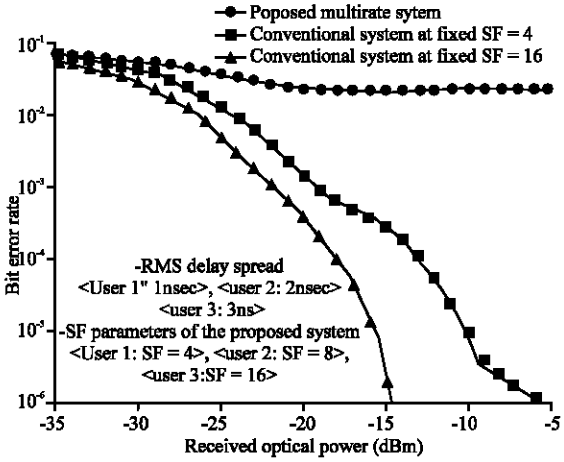

Fig. 8: BER performance comparison of the entire network for the proposed multi-rate OCDMA versus fixed rate OCDMA for three users

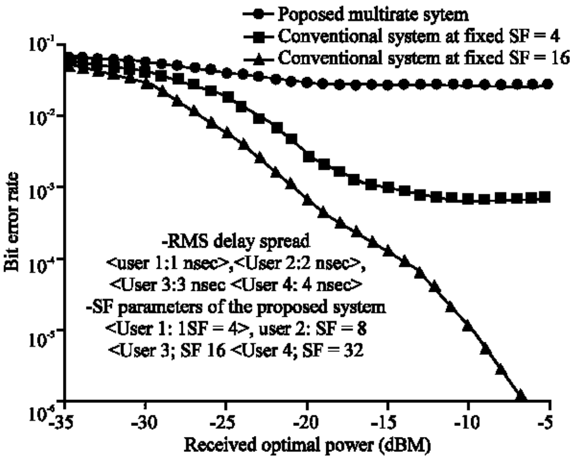

Fig. 9: BER performance comparison of the entire network for the proposed multi-rate OCDMA versus fixed rate OCDMA for four users

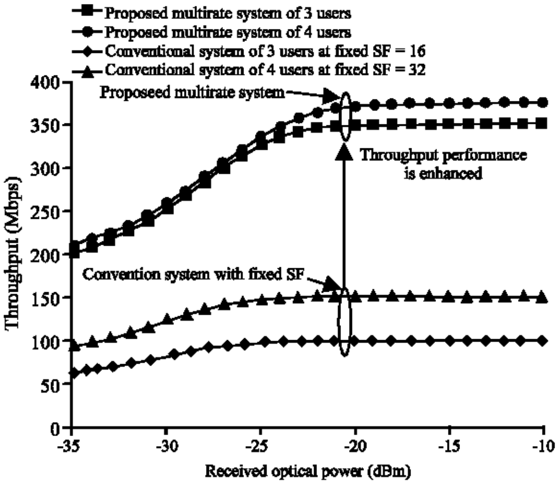

Fig. 10: Throughput performance comparison of the entire network for the proposed multi-rate OCDMA versus fixed rate OCDMA

Table 1: Simulation parameters equations

Mixture ratios	$K_{red} = 1$, $K_{green} = 0.89$, $K_{blue,} = 2.51$
O/E conversion efficiencies (mW)	$Y_{red} = 0.52$, $y_{green} = 0.50$ $y_{blue} = 0.45$
Spread chip rate	800 McPs
Spread codes	OVSF codes
Range of SF	4, 8, 16 and 32
Background noise power	1 mW
Noise model	AWGN
Optical channel model	Diffuse channel with RMS delay spread, 1-4 (nsec)
Number of samples per spread chip	4
Field of view of a receiver	74.0°
Index of optical concentrator	1.5
Physical of a PD	1.0 cm^2

conventional systems as shown in Fig. 10. In the case of the conventional systems with the minimum SF (i.e., SF = 4), the BER performance is severely degraded. This is because the effects of inter-code interference which is caused by MAI are greater than the spreading diversity gain.

CONCLUSION

In the diffuse channel, there are many reflected optical waves which is caused by walls or obstacles and it leads to the multipath dispersion. The DC gain of the diffuse channel depends on the RMS delay spread conditions, so, adaptive multi-rate systems are required. To this end, we proposed the multi-rate OCDMA system for the downlink VLC networks based on OVSF codes. Although, the BER performance of the proposed system is degraded than the conventional systems with the maximum SF conditions, the throughout performance can be significantly improved as compared with them. Through, the simulation results, we demonstrated those effectiveness of the proposed system.

ACKNOWLEDGEMENTS

This research was supported by the MSIP (Ministry of Science, ICT and Future Planning), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2016-H8501-16-1007) supervised by the IITP (Institute for Information and communications Technology Promotion). This research was supported by the MSIP (Ministry of Science, ICT and Future Planning), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2016-R2718-16-0012) supervised by the IITP (Institute for Information and communications Technology Promotion)

REFERENCES

Barry J.R., J.M. Kahn, W.J. Krause, E.A. Lee and D.G. Messerschmitt, 1993. Simulation of multipath impulse response for indoor wireless optical channels. IEEE J. Sel. Areas Commun., 11: 367-379.

Carruthers, J.B. and J.M. Kahn, 1997. Modeling of nondirected wireless infrared channels. IEEE Trans. Commun., 45: 1260-1268.

Hasegawa, K., R. Shimura and I. Sasase, 2007. OVSF code allocation and two-stage combining method to reduce intercode interference in OFCDM system. Electron. Commun. Jpn. Part I. Commun., 90: 16-24.

Karunatilaka, D., F. Zafar, V. Kalavally and R. Parthiban, 2015. LED based indoor visible light communications: State of the art. IEEE. Commun. Surv. Tutorials, 17: 1649-1678.

Kim, K. and K. Lee, 2016. Appropriate RLL coding scheme for effective dimming control in VLC. Electron. Lett., 52: 1622-1624.

Lee, H., S.W. Kim and J.B. Kim, 2016. The study on divide about data traffic use between mobile user groups. Intl. J. Multimedia Ubiquitous Eng., 11: 189-202.

Liu, L. and F. Adachi, 2006. 2-Dimensional OVSF spread/chip-interleaved CDMA. IEICE. Trans. Commun., 89: 3363-3375.

Pakravan, M.R. and M. Kavehrad, 2001. Indoor wireless infrared channel characterization by measurements. IEEE. Trans. Veh. Technol., 50: 1053-1073.

Prucnal, P.R., 2005. Optical Code Division Multiple Access: Fundamentals and Applications. CRC Press, Boca Raton, Florida, USA., ISBN-13:978-1-4200-2661-0, Pages: 369.

Saadi, M., L. Wattisuttikulkij, Y. Zhao and P. Sangwongngam, 2013. Visible light communication: Opportunities, challenges and channel models. Intl. J. Electron. Inf., 2: 1-11.

Salehi, J.A., 2007. Emerging optical CDMA techniques and applications. Internat. J. Opt. Photon., 1: 15-32.

Shah, J., 2003. Optical code division multiple access. Opt. Photonics News, 14: 42-47.

Shi, F. and H. Ghafouri-Shiraz, 2016. Performance analysis of two new code families for spectral-amplitude-coding optical CDMA systems. J. Lightwave Technol., 34: 4005-4014.

Stok, A. and E.H. Sargent, 2002. The role of optical CDMA in access networks. IEEE. Commun. Mag., 40: 83-87.

Tseng, Y. and C. Chao, 2002. Code placement and replacement strategies for wideband CDMA OVSF code tree management. IEEE Trans. Mobile Comput., 1: 293-302.

Yi, Y., C. Li and K. Lee, 2013. Optimum spread code applied in indoor visible light data transmission for optical multipath dispersion reduction. IETE. Tech. Rev., 30: 233-239.

Yuichi, T., K. Toshihiko, H. Schinichiro and N. Masao, 2003. Indoor visible light data transmission system utilizing white LEDs. IEICE Trans. Commun., E86-B: 2440-2454.