High Spectrum Efficiency of MIMO-SC-FDMA for Optical Wireless Communication Systems

Kidsanapong Puntsri[1*] and Puripong Suttisopapan[2]

Received: May 10, 2019; Revised: July 12, 2019; Accepted: July 24, 2019

Abstract

This work aimed to present high spectrum efficiency of single carrier frequency division multiplexing (SC-FDM) together with multiple-input multiple-output (MIMO) for optical wireless communication (OWC) systems. In order to improve signal to noise ratio (SNR), maximum ratio combining (MRC) with frequency diversity was employed. It was compared with the zero forcing detection in higher order MIMO system. Additionally, at the receiver end, due to small diameter size of the avalanche photodetector (APD), the numbers of receiver up to 100 elements were therefore practically applicable. To analyze the proposed systems over OWC channel, the numerical simulation method was used and multi-path indoor environment was assumed. By applying the proposed diversity method, the results clearly showed that the SNR was significantly improved and the high order M-ary QAM (quadrature amplitude modulation) can also be achieved. Furthermore, for 256-QAM, the error free transmission can be achieved with SNR of only 30 dB with 6 number of antennas. In zero forcing detection, the transmission speed was higher than the MRC system when compared with the same bit per symbol. However, it gave higher BER.

Keywords: Multiple-Input Multiple-Output; Single Carrier Frequency Division Multiplexing; Optical Wireless Communication Systems; Intensity Modulation/Direct Detection

[1] *Faculty of Engineering, Rajamangala University of Technology Isan, Khonkhaen Campus*
[2] *Faculty of Engineering, Khon Kaen University*
[*] *Corresponding Author E - mail Address: kidsanapong.pu@rmuti.ac.th*

Introduction

Optical wireless communication (OWC) is very attractive to study and develop. OWC has many advantages, such as high bandwidth and no interference from radio frequency (RF) signals [1] - [2], and it is very secure in communication systems. Therefore, many applications including both free space [1] - [2] and underwater [3] are investigated for the possibility to implement it. In wireless systems using RF, diversity techniques are usually used to speed up data rate and/or gain the signal to noise ratio (SNR). There are many diversity techniques proposed in literature, e.g., maximal ratio combining (MRC), equal gain combining (EGC), selected combining (SC) or space-time block coding (STBC) [4]. Due to a promising performance, it is worth mentioning that the combination between diversity techniques and advance modulation format together, such as orthogonal frequency division multiplexing (OFDM) could be an emerging technology in the future [5].

OFDM is a multicarrier communication system which has many advantages when compared to a single carrier. Moreover, the intersymbol interference (ISI) can be solved by adding a cyclic prefix (CP) in the front of each OFDM symbol. Therefore, it can provide very high spectrum efficiency. OFDM also makes communication systems simple to implement in hardware. However, its major disadvantage is a high peak to average power ratio (PAPR) [4], which causes nonlinearity when passing the signal to the amplifier. To reduce the PAPR, the single carrier frequency division multiplexing (SC-FDM) is replaced and at least 3dB lower PAPR can be obtained over conventional OFDM. Therefore, it is very attractive to investigate and it already becomes a standard for Long Term Evolution (LTE) [6]. However, in OWC system, only a few SC-FDM works are investigated.

SC-FDM for OWC has been first experimentally investigated by Puntsri, K. [7]. The experimental results demonstiated that SC-FDM with 128-QAM can be practically implemented to attain a very spectrum efficiency at rate 4.56 b/s/Hz. However, multiple-input multiple-output (MIMO) combined with SC-FDM (MIMO-SC-FDM) for OWC is not yet examined in the literature review. Only MIMO-SC-FDM in wireless systems is shown. MIMO is a multiple transmitter antennas and receiver antennas communication systems and it is one of the best ways to gain up diversity and SNR. Especially, the joint design of large/massive MIMO and advance modulation format will be an emerging technology in the future.

MIMO for OWC has been investigated by only a few researchers. Berenguer, P. W. el al. [8] has presented a field trial of OWC for a robotic manufacturing environment. It has been shown that moderate data rates, high reliability, and low latency can be achieved. The channel measurements and transmission were also done in this work. The MIMO size

ISSN 2672-9369 (Online)

of 8 × 6 was considered and the results showed that the SNR is acceptable if a line-of-sight (LOS) is available. However, when an LOS is obstructed by small movements and rotations, it would lead to sudden fades of 10 - 20 dB power. From the results, it can be concluded that MIMO OWC is suitable for industrial wireless applications.

Ntogari, G. et al. [9] conducted a comparison between STBC systems with two transmitted antennas and single-input single-output (SISO) systems, where the same total optical transmit power was considered, in coherent OWC systems. STBC improves the capacity coverage area and requires less transmitting power. Additionally, MIMO for visible light communication (VLC) application was shown by Chen, C. et al. [10]. The non-Hermitian symmetry (NHS-OFDM) modulation method and an imaging angle diversity receiver were proposed. The results showed that MIMO system is very useful and it has a lot of benefit for high speed communication systems in indoor wireless communications. Navidpour, S. M. et al. [11] has proposed the system design and the performance analysis of MIMO method for coherent OWC. The mitigated atmospheric turbulence effects were considered. The phase noise impairment was compensated in electrical domain. Furthermore, many diversity combining methods were employed and compared, where the gamma-gamma turbulence, K-distributed turbulence, and negative exponential turbulence were adopted for free space channels.

From the literature reviews, in this work, the large MIMO with high spectrum efficiency for SC-FDM is studied and analyzed, where the MRC and frequency diversity for SC-FDM in OWC systems is proposed. In order to conduct numerical simulation, a multi-paths OWC channel is assumed and the number of more than 50 receiver antennas is considered. The system performance is measured in terms of bit error rate (BER) against signal to SNR. Additionally, the Reed-Solomon (RS) code with hard decision is also employed to reduce BER of system performance. The results showed that the system performance is significantly improved and a very large M-ary QAM order can be offered. Moreover, bit error free transmission can be achieved at only a few receiver antennas and SNR for MRC scheme.

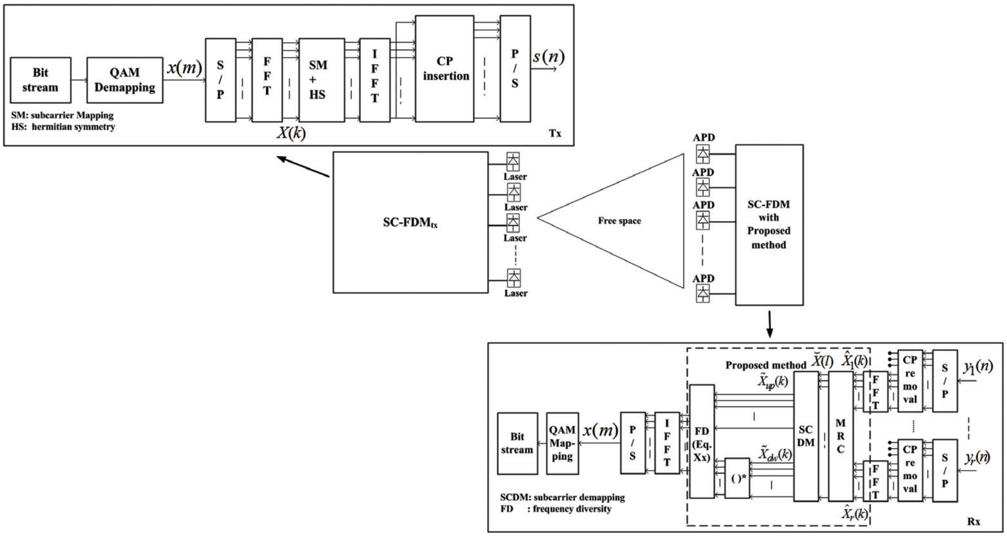


Figure 1 System model used for massive SIMO-SC-FDM in OWC Systems

SC-FDM with MIMO in OWC systems

The detailed of SC-FDM system with MIMO for OWC systems is shown in Figure 1. As can be seen, the SC-FDM system is similar to OFDM, only additional FFT and IFFT computation are required for the transmitter and receiver, respectively. First, the bit streaming is fed in to QAM-mapping unit to group the number of bits into a symbol, which is denoted by $x(m)$. The mapped symbol is converted to frequency domain using fast Furrier transform (FFT) processing, defined by $X(k)$, with the size of N_{sb} and $k = 0 \ldots N_{SB} - 1$. N_{SB} as the number of sub band. Next, the subcarrier mapping is followed to setup the input to the invert FFT (IFFT) with the size of N_C. In this work, the interleaved FDM was used, where it gave the lowest PAPR, as reported in [7]. Additionally, for OWC, the intensity modulation/direct detection (IM/DD) was needed. Therefore, the Hermitian symmetry was adapted to obtain the SC-FDM, which only had real (or only imaginary) component. The subcarrier mapping established the Hermitian symmetry input for IFFT, where the mapped subcarrier is given by equation (1)

$$\tilde{X} = [\underbrace{0\ X(0) \ldots 0\ X(N_{sb}-1)\ 0}_{\tilde{X}_{up}}\ \underbrace{0\ X^*(N_{sb}-1)\ 0 \ldots X^*(0)}_{\tilde{X}_{dw}}], \qquad (1)$$

hence, $\tilde{X}$ is subcarrier mapped vector with length of $l = 0 \ldots N_C - 1$. $\tilde{X}_{up}$ is the vector of the first haft and $\tilde{X}_{dw}$ is the vector of the second haft of $\tilde{X}$, respectively. As can be seen, $\tilde{X}_{dw} = \tilde{X}_{up}^*$, where the index of $\tilde{X}_{dw}$ is reversed order of $\tilde{X}_{up}$.

Then, a cyclic prefix (CP) is added to prevent the ISI due to the dispersive free space channel. Finally, the transmitted signal, which included CP, is denoted by $s(n)$. For more than one antennas, $s_i(n)$ denoted for the transmitted signal with i element, where $i = 1...nTx$ and nTx is the number transmitted antenna.

At the receiver, the received signal at the r th antennas is denoted by $y_r(n)$, which is expressed by

$$y_r(n) = s_i(n) \otimes h_r(n) + z_r(n), \tag{2}$$

where $r = 1...nRx$ and nRx is the number of received antenna. $h_r(n)$ is free space channel and $z_r(n)$ is the noise component, which is modeled by additive white Gaussian noise (AWGN) with zero mean and the variant is σ_{noise}^2. $\otimes$ is convolution operator. $r = 1...nRx$ and nRx is the number of receive antennas.

From equation (2), the CP is removed and $y_r(n)$ which are only the useful samples remain and are fed in to the FFT. The signal after taking FFT is given by equation (3):

$$\hat{X}_r(l) = \sum_{i=1}^{nTx} \sum_{r=1}^{nRx} \tilde{X}_i(l) \cdot H_{i,r}(l) + Z_r(l), \tag{3}$$

hence, $H_r(l)$ is the free space channel and $Z_r(l)$ is AWGN noise.

MRC receiver

Now, MRC is detailed, where only one transmitted antenna is employed and the combination receiver of all received branches is expressed by equation (4)

$$\begin{aligned} \breve{X}(l) &= \frac{\tilde{X}(l) \cdot \sum_{r=1}^{nRx} H_r(l) H_r^*(l) + \sum_{r=1}^{nRx} Z_r(l) H_r^*(l)}{\sum_{r=1}^{nRx} H_r(l) H_r^*(l)} \\ &= \breve{X}(l) + \frac{\sum_{r=1}^{nRx} Z_r(l) H_r^*(l)}{\sum_{r=1}^{nRx} H_r(l)^2} \end{aligned}. \tag{4}$$

Next, subcarrier demapping is done in the following, where it strips out all zeros and only the useful information data symbol remains. Here, because of Hermitian symmetry input setup likes equation (1), the second half conjugated one of the first half, which are denoted by $\breve{X}_{up}$ and $\breve{X}_{dw}$ for the first and the second, respectively. Therefore, if we conjugate $\breve{X}_{dw}(k)$ the, the frequency diversity can be done easily by equation (5):

$$\breve{X} = \frac{\breve{X}_{up} + \breve{X}_{dw}^{*}}{2}, \tag{5}$$

where $\widehat{X}$ is the signal vector after formulating frequency diversity with the length of N_{sb} and the noise component reduced by divided by two. Next, $\widehat{X}$ is fed in to IFFT and QAM demapping to map a QAM symbol in to bit streaming in the finally process.

Zero forcing receiver

In this section, the zero forcing receiver is detailed. In this work, the system consisted of two transmitters with two and four receivers. The zero forcing equalization must satisfy condition that $WH = I$, where W is the weight gain equalization and it is given by $W = \left(H^{H}H\right)^{-1}H^{H}$. Therefore the zero forcing equalization is expressed by (equation (6)) [4]

$$\begin{aligned} X_{ZF}^{\%} &= WY \\ &= \left(H^{H}H\right)^{-1}H^{H}HX + Z \end{aligned} \tag{6}$$

$X_{ZF}^{\%}$ is the estimated received signal using zero forcing equalization. $Y = FFT\left(y(n)\right)$ and $y(n)$ is equation (2). Additionally, this is no diversity but, full rate of communication systems can be achieved.

Simulation model

The system considered for this work is shown in Figure 1. There is one nTx SC-FDM transmitter and nRx receivers. The MIMO free space channel impulse response from the transmitter to the receiver r, where $r = 1...nRx$, is modeled by equation (7) [11] - [12]

$$h_r(n) = \eta_r \cdot \frac{6a_r^{6}}{\left(n + a_r\right)^{7}}, \tag{7}$$

hence, $h_r(n)$ is the OWC channel response. $a_r = 12\sqrt{11/13} \cdot \tau_{rms,r}$ is the normalized factor of the root mean square channel delay spread which is denoted by $\tau_{rms,r}$. η_r is the ling-of-sight links, which is expressed by equation (8):

$$\eta_r = \frac{(m+1)A}{2\pi d_r^2}\cos^m(\alpha_r)\cos(\beta_r). \tag{8}$$

Hence, $-\frac{\pi}{2} \le \alpha_r \le \frac{\pi}{2}$ and $-\frac{\pi}{2} \le \beta_r \le \frac{\pi}{2}$. Unless, h_r will be equaled zeros. A is the active area of the avalancephoto detector (APD) and the order of Lambertian emission, denoted by m, is given by equation (9)

$$m = \frac{-\ln(2)}{\ln(\cos(\varphi_{1/2}))}, \tag{9}$$

where $\varphi_{1/2}$ is the semiangle at half-power of transmit power.

In this work, $N_C = 1024$, $N_b = N_C/4 = 256$ and the number for CP is 128 $(= N_C/8)$ were assumed. The number of M-QAM and number of receiver antenna were investigated. Additionally, the simulated parameters are as follows: $\varphi_{1/2} = 60^\circ$, then $m = 1$, $A = 15mm^2$, $d_r = 2m$ $\alpha_r 90^\circ$ and $\beta_r = 90^\circ$.

Simulation Results

The numerical simulations using Matlab are discussed in this section. The system performance was analyzed in terms of BER and the system design parameters were examined.

Firstly, the single input multiple output (SIMO) with diversity schemes including MRC and frequency diversity was investigated. The number of receive antenna of 50 elements was assumed, (nRx = 50). 256-QAM was used and the BER result is shown in Figure 2. As can be seen, the proposed MRC with frequency diversity gave the lowest BER and the SNR gained a lot when compared with the case of no diversity. It can clearly be seen that the system performance was significantly improved.

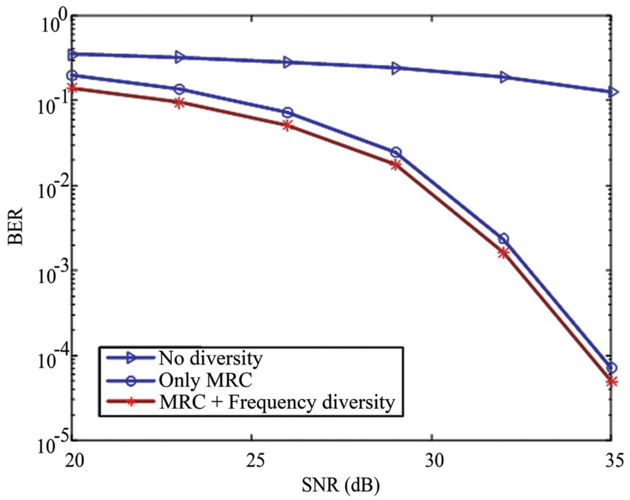


Figure 2 BER performance versus SNR for 256-QAM with various diversity schemes

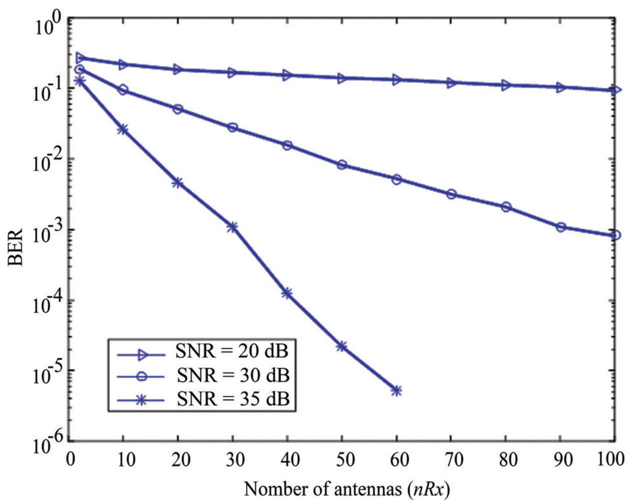


Figure 3 BER performance against the number of antennas (nRx) for 256-QAM with the SNR of 20 dB 30 dB and 35 dB

Figure 3 plots the BER against the number of antennas in which this value was varied from 2 to 100 elements and 256-QAM was adopted. The BER for the SNR of 20 dB 30 dB and 35 dB were compared. The results showed that when the number of antenna was increased, the BER reduced. This is because the SNR gain was enhanced. Especially, for the SNR of 35 dB at 60 elements of antennas, the BER free can be achieved.

Figure 4 depicts the comparison of BER performance with SNR for various modulation orders of M ary QAM. The number of antennas for 60 elements was assumed. As can be seen, if the SNR increased, the BER reduced for all M-QAM. To achieve error free, the SNR of more than 21 dB, 27 dB and 33 dB were required for 16-QAM, 64-QAM and 256-QAM, respectively. Additionally, to reduce the number of antennas, a coding method would be required. For this work, the Reed–Solomon (RS) error correction code with hard decision decoding was adopted. In this test, 256-QAM with SNR=30 dB was assumed.

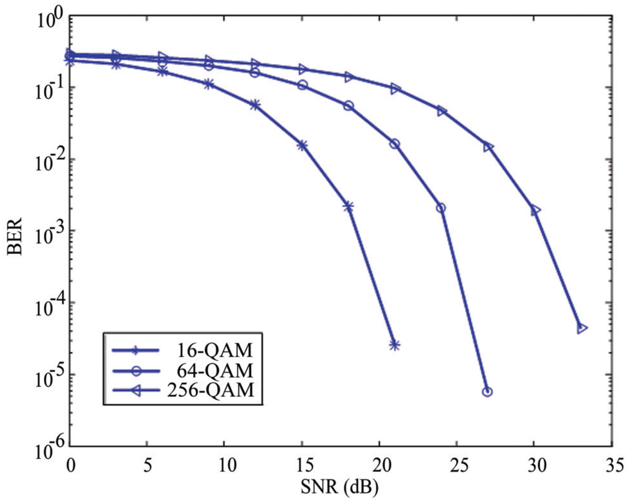


Figure 4 BER performance versus M-QAM with $nRx = 60$

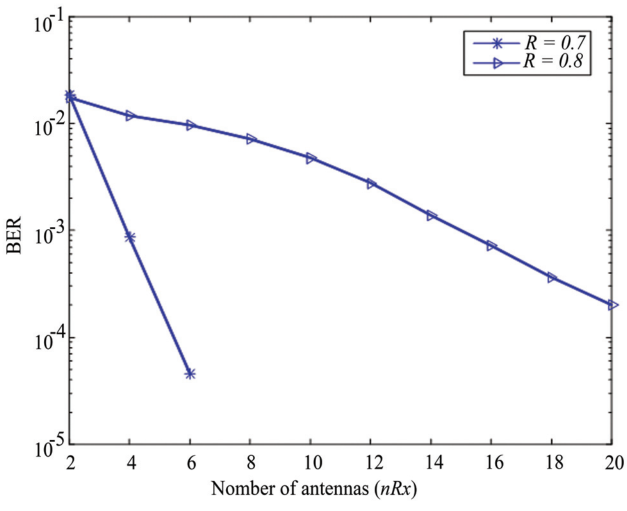
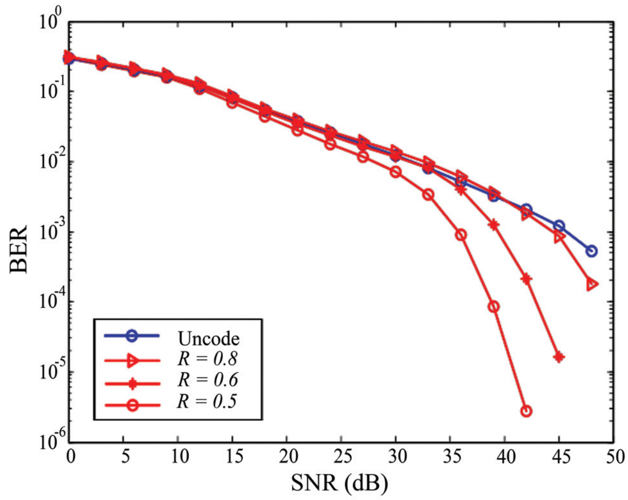


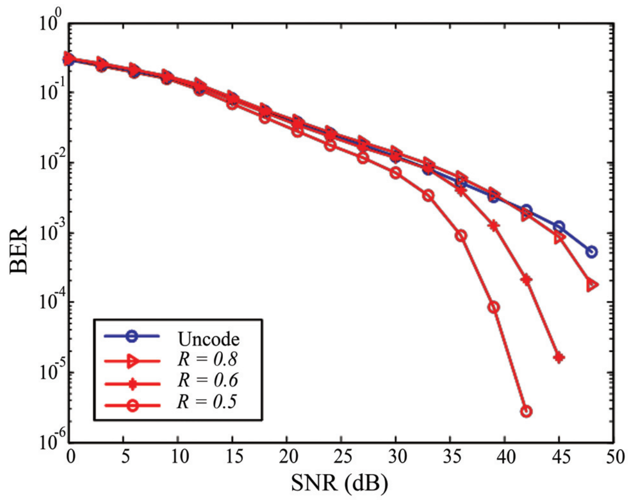
Figure 5 BER performance against SNR for 256-QAM with various coding gain (R)

From figure 5, by using the RS code of rate 0.7 and 0.8 and as can be seen, when the coding gain is reduced, the BER decreased. Additionally, by referring to Figure 3, the nRx could be reduced more by using less coding gain; however, the complexity processing would be high when compared with only the MRC and frequency diversity were used. The other way around, if the *nRx* could be decreased, the receiver size would be more compact. It is a trade-off and it depends on the design needed.

Second, MIMO scenario with zero forcing detection was investigated. The 2 × 2 MIMO and 4 × 4 MIMO were presented and the result is shown in Figure 6(a) and 6(b), respectively. 16-QAM was used in this case.



(a) 2 × 2 MIMO with various coding gain (*R*)



(b) 4 × 4 MIMO with coding gain of 0.5

Figure 6 BER performance versus SNR for 16-QAM

From Figure 6, it can be seen that the BER reduced when the SNR increased for both 2 × 2 and 4 × 4 MIMO. Additionally, for uncode, the BER was higher than the coded.

Especially, 4 × 4 MIMO had very strong BER sensitivity. Moreover, the higher code rate, the lower BER. However, when comparison were made between the zero forcing method with the MRC systems from Figure 3, 5 and 6, the BER of zero forcing was higher than MRC. However, the zero forcing receivers gave higher communication speed.

Conclusions

An enhancement of system performance for OWC using MIMO SC-FDM was proposed in this work. MRC together with frequency diversity was employed to recover the information data and can be used to gain up the SNR. A huge M-QAM and large antennas order were also considered. To verify the system performance, the numerical simulation method was used. The results showed that the BER decreased when the number of antenna was increased. Additionally, at a higher SNR, the number of antenna requirement to get error free was reduced. Especially, when the RS-code was applied, the SNR was exponentially gained. For the coding gain of 0.7, the antennas of only 6 elements were required to obtain error free for 256-QAM. For zero forcing detection, it gave higher BER; however, the transmission rate was more than the MRC system, when compared at the same bit per symbol.

Acknowledgements

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper. Additionally, we gratefully acknowledge everyone from my department for the support provided. This research project is supported by Rajamagala University of Technology Isan, Contract No. ENG 17/62.

References

[1] Mesleh, R. and AL-Olaimat, A. (2018). Acousto-Optical Modulators for Free Space Optical Wireless Communication Systems. **Journal of Optical Communications and Networking**. Vol. 10, Issue 5, pp. 515-522. DOI: 10.1364/JOCN.10.000515

[2] Liu, X., Gong, C., and Xu, Z. (2017). Sequential Detection for Optical Wireless Scattering Communication. **Journal of Optical Communications and Networking**. Vol. 9, Issue 9, pp. D86-D95. DOI: 10.1364/JOCN.9.000D86

[3] Zeng, Z., Fu, S., Zhang, H., Dong, Y., and Cheng, J. (2017). A Survey of Underwater Optical Wireless Communications. **IEEE Communications Surveys & Tutorials**. Vol. 19, No. 1, pp. 204-238

[4] Cho, Y. S., Kim, J., Yang, W. Y., and Kang, C. G. (2010). **MIMO-OFDM Wireless Communications with MATLAB®**. John Wiley and Sons. DOI: 10.1002/9780470825631

[5] Azhar, A. H., Tran, T., and O'Brien, D. (2013). A Gigabit/s Indoor Wireless Transmission Using MIMO-OFDM Visible-Light Communications. **IEEE Photonics Technology Letters**. Vol. 25, Issue 2, DOI: 10.1109/lpt.2012.2231857

[6] Abu-Ali, N., Taha, A. M., Salah, M., and Hassanein, H. (2014). Uplink Scheduling in LTE and LTE-Advanced: Tutorial, Survey and Evaluation Framework. **IEEE Communications Surveys & Tutorials**. Vol. 16, No. 3, pp. 1239-1265. DOI: 10.1109/SURV.2013.1127.00161

[7] Puntsri, K. (2018). Experimental Demonstration of Hhigh Spectral Efficiency SC-FDMA with Soft Clipping for Optical Wireless Communication Systems. **IET Optoelectronics**. Vol. 12, Issue 2, pp. 80-85. DOI: 10.1049/iet-opt.2017.0073

[8] Berenguer, P. W., Schulz, D., Hilt, J., Hellwig, P., Kleinpeter, G., Fischer, J. K., and Jungnickel, V. (2018). Optical Wireless MIMO Experiments in an Industrial Environment. **IEEE Journal on Selected Areas in Communications**. Vol. 36, Issue 1, pp. 185-193. DOI: 10.1109/JSAC.2017.2774618

[9] Ntogari, G., Kamalakis, T., and Sphicopoulos, T. (2012). Analysis of Indoor Multiple-Input Multiple-Output Coherent Optical Wireless Systems. **Journal of Lightwave Technology**. Vol. 30, No. 3, pp. 317-324. DOI: 10.1109/JLT.2011.2176553

[10] Chen, C., Zhong, W., and Wu, D. (2017). On the Coverage of Multiple-Input Multiple-Output Visible Light Communications [Invited]. **IEEE/OSA Journal of Optical Communications and Networking**. Vol. 9, Issue 9, pp. D31-D41. DOI: 10.1364/JOCN.9.000D31

[11] Navidpour, S. M., Uysal, M., and Kavehrad, M. (2007). BER Performance of Free-Space Optical Transmission with Spatial Diversity. **IEEE Transactions on Wireless Communications**. Vol. 6, Issue 8, pp. 2813-2819. DOI: 10.1109/TWC.2007.06109

[12] Wu, L., Zhang, Z., and Liu, H. (2013). MIMO-OFDM Visible Light Communications System with Low Complexity. **2013 IEEE International Conference on Communications (ICC)**. 9-13 June 2013, Budapest, Hungary, pp. 3933-3937. DOI: 10.1109/ICC.2013.6655172