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Multi-users different rates visible light communication system for sixth-generation multimedia applications

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ABSTRACT. The two most significant issues that communication engineers have been confronting since the development of fifth-generation wireless networks are bandwidth increase and energy-saving techniques in data transmission. We present an innovative solution for utilizing a multi-user different-rates visible light communication (VLC) system for sixth-generation applications. Such a solution takes advantage of orthogonal frequency division multiple access (OFDMA) with orthogonal codes as multiple access communication networks. For the achievement of energy-saving and wide beam width of the optical source, the light emitting diode is often used as a transmitter. Furthermore, one of the most popular orthogonal codes in use is the double length modified prime code, which has been utilized for enhancing communication network security and network capacity. Most importantly, the performance of the network is evaluated versus the number of users, taking into consideration the amount of noise resulting from the multiple access interference, shot noise, and thermal noise. The error vector magnitude has also been considered for performance analysis and results. Significantly, the obtained results show the possibility of accommodating 110 users at an error rate of no more than 10^{-9} and a data rate per user of 50 Gbps.

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Keywords: fifth generation; visible light communication; orthogonal frequency division multiple access; sixth generation

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1 Introduction

When comparing the fifth generation (5G) and sixth generation (6G) of wireless networks, the lateral generation is known to provide relatively greater capacity, fast speed, and very low latency.[1] These advantages are crucial for supporting new applications, for example, surreal virtual reality, fine medicine, and intelligence prediction. The most recent studies suggest the use of existing 5G architecture for 6G implementations.[2,3] Several countries have released research plans focusing on the development of 6G in recent years.[4–6] The European Union has also funded a research plan for 6G technologies for studying the next generation of terabit wireless network channel modulation techniques, the advancement in channel coding, and forward error correction coding. One of the aforementioned countries, which includes the Republic of China, has funded a research project to examine the ability of the 6G systems for the purpose of fulfilling the anticipated increase in future demands of the internet of things. Such demands include sensing, medical imaging, and augmented reality. Funded research on "6Genesis" has also come from the

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Academy of Finland in Helsinki, which is undertaking a holistic project covering all aspects of 6G. Several American universities as well as the governments of South Korea and the United Kingdom have launched research projects on 6G technologies, covering a range of subjects such as quantum technology, terahertz-based 6G wireless networks, and cell-free work technique.[7]

Among the variety of 6G visions is ultrafast speed communication, which aims to increase the data rate from 100 to 1000 times faster than the rate typically provided by 5G. This can be achieved using a multi-band high-spread spectrum to produce data rates from hundred Gbps to several Tbps using optical integrated encoder/decoder.[8] Additionally, from the capacity point of view, the 6G network must be able to accommodate larger than trillion level objects instead of the currently billion level objects of 5G. Throughout the literature, some potential techniques have been suggested to meet the requirements of the 6G networks, for example:[3–7]

1. Multi-band ultrafast speed transmission
   a. mm-wave band,
   b. visible light (VL) frequency band, and
   c. THz band (0.1 to 10 THz)
2. Super flexible integrated network for the purpose of the internet of everything
   a. flexible heterogeneous network,
   b. space-terrestrial integrated network, and
   c. flying base station
3. Multi-mode multi-domain joint transmission
   a. multi-mode ultra-massive multiple-input multiple-output,
   b. orbital angular momentum-based mode division multiplexing, and
   c. multi-domain index modulation
4. Intelligent transmission
   a. machine learning,
   b. big data techniques, and
   c. multidisciplinary techniques

Common challenges that prevent the optimal utilization of 6G are specified in the following along with their suggested solutions.[9] The first problem is the power source, and the recommended solution is to use a hybrid power supply that uses wireless energy harvesting and wireless power transfer.[10] The second problem is network security, which is addressed by utilizing well-integrated multi-level security that uses the distributed management mechanism.[11] The third problem relates to the constraints imposed by hardware design. The use of the visible light communication (VLC) for indoor communications provides a great speed for data transmission compared to the Wi-Fi modems, and this is very important for 6G mobile applications.[12] The implementation of optoelectronic integration using smaller modems and antennas is advised as a solution. For multi-band frequency applications, there are many division multiplexing techniques that could be used, where the orthogonal frequency division multiplexing (OFDM) technique is the most appropriate choice due to the following advantages:[9–11]

1. Efficient use of the frequency spectrum for signal overlap.
2. More resistant to frequency selective fading than single carrier systems.
3. Elimination of inter-symbol interference and inter-frequency interference.
4. Ability to recover symbols lost using channel coding and interleaving.
5. It is a simpler channel equalization than the equalization techniques used in single-carrier systems.
6. OFDM is computationally efficient in modulation and demodulation functions by the utilization of the fast Fourier transformation technique.

7. It provides good protection against co-channel interference and impulsive parasitic noise.

The main contribution of this paper is represented in introduction of a multi-user optical wireless communication (OWC) system utilizing the VL frequency band. This VL frequency band has been divided into optical subbands using OFDM technique, and the data are optically spread using the orthogonal double length modified prime code (DLMPC). These techniques provide system bit error rate (BER) performance, system capacity, and system security improvements based on hybrid power supply and integrated optical encoders/decoders. The BER performance and error vector magnitude (EVM) have been analyzed as a function of the number of active users provided by the network, wireless channel parameters, and transmission rate. This paper is organized as follows: Sec. 2 introduces the proposed system block diagram, channel model, and system performance analysis. Section 3 presents the obtained BER simulation and discusses the results. Section 4 concludes the research presented in this paper.

2 Proposed System Architecture and Modeling

The proposed OFDMA-OWC system block diagram is shown in Fig. 1. The OFDM is used as a digital multi-carrier modulation as in Refs. 13–25. The OFDM signal is I/Q encoded by the orthogonal DLMPC, which was introduced in Refs. 26–28 using the optical Mach-Zehnder modulator. The purpose of designing this code is to obtain a better BER performance, system security improvement, and enhanced system capacity in comparison with other relevant codes used in coherent optical transmission. Figure 1 shows all the N encoded data that are combined using an optical combiner with dimension NX1. The combined signals are fed to the wireless channel via the pointing and tracking subsystem.

The OWC channel is represented by the gamma–gamma turbulence model, and all losses are considered in the BER performance evaluation, such as atmospheric, optical, window, pointing, visibility, and beam divergence losses.[29–41] At the receiving end, however, the received signal is first split by the 1XN splitter (i.e., the reverse operation of the combiner at the transmitting end) and then decoded by the optical decoder integrated at the splitter output. The decoded optical

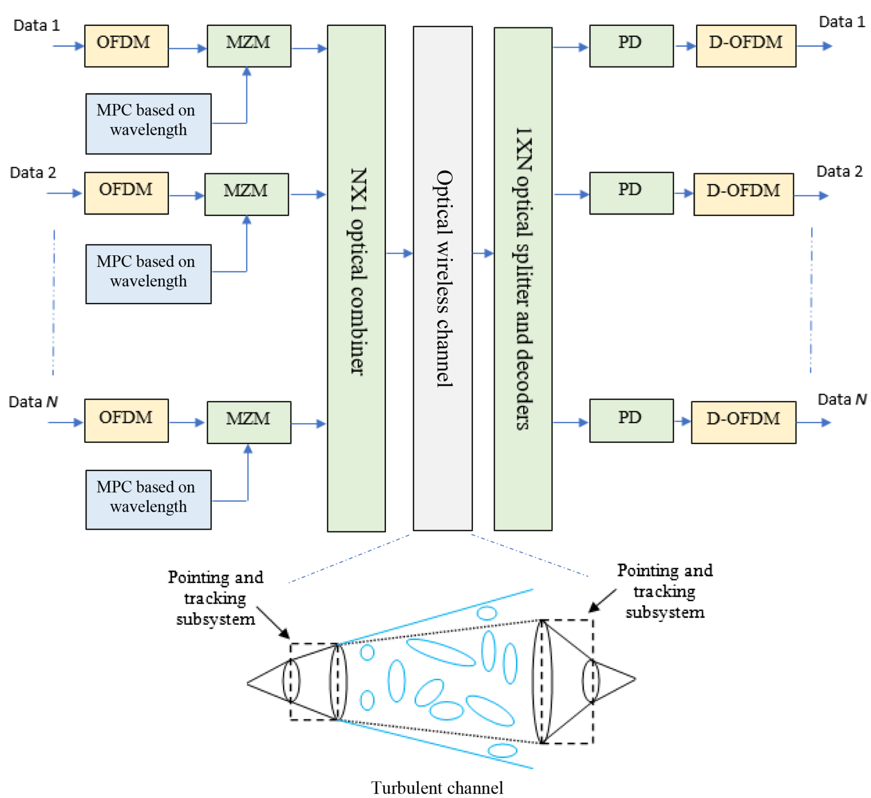

Fig. 1 The proposed OFDMA-OWC system model.

Table 1 Link parameters.

Parameter	Parameter definition	Units
η_t	Transmit optical efficiency	Unit-less
η_A	Transmit aperture illumination efficiency	Unit-less
λ	Transmitted wavelength	μm
L_{atm}	Absorption fractional loss due to transmitting media	Unit-less
L_{pol}	Mismatch loss between transmitter and receiver polarization	Unit-less
A_r	Photo-detector aperture	mm^2
A_t	Transmitter aperture	mm^2
η_r	Collecting efficiency of optical receiver	Unit-less
L_{tp}	Transmitting pointing loss	Unit-less
L_{rp}	Receiving pointing loss	Unit-less
d	Distance separation between transmitter and receiver	km

signal is converted to an electrical one using the balanced PIN photo-detector to reduce the noise and interference. Finally, the electrical OFDM signal is demodulated using the OFDM demodulator.

The wireless link power budget equation can be expressed by the following equation according to the link parameters, which are illustrated in Table 1[28]

$$P_r = P_t\left(\eta_t\eta_A\frac{4\pi A_t}{\lambda^2}\right)L_{\mathrm{tp}}L_{\mathrm{atm}}L_{\mathrm{pol}}L_{\mathrm{rp}}\left(\frac{A_r}{4\pi d^2}\right)\eta_r, \tag{1}$$

where P_t and P_r are the optical power transmitted and optical power received, respectively. However, for large-scale refraction and small-scale scattering effects, the gamma–gamma channel model is recommended.

The utilized DLMPC has a code length L, the length represents the number of chip pulses in this code, and the code weight W represents the number of chip pulses having a logic level 1, whereas the remaining chip pulses are 0. In Ref. 28, the authors present an example for the method of the code construction, and also demonstrate its correlation characteristics according to the prime number $P = 5$. The code length, code weight, and the number of available code sequences only depend on this prime number and can be defined as in the following Eqs. (2)–(4). The number of active users sharing the system may be defined by Eq. (5).[27–29] This code has an important advantage because it has a double length. This advantage represented in the system security because when the code is long, it protects the system from spying

$$L = 2P^2, \qquad P \in \{1, 3, 5, 7, 11, \ldots, \text{etc.}\}, \tag{2}$$

$$L = 2P - 1, \qquad P \in \{1, 3, 5, 7, 11, \ldots, \text{etc.}\}, \tag{3}$$

$$m = P^2, \qquad P \in \{1, 3, 5, 7, 11, \ldots, \text{etc.}\}, \tag{4}$$

$$N = i, \qquad i \in \{0, 1, 2, 3, \ldots, m\}, \tag{5}$$

The user power of the OFDM signal after the photo-detector can be expressed as[8–10]

$$P_{\mathrm{user}} = \Re\left[\frac{S}{L}\right](W - 1)\sum_{n=1}^{N} C_n e^{j2\pi f_n t}, \tag{6}$$

where $\Re$ is the photo-detector responsivity, S is the optical power received, f_n is the subcarrier frequency of user number n, $n \in \{1,2,3,\ldots,N\}$, and C_n is the complex bit when $n = N$. In addition, the subcarrier frequency and the photo-detector responsivity can be defined as

$$f_n = \frac{n-1}{N}, \tag{7}$$

$$\Re = \frac{\eta e}{hv}, \tag{8}$$

where η is the photo-detector quantum efficiency, e is the electron charge, h is the Planck constant, and v is the operating frequency. The shot and thermal noises variance may be expressed as

$$\sigma^2_{\text{shot}} = \frac{2eSB\Re}{L}(W+1), \tag{9}$$

$$\sigma^2_{\text{th}} = \frac{4k_B T_n B}{R_L}, \tag{10}$$

where B is the receiver electrical bandwidth, k_B is the Boltzmann constant, T_n is the receiver noise temperature, and R_L is the receiver load resistance. Then the signal to noise ratio (SNR) can be expressed as in Eq. (11), considering the effect of dark current and assuming the probability of sending bit 1 of any user is 0.5

$$\text{SNR} = \frac{P^2_{\text{user}}}{\frac{\sigma^4_{\text{shot}}(P)(W)N}{8(W+1)(B)B_{\text{optical}}} + \sigma^2_{\text{shot}} + \sigma^2_{\text{th}}}, \tag{11}$$

where B_{optical} is the receiver optical bandwidth, and hence the BER may be expressed based on the Gaussian distribution as

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\frac{\sqrt{\text{SNR}}}{2}\right). \tag{12}$$

The EVM is a recently introduced metric used in measuring the quality of the optical signal alongside with the BER and throughput performances in OWC and all optical systems. For N randomly transmitted symbols, the EVM is defined as the root mean square value of the difference between the received error vector and the ideal transmitted vector. On the other hand, the BER for M-ary modulation can be expressed as a function of the EVM, which is illustrated as[11]

$$\text{BER} = \frac{1-\frac{1}{\sqrt{M}}}{0.5\ \log_2(M)}\text{erfc}\left(\sqrt{\frac{3}{2(M-1)\text{EVM}^2}}\right), \tag{13}$$

where, M is the system multiplicity or the order of M-ary modulation technique. And, therefore, the EVM is expressed as follows:

$$\text{EVM\%} = \frac{\text{BER}_{\text{max}} - \text{BER}}{\text{BER}} * 100\%. \tag{14}$$

3 Simulation Results

Figure 2 shows the BER performance versus the transmission distance when the transmitted power equals to 10 dBm and prime number 11. In addition, the figure illustrates the BER performance comparison between the system that uses the DLMPC only and the other one that uses the DLMPC with the OFDM modulation technique.

The result indicates that the BER performance will be degraded when the transmission distance increases. This is due to the increase of channel attenuation, which proportionally increases as distance extends between transmitter and receiver. Furthermore, Fig. 2 shows that a system using OFDM modulation outperforms other systems at any transmission distance, which is due to the better detection at the receiving end. The system can transmit over 70 km transmission distance at 10^{-9} error rate. Figure 3, however, shows that when the transmitted power is increased to 30 dBm, the overall system improves. Consequently, this system has the ability to transmit over a transmission distance that is >100 km at BER performance that is < 10^{-9}. This is due to the greater received power, and hence an improved SNR.

Figure 4 shows the BER performance versus the data rate at full load communication, $N = 110$ users, for the system uses the DLMPC in comparison with the system uses the DLMPC and OFDM. This result shows that each user in the first system can transmit

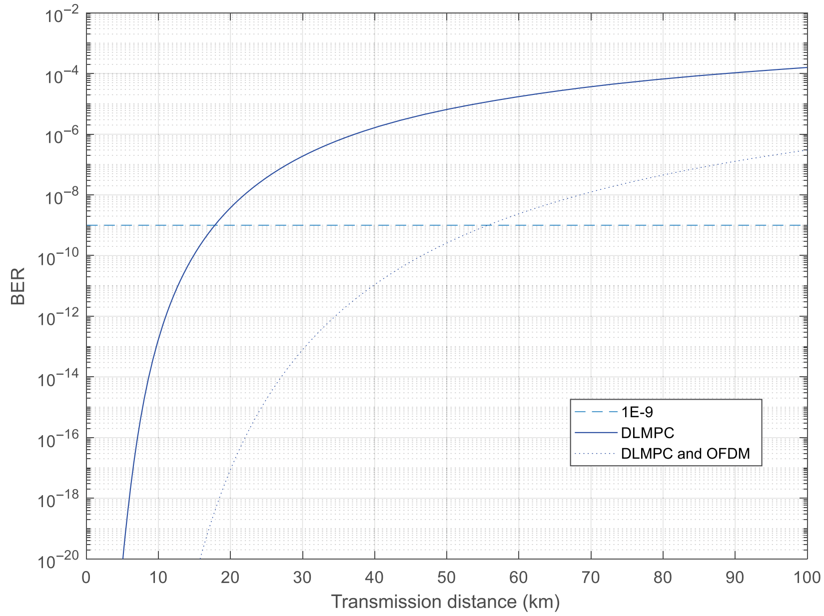

Fig. 2 BER performance versus the transmission distance, when $P_t = 10$ dBm and $P = 11$.

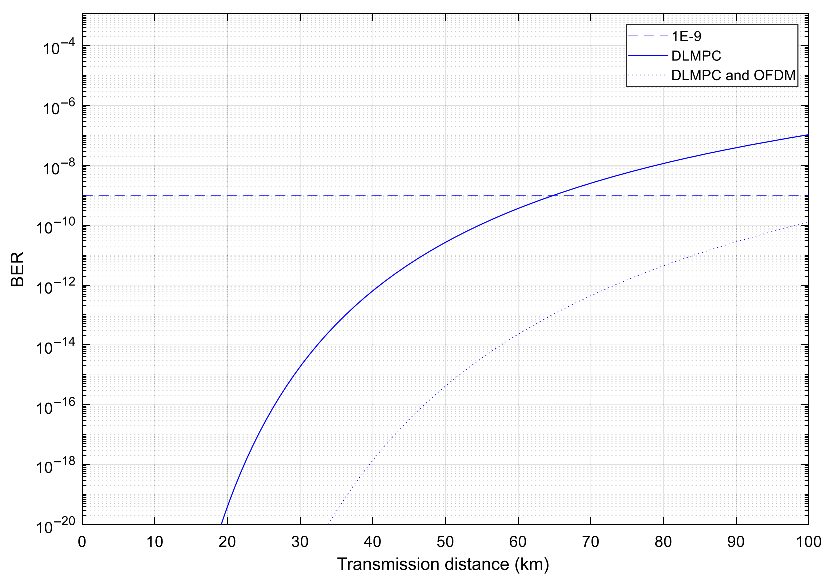

Fig. 3 BER performance versus the transmission distance, when $P_t = 30$ dBm and $P = 11$.

19 Gbps at 10^{-9} BER performance, whereas in the second one each user can transmit 50 Gbps at the same performance. Also, the second system outperforms the first one at any value of data rate. This is due to the available frequency spectrum of the OFDM modulation technique.

Figure 5 shows the BER performance of the system that uses the DLMPC in comparison to the other system that use DLMPC and OFDM techniques versus the number of active users when $P = 11$ at optical power received -17 dBm. The results illustrate that with the same number of active users, the system uses the DLMPC and OFDM outperforms the other one. This is due to the difference in the amount of multiple access interference (MAI) between them. In general, the BER performance degrades when the number of active users increases, this is due to the increase in MAI.

Figure 6 shows the EVM% versus the optical SNR (OSNR). This result illustrates that at any value of the EVM the OFDMA-DLMPC hybrid multi-band code sequence outperforms the other DLMPC only without using the OFDMA. Also, at any value the error magnitude is lowest when the hybrid multi-band code is recommended. For example, at 10 dB OSNR, the EVM% are 6%,

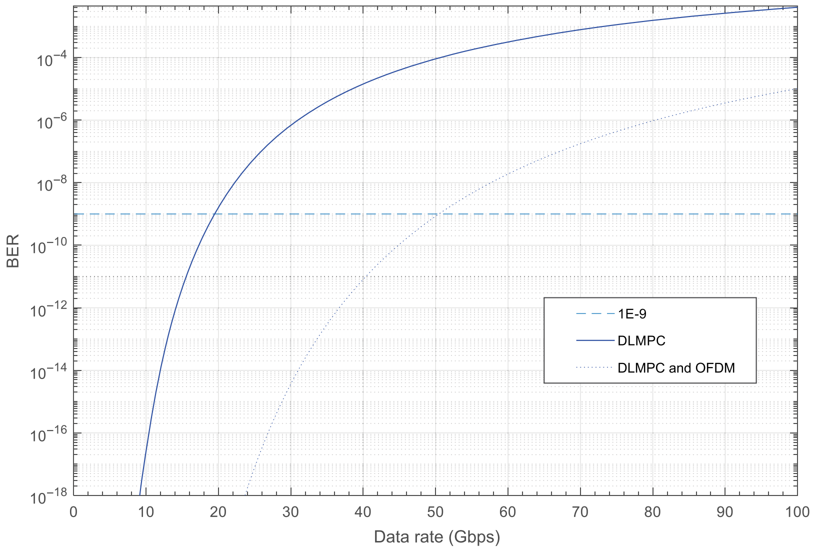

Fig. 4 BER performance versus data rate, when $N = 110$ and $P = 11$.

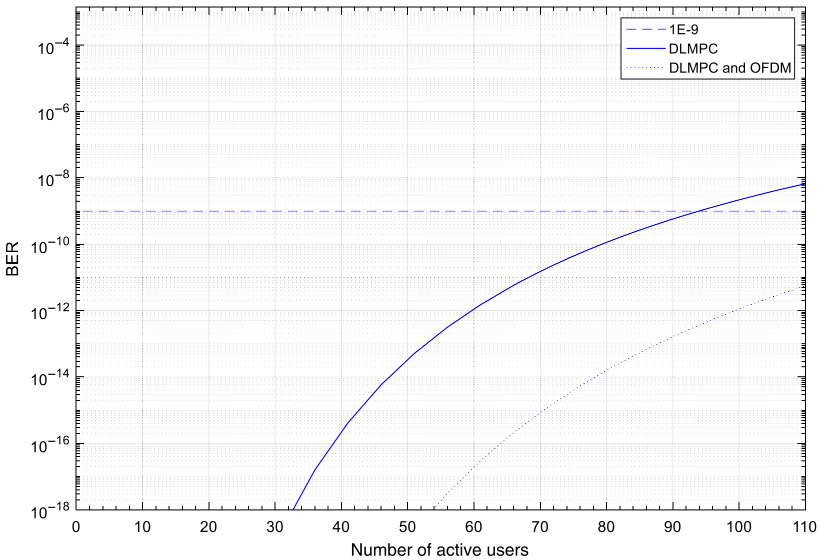

Fig. 5 BER performance versus the number of active users, when $P_r = -17$ dBm and $P = 11$.

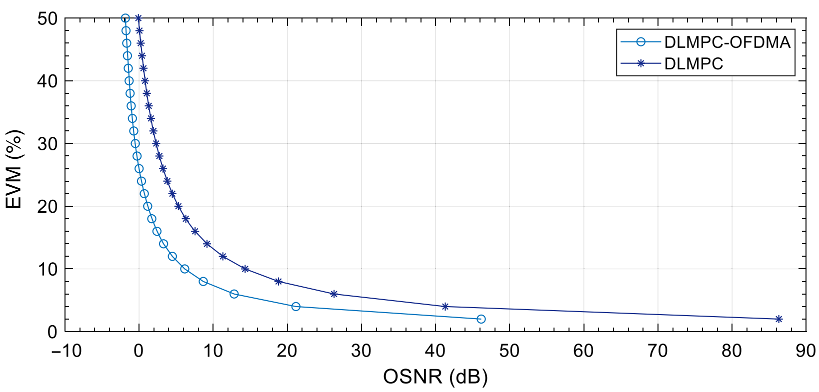

Fig. 6 EVM performance versus the OSNR, when $P = 11$.

Table 2 Comparison between the proposed work and the other in literature.

Ref.	Used technique	BER	Number of users	Security improvement	Bit rate (Gb/s)
9	OFDM	$>10^{-9}$	10	Not exist	100
10	OFDM	$>10^{-9}$	15	Not exist	50
35	OFDM	$>10^{-9}$	12	Not exist	40
39	OFDM	$>10^{-9}$	20	Not exist	25
This work	DLMPC-OFDM	$=10^{-9}$	110	Exist	50

and 13% for DLMPC-OFDMA and DLMPC, respectively. This is due to the advantages of the OFDMA technique.

Table 2 present a comparison between the proposed work and the other related work in literature. This comparison indicates that the use of the DLMPC-OFDM technique gives high improvement in the number of users that can share the network comparing with the other systems that use only the OFDM technique. Also, the proposed system has improvement in the system security due to the use of the DLMPC sequence that is not used in the other systems.

4 Conclusion

In this paper, a new OWC model was proposed that works in the VL frequency range using the OFDM techniques, and which uses one of the important codes in the optical networks. This proposed model aims to increase the number of users in the 6G of mobile networks. The DLMPC code was used to improve network security and enhance the network BER performance. After discussing the challenges mobile networks will face with 5G, some solutions have been put forth and used with the proposed new DLMPC-OFDM technique introduced in this paper. Finally, the results indicated that the use of this technique outperforms the other systems that do not use this technique in terms of the data rate, the number of users and BER performance, as the system can accommodate 110 users at a data transmission rate 50 Gbps for each user.

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