3 Gb/s Broadband Spectral Amplitude Coding – Optical Code Division Multiple Access (SAC-OCDMA) Based on Multi Diagonal and Walsh Hadamard Codes

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Abstract —The importune need of the subscribers to the vast speed of the download in the internet, motivate the researchers to discover new technologies such as Spectral Amplitude Coding-Optical Code Division Access (SAC-OPDMA) system. SAC-OCDMA is widely used in asynchronous network. This research is dedicated on the investigation of 3Gb/s broadband SAC-OCDMA for fifteen users based on Multi Diagonal (MD) and Walsh Hadamard (WH) codes. Since these codes have many important advantages such as zero cross-correlation, so they support the system the ability of removing the Multiple Access Interference (MAI). For increasing the number of the users sharing the same bandwidth is affordable or possible without using method of amplification or dispersion compensation fiber. The system is designed and simulated using OptiSystm version 7 and OptiGrating version 4.2. The results demonstrate the carrying out of transmission distance of 50 km, where the users' information reach the destination at BER lower than the floor value 10^{-9} for SAC-OCDMA based on MD code. Moreover, the BER of SAC-OCDMA system decreases as the power of the transmitted power increases, where the minimum obtained BER for MD code is10^{-34}, while it is10^{-10} for WH code.

Index Terms—Spectral Amplitude Coding-Optical Code Division Multiple Access (SAC-OCDMA), Fiber Bragg Grating (FBG), Multi Diagonal (MD), Walsh Hadamard (WH), codes, Multiple Access Interference (MAI), Bit Error Rate (BER)

I. INTRODUCTION

At this point in time, the increasing use of the networks simultaneously by the enormous number of subscribers is pushing toward the implementation of the optical code division multiple accesses OCDMA. OCDMA has the ability to contribute in the progress of multimedia services and asynchronous access networks, high levels of transmission information security and huge bandwidth. In addition to that low attenuation and Multiple Access Interference (MAI) led to the widely use in a lot of applications. MAI is generated due to simultaneous transmitting of data by a variety numbers of users through shared channel [1]. Phase induced intensity noise (PIIN), shot noise, and thermal noise are the types of noises that affect the operation of OCDMA system and deteriorate its performance [2]. Because of the overlapping between the spectral components of different users, the PIIN is related to the MAI [3]. The spectral amplitude coding OCDMA (SAC-OCDMA) has been used to get rid of the MAI. SAC technique was first demonstrated by [4]. SAC-OCDMA system is based on the encoding spectrally the light of incoherent laser source to modulate the electrical signal using external modulator as the intensity of different spectral components. Temporal and spectra are the approaches of encoding the OCDMA, that can be arranged into two classifications; Composing the coded optical signal by using optical tapped delay lines to get the temporal OCDMA is the first type of encoding in time domain [4]. On the other hand, shaping the amplitude or the phase of the incoherent laser source is based on the spectral coding of the OCDMA [5], [6]. There are varieties types of codes have been favored in dealing with the SAC-OCDMA to be broadly employed in local area networks. These codes involved an optical orthogonal code, a prime code, an Enhanced Double Weight (EDW) code, a Modified Frequency Hopping (MFH) code, a Modified Quadratic Congruence (MQC) code, a Random Diagonal (RD) code [7], [8], a Modified Double Weight (MDW) code, Walsh Hadamard (WH) code and Zero Cross Correlation (ZCC) code [9], [10]. Nevertheless, all of these codes are limited about some parameter for example the length of the code for OOC and EDW, the limitation of the construction for the MQC and MFH codes, as the weight number increases, the cross correlation increases for the prime, WH and RD codes [9]. WH code has shorter length and zero cross correlation. The best property among all the above codes is the MD code due to zero cross correlation, but it is longer than the WH code [10]. The multi-diagonal code is built form a combination of diagonal matrices. The benefits of this code are; (1) zero cross-correlation code which reject the MAI, where W is the code weight and K is the number of subscriber. (2) getting the easy choice for the parameters W and K over other code. (3) straight forward design. (4) a large number of subscribers in contrast to other types of codes such as MQC or RD codes. (5) no overlapping of users spectrum [11]. Therefore, suitable design of codes is essential to

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eliminate the MAI. The implementation of optimum spectrally encoding is accomplished, where an incoherent SAC-OCDMA system was experimentally illustrated for seven users [12]. Using the dispersion compensation fiber Bragg grating or erbium doped fiber amplifier or utilizing both of them are implemented to improve the BER performance of SAE-OCDMA system with three and seven users [13].

The modeling of coherent SAC-OCDMA was simulated to get the acceptable BER of 10^{-9} for 92 active users at data rate of 16 Gb/s [8]. The simulation of SAC-OCDMA based on MD code for ten users is performed by encoding the splitting optical output of the light emitting diode and the performance was evaluated in term of 10^{-14}BER [11]. The numerical optimization of the FBG response to maximize the achievable capacity of an incoherent SAC-OCDMA system was developed experimentally for seven users [12]. The results of the previous article report that the BER of the system was 2.7 $\times 10^{-8}$ at 622 Mb/s using 9.6 nm optical band for seven users and it is less than 10^{-9} for five users. Good comparison of incoherent SAE-OCDMA system based WH code for 3 and 7 users is simulated with and without DCFBG or EDFA and with both of them [13].

Most of the above former researches are limited to the number of subscribers as three or seven user. If it increases, the BER performance has to be of less than10^{-9}.

This research article aims firstly to investigate the best performance of fifteen users using MD and WH codes to transmit the simultaneous data for users and secondly to carry out comparison of this system performance based on both codes.

This paper is organized as follows. Section two explains the modeling of the SAC-OCDMA system which includes the fiber Bragg grating, the design of the codes generating the spectral wavelength. SAC-OCDMA system design is detailed in section three. Then section four demonstrates and discusses the results that obtained from the simulation of the system. Finally the conclusions are briefly reported in section five.

II. Modeling

The concepts of the SAC-OCDMA, fiber Bragg grating (FBG), and the two types of the spectral amplitude encoding are detailed in this section.

A. SAC-OCDMA System

The broadband SAC-OCDMA systems have been made use of the property of FBG as encoders/decoders, where a certain spectral code is created for each user in the network. SAC-OCDMA transmits the modulated optical signal of the incoherent laser source through a common wide bandwidth optical channel [14]. The FBG is performing in sending data that delivers from the broadband, cuts out all spectral content and reject the frequencies involved in the user's definite spectral code. SAC-OCDMA asynchronously allows the accessing of all users to a common optical bandwidth in network and without synchronization. The received signal is detected using detection technology, where the MAI is removed from the encoded signal using either MD or WH code. These codes have low or zero cross correlation. The final stages are the low pass filter and the BER measure.

B. Fiber Bragg Grating

A fiber Bragg grating is a periodic change of the core's refractive index (RI) along a definite length of an optical fiber created by using an intense Ultra Violet (UV) light source through point-by-point. When light of a broadband source propagates from one side of the fiber, only appropriate wavelength which satisfies Bragg condition will be reflected while the others are transmitted without any loss. Periodic changes in RI reflect the arriving wave forward and valuably form a back reflected power peaked at a center wavelength defined by the grating characteristics [10], [15]. Thus the Bragg wavelength or the center wavelength of the grating (λ_B) can be written by the following formula [16], [17]:

$$\lambda_B = 2n_{eff}\,\Lambda \tag{1}$$

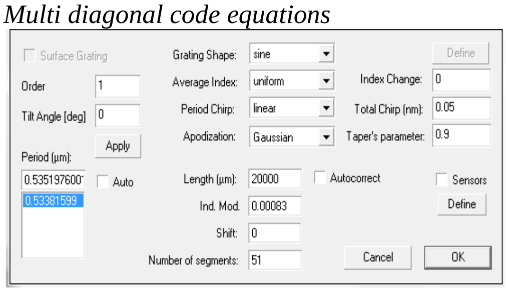
where n_{eff} is the effective refractive index of fiber core and Λ is the grating period.

The arrayed FBG is designed based on WH and MD codes to get the spectral encoding of the transmitted data of fifteen users. The main suitable properties such that the shape and length of the grating, the average index, the apodization, chirp period, number of segments and the index modulation for both codes are chosen as illustrated in the profile 1 for both types of codes.

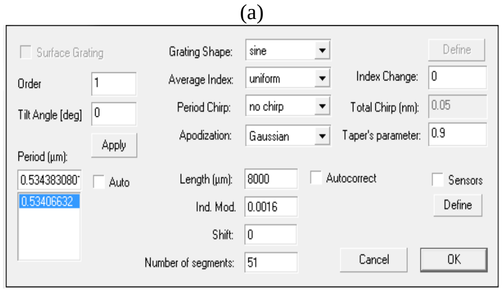
C. The Codes Design of the System

Two types of codes are utilized to encode the data spectrally based on the fiber Bragg grating.

1) Multi diagonal code equations



(a)



(b)

Profile 1 Arrayed FBG Encoder based on (a) Walsh code (b) Multi Diagonal code.

Since the MD code is unipolar code and has zero cross-correlation, therefore, it is appropriate to be employed in SAC-OCDMA systems. The MD code can be typically described by the following parameters (N, W, λ_c), where (N) is the code length (number of total chips), (W) is the code weight (chips that have a value of 1), and (λ_c) is the cross correlation between codewords. To design MD code, identity matrix or unit matrix of size (N) is the (N-by-N) square matrix with ones on the main diagonal and zeros elsewhere as in (2) [10].

$$I_1 = [1],\ I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{2a}$$

$$\mathrm{I_N} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & \dots & 1 \end{bmatrix} \tag{2b}$$

The orthogonal matrix is a square matrix whose rows and columns are of real values and they are considered as unit vectors. That is to say, the matrix A will be orthogonal if its transpose is equal to its inverse matrix.

$$A^T A = A A^T = I \tag{3}$$

On the other hand, $A^T = A^{-1}$ (4)

The MD code has zero cross-correlation means that λ_c=0. The MD matrix consists of a (K×N) matrix where K is the number of rows which present the number of users and N is twice the number of users, code weight (W) should be more than 1 (W=2) [10,11,18]. The rows determine the number of subscribers (K). Notice that the association between code weight (W), code length (N) and number of subscribers (K) can be expressed as in (5)

$$N = W \times K \tag{5}$$

For fifteen users, the code length for each code word are implemented with W=2 and K=15 will be 30. Thus, the MD matrix can be created as in (6)

$$\mathrm{MD} = [\quad]_{15\times 30} \tag{6a}$$

$$\mathrm{MD} = \begin{bmatrix} \text{code word1} \\ \text{code word2} \\ \text{code word3} \\ \text{code word4} \\ \text{code word5} \\ \text{code word6} \\ \text{code word7} \\ \text{code word8} \\ \text{code word9} \\ \text{code word10} \\ \text{code word11} \\ \text{code word12} \\ \text{code word13} \\ \text{code word14} \\ \text{code word15} \end{bmatrix} \tag{6b}$$

Alternatively, each row in the MD matrix determines code word for one of fifteen users, i.e.

MD=

$$\begin{bmatrix}
1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1 \\
0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0 \\
0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0 \\
0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\
0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0
\end{bmatrix}$$

(6c)

2) Walsh hadamard code

This paper aims to study and simulate the performance of fifteen subscribers with the absence of multiple access interference (MAI). Since a large number of subscribers are shared the same bandwidth and trend to obtain the best BER performance, excellent properties (i.e. with a defined cross correlation) of codes should be chosen such as WH code. The Walsh-Hadamard transform is non-sinusoidal, orthogonal transformation technique that decomposes a signal into a set of rectangular or square waves of +1 or-1 values. Walsh-Hadamard transforms are also known as Hadamard. The Hadamard matrix H of order n is defined as an n.n matrix of ones and zeros in which '$H H^T = n I_n$' (I_n is the n.n identity matrix). A Hadamard matrix is similar to n.n matrix of '1s' and '-1s' in which any two apparent rows agree in n/2 positions (and disagree in absolutely n/2 position). Thus the entire matrix can be written without the '1s' and '-1s' and could be written as a matrix of ones and zeros. The Hadamard matrices are existent for any value of n that is a multiple of 4. The case of n of power 2 will be principally concerned, in which these matrices are presented [9]. The construction of long code word is started by small size Hadamard matrix of order 2. If H is a Hadamard matrix of order n, then

'$\begin{bmatrix} +H & +H \\ +H & -H \end{bmatrix}$' is a Hadamard matrix of order $2n$.

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{7}$$

If (-1) is presented by (0) then, $H_2 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$, and H_4 will be as in (8)

$$H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

Then the order of the matrix is increased to 8 and 16 by deriving them from the lower order one as in (9)

$$H_8 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix} \quad (9)$$

$$H_{16} = \begin{bmatrix} 1&1&1&1&1&1&1&1&1&1&1&1&1&1&1&1 \\ 1&0&1&0&1&0&1&0&1&0&1&0&1&0&1&0 \\ 1&1&0&0&1&1&0&0&1&1&0&0&1&1&0&0 \\ 1&0&0&1&1&0&0&1&1&0&0&1&1&0&0&1 \\ 1&1&1&1&0&0&0&0&1&1&1&1&0&0&0&0 \\ 1&0&1&0&0&1&0&1&1&0&1&0&0&1&0&1 \\ 1&1&0&0&0&0&1&1&1&1&0&0&0&0&1&1 \\ 1&0&0&1&0&1&1&0&1&0&0&1&0&1&1&0 \\ 1&1&1&1&1&1&1&1&0&0&0&0&0&0&0&0 \\ 1&0&1&0&1&0&1&0&0&1&0&1&0&1&0&1 \\ 1&1&0&0&1&1&0&0&0&0&1&1&0&0&1&1 \\ 1&0&0&1&1&0&0&1&0&1&1&0&0&1&1&0 \\ 1&1&1&1&0&0&0&0&0&0&0&0&1&1&1&1 \\ 1&0&1&0&0&1&0&1&0&1&0&1&1&0&1&0 \\ 1&1&0&0&0&0&1&1&0&0&1&1&1&1&0&0 \\ 1&0&0&1&0&1&1&0&0&1&1&0&1&0&0&1 \end{bmatrix} \quad (10)$$

III. SAC-OCDMA System Design

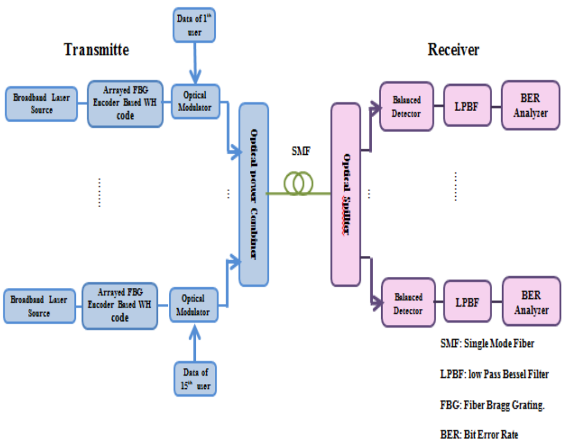


Fig. 1. Block diagram of SAC-OCDMA system

The main components of the SAC-OCDMA system are presented in Fig. 1. Data Transmission of fifteen subscribers is firstly generated by encoding the information of each of them using Walsh Hadamard code. The broadband source output light will produce the addresses of each subscriber in terms of power spectral by exploiting the flexibility property of the arrayed FBG to be functioned as encoder. Thus the multi FBG will filter out a certain range of wavelength except that associated a certain subscriber. The 200 Mb/s signal bit rate data, which is a nonreturn-to-zero (NRZ) pseudo random binary sequence (PRBS) and used to modulate the optical complex spectrum using the Mach-Zehender (MZ) as an external optical modulator. The fifteen signals are combined by power combiner and then propagate through single mode fiber (SMF). The SAC-OCDMA transceiver system is modelled assuming transmitter of broadband white laser source operating at 1550.75 nm wavelength with power of 9.6×10^{-15} W, MZ modulator of 60 dB extinction ratio which generate an optical signal launching through 10 km SMF operating at C band as a reference wavelength with 0.2 dB/km attenuation, 16.75 ps/nm.km dispersion and 0.075 ps/nm^2 km dispersion slop. Using this transmitter, a signal of 200Mb/s NRZhas PIN photo detector receiver of 1 A/W responsivity, 5 nA dark current, and 1×10^{-23} W/Hz thermal nose. Unless otherwise stated, the parameters of the simulated system are set as listed in Table I.

TABLE I. THE PARAMETERS OF SIMULATED SYSTEM.

Component	Parameter	Value
System Layout	Bit rate	10Gb/s
	Sequence length	1024 bits
	Samples per bit	64
	Number of samples	65536
White laser source	Power	1.96e-014W
Optical modulator	Extinction ratio	60 dB
Bessel filter	3 dB bandwidth	0.7 * bit rate (MHz)

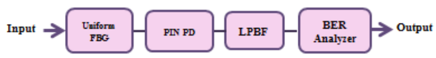


Fig. 2. Detection of SAC-OCDMA based MD code

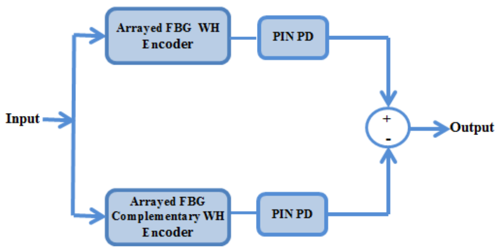


Fig. 3. Block diagram of balanced detector.

The effect of Group velocity dispersion (GVD) and Self phase modulation (SPM) are activated. The received signal is split into fifteen outputs to be detected using detection circuit, where each type of encoding has special technique of detection. The detector of SAC-OCDMA based MD code consists of uniform FBG decoder, PIN detector, low-pass Bessel filter (LPBF), and BER analyzer as shown in Fig. 2. The uniform FBG decoder is set at a certain value of wavelength according to that center wavelength value of the spectral encoding based on MD code at the transmitter. PIN detector whose properties are as aforementioned, is followed the FBG decoder to detect the decoded signal which is then filtered from interfered signal using LPBF of bandwidth equals to 0.7 of the signal bit rate. SAC-OCDMA using WH code is detected by utilizing the balanced detection technique which is detailed in Fig. 3. The received input signal to the balanced detector is spilt into two branches. The upper part consists of array FBG decoder and PIN photo detector in order to decode the complex spectrum, while the lower one decodes the complementary spectral wavelength that is orthogonal to the FBG (i.e. the frequency bins are not involved in the complex one). The two outputs are subtracted, then to overcome the MAI completely, LPBF has the same bandwidth as that used for detection of MD system. The BER performance is measured using BER analyzer.

However, the design of spectral amplitude coding to generate different orthogonal codes for fifteen users is simulated using OptiGrating software package version 4.2. The properties of array FBG is designed for MD code by setting the parameters of eight arrayed FBGs components as displayed in profile 1. The basic of orthogonal encoding is performed using Walsh-Hadamarad code, where the values of the center wavelength of the grating and the corresponding calculating period using equation (1) are shown in Table II. Using OptiGrating software, the complex power spectral density of the first, seventh, and fifteenth users are illustrated as shown in Fig. 4, where the transmitted signal in red color and reflected in blue color. The waveform of high level amplitude in dB (blue) presents the wavelength of the FBG that is used to encode each user using Walsh code. Each (-1) in the Hadamard matrix is represented by one of the wavelength of the eight array FBG so each code word is a waveform of eight wavelength of different values as given in Table III. The complementary complex spectrum is used to generate the wavelengths of eight array FBGs which are based on the bits of (+1) in Walsh Hadamard matrix. The addresses of the users are in terms of zeros '0' and ones '1', where '1' is presented by wavelength (i.e. the center wavelength of FBG). The character 'F' means FBG, for example the first user has the spectral code 'F1-F3-F5-F7-F9-F11-F13-F15, means that the FBG's are the first, the third, the fifth, seventh, the ninth, the eleventh, the thirteenth, and the fifteenth.

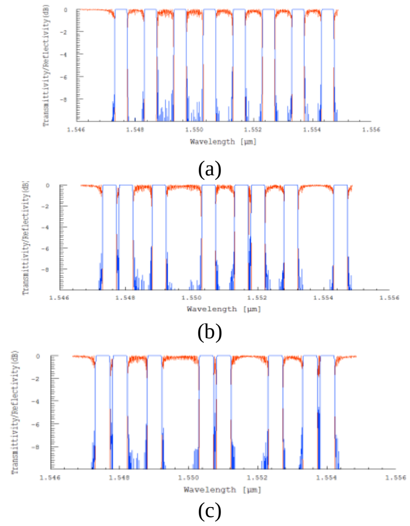


Fig. 4 Transmission and Reflection spectral density of the Array FBG in (dB) based on WH for (a) user 1, (b) user 7, (c) user 15.

IV. Results and Discussionl

The BER performance of SAC-OCDMA system is implemented using OptiSystem version 7.0 package simulator and exporting of the spectral amplitude encoding for fifteen users is simulated using OptiGrating 4.2. The system is operated at bit rate of 3 Gb/s and the data of fifteen users is simultaneously transmitted along distance of 10 km through optical fiber. The obtained results of the system are demonstrated and discussed in the following subsections.

A. Results of Spectral Amplitude Encoding and Eye Pattern

The difference in the spectral wavelength using MD and WH codes of SAC-OCDMA system is obviously seemed in the demonstration of these spectral that obtained by the OptiSystem simulator in Fig. 5 and Fig. 6, using MD and WH respectively. Fig. 7 and Fig. 8 clarify how the BER performance of SAC-OCDMA system based on MD code is more valuable than that system built from WH code, where the highest values are reached to $10^{-30}$and 10^{-9} for MD and WH codes, respectively.

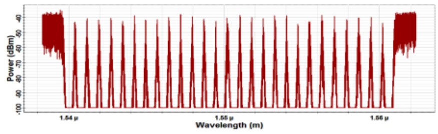
TABLE II. THE CENTER WAVELENGTH CORRESPONDING TO THE PERIOD OF GRATING.

Period of Grating (nm)	Wavelength(nm)
532.786800106	1547
532.959001060	1547.5
533.131200106	1548
533.303400106	1548.5
533.475600106	1549
533.647800106	1549.5
533.820000106	1550
533.992200106	1550.5
534.164400105	1551
534.336600106	1551.5
534.508800106	1552
534.681000106	1552.5
534.853200106	1553
535.025400106	1553.5
535.197600106	1554
535.369800211	1554.5

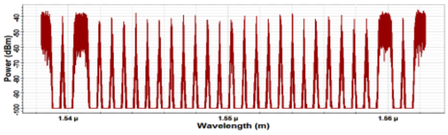
TABLE III. HADAMARD MATRIX OF EIGHT ARRAY FBGS.

Seq.	Address of the user	wavelength
1	1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0	F1-F3-F5-F7-F9-F11-F13-F15
2	1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0	F2-F3-F6-F7-F10-F11-F14-F15
3	1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1	F1-F2-F5-F6-F9-F10-F13-F14
4	1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0	F4-F5-F6-F7-F12-F13-F14-F15
5	1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1	F1-F3-F5-F6-F9-F11-F12-F14
6	1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1	F2-F3-F4-F5-F10-F11-F12-F13
7	1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0	F1-F2-F4-F7-F9-F10-F12-F15
8	1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0	F8-F9-F10-F11-F12-F13-F14-F15
9	1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1	F1-F3-F5-F7-F8-F10-F12-F14
10	1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1	F2-F3-F6-F7-F8-F9-F12-F13
11	1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0	F1-F2-F5-F6-F8-F11-F12-F15
12	1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1	F4-F5-F6-F7-F8-F9-F10-F11
13	1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0	F1-F3-F4-F6-F8-F10-F13-F15
14	1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0	F2-F3-F4-F5-F8-F9-F14-F15
15	1 0 0 1 0 1 1 0 0 1 1 0 1 0 0	F1-F2-F4-F7-F8-F11-F13-F14

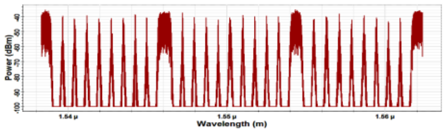
*: sequence of the users



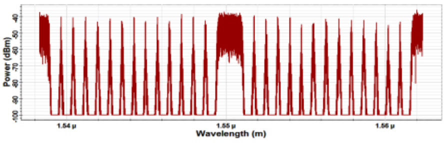
(a)



(b)

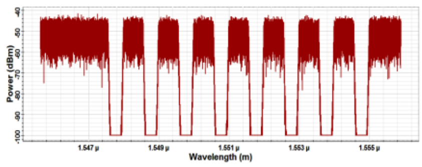


(c)

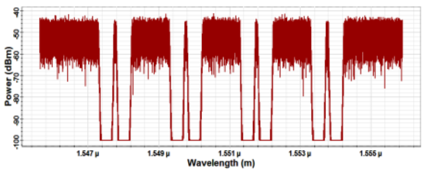


(d)

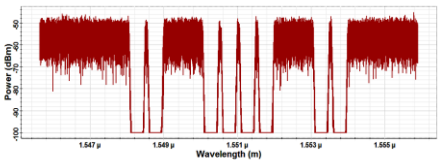
Fig. 5. Power spectral density of the array FBG based on MD codefor (a) 1st user (b) 3rd user (c) 10th user (d)15th user.



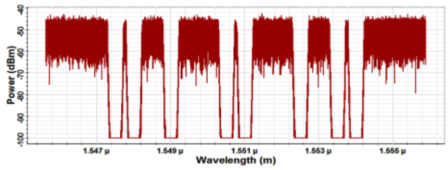
(a)



(b)

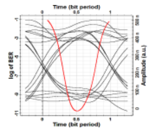


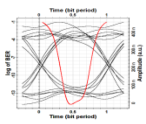
(c)

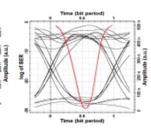


(d)

Fig. 6. Power spectral density of the array FBG based on WH code for (a) 1st user (b) 3rduser (c) 10th user (d) 15th user.

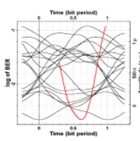


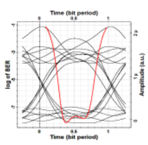


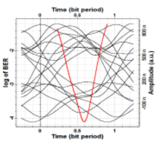


(a) (b) (c)

Fig. 7. Eye pattern of SAC-OCDMA based on MD code for (a) 2nd user, BER=10^{-11} (b) 8th user, BER=10^{-15} (c) 13th user, BER=10^{-30}.





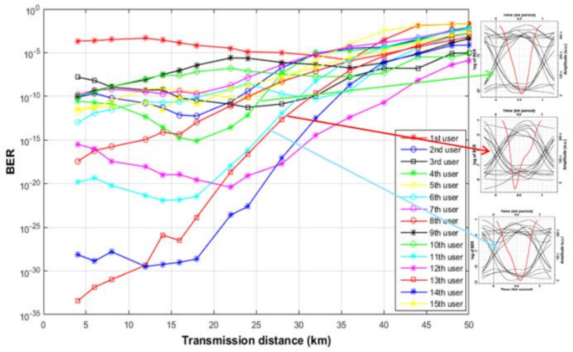


(a) (b) (c)

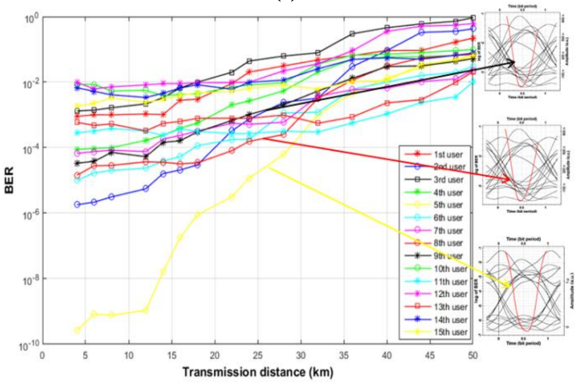
Fig. 8. Eye Pattern of SAC-OCDMA Based on WH code for (a) 1st user, BER=10^{-3}, (b) 5th user, BER=10^{-9}, (c) 7th user, BER=10^{-4}.

B. Effect of Transmission Distance

The information of the fifteen users of incoherent SAC-OCDMA system shares the same channel bandwidth, which propagates through SMF operating at C band wavelength (i.e. low attenuation and the spreading of the transmitted optical pulses increased as the distance of transmission is increased). This clearly seems in Fig. 9, since the dispersion increases as the transmission is extended to longer distance and causes the interference which produced from the broadening of multiple optical pulses sending simultaneously through the fiber and generating MAI. The BER is lower at the short distance, but it will be higher as the fiber length enlarges as displayed in Fig. 9. The performance of broadband SAC-OCDMA using MD code (shown in part (a)) is better than that of using WH code (in (b) of the Fig. 9), this trend due to zero cross-correlation property of MD code. The values of BER of most of the users are around (10^{-10}-10^{-20}) and (10^{-6}-10^{-2}) using MD code and WH code, respectively.



(a)

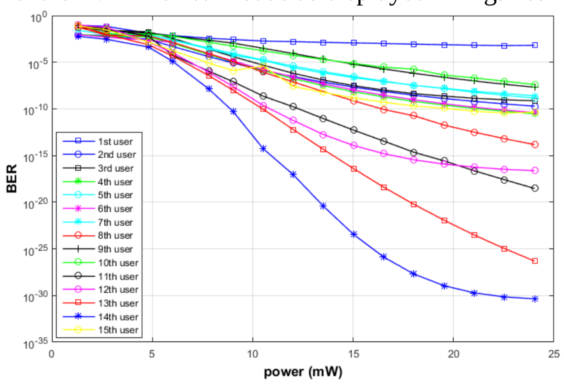


(b)

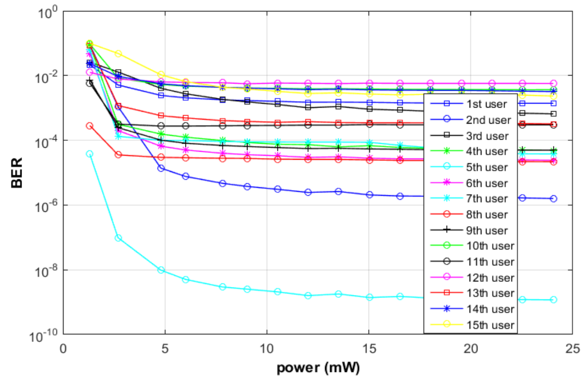
Fig. 9. Transmission distance of SAC-OCDMA using: (a)MD Code, (b) WH Code.

C. Effect of Input Power

The power of the incoherent source (white laser source) is one of the factors that affect the operation and performance of SAC-OCDMA system. Our proposed system is designed for sharing fifteen users the same bandwidth simultaneously, as consequence the interference among their data will appear even if it is of small amount which produces dispersion effect on the launched signals through the fiber link. Because of the non-linear effects of the optical link such as group velocity dispersion and cross-phase modulation and self-phase modulation which are increased with increasing the transmitted power. The BER of SAC-OCDMA system decreases as the power of the transmitted power increases where the minimum obtained BER for MD code is10^{-34}, while it is 10^{-10} for WH code as displayed in Fig. 10.



(a)



(b)

Fig. 10. BER versus transmitted power of SAC-OCDMA system using: (a) MD Code, (b) WH code.

D. Effect of Number of the Users

This section demonstrates and discusses the performance of the incoherent SAC-OCDMA system for both codes against varying the number of users with keeping the signal bit rate for each user and the transmission distance at 200 Mb/s and 10 km, respectively. Table IV lists the BER performance for each user starting the operation of the system contains on three users, then for four, five, and so on until it reaches to fifteen users. Since the MD code has zero cross-correlation and its simplicity of the design allows a large number of users occupy a common media of communication, the BER performance of the system using this code (as displayed in Table IVa), is of higher quality than that using WH code as displayed in (Table IVb). Regardless of the orthogonality between the spectral components of WH code but the grating wavelengths are too close to each other. Furthermore, the MD system contains a small number of users, the BER approximately is within the range of 10^{-34}, to10^{-11} and as a large number of users share the same optical fiber, the range will be around 10^{-12}, to 10^{-10}. Because of the increasing the dispersion and the nonlinear effect of the optical fiber will produce the MAI between the data of fifteen user, as consequence, the BER is also of higher values as the number of the users increases for WH code. Then the range of BER is (10^{-14}, to 10^{-4}) and (10^{-5}, to 10^{-3}) for small number of users and large number of users, respectively.

TABLE IV(A). BER OF DIFFERENT NUMBER OF USERS FOR SAC-OCDMA SYSTEMS BASED MD CODE.

User	BER of 3 users system	BER of 4 users system	BER of 5 users system
1st	1.405×10^{-14}	4.338×10^{-14}	2.380×10^{-13}
2nd	7.961×10^{-22}	1.548×10^{-20}	5.082×10^{-22}
3rd	3.721×10^{-24}	2.853×10^{-12}	4.733×10^{-11}
4th		1.913×10^{-33}	9.140×10^{-22}
5th			4.530×10^{-34}

TABLE IV(A). CONT.

User	BER of 6 users system	BER of 7 users system	BER of 8 users system
1st	9.935×10^{-11}	2.018×10^{-9}	1.008×10^{-8}
2nd	4.841×10^{-19}	5.267×10^{-18}	7.545×10^{-17}
3rd	3.696×10^{-10}	1.125×10^{-8}	8.516×10^{-9}
4th	2.194×10^{-19}	6.815×10^{-18}	3.814×10^{-18}
5th	2.161×10^{-14}	1.151×10^{-13}	9.825×10^{-13}
6th	1.405×10^{-34}	2.041×10^{-15}	3.060×10^{-17}
7th		1.997×10^{-18}	1.688×10^{-13}
8th			4.834×10^{-18}

TABLE IV(A). CONT.

User	BER of 9 users system	BER of 10 users system	BER of 11 users system
1st	2.103×10^{-8}	4.625×10^{-7}	3.106×10^{-6}
2nd	9.635×10^{-18}	4.332×10^{-16}	3.943×10^{-16}
3rd	2.636×10^{-9}	3.263×10^{-9}	1.558×10^{-10}
4th	4.817×10^{-17}	5.377×10^{-16}	9.632×10^{-15}
5th	7.543×10^{-13}	4.609×10^{-13}	3.646×10^{-13}
6th	1.239×10^{-17}	8.534×10^{-16}	3.420×10^{-15}
7th	4.042×10^{-11}	1.858×10^{-12}	6.170×10^{-13}
8th	6.961×10^{-20}	2.964×10^{-21}	6.495×10^{-25}
9th	9.337×10^{-31}	5.888×10^{-15}	2.237×10^{-15}
10th		5.902×10^{-23}	8.596×10^{-16}
11th			3.935×10^{-22}

TABLE IV(A). CONT.

User	BER of 12 users system	BER of 13 users system	BER of 14 users system	BER of 15 users system
1st	4.688×10^{-5}	1.000×10^{-4}	1.893×10^{-4}	4.573×10^{-4}
2nd	3.075×10^{-14}	4.152×10^{-13}	1.323×10^{-12}	4.980×10^{-11}
3rd	3.193×10^{-15}	3.953×10^{-9}	3.474×10^{-9}	5.060×10^{-10}
4th	7.221×10^{-15}	1.174×10^{-13}	3.573×10^{-13}	4.621×10^{-12}
5th	3.467×10^{-12}	1.010×10^{-11}	7.777×10^{-11}	2.381×10^{-10}
6th	2.156×10^{-14}	2.881×10^{-13}	1.093×10^{-12}	8.457×10^{-12}
7th	1.544×10^{-12}	4.958×10^{-11}	5.550×10^{-10}	6.230×10^{-10}
8th	7.726×10^{-25}	1.045×10^{-18}	3.977×10^{-17}	2.141×10^{-16}
9th	5.876×10^{-12}	1.639×10^{-11}	7.498×10^{-11}	2.975×10^{-9}
10th	1.482×10^{-14}	1.675×10^{-11}	2.631×10^{-10}	3.651×10^{-9}
11th	5.969×10^{-36}	6.544×10^{-35}	4.715×10^{-30}	9.911×10^{-22}
12th	1.729×10^{-28}	1.643×10^{-27}	1.646×10^{-24}	1.311×10^{-17}
13th		2.089×10^{-35}	1.275×10^{-31}	2.496×10^{-30}
14th			5.073×10^{-74}	1.161×10^{-30}
15th				8.445×10^{-12}

TABLE IV(B). BER OF DIFFERENT NUMBER OF USERS FOR SAC-OCDMA SYSTEMS BASED WH CODE.

User	BER of 3 users system	BER of 4 users system	BER of 5 users system
1st	2.650×10^{-47}	2.678×10^{-41}	1.282×10^{-32}
2nd	2.918×10^{-16}	2.255×10^{-6}	8.426×10^{-6}
3rd	1.127×10^{-24}	2.915×10^{-10}	1.837×10^{-9}
4th		1.490×10^{-22}	6.289×10^{-17}
5th			3.955×10^{-16}

TABLE IV(B). CONT.

User	BER of 6 users system	BER of 7 users system	BER of 8 users system
1st	3.354×10^{-23}	6.125×10^{-14}	5.040×10^{-6}
2nd	1.496×10^{-5}	3.900×10^{-6}	5.716×10^{-5}
3rd	7.253×10^{-7}	8.120×10^{-9}	1.063×10^{-7}
4th	3.529×10^{-15}	1.815×10^{-24}	1.754×10^{-10}
5th	7.719×10^{-33}	8.230×10^{-25}	2.194×10^{-20}
6th	9.625×10^{-10}	1.577×10^{-7}	4.318×10^{-10}
7th		1.896×10^{-5}	1.198×10^{-5}
8th			1.237×10^{-7}

TABLE IV(B). CONT.

User	BER of 9 users system	BER of 10 users system	BER of 11 users system
1st	3.926×10^{-5}	1.749×10^{-5}	7.471×10^{-5}
2nd	2.525×10^{-4}	3.089×10^{-5}	2.324×10^{-5}
3rd	1.621×10^{-7}	1.100×10^{-6}	3.349×10^{-8}
4th	1.877×10^{-9}	1.606×10^{-8}	3.822×10^{-7}
5th	8.472×10^{-18}	7.114×10^{-16}	4.122×10^{-17}
6th	4.261×10^{-10}	1.263×10^{-7}	2.290×10^{-6}
7th	5.705×10^{-6}	6.784×10^{-6}	2.265×10^{-6}
8th	1.286×10^{-6}	3.522×10^{-7}	2.062×10^{-6}
9th	2.042×10^{-8}	5.426×10^{-7}	1.831×10^{-8}
10th		9.780×10^{-3}	8.942×10^{-3}
11th			1.200×10^{-3}

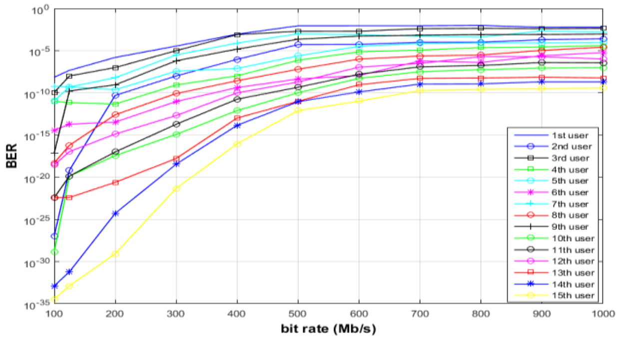
TABLE IV(B) CONT.

User	BER of 12 users system	BER of 13 users system	BER of 14 users system	BER of 15 users system
1st	5.689×10^{-5}	6.205×10^{-5}	6.395×10^{-4}	1.365×10^{-3}
2nd	7.015×10^{-5}	2.441×10^{-4}	8.124×10^{-5}	1.565×10^{-6}
3rd	2.834×10^{-7}	2.426×10^{-7}	2.260×10^{-4}	6.373×10^{-4}
4th	1.507×10^{-7}	8.544×10^{-7}	3.681×10^{-5}	4.681×10^{-5}
5th	1.692×10^{-12}	1.069×10^{-12}	1.087×10^{-9}	1.087×10^{-9}
6th	4.441×10^{-6}	2.104×10^{-5}	3.889×10^{-5}	2.371×10^{-5}
7th	3.749×10^{-8}	2.505×10^{-7}	5.830×10^{-6}	7.593×10^{-5}
8th	6.207×10^{-7}	1.626×10^{-6}	1.391×10^{-5}	2.702×10^{-5}
9th	7.987×10^{-7}	4.216×10^{-7}	2.490×10^{-6}	5.321×10^{-5}
10th	7.653×10^{-3}	6.899×10^{-3}	5.787×10^{-3}	3.662×10^{-3}
11th	6.016×10^{-5}	1.276×10^{-4}	6.952×10^{-5}	3.194×10^{-4}
12th	1.021×10^{-28}	4.863×10^{-3}	6.224×10^{-3}	5.748×10^{-3}
13th		1.033×10^{-7}	2.620×10^{-4}	3.258×10^{-3}
14th			1.453×10^{-4}	3.403×10^{-3}
15th				2.421×10^{-3}

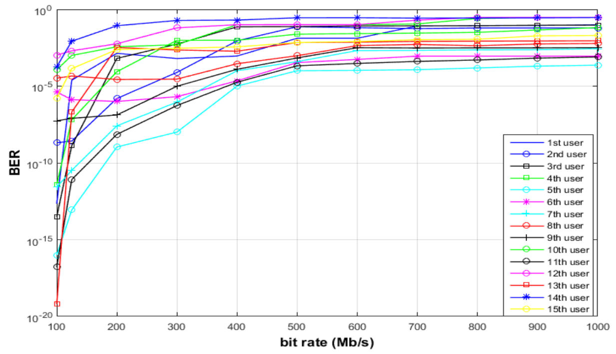
E. Effect of Bit Rate of the System

The broadband SAC-OCDMA system using the two types of codes is operated at different values of bit rate to transmit the data of fifteen subscribers through a constant distance of 10 km. Fig. 11 parts a and b shows the BER system performance as a function of bit rate using MD and WH codes, respectively. For both codes, the BER increases gradually at lower bit rate, then slowing varies until it becomes stable. However, the advantages of the MD code; such as the flexibility, the ease in the design, the absence of the overlapping, and the zero cross-correlation make the SAC-OCDMA to be the most attractive quality of encoding. Utilizing the two codes and approximately for all the users, as the bit rate is raising from 100 to 500 Mb/s the BER increases. Furthermore the curves are smaller increasing from (500 to 700) Mb/s and will be constant within the range of 10^{-6} to 10^{-3} BER up to 1 Gb/s. From Fig. 11b, using WH code the

BER curves will be stable around 10^{-3} to 10^{-1} as the bit rate is raising from 500 Mb/s to 1 Gb/s.



(a)



(b)

Fig. 11. BER Versus the bit rate of SAC-OCDMA system using: (a)MD Code, (b) WH Code.

V. Conclusion

The objective of our research is to investigate the performance of broadband SAC-OCDMA system for fifteen users based MD code which is compared with that of WH code without using any type of amplification or dispersion compensation fiber. Generally, the results reveal that the system with MD spectral amplitude encoding is more valuable than that using WH code. However, the values of BER for most users with MD are superior to that with WH, this trend due to its great features whose essential one is the zero cross-correlation. Moreover, the system of fifteen users based MD code; it is observed that the BER of most users sharing a common bandwidth is lower than 10^{-9}, which is more valuable than that utilizing WH code.

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