Optical Engineering

OpticalEngineering.SPIEDigitalLibrary.org

Review on developments in all-optical spectral amplitude coding techniques

Simarpreet Kaur
Simranjit Singh

SPIE.

Simarpreet Kaur, Simranjit Singh, "Review on developments in all-optical spectral amplitude coding techniques," *Opt. Eng*. **57**(11), 116102 (2018), doi: 10.1117/1.OE.57.11.116102.

Optical Engineering 57(11), 116102 (November 2018)

REVIEW

Review on developments in all-optical spectral amplitude coding techniques

Simarpreet Kaur* **and Simranjit Singh**
Punjabi University, Department of Electronics and Communication Engineering, Patiala, Punjab, India

Abstract. The focus of this work is to consolidate a review of accomplished research in the field of optical code division multiple accesses (OCDMA), to outline the state-of-the-art comparison, and to recognize the prominent trends as well as limitations. Code division multiple access (CDMA) has prospered as a vital solution for numerous applications such as cellular mobile communication-based wireless network technology and wired/wireless local area networks that include areas of unlicensed industry, medicine, and science. Due to the commercial utilization of the various advantages of CDMA, it has raised the matter of whether optical technology reliant communications provide the noteworthy advantages to optical networks as well as what are the technologies that facilitate optical chip-based (code division) networks. Aforementioned matter has been addressed in the context of the incorporation of OCDMA in the systems through several experiments of laboratory-based test-bed investigations, field trials, and simulation analysis of multiple users in the recent research works. The performance of OCDMA has an edge over wavelength division multiplexing and offers an unmatched capacity that is seen through simulations. To cater the explosive expansions in internet application, different spectral amplitude codes have been proposed till now. We present a review of the different spectral amplitude codes based on the reported works in spectral amplitude code OCDMA systems. For the purpose of state-of-the-art comparison, parameters considered are data speeds, advanced modulation formats, bit error rate, extinction ratio, decision algorithms, photonic efficiencies of photodetectors, frequency bands, signal-to-noise ratio, forward error correction, photodetector noises, etc., and simulations are carried out in similar input environments. We explore the advantages/limitations of the spectral amplitude codes, recent progress in the technology, practical works on spectral amplitude coding (SAC) throughout the world, encryption–decryption techniques, all-optical methods, literature comparison, future scope, and applications of the SAC-OCDMA codes. [DOI: 10.1117/1.OE.57.11.116102]

Keywords: spectral amplitude coding optical code division multiple access; multiple access interference; enhanced double weight code; multidiagonal code; modified double weight code; Walsh–Hadamard code; pulse width broadening.

Paper 180512V received Apr. 22, 2018; accepted for publication Oct. 23, 2018; published online Nov. 20, 2018.

1 Introduction

Optical code division multiple access (OCDMA) system is a future technology to eliminate the problem of traffic growth and multiple user access on the internet in optical networks.[1] Enhanced information security is often said to be inherent in OCDMA technology due to its coded nature. If multiple codes with long code length function all together, it is nearly impossible for an eavesdropper to get any significant information because of multiple access interference (MAI) caused by all the transmitting users, and also it is difficult to jam the noise like OCDMA-encoded signal that the literature survey revealed otherwise.[2,3] In the last few years, studies discovered that OCDMA systems are vulnerable to eavesdropping and jamming attacks. The physical layer of the OCDMA network can be attacked by an eavesdropper to intercept the data by launching an interferer signal, which will jam the system. The interferer signal can be selected by an eavesdropper through cross correlation between code words of authentic users.[4,5] A jamming attack can easily manipulate information being transmitted if the signals have the same frequency band as of the data signal. In addition, the increase in the number of attacks as well as in diverse methods of the attacks is becoming more difficult to tackle, and it further makes information security a crucial issue in OCDMA networks.

The explosive increase in information exchange on the Internet ameliorates the transmission of sensitive and private data through networks reliant on optical fibers. In high-speed optical networks, the most vital multiple access technique practiced is spectral amplitude coding (SAC) because the absence of any frequency synchronizations and dedicated time, which makes it a flexible coding scheme. Also the performance of the system depends on the number of coded users, which successively rely on the cardinality of the OCDMA code taken into consideration. The number of users can be increased in OCDMA systems by employing the codes with large cardinality. But increase in the code cardinality with enhanced properties is a problematic task in OCDMA systems. Also extensive information exchange on the optical networks leads to network security breaching of confidential information, which, in addition, increase by easily tapping the signal with low-priced equipments. Network security in physical layer, therefore, emerges as compelling request in future generation optical fiber-based networks. OCDMA is a potential technology to remove the troubles of ever-increasing data traffic as well as multiple end users in the networks. Because of the coded nature of the OCDMA systems that are perceived as the secured systems and if more than one user operates at the same time, it increases the security of the system against the eavesdropper

---

*Address all correspondence to: Simarpreet Kaur, E-mail: kaursimarpreet1291@gmail.com

and jammer. In recent times, numerous research studies revealed that code division systems are susceptible to attacks such as noise interference from an unauthorized user and eavesdropper. Network security can be breached by an eavesdropper with the number of combinations of the chips based on metadata, and a jammer signal can alter the authorized user information by interfering it with false data at the same frequency band as the authentic user. Therefore, problem of network security breaching is a prominent shortcoming in the OCDMA systems.

The performance of the OCDMA system is limited by shot noise, beat noise, thermal noise, MAI, and cross correlation existing among multiple users, out of which the dominating source of noise is MAI.[6,7] Numerous one-dimensional code schemes have been designed and implemented in the literature review to eliminate the MAI among multiple users but comes with various shortcomings. Various one-dimensional code schemes such as Walsh–Hadamard code, multidiagonal (MD) code, diagonal double weight (DDW) code, modified double weight (MDW) code, and enhanced DDW code have been implemented in the literature survey. Walsh–Hadamard code employs the balanced detection scheme. The code construction cannot be implemented according to the precise number of users and as the code length increases, the cross correlation also increases.[8–12] In DDW code, the code length does not enhance abruptly with boost in number of users but the cross correlation will always occur between the two users.[13–16] MDW code is basically a customized adaptation of the double weight code, where the weight of the code is any even number larger than 2. Better code weight increases the signal-to-noise ratio of the received signal.[17–19] MD codes employ data and code segment to produce the code; along with it there exists a trade-off between the cross correlation and the length of the code.[20–24] Enhanced double weight (EDW) code had a limitation of the code weight of any odd number >1, which was further eliminated with the usage of the algorithms. Thus now there is a flexibility to choose any code weight to construct a basic matrix. EDW code is able to deliver better security with short code length, but there exists a cross correlation of 1.[25–30]

Extensive literature survey makes us familiar with the challenges in the SAC-OCDMA systems, and it is perceived that there is peer pressure on the aforementioned system to deliver and cater high data rate services along with large cardinality due to a large number of users. Generally, the performance of the systems depends on the nature of OCDMA code and number of users. MAI problems can be coped up by designing optimal codes and deploying state–of-the-art architectures to support large end users. Different codes have been demonstrated to eliminate the MAI in OCDMA systems but they suffered from the limitations by various ways. Some of the limitations are large code lengths, variable cross correlation, and restriction of the code to design it for any number of users. Major problems in the SAC-OCDMA codes are: (i) bandwidth inefficiency, (ii) differential/subtraction detection, (iii) code generation complexity, and (iv) cross correlation. Therefore, in order to enhance the potential of the current optical systems, further work requires to be accomplished with the architectures reliant on enormous available network topologies by incorporating enhanced codes. So far, the performance of OCDMA systems by employing effective coding is validated at low bit rates and wide frequency spacing. Hence, it is required to address the wavelength division multiplexing (WDM) systems with compatible OCDMA systems that can serve high data rate services and facilitate a large number of users with acceptable BER.

Practical scenarios and implementations have been reported in the literature, and we have listed some of the practical works for different SAC-OCDMA codes. Walsh–Hadamard codes were implemented on hardware as well as on simulation in IIT Delhi, India.[31] The author presented that orthogonal Walsh–Hadamard codes are error correcting codes and generally incorporated in the error free systems. This paper explores modeling of Walsh codes and Hadamard matrices as a finite orthogonal vector space. Theoretical studies on WH codes are carried out in France for wireless body area network (WBAN) that caters health care services.[32] Basic work was here to suppress the interference using WH codes in WBANs. The Walsh–Hadamard code design using optical nonlinear material was presented in India using nonlinear optics. Nonlinear optics has augmented attention for all-optical signal processing in high-speed photonic networks due to its inherent attributes of polarization. The performance of helicopter satellite communication using Walsh–Hadamard code under the periodic blockage environment was investigated in Vietnam.[33] WH codes are mainly preferred for parameter evaluation and harmonization in a multibeam state for video broadcasting via satellites due to their orthogonality property, Czech Republic.[11] In Taiwan,[12] a hardware implementation and simulation of unipolar and bipolar WH codes was done and results revealed that the BER in case of bipolar coding of WH exhibited better results than unipolar coding. Performance analysis of band-limited baseband synchronous code division with the orthogonal-independent component analysis spreading sequences was compared with Walsh–Hadamard sequences, and practical was also accomplished in the Next Generation Mobile Communications Laboratory, RIKEN, Japan.[34] An appropriate decoding technique for SAC-OCDMA-based secured distributed vibration sensor was investigated and practically implemented in Ref. 35. Walsh–Hadamard codes have some limitations, and therefore, other SAC-OCDMA codes are also demonstrated over the globe. The performance of DDW codes was studied analytically to raise the presentation and cardinality of SAC-OCDMA systems in Malaysia.[36] BER results revealed that single photodetector in DDW provides good performance. MDW codes were introduced by the enhancement of DDW codes as presented in Ref. 13 and analyzed the SAC-OCDMA system performance using MDW code with NAND detection technique with theoretical study and simulation experiments. Hybrid subcarrier multiplexing incorporating multidiagonal codes OCDMA technology was explored mutually, i.e., mathematically and by simulation in Ref. 37. In Refs. 23 and 38, the work was done on the theoretical evaluation of MD codes and results revealed that these codes provide better results than existing SAC-OCDMA codes of that time.

Section 1 elaborates the introduction of optical code division multiplexing, SAC. The remainder of this paper is structured as follows. Section 2 explains various coding techniques. Section 3 describes the basic code construction of the WH code, MD code, MDW code, and EDW code.

Section 3 explains the basic generalized simulation setup involved in the construction code in the simulatory environment. Section 4 discusses working model of OCDMA codes and the results received by comparing aforementioned codes in terms of BER, SNR, quality of the received signal, applying different algorithms, variation of the distance, and data rates in the similar simulatory environment. A zero cross-correlation code is described and its code construction is given in Sec. 5. Recent trends and technologies used in OCDMA are mentioned in Sec. 6. Section 7 explains future scope and Sec. 8 concludes this paper.

2 Different Encoding Techniques

With the rapid increase in the bandwidth hungry internet services, there is augmentation of high data rate demands. Optical code division came out to be a premier and attractive solution for high data rate supported optical communication systems. Numerous research articles were reported to enhance the bit rate of the OCDMA systems. However, due to optical to electrical and electrical to optical conversion, a bottleneck is introduced in the systems that limit the high data rate supportability. In order to increase the potential of the OCDMA systems, all-optical systems are the prominent and ultimate solution to cater the ever-increasing demands. An all-optical system with conversion of non-return to zero into incoherent OCDMA system is proposed in Ref. 39 using optical nonlinear effects such as cross gain modulation in semiconductor optical amplifier. All-optical processing was a key factor to enhance the optical signal-to-noise ratio of the system, and there was an increment of 20 in optical signal to noise ratio. In Ref. 40, the work was accomplished on an all-optical system with the incorporation of time-wavelength OCDMA chips in ring networks. The system rate was ultrafast and was based on asymmetrical demultiplexer. Demonstrated results revealed that the system had the capability to support 2.5 Gb/s data rate and facilitated the growth of all-optical OCDMA add drop multiplexers. With the developments of OCDMA systems, there exists other limitations of system security and is an important issue to be addressed. Physical layer security has attracted much attention because of the increase in network security breaching issues. Physical security prospective was outlined in Ref. 41 and described the various encoding schemes in OCDMA. All-optical data encryption is a potential and necessity for providing an unprecedented degree of security. This encryption in all-optical domain was done with different methods such as using all-optical logic gate, data hiding, cryptography, and multicode keying (MCK). The advanced coding schemes are explained in Sec. 5.

2.1 *Spectral Amplitude Coding*

SAC is a prominent OCDMA technology that rapidly grows in all-optical processing. It provides an ultimate solution to cope with MAI by incorporating in-phase cross-correlation codes. Basically, in order to eliminate MAI as well as to keep signal at their fixed chip slots, all the codes need high autocorrelation and low cross correlation. In SAC-OCDMA systems, wavelengths are encrypted based on the blocking and allowing process as permitted by code matrix. In other words, wavelengths are encrypted according to code signature. SAC reliant on code sequences with particular properties to uphold a suitable degree of orthogonality between coded signals of different users. Basically, transmitter unit of the SAC-based systems has binary data generator, optical source, pulse generator, modulators, power splitters, and multiplexers. In order to slice different frequencies from wideband spectrum (given by light source typically light emitting diode), fiber Bragg gratings (FBGs) are employed in the transmitter for wavelength selection according code matrix. Similarly, selecting particular user's code chips, again FBGs are incorporated followed by basic receiver unit, which consists of photodetector, electrical filters, and error detectors. All the users share same bandwidth of fiber optic. Detection of SAC codes mainly accomplish through balanced detection scheme, in which more than one photodetector is employed and it has advantage to quell MAI by selecting only authentic user chips of respective code. It takes the advantage that it is appropriate for point to multipoint communication by spending low cost and provides cost efficient solution to the network.

3 Code Construction

Various code schemes are used such as Walsh–Hadamard code, MD code, MDW code, and EDW code, to encrypt and decrypt the data in the SAC-OCDMA system. These codes are constructed using certain logical patterns, which are known to the authorized users only.

3.1 *Walsh–Hadamard Code*

CDMA communication system can make use of Hadamard codes in a number of ways. The Hadamard code can be defined as a row of Z element of the $Z \times Z$ Hadamard matrix H_M, which is madeup of 0,1 binary values, where $Z = 2^M$ is engendered by the foundation matrix, which is as follows:

$$H_1 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}, \tag{1}$$

For $M = 2$, the Hadamard matrix is formed as shown beneath:

$$H_2 = \begin{bmatrix} H_1 & H_1 \\ H_1 & H_1 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix}.$$

Unipolar Hadamard matrix H_M has the following properties:

a. M has to be more than 2.
b. Code length $N = 2^M$.
c. Code weight $W = 2^{M-1}$.
d. User $K = 2^M - 1$ (The case $K = 1$ has been expelled as the row of the unipolar Hadamard matrix is all ones).
e. The ratio of $\frac{w}{\lambda} = 2$ (i.e., λ is the cross-correlation properties).

In $Z \times Z$ Hadamard matrix, every row is different from other row by just $Z/2$ positions. So all the rows apart from the first row contains $Z/2$ (0)'s and $Z/2$ (1)'s. This

Table 1 State-of-the-art comparison of Walsh–Hadamard codes.

Reference	Work	Bit rate	Channel spacing	Cross correlation	Modulation	All-optical operation	Q-factor/BER
Yen and Huang[42]	Walsh–Hadamard OCDMA system with data hiding	2 Gb/s	100 GHz	N/2	BPSK	FBGs for coding, decoding, and optical steganography	10^{-17} (BER) at noise power −28 dBm
Yen et al.[34]	Walsh–Hadamard codes	200 Mb/s	50 GHz	N/4	Unipolar and bipolar coding	Subtractions-based detection with FBGs	10^{-45}, 10^{-12} BER at 0 dBm for bipolar and unipolar system, respectively
Bharti et al.[43]	Walsh–Hadamard code design and two-code keying for dispersion reduction	200 Mb/s	100 GHz	N/2	NRZ	All-optical two-code keying	Q-factor of 9.7 was observed at 80 km
Hamzeh and Kavehrad[44]	Complementary Walsh–Hadamard codes in free space systems	622 Mb/s	100 GHz	N/4	PPM	Synchronous OCDMA using complementary Walsh–Hadamard codes	BER of 10^{-9} when channel exhibit high-temporal correlation
Jazayerifar and Salehi[45]	Error correcting code (Walsh–Hadamard) in space	10 Mb/s	1 nm	N/2	PPM and OOK	Wavelength-based WH code generation in optical domain	Error at $10^{-2.5}$ variance of fading was 10^{-14} using space diversity + ppm + correlator + two-path diversity

code is able to support 2^{M-1} amount of users. Therefore, it is concluded that it is bandwidth inefficient code and has inflexible code construction, as the number of users augments, cross correlation also increases and thus requires more number of filters. For detection, differential/subtraction scheme is used, which leads to MAI, also code construction is complex (Table 1).

3.2 *Multidiagonal Code*

MD code is a $K \times N$ matrix, which depends upon the number of users (K) and code weight (W). There is flexibility to choose the code weight, but it has to be greater than ($W > 1$). The MD code construction is as follows:

- First, choose the number of subscribers (K) and decide the desired value of the weight (W).
- According to the K and W, i and j are defined, where $i = 1,2,3\ldots,K$ and $j = 1,2,3,\ldots,W$.
- The position matrix is defined as

$$F_{i,j} = \begin{cases} (i_n + 1 - i), & \text{when } j = \text{even number} \\ i, & \text{when } j = \text{odd number} \end{cases} \tag{2}$$

$$F_{i,1} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ \vdots \\ K \end{bmatrix}, \quad F_{i,2} = \begin{bmatrix} K \\ \vdots \\ 3 \\ 2 \\ 1 \end{bmatrix},$$

$$F_{i,3} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ \vdots \\ K \end{bmatrix}, \quad F_{i,W} = \begin{bmatrix} K \\ \vdots \\ 3 \\ 2 \\ 1 \end{bmatrix}. \tag{3}$$

- Every element in $F_{i,j}$ signifies the value of 1 in matrices with $K \times K$ dimensions:

$$Q_{i,1} = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}_{K\times K},$$

$$Q_{i,2} = \begin{bmatrix} 0 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 0 \end{bmatrix}_{K\times K},$$

$$Q_{i,W} = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}_{K\times K}. \tag{4}$$

- The whole grouping of diagonal matrices gives the MD code and matrix of power $K \times L$:

Table 2 State-of-the-art comparison of MD codes.

Reference	Work	Bit rate	Channel spacing	Cross correlation	Modulation	All-optical operation	*Q*-factor/BER
Abd et al.[46]	1.6 Tb/s optical system based on MD	16 Gb/s per channel	100 GHz	0	NRZ	Comparison of all-optical MD, random diagonal and MQC codes	BER of 5.1×10^{-21}, 2.4×10^{-12}, and 4.1×10^{-9} for the MD, RD, and MQC, respectively
Kaur[16]	MD codes in free space	5 Gb/s	100 GHz	0	OOK	Code generation with all-optical wavelengths	10 km is reached with BER of 10^{-35} under clear weather with MD codes
Abd et al.[22]	Comparison of MD codes with RD and MQC with direct detection	10 Gb/s	100 GHz	0	NRZ	FBG direct detection	BER of 1.1×10^{-13} at 40 km with direct detection MD codes
Rana and Gupta[47]	XOR gate based MD code OCDMA system	10 Gb/s	0.8 nm	0	NRZ, RZ	All-optical XOR gate and direct detection	4.3 *Q* factor of NRZ at 5 km and 4.2 of RZ at 5 km
Abd et al.[23]	MD codes at high data rate	12 Gb/s, 15 Gb/s	100 GHz	0	NRZ	All-optical wavelength coding	At 12 Gb/s, 20 km, MD codes, and 20 users show BER of 10^{-10}

$$[\,Q_{i,1} \quad Q_{i,2} \quad \cdots \quad Q_{i,W}\,]_{K\times L},$$

$$\text{i.e., MD} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,L} \\ \vdots & \ddots & \vdots \\ a_{i_{n,1}} & \cdots & a_{i_{n,L}} \end{bmatrix}. \tag{5}$$

MD code has few pros and cons, which are: MD codes perform better when large code lengths and number of users are required. Orthogonality is achieved because cross correlation is always zero, therefore, it is suitable for metropolitan area network. Direction direct detection scheme is used, code construction is simple, and there is flexibility in maintaining the code weight, which is $W > 1$. These codes are bandwidth inefficient code (Table 2).

3.3 *Modified Double Weight Code*

MDW code is a $K \times N$ matrix having two vital components in the fundamental matrix of MDW codes and they are

$$\text{basic code length}\, N_B = 3\sum_{j=1}^{\frac{W}{2}} j, \tag{6}$$

$$\text{basic number of users}\, K_B = \frac{W}{2} + 1, \tag{7}$$

where N_B denotes the basic code's column size and K_B is the basic code's row size.

In this code, there is a cross correlation of 1 but in some combinations of codes there is a possibility of zero cross correlation as well. From the basic code construction, it is evident that maximum cross correlation is equal to 1. The weight of this code is an even number and should always be more than 2. The chips combination is maintained as "1 2 1" for every three columns for every successive pairs of codes (Table 3).

3.4 *Enhanced Double Weight Code*

In double weight spectral amplitude codes, the first and foremost step is to construct a base matrix, which entirely reliant on the number of users.[51,52] Base matrix is repeated diagonally and this repetition for the construction of the code is termed as mapping technique. The size of the base matrix as well as users decide the length of the code. Increment of the code length due to mapping is not constant. Double weight, MDW, and EDW codes have a property that they have maintained cross correlation of almost one among different users. Aforementioned codes have the same mapping technique despite the different code construction algorithms. Here a discussion on the general algorithm code construction for EDW codes has been done without mapping for $W > 2$. This code construction is free from the mapping and maintains the cross correlation of 1. The length of the code remains constant for each additional user. Let us discuss a example that if length of code is 9 for 3 users, then for 4 users length of the code comes out to be 12 and so on (increment of 3 for each user).

A generalized code construction without mapping is given below. In EDW code construction, first of all, choose the value of weight (W) and also decide the desired no. of users (N). Code length is given as

Table 3 State-of-the-art comparison of MDW codes.

Reference	Work	Bit rate	Channel spacing	Cross correlation	Modulation	All-optical operation	Q-factor/BER
Kumawat and Kumar[30]	MDW codes without mapping	1.25 Gb/s, 2.5 Gb/s, and 5 Gbps	100 GHz	1	OOK	Direct detection and balanced detection were compared and algorithm was proposed to design MDW codes for even and odd weights without mapping	Users supported were 34, 19, and 10 for data rate 1.25 Gbps, 2.5 Gbps, and 5 Gbps, respectively, at BER of 10^{-9}
Norazimah et al.[48]	MDW with different detections	622 Mb/s	100 GHz	1	NRZ	All-optical detections such as complementary detection, AND detection, and spectral direct detection	BER 10^{-9} for AND detection for 622 Mb/s
Aljunid et al.[49]	Comparison of MDW, Walsh–Hadamard codes and modified frequency hopping codes	2.5 Gb/s and 5 Gb/s	0.8 nm	1	OOK	All-optical subtraction detection	BER was 10^{-9} for 40 users in case of MDW and 10^{-2} for WH codes at same parameters
Arief et al.[50]	Comparison of 1-D MDW and 2-D MDW codes	622 Mb/s	NA	1	OOK	FBGs for encoding and decoding	BER of 10^{-9} For 252 users for 2-D MDW and 1-D MDW can only accommodated 40 users
Ahmed et al.[17]	NAND subtraction scheme based on MDW	622 Mb/s	0.8 nm	1	Not mentioned	All-optical NAND detection	BER of 10^{-11} at 50 km for NAND-based detection and 10^{-9} for AND detection

$$L = N * (W - 1) \quad \text{for } W \quad \text{and} \quad N. \tag{8}$$

Basic matrix (M) of size $2\times (W-1)$ is constructed as shown as follows:

$$M = \begin{vmatrix} R_1 \\ R_2 \end{vmatrix} = \begin{vmatrix} \left[\frac{w-2}{2}\right]0\ s\ \left[\frac{w+1}{2}\right]1s \\ \left[\frac{w}{2}\right]1\ s\ \left[\frac{w-1}{2}\right]0s \end{vmatrix}_{2\times(W-1)}. \tag{9}$$

The complete code set is represented by matrix U of size $N \times L$ for N users. The construction involves three steps, in which a liaison matrix $U*$ is first formed. M is repeated $N-1$ times in $U*$ as shown as follows:[30]

$$U^{*} = \begin{vmatrix} R_1 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ R_2 & R_1 & \cdots & \cdots & \cdots & \cdots & \vdots \\ \cdots & R_2 & R_1 & & \cdots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & & \ddots & \vdots \\ \vdots & \vdots & \vdots & \ddots & & R_1 & \vdots \\ \cdots & \cdots & \cdots & \cdots & & R_2 & \cdots \end{vmatrix}. \tag{10}$$

To completely fill all columns, basic matrix rows R_1 and R_2 are added to last row and first row of the last column of matrix $U*$, respectively, as shown as follows:

$$U^{**} = \begin{vmatrix} R_1 & \cdots & \cdots & \cdots & \cdots & \cdots & R_2 \\ R_2 & R_1 & \cdots & \cdots & \cdots & \cdots & \vdots \\ \cdots & R_2 & R_1 & & \cdots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \ddots & & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & & R_1 & \vdots \\ \cdots & \cdots & \cdots & \cdots & & R_2 & \cdots \end{vmatrix}_{N\times L}. \tag{11}$$

The complete code set is obtained by filling up empty places in $U**$ with zeros:

$$U = \begin{vmatrix} R_1 & 0 & 0 & \cdots & \cdots & \cdots & R_2 \\ R_2 & R_1 & 0 & \cdots & \cdots & \cdots & 0 \\ 0 & R_2 & 0 & & \cdots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \ddots & & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & & R_1 & 0 \\ 0 & 0 & 0 & \cdots & & R_2 & R_2 \end{vmatrix}_{N\times L}. \tag{12}$$

Algorithm is stated as:

- Choose W, N and compute the code length L.
- Construct M as per Eq. (9)
- Repeat M in $U*$ as per Eq. (10)
- R_1 and R_2 are added to $U**$ as per Eq. (11) and empty places in $U**$ are filled with zeros to complete code construction for all users.
- In EDW, there is a flexibility to choose the weight of the code and there is a cross correlation of 1 (Table 4).

Table 4 State-of-the-art comparison of EDW codes.

Reference	Work	Bit rate	Channel spacing	Cross correlation	Modulation	All-optical operation	*Q*-factor/BER
Zahid et al.[53]	Analysis of EDW OCDMA	622 Mb/s	100 GHz	1	Not mentioned	Detection with FBGs	BER of 10^{-9} was obtained at 60 km
Ahmed et al.[54]	NAND detection of EDW codes	622 Mb/s	0.8 nm	1	OOK	All-optical NAND gate	10^{-9} BER for EDW with NAND detection for 110 users and 10^{-8} for complementary detection
Norazimah et al.[48]	EDW with different detections	622 Mb/s	100 GHz	1	NRZ	All-optical detections such as complementary detection, AND detection, and spectral direct detection	BER 10^{-9} for AND detection for 622 Mb/s
Kumawat and Kumar[30]	EDW codes without mapping	1.25 Gb/s, 2.5 Gb/s, and 5 Gbps	100 GHz	1	OOK	Direct detection and balanced detection were compared and algorithm was proposed to design EDW codes for even and odd weights without mapping	Users supported were 34 at BER of 10^{-9}
Kumawat and Kumar[55]	EDW for with diff. detections	622 Mb/s	100 GHz	1	NRZ	FBG-based different detections	*Q* factor 7 at 180 km

4 Working Model of OCDMA Codes

The block diagram of SAC-OCDMA is revealed in Fig. 1. It comprises a light source, an encoder, modulator, and user data at the transmitter section of each user. The wavelengths considered here are taken from C band (1531 to 1565 nm). The output of each user is pooled and commenced onto the optical fiber. At the receiving side, first the inward signal is divided and propelled to the decoding section of each user. The code is engendered by opting for the wavelengths from the optical signal of the broadband source (laser array). Wavelengths are chosen in accordance of the code matrix. Codes from diverse users are merged before they are instigated into the optical fiber. At the receiver, the received signal is divided using demux and the authorized user extracts the original data using optical filters of specific wavelengths, which are entirely reliant on the spectral code chips of a particular user and is a direct detection method.

Comparison between different coding schemes is carried out under the similar environment, i.e., by considering the same input parameters. In Fig. 2, BER is worse in the case of Walsh–Hadamard code due to cross correlation of 2, which means that the data of two users interfere at two wavelengths due to which there are more errors in desired data reception. The performance of Walsh–Hadamard code is followed by double diagonal weight codes due to the cross correlation of 1. MD codes exhibit better performance as compared to DDW codes because of the presence of multi-wavelengths (>2). Thus SNR increases due to the presence of multiples 1's consequently log BER decreases. EDW has the best performance among aforementioned codes due to better chip combination.

From Fig. 3, which represents quality variation with distance increase, we can conclude that the EDW has the best quality factor with increasing distance as compared to other code schemes, but after 30 km it is surpassed by Walsh–Hadamard code due to the nonlinear effects in the optical fiber, but again after 40 km attenuation increases again and it decreases the overall power level inside the optical fiber. DDW has the worst performance due to low SNR.

In Fig. 4, evaluation of compressed spectrum return to zero and duo-binary return to zero advanced modulation formats is accomplished in different SAC-OCDMA codes in terms of BER at varied data speeds. It is perceived from the investigation that there is performance betterment in the codes, which incorporate Duo-binary return to zero (DRZ) format as compared to carrier suppressed return to zero (CSRZ). Increase in data rate causes decrease in the time of bit slots that are reserved for the each pulse and ultimately effect of pulse broadening (dispersion) becomes more aggravated. This phenomenon exhibits more errors in the received chip code-based pulses. Results revealed that maximum correct code detection is in EDW codes with DRZ codes followed by CSRZ. Worst BER is observed in WH codes with CSRZ. Performance betterment is more in DRZ due to transmission of R bits/s using $R/2$ Hz of bandwidth. Most noteworthy benefit of this format is tolerance of pulse width broadening (PWB) and narrowband optical filtering.

In Fig. 5, as the photonic efficiency of photodetector PIN is increasing, the detected bit error rate decreases of all the SAC-OCDMA codes. At the fixed carrier power of 0 dBm, from 10% to 90%, the BER is tremendously depressed about 500% in case of EDW and ~255% in WH. So WH shows

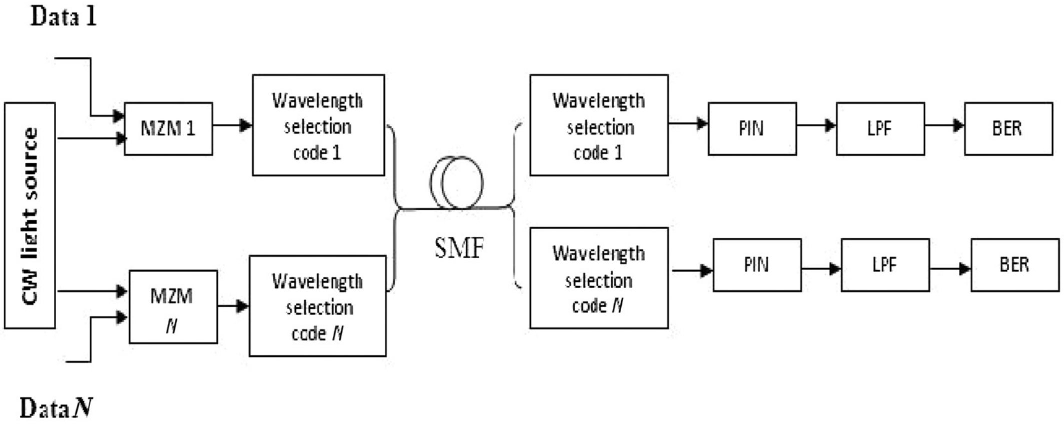

Fig. 1 Basic block diagram of different coding schemes.

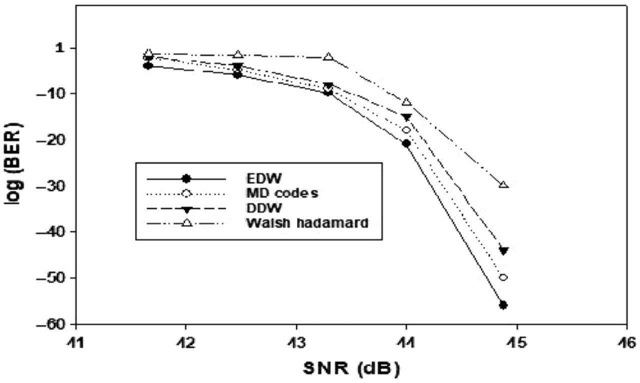

Fig. 2 Receiver's BER for different OCDMA codes with variation of SNR per code chip.

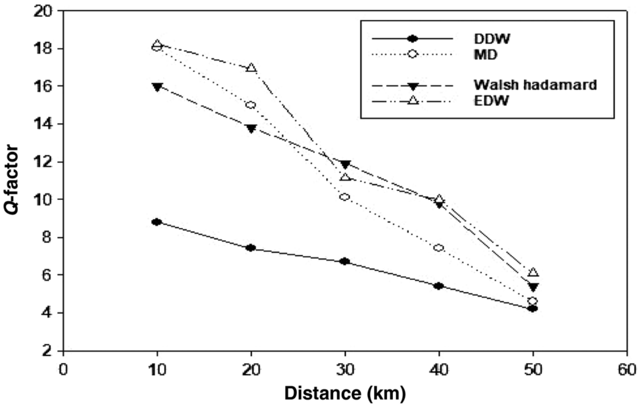

Fig. 3 Variation of received quality with different lengths of SMF-28.

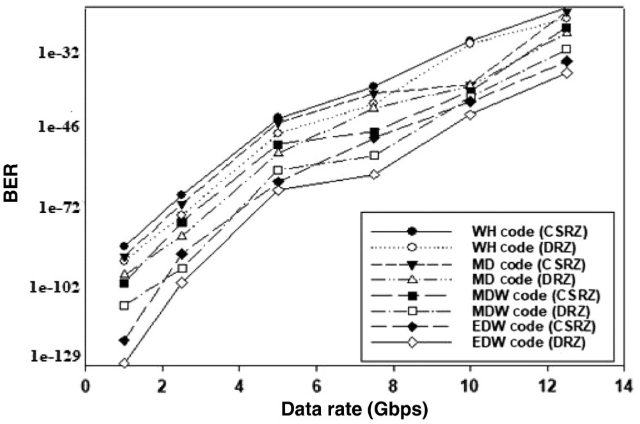

Fig. 4 Performance comparison of various SAC-OCDMA codes at different chip rates using DRZ and CSRZ.

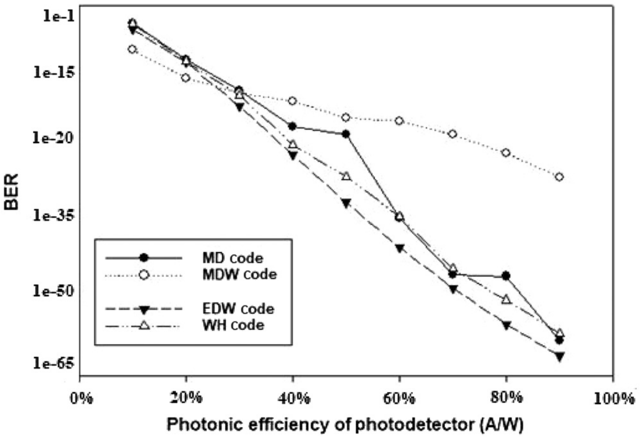

Fig. 5 Effect of photonic efficiency of photodetector on different SAC-OCDMA codes in terms of BER (for $W = 4$).

the worst performance and EDW provides the best performance at varied photonic efficiency of photodetector PIN. Therefore, from this figure, it was evident that the optimal region of PIN efficiency is between 60% and 90%, where the reduction in errors is fluctuated not to greater extent.

Signal-to-noise ratio is an important parameter to evaluate the performance of the system and another significant parameter is frequency band of operation. The use of conventional band is reported widely, however, due to the high-capacity demands: we need to pack the more number of channels to optical fiber. High capacity, inturns, puts the pressure on the researchers to demonstrate the systems in other frequency bands also. So the performance of different frequency bands such as O-band, S-band, C-band, and L-band is compared in Fig. 6 for different SAC-OCDMA codes in terms of SNR. This work is accomplished with forward error correction (FEC) and without FEC. It is perceived that EDW

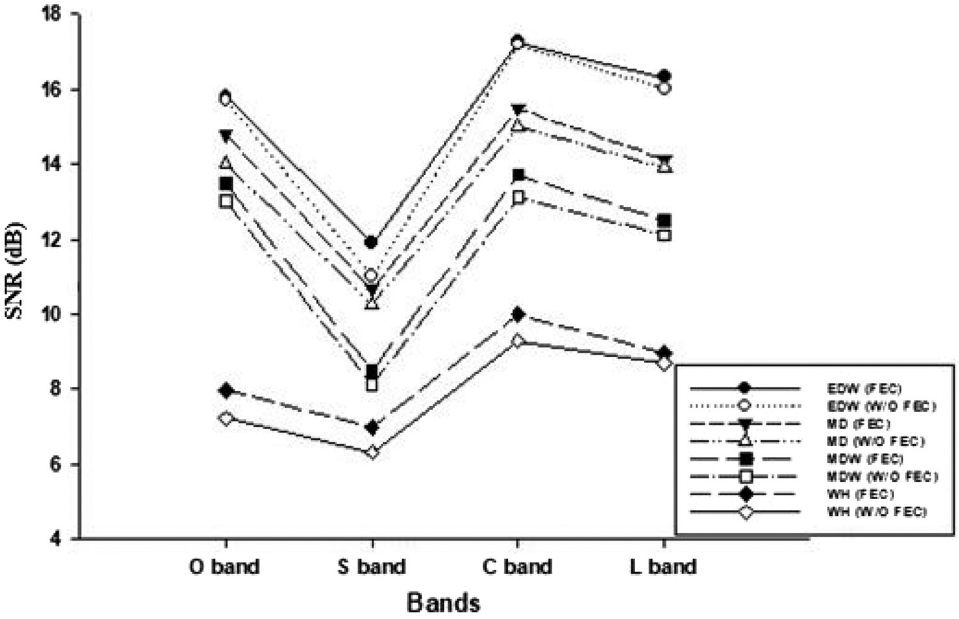

Fig. 6 Variation of SNR of various codes in different optical windows with/without FEC.

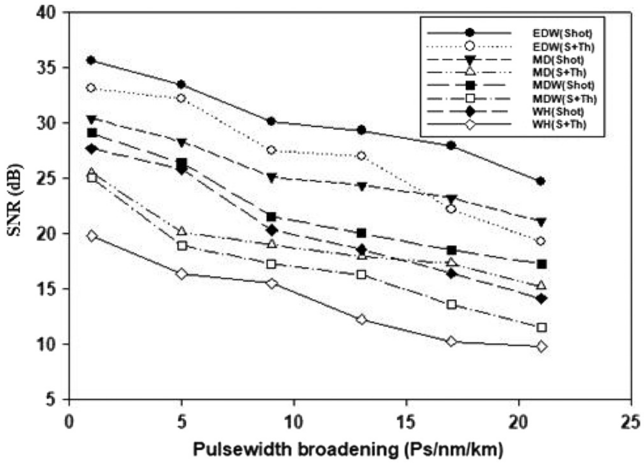

Fig. 7 Comparison of SNR versus pulsewidth broadening by considering shot and thermal noise.

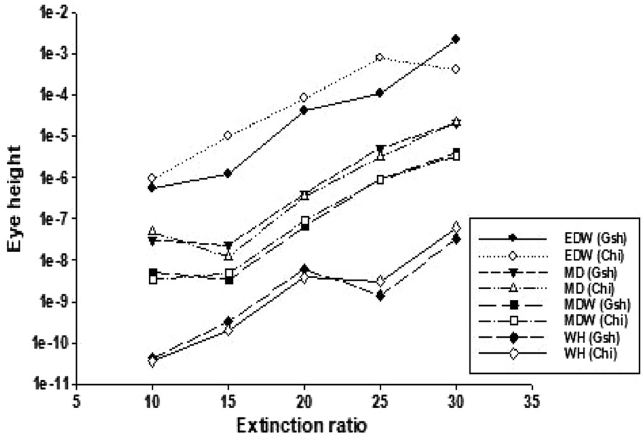

Fig. 8 Change in eye height due to modulator's extinction ratio using Gaussian and chi-squared algorithm.

codes with FEC provide the highest SNR and WH codes without FEC give minimum SNR. FEC basically improves the performance due to the redundant codes or error corrective codes. SNR trends in different frequency bands in the system are as follows: EDW (FEC) > EDW (W/o FEC) > MD (FEC) > MD (W/o FEC) > MDW (FEC) > MDW (W/o FEC) > WH (FEC) > WH (W/o FEC). Codes provide optimal SNR in C-band due to less attenuation, dispersion, and scattering as compared to other bands. From the observations, it is evident that S-band is not recommended to use for getting good performance.

Moreover, PWB is a major cause of the error in the system and becomes very severe at high data rates. Here in Fig. 7, we have varied the pulse width of the signals according to the values within the range as given by the International Telecommunication Union. With the increase in the time of the pulse, SNR of system decreases. Effects of shot noise only and shot + thermal noise are studied and compared in the system for all aforementioned codes. WH codes are least performed codes followed by modified diagonal codes. Out of all the four codes, EDW again gives the maximum SNR. It is also important to note that combined effects of shot and thermal lowers the SNR significantly.

Figure 8 shows the eye height of the received signal with respect to different algorithms used for their calculation is taken for different OCDMA codes at varied extinction ratios. Eye height is calculated as

$$E_H = (\mu_1 - 3\sigma_1) - (\mu_0 + 3\sigma_0), \tag{13}$$

σ_0 is the standard value of sample 0, σ_1 is the standard value of sample 1, μ_0 is the average value of sample 0, and μ_1 is the average value of sample 1.

Gaussian for the standard deviation σ_0 and σ_1 is, BER

$$P_e = \frac{M}{N+M} P_{eo} + \frac{N}{N+M} P_{e1}. \tag{14}$$

P_0 and P_1 are the probability of symbols. M and N are the samples for 0, 1, respectively,

$$P_{e0} = \frac{1}{2}\mathrm{erfc}\left(\frac{S-\mu_0}{\sqrt{2}\sigma_0}\right), \tag{15}$$

$$P_{e1} = \frac{1}{2}\mathrm{erfc}\left(\frac{\mu_1 - S}{\sqrt{2}\sigma_1}\right), \tag{16}$$

μ_0 is the average value of sample 0, μ_1 is the average value of sample 1, and S is the threshold value, Σ_0 and σ_1 are the sample value standard deviation.

Chi-squared algorithm for M sampled value for logic 0 and N for logic BER is

$$P_{e1} = \frac{1}{2N}\sum_{i=1}^{N}\mathrm{erfc}\left(\frac{\mu_{1i} - S}{\sqrt{2}\sigma_{1i}}\right), \tag{17}$$

$$P_{e0} = \frac{1}{2M}\sum_{i=1}^{M}\mathrm{erfc}\left(\frac{S-\mu_{0i}}{\sqrt{2}\sigma_{0i}}\right). \tag{18}$$

If there is noise mixed, then it is modified as

$$P_e = \sum_{i=1}^{S}\frac{N_p}{N}\mathrm{erfc}\left(\frac{\mu_i - S}{\sqrt{2}\sigma_i}\right), \tag{19}$$

N_p is the no. of 1 occurs, N is the total patterns, μ_i is the average value of sample, σ_0 is the standard value of sample, and S is the threshold 1 value.

Probability of error is

$$P_e = \frac{M}{N+M}\int_{S}^{\infty} f_{\;2}(x/0) + \frac{N}{N+M}\int_{-\infty}^{S} f_{\;2}(x/1). \tag{20}$$

The algorithms used were Gaussian and chi-squared, and it is seen that there is slight improvement in the performance of the codes with the use of chi-squared algorithms. Also the effect of ER is that its low value cause troubles to the receiver for the calculations of 1's and 0's. ER is basically a ratio in two optical powers. Eye height is highest in EDW (chi-squared) and least in WH (Gaussian) after 20 dB of ER. Therefore, it is recommended to use high ER to achieve more eye height.

In Fig. 9, we have tried to investigate different SAC-OCDMA codes in our proposed work at different time instances of the bit period. Its depicts the comparative analysis of maximum Q-factor received with respect to time of any transmitted bit for EDW code with conventional codes such as WH code, MD code, and MDW codes. Maximum Q-factor of 17.47, 15.23, 14.67, and 9.93 are observed in case of EDW, MD, MDW, and WH codes, respectively. The highest quality of signal is achievable in the case of EDW as it is a bandwidth efficient code due to shoeter code length, whereas a longer code length of WH codes makes it a bandwidth inefficient code and higher value of cross-correlation deteriorates the quality of the received signal.

By implementing and analyzing performance of diverse SAC codes, it is evident that cross correlation is a major performance degradation factor among multiple users. Multidiagonal codes have zero cross correlation but code construction of MD codes is complex, and moreover it has greater code lengths, which waste the bandwidth. On the contrary, EDW, MDW, and WH codes have cross correlation, which is the major cause of MAI.

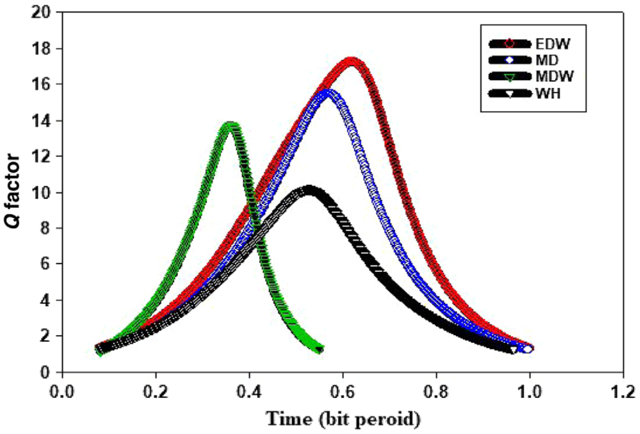

Fig. 9 Maximum Q-factor versus time (bit period) at 10 Gbps for different SAC-OCDMA codes.

Comparison between different coding schemes is carried out under a similar environment, i.e., by considering the same input parameters. From Figs. 2 and 3, it is perceived that due to better chip combination, less cross correlation than Hadamard codes, less code length (greater bandwidth efficiency) than MD codes, and greater SNR due to the presence of more no. of 1's than DDW codes, EDW codes are found out to be optimal and best performing in the demonstrated system investigation.

Figure 4 shows the performance betterment of the system using EDW codes and DRZ advanced modulation format. DRZ is superior to CSRZ due to transmission of R bits/s using $R/2$ Hz of bandwidth. The most noteworthy benefit of this DRZ format is tolerance of PWB and narrowband optical filtering.

In Fig. 5, as the photonic efficiency of photodetector PIN is increasing, the detected bit error rate decreases of all the SAC-OCDMA codes. At the fixed carrier power of 0 dBm, from 10% to 90%, the BER is tremendously depressed about 500% in case of EDW and ~255% in WH. So WH shows the worst performance and EDW provides the best performance at varied photonic efficiency of photodetector PIN. Therefore, from Fig. 5, it was evident that the optimal region of PIN efficiency is between 60% and 90%, where the reduction in errors is fluctuated not to greater extent.

The performance of different frequency bands such as O-band, S-band, C-band, and L-band is compared in Fig. 6 for different SAC-OCDMA codes in terms of SNR. This work is accomplished with FEC and without FEC. It is perceived that EDW codes with FEC provide the highest SNR at C-band and WH codes without FEC give minimum SNR. From observations, it is evident that S-band is not recommended to use for getting good performance.

Figure 7 shows that with the increase in the time of the pulse, SNR of the system decreases. WH codes are the least performed codes followed by modified diagonal codes. Out of all the four codes, EDW again gives the maximum SNR. It is also important to note that combined effects of shot and thermal lowers the SNR significantly.

Figure 8 shows the eye height of the received signal with respect to Gaussian and chi-squared algorithm. Eye height is highest in EDW (chi-squared) and least in WH (Gaussian) after 20 dB of ER. Therefore, it is recommended to use high ER to achieve more eye height.

In Fig. 9, we have tried to investigate different SAC-OCDMA codes in our proposed work at different time instances of the bit period. Maximum Q-factor of 17.47, 15.23, 14.67, and 9.93 are observed in case of EDW, MD, MDW, and WH codes, respectively.

To remove the existing limitations and for making code bandwidth efficient and making code construction simpler, an SAC-OCDMA code, i.e., diagonal identity matrix (DIM) code has been designed with zero cross correlation and with the flexibility to choose code weight.

5 Diagonal Identity Matrix Codes

The generalized code construction algorithm is explained below. The code construction steps and algorithm is described as:

Step 1: Choose the value of number of users (K) and weight of code $W = 2,3,4,\ldots,N$ for every user.

Step 2: Calculate the length of the code as:

$$L = K * W \tag{21}$$

Step 3: Size of basic balanced matrix

$$I_B = 2 \times W \,(\text{balanced})$$

Step 4: Basic matrix of order $Y \times Z$ is constructed for any number of users as

$$I_B = \begin{pmatrix} \text{UE} \\ \text{LE} \end{pmatrix} = \begin{bmatrix} (W/2)1'\text{s} & (W-2)0'\text{s} \\ (W+2/3)0'\text{s} & (W+1/2)1'\text{s} \end{bmatrix}_{YXZ}, \tag{22}$$

where UE is the upper end and LE is the lower end

Step 5: The complete code set is represented by matrix M of size $K \times L$ for K users. The construction of M involves three steps, in which an intermediary matrix M^1 is first constructed. I_B is repeated $K-1$ times in M as shown:

$$M^1 = \begin{pmatrix} \text{UE} & \cdots & \cdots & \cdots & \cdots & \text{LE} \\ \text{LE} & \text{UE} & \cdots & \cdots & \cdots & \cdots \\ \cdots & \text{LE} & \text{UE} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \text{LE} & \text{LE} & \cdots & \\ \cdots & \cdots & \cdots & \text{LE} & \text{UE} & \end{pmatrix} \tag{23}$$

Repeat the process for $K \times L$ times as shown in matrix M^2

$$M^2 = \begin{pmatrix} \text{UE} & \cdots & \cdots & \cdots & \cdots & \text{LE} \\ \text{LE} & \text{UE} & \cdots & \cdots & \cdots & \cdots \\ \cdots & \text{LE} & \text{UE} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \text{LE} & \text{UE} & \cdots & \\ \cdots & \cdots & \cdots & \text{LE} & \text{UE} & \end{pmatrix}_{K\times L}. \tag{24}$$

Fill zeros in the empty spaces of matrix M^2 to make final matrix M as given as follows:

$$M = \begin{pmatrix} \text{UE} & 00 & 00 & 00 & 00 & \text{LE} \\ \text{LE} & \text{UE} & 00 & 00 & 00 & 00 \\ 00 & \text{LE} & \text{UE} & 00 & 00 & 00 \\ 00 & 00 & \text{LE} & \text{UE} & 00 & 00 \\ 00 & 00 & 00 & \text{LE} & \text{UE} & 00 \end{pmatrix}_{K\times L} \tag{25}$$

5.1 Flow Diagram of the Implementation of the Proposed Code Scheme

To define the security of the system, two parameters are taken into consideration, i.e., autocorrelation and cross correlation. Autocorrelation in a code defines the number of 1's existing within a code. Higher autocorrelation leads to better signal-to-noise ratio at the receiver side and better signal quality but on the other side it can lead to interference between the bandwidths of number of bits due to which the desired quality of the signal deteriorates:

$$\text{auto-correlation}: Ax, x = \sum_{n=0}^{n-1} C[x]C[x]$$

$$\text{where } 0 < m < N-1, \tag{26}$$

$$\text{cross correlation}: Cx, y = \sum_{n=0}^{n-1} C[x]C[y]$$

$$\text{where } 0 < m < N-1. \tag{27}$$

Cross correlation occurs between the code words of two different users. It is basically an issue in existing coding schemes as it leads to MAI between the number of users and makes it possible for the eavesdropper to detect the wavelengths of the code of the authorized data. DIM codes have autocorrelation of 2 and cross correlation of 0. Figure 10 shows how the DIM code is constructed and implemented.

Figure 11 shows the variation of quality factor due to laser linewidth. The spectrum of the carrier signal includes sidebands or divergence of spectrum around desired carrier signal is termed as laser linewidth. As the laserwidth increases, the divergence of spectrum multiplies with that of the carrier signal and the dispersion factor also gets involved. So the quality of the signal deteriorates as the laser linewidth increases. Signal quality deteriorates more in case of EDW than DIM because cross correlation exists in EDW, which causes MAI between simultaneous users, and this unwanted factor is absent in DIM code.

Figure 12 shows the effect of signal-to-noise ratio on the extinction ratio. Extinction ratio at receiver is the difference

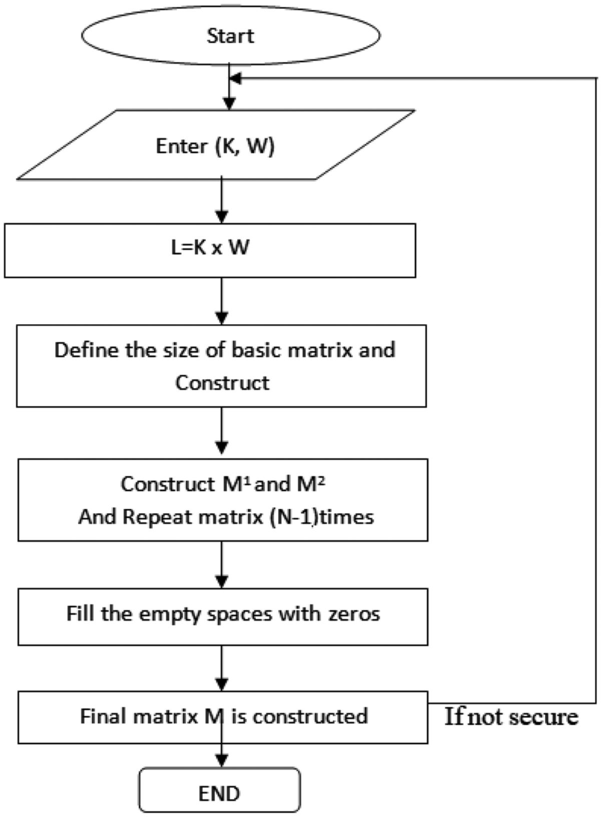

Fig. 10 Flow diagram to construct DIM.

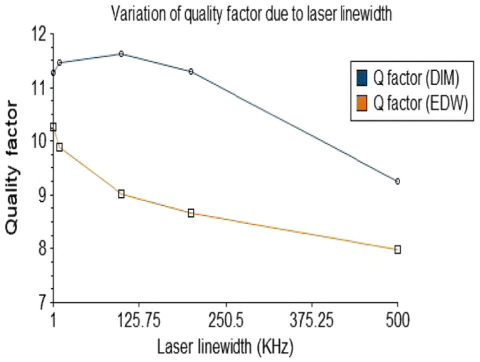

Fig. 11 Variation of quality factor due to laser linewidth.

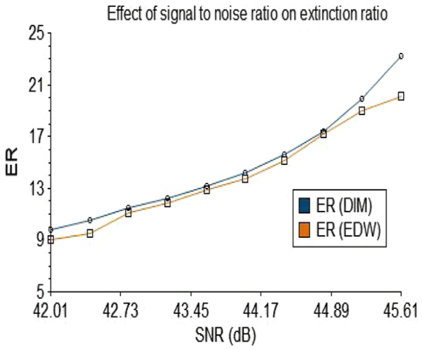

Fig. 12 Effect of signal to noise ratio on extinction ratio.

of received amplitude of digital logic level "1" and "0." It is evident that the greater the difference in two levels, the better the performance is of the system in terms of signal-to-noise ratio. In other words, if we increase SNR in both the proposed codes, extinction ratio increases. DIM code provides enhanced results as compared to EDW codes due to zero cross correlation and longer code length.

6 Advanced Encrypting Techniques

6.1 *All-Optical OCDMA Encryption Using Logic Gates*

Confidentiality and data security are required for the high-speed optical communication systems for reliable operations, and this can be achieved using all-optical encryption/decryption as depicted in Figs. 13 and 14. All-optical logic gates are right candidate to fulfill the aforementioned requirements. An OCDMA system with all-optical XOR gate-based encryption was demonstrated in Ref. 51, which did the task of code swapping and enhanced the system security. Two designs of OR and AND gates were introduced in Ref. 52 based on photonic crystal. Their simplicity and reliability as well flexible operation makes then suitable for future generation optical communication systems. An all-optical interference suppressed OCDMA system with advanced binary optical logic gates were presented in Ref. 56. Since the performance restriction of optical fiber reliant systems is the conversion from O/E domains for optical receivers, the interference abolition was performed in the optical domain. In Ref. 57, a flexible incoherent OCDMA system was demonstrated with one-time pad with XOR gating, which provides access to multiple users to establish communication among them at OC-24 data rate and the system offered a bit error rate of $< 10^{-12}$. Semiconductor optical amplifier-based XOR gate was employed in the multidiagonal coding reliant OCDMA system for data security.[47] SOAs were placed in MZI configuration to realize all-optical XOR gate. The proposed system architecture was acknowledged as good for military communication services. Subcarrier multiplexed and NAND gate subtraction incorporated spectral amplitude coded OCDMA was demonstrated in Ref. 58. Double weight codes were studied and NAND gate was used for the security enhancement and to suppress interferences. The performance of SAC-OCDMA was investigated by taking NAND subtractions into account, and the code used was EDW code. It was perceived that NAND gate detection was enhanced than complementary detection.[54]

6.2 *Cryptography in OCDMA*

As the development of OCDMA systems takes place rapidly, at the same time strategies of an eavesdropper are also increasing day by day such as interception of code, energy detection, and differential detection. OCDMA systems are inherently coded in nature, but these strategies of the eavesdropper threaten the optical communication systems. In Ref. 59, a cryptography algorithm with OCDMA systems was combined and it made sure that the eavesdropper does not detect the coded information. Therefore, the security of the physical layer enhanced successfully. Data security is offered by the source cryptography and security of time-wavelength codes was discussed in Ref. 60.

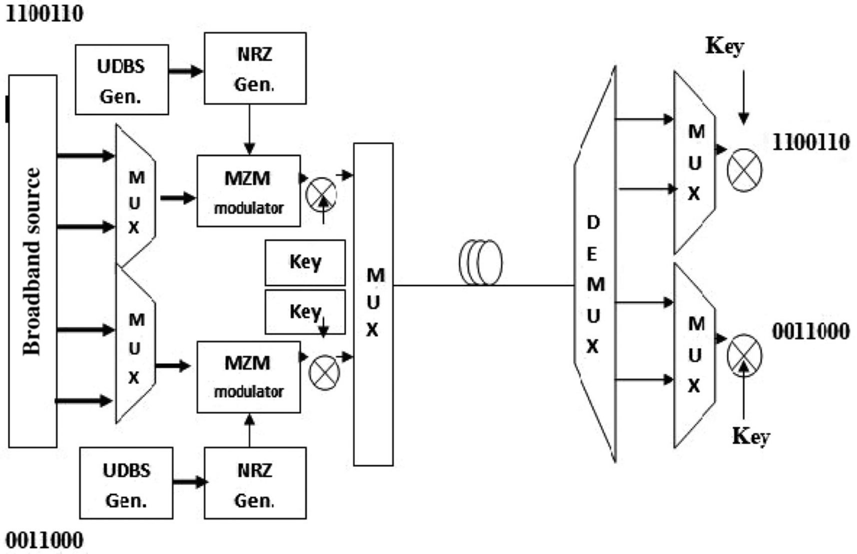

Fig. 13 Block diagram of all-optical XOR gate encrypted/decrypted SAC-OCDMA system.

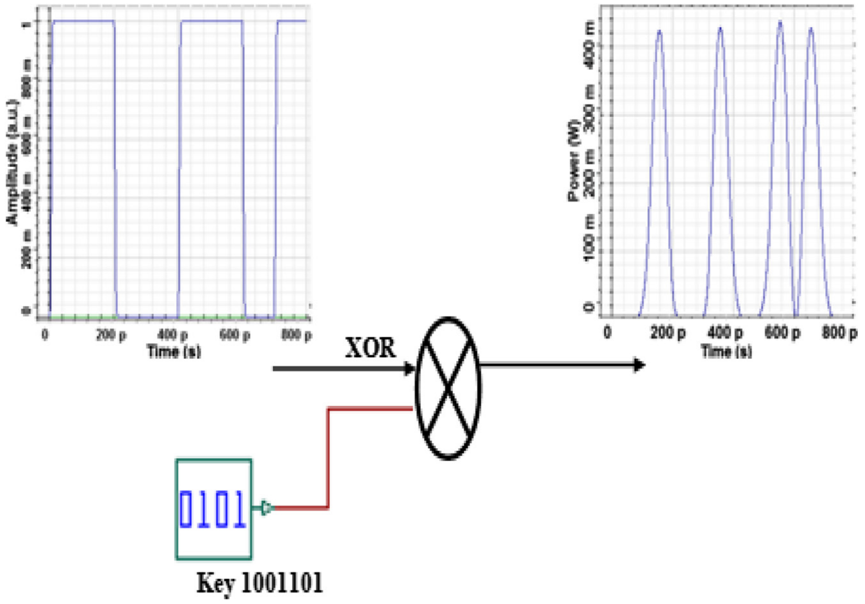

Fig. 14 Random key-based all-optical encrypted data after XOR operation.

They explained that the degree of security in OCDMA systems is dependent on different parameters such as high input power and less number of users. High power makes the system more prone to an eavesdropper. The probability of correct code word detection for an eavesdropper increases if single or fewer numbers of users are carrying information. Sometimes, due to the metadata and code detection, an eavesdropper can decode the information and, that time, even multiple users cannot increase the system security. On the contrary, cryptography has no impact of these factors and it enhances the system security to maximum extent. The physical layer security of passive optical networks (PON) is examined inside a meticulous crypto analysis outline.[61] In Ref. 62, a simulation of an all-optical cryptography system, which is independent of bit rate and has transparency to modulation patterns, was considered. Encryption includes signal spectral segmentation pursued by two encoding stages that entail various attenuations and delays to each of the spectral segments.

6.3 *Multicode Keying*

MCK encryption is used to cope with issues like eavesdropping of the information in OCDMA systems. Large cardinality of the chips in the codes and tree structure of code word are examined nowadays due to requirement of greater number of users. Large cardinality and tree structured code word have the ability to boost system security by employing MCK. In Ref. 63, multicode key-based all-optical encryption was proposed and demonstrated in simulator as well as results were verified by designing hardware of the system in China. Moreover, theoretical analysis was also performed

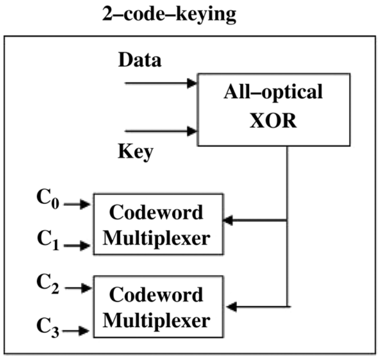

Fig. 15 All-optical designs for the MCK encryption with code word multiplexer.

to show code switching and working of encryption.[64,65] Figure 15 shows the block diagram of MCK in the OCDMA system.

A physical layering of OCDMA was performed in Ref. 66 with XOR gating and a data randomizer with cipher text key (MCK). Data scrambler (randomizer) was incorporated to create chaos after cipher text and eliminate the large strings of 1's and 0's so that the eavesdropper does not get the right sequence. Benefit of scrambler is that it can be employed to digital and continuous signals but encryption can only be accomplished for digital domain. It makes the system less vulnerable to network security breaching issues. MCK scheme was also demonstrated for SAC-OCDMA network in Ref. 67. Users were given the several signature sequences for physical layer confidentiality enhancement of the system. MCK is also termed as multiple bits per symbol and can support high data rates.[68,69] Brute force technique for calculation of searching time was taken in this work against the eavesdropper and bit correct interception were calculated for multiple as well as single user. It was perceived that security performance of coded chips can be enhanced by employing MCK.

6.4 *Steganography in OCDMA*

Optical steganography is a supplementary coating of security that can enhance data encryption by trouncing the information transmission beneath the public channel. Optical steganography for data-hiding was proposed and studied with hardware by means of group velocity dispersion in an optical network. The authorized channel was covered under the public channel, and this was tested for OCDMA systems and WDM systems. At the receiver side, covered channels were realized through dispersion management. Results were shown in the form of BER and eye diagrams. Polarization modulator-based code-shift-keying (CSK) data modulation and OCDMA encryption/decryption was demonstrated in Ref. 70, where an incoherent light source was required as shown in Fig. 16. Due to dispersion elements, time of the each pulse increases and as a result it decreases the amplitude of the pulse, which can be used for the data hiding. Binary phase shift was considered in Refs. 42 and 71, and the dispersed signal was retrieved by a balance detector.

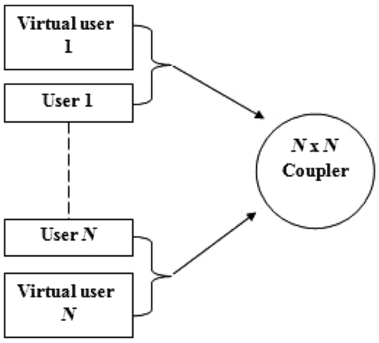

Fig. 17 Virtual user and real user against eavesdropper attack.

6.5 *Virtual User Scheme in OCDMA Systems*

In OCDMA systems, a huge number of users increase the confidentiality of the system due to the problem in the correct code word detection at eavesdropper. However, probability of correct code word detection is more when low numbers of users were carrying information of the system. A method to solve the issues of network breaching, when a single user is in operation, was proposed in OCDMA systems.[72] By forcing the eavesdropper to detect multiple signals simultaneously, the eavesdropping attack on the targeted signal can be avoided. This can be done by incorporating a virtual user in the system as shown in Fig. 17. A virtual user environment is created in the network by incorporating a virtual user with every authorized user. A virtual user will enhance the confidentiality of an OCDMA

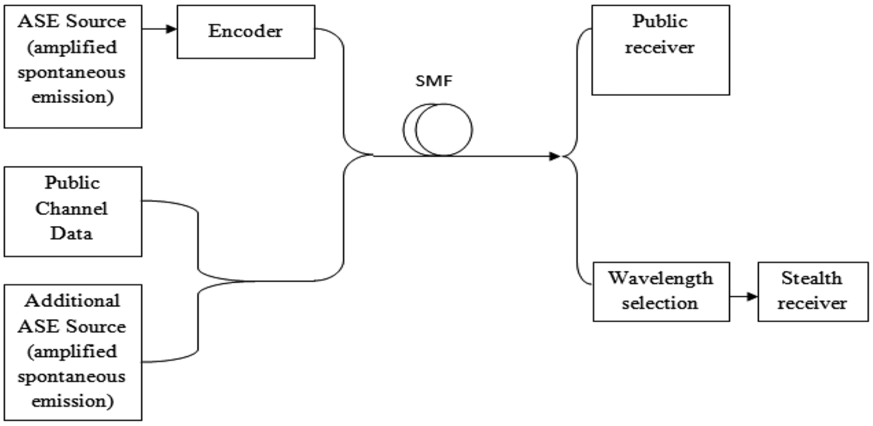

Fig. 16 Block diagram of CSK-OCDMA-based optical stealth transmission system.

system by always transmitting in parallel to the authorized user. The pseudorandom noise is used as the data input to the virtual user. Both users are encoded using different codes and then multiplexed before transmitting the signal over the optical fiber. This virtual user acts as an interferer and appears as an authorized user to the eavesdropper; this would prevent eavesdropping. Hence, the presence of multiple users makes it more difficult to sift the data. In the VUS, twice as many codes are needed as compared to conventional OOK-OCDMA because each authorized user has its own virtual user, which requires a unique code. This results in wasting half of the code words on the virtual users. In order to minimize the wastage of network resources, the virtual user scheme is slightly modified by introducing a common virtual user for all the users. This means each user has its dummy user but the same code word is shared among all the dummy users, which will become active only whenever the authorized user is isolated in the network, this will increase only the hardware cost but does not degrade the system performance by decreasing the number of simultaneously active users from the given code set.

Demonstrated work used the virtual user to create chaos along with the authentic user as depicted in Fig. 17. Likelihood of code detection of a single user reduces due to the virtual user and accompaniment of distinct progression of virtual user eliminates the incidence of single user's code in the channel.

7 Future Scope

OCDMA is based on the principle that chips are mapped according to the user code relation. Therefore, it is operational in the high-speed asynchronous broadcast local area network (LAN). Optical code division provides larger multiple channels as compared to spectral division of wavelength division multiple access. System architectures are also less complex due to asynchronous transmission in comparison to time division. Multiclass data or different services traffic can be operational by incorporating diverse lengths of codes at the same time. The inspiration for LAN network of OCDMA is fortified by the anticipation that LAN traffic patterns are active at the same time based on the characterization of burstiness. A PON with employment of OCDMA codes can be realized in the tree topology. Unique code lengths and decodes are placed at optical network units (ONUs) with correspondence to optical line terminal encoder. OCDMA PON is superior to LAN due to the fact that the signal transmitted by one ONU never reaches to other ONU. More determined offerings can be set up by mapping universal IP addresses to codes of optical code division. A wavelength routing MAN may be offered for virtual private network (VPN) connections. The most important aim of a VPN is to offer secure data connections over network security threatened platforms. The optical code chips' signals provide improved security as well as can be decoded only with authorized wavelength selection. Optical processing, which comprises of splitting and accumulation, makes VPN system less complex by elimination of the multiplexing, which is in electronic domain. Potential of light-tree ability at the MAN networks level can be practiced to facilitate the establishment of multipoint VPN. Time division-based image transmission needs the pixel streams of different users by performing their serial to parallel (s/p) conversions. At the end node, prior to the images retrieving from pixel, each user stream of pixels must be differentiated by using s/p conversion. For the elimination of these conversions and bottleneck in the communication, optical CDMA is demonstrated. Also the use of OCDMA in ROF systems offers the larger channel count and supports good data rates.

From the reported works in SAC-OCDMA, precise topics have been acknowledged, which have a scope for future research. Existing SAC-OCDMA codes suffered from various performance limitations and code generation issues such as cross correlations, MAI, long code lengths, bandwidth inefficiency, cost, complexity, and failure in desired user code generation. To cope with these issues, this work can be done for the code generation that provides zero cross correlation, less MAI, bandwidth efficiency, etc. However, zero cross-correlation DIM codes are constructed in this work but further enhancements and comparisons are required using DIM code. Moreover, security breaching in OCDMA systems is an important issue to be addressed, and a highly confidential system is required. These systems are vulnerable to eavesdropping and jamming, which are external intruders in the authorized users communications. Different approaches such as wavelength conversion for antijamming, cryptography, code word swapping, data hiding under public channels, and encryption through logic gates against eavesdropping are prominently used in OCDMA security enhanced systems. However, cost and complexity are key issues in aforementioned techniques. Therefore, in near future, confidentiality enhancement of OCDMA system is a good area for research. All-optical encryption is also a promising field for high-speed OCDMA systems to combat with security issues.

8 Conclusion

SAC based on code chips was performed by simulations/experiment test bed trials over fiber-optic cables. We effectively explored numerous architectures from extremely synchronized point-2-point (p2p) systems to minimum spectral matched OCDMA. From the results, it is perceived that cross correlation among users is a prominent limitation that deteriorates the performance and needs to be addressed. Demonstrations of SAC-OCDMA with coherent optical sources using optical filters have persuasively confirmed that the use of zero cross-correlation codes (multidiagonal codes) or minimizing the spectral interferences from Walsh–Hadamard to EDW codes improves the system performance. For the fulfillment of the ever-increasing demands of applications such as online games and VoIP, various OCDMA codes are demonstrated in the literature and we made a comparison of Walsh–Hadamard, DDW, MDW, and EDW, and multidiagonal codes with similar input parameters in this work. Results revealed that EDW codes performed the best in terms of BER, SNR, eye height, and WH codes due to less spectral interference from desired chip combinations. It is noteworthy that several parameters such as duo-binary pulse shape, C-band wavelength window, FEC, chi-squared algorithm, and photonic efficiencies of photodetectors between 60% and 90% are optimal in proposed comparison of SAC codes at varied data rates. A cost effective, simple code construction, and zero cross correlation-based DIM code is demonstrated in this work.

Also recent trends and the future of the OCDMA technology are also elaborated.

References

1. R. S. Kaler, T. S. Kamal, and A. K. Sharma, "Simulation results for DWDM systems with ultra-high capacity," *Int. J. Fiber Integr. Opt.* **21**(5), 361–369 (2002).
2. S. Singh and R. S. Kaler, "Investigation of hybrid optical amplifiers for dense wavelength division multiplexed system with reduced spacings at higher bit rates," *Int. J. Fiber Integr. Opt.* **31**(3), 208–220 (2012).
3. S. Singh and R. S. Kaler, "Performance evaluation of 64 × 10 Gbps and 96 × 10 Gbps DWDM system with hybrid optical amplifier for different modulation formats," *Optik* **123**(24), 2199–2203 (2012).
4. S. Singh and R. S. Kaler, "Investigation of hybrid optical amplifiers with different modulation formats for DWDM optical communication system," *Optik* **124**(15), 2131–2134 (2013).
5. S. Singh and R. S. Kaler, "Novel optical flat gain hybrid amplifier for dense wavelength division multiplexed system," *Photonics Technol. Lett.* **26**(2), 173–176 (2014).
6. R. Kaur, R. Randhawa, and R. S. Kaler, "Performance evaluation of optical amplifier for 16 × 10, 32 × 10 and 64 × 10 Gbps WDM system," *Optik* **124**(8), 693–700 (2013).
7. R. Singh, "Performance comparison of dispersion compensation techniques on 40 Gbps OTDM system at S-band and C-band over different fibre standards," *Optik* **126**(4), 391–393 (2014).
8. Z. Wei, H. M. H. Shalaby, and H. Ghafouri-Shiraz, "Modified quadratic congruence codes for fiber Bragg-grating-based spectral-amplitude-coding optical CDMA systems," *J. Lightwave Technol.* **19**(9), 1274–1281 (2001).
9. N. Hathi et al., "Analysis of the influence of Walsh–Hadamard code allocation strategies on the performance of multi-carrier CDMA systems in the presence of HPA nonlinearities," in *13th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Communications*, Portugal, pp. 1305–1309 (2002).
10. S. Jos, P. Kumar, and S. Chakrabarti, "Performance comparison of orthogonal Gold and Walsh–Hadamard codes for quasi-synchronous CDMA communication," *Lect. Notes Comput. Sci.* **5408**, 395–399 (2009).
11. T. Kojima and S. Fujiwara, "Performance of Walsh–Hadamard code division multiplexing in helicopter satellite communications," in *IEEE Int. Conf. on Advanced Technologies for Communications (ATC)*, Vietnam, pp. 622–665 (2015).
12. B. Suesser-Rechberger, W. Gappmair, and A. Ginesi, "Performance of Walsh–Hadamard codes used for timing recovery in a DVB-S2x multi-beam scenario," in *IEEE 10th Int. Symp. on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, Czech Republic (2016).
13. W. A. Imtiaz and N. Ahmad, "Cardinality enhancement of SACOCDMA systems using new diagonal double weight code," *Int. J. Commun. Networks Inf. Secur.* **6**(3), 106–112 (2014).
14. N. D. Keraf et al., "The evolution of double weight codes in spectral amplitude coding OCDMA," *Lect. Notes Electr. Eng.* **315**, 129–140 (2015).
15. G. Kaur and G. S. Bal, "Performance analysis of SAC-OCDMA in free space optical medium using DDW code," *Optik* **133**, 36–42 (2017).
16. G. Kaur, "Performance analysis of SAC-OCDMA in free space optical medium using MD and DDW code," in *2nd Int. Conf. on Recent Advances in Engineering and Computational Sciences (RAECS)* (2015).
17. N. Ahmed, S. A. Aljunid, and R. D. Ahmad, "Novel OCDMA detection technique based on modified double weight code for optical access network," *Elektron. Elektrotech.* **18**(8), 117–121 (2012).
18. S. Gupta and A. Goel, "Advance method for security enhancement in optical code division multiple access system," *IETE J. Res.* **64**, 17–26 (2017).
19. A. Kaur and G. Singh, "Performance comparison of various detection techniques for SAC–OCDMA system using DW and MDW code," in *Int. Conf. and Workshop on Computing and Communication (IEMCON)*, pp. 1–6 (2015).
20. A. Salehi, "Code division multiple access technique in optical fiber networks—Part I: fundamentals principles," *IEEE Trans. Commun.* **37**, 824–833 (1989).
21. I. B. Djordjevic, B. Vasic, and J. Rorison, "Multi-weight unipolar codes for spectral-amplitude-coding optical CDMA systems," *IEEE Commun. Lett.* **8**, 259–261 (2004).
22. T. H. Abda et al., "Modeling and simulation of multi diagonal code with zero cross correlation for SAC-OCDMA networks," in *2nd Int. Conf. on Photonics* (2011).
23. H. Abda et al., "Impact of multi-diagonal code on high-speed spectral amplitude coding optical code division multiple-access networks," *Arabian J. Sci. Eng.* **38**, 2389–2397 (2013).
24. N. Jellali, F. Moez, and M. Najjar, "Performance enhancement of OCDMA system based on 3D-multi-diagonal codes," in *IEEE 13th Int. Wireless Communications and Mobile Computing Conf. (IWCMC)*, Spain, pp. 2105–2108 (2017).
25. M. K. Abdullah et al., "Performance of OCDMA systems with new spectral direct detection (SDD) technique using enhanced double weight (EDW) code," *Opt. Commun.* **281**(18), 4658–4662 (2008).
26. F. N. Hasoon et al., "Spectral amplitude coding OCDMA systems using enhanced double weight code," *J. Eng. Sci. Technol.* **1**(2), 192–202 (2006).
27. M. Noshad and K. Jamshidi, "Code family for modified spectral-amplitude-coding ocdma systems and performance analysis," *IEEE/OSA J. Opt. Commun. Networking* **2**(6), 344–354 (2010).
28. A. Zahid, F. Hasoon, and S. Shaari, "New code structure for enhanced double weight (EDW) code for spectral amplitude coding OCDMA system," in *Int. Conf. on Future Computer and Communication, ICFCC*, pp. 658–661 (2009).
29. A. Arief et al., "Cardinality enhancement of spectral/spatial modified double weight code optical code division multi-access system by PIIN suppression," *Optik* **124**(19), 3786–3793 (2013).
30. S. Kumawat and M. R. Kumar, "Generalized optical code construction for enhanced and modified double weight like codes without mapping for SAC-OCDMA systems," *Opt. Fiber Technol.* **30**, 72–80 (2016).
31. K. Singhal, "Walsh codes, PN sequences and their role in CDMA technology," Term paper, EEL 201, IIT Delhi, pp. 1–4, 2012, https://pdfs.semanticscholar.org/5963/793d3cc95aea091f9cf89ff340f48d19348c.pdf
32. M. Ali et al., "Inter-WBANs interference mitigation using orthogonal Walsh–Hadamard codes," in *27th Annual IEEE Int. Symp. on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Valencia, Spain (2016).
33. S. Mandal et al., "Walsh–Hadamard code design using optical nonlinear material," in *Devices for Integrated Circuit*, IEEE (2017).
34. C. T. Yen et al., "Performance analysis of dual unipolar/bipolar spectral code in optical CDMA systems," *J. Appl. Res. Technol.* **11**(2), 235–241 (2013).
35. R. Takahashi and K. Umeno, "Performance comparison of band-limited baseband synchronous CDMA using between Walsh–Hadamard sequence and ICA sequence," http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.332.1196&rep=rep1&type=pdf
36. A. Taiwo et al., "Practical investigation of suitable decoding technique for SAC-OCDMA based vibration sensing," *IET Optielectron.* **10**(6), 227–232 (2016).
37. N. Ahmed et al., "Performance improvement of SAC-OCDMA system using modified double weight (MDW) code for optical access network," *Sci. Res. Essays* **7**(7), 796–804 (2012).
38. T. H. Abd et al., "Performance improvement of hybrid SCM SAC-OCDMA networks using multi-diagonal code," *Sci. Res. Essays* **7**(11), 1262–1272 (2012).
39. M. L. F. Abbade et al., "An all-optical OCDMA encoder with simultaneous signal regeneration based on cross-gain modulation in semiconductor optical amplifiers," in *Int. Conf. on Transparent Optical Networks (ICTON)* (2012).
40. C.-S. Bres et al., "All-optical OCDMA code-drop unit for transparent ring networks," *IEEE Photonics Technol. Lett.* **17**(5), 1088–1090 (2005).
41. Z. Wang, M. P. Fok, and P. R. Prucnal, "Physical encoding in optical layer security," http://ee.princeton.edu/research/prucnal/sites/default/files/RP_Journal_22451439%20_116.pdf
42. C.-T. Yen and G.-J. Huang, "Optical steganography transmission of optical CDMA signals over a public BPSK channel," *Eng. Comput.* **33**(6), 1810–1824 (2016).
43. M. Bharti, A. K. Sharma, and M. Kumar, "Simulative analysis of 2-code keying approach using Walsh–Hadamard codes to enhance security and reduce dispersion in OCDMA system," in *Int. Conf. on Data Mining and Intelligent Computing (ICDMIC)* (2014).
44. B. Hamzeh and M. Kavehrad, "OCDMA-coded free-space optical links for wireless optical-mesh networks," *IEEE Trans. Commun.* **52**(12), 2165–2174 (2004).
45. M. Jazayerifar and J. A. Salehi, "Atmospheric optical CDMA communication systems via optical orthogonal codes," *IEEE Trans. Commun.* **54**(9), 1614–1623 (2006).
46. T. H. Abda et al., "Modelling and simulation of a 1.6 Tb/s optical system based on multi-diagonal code and optical code-division multiple-access," *Ukr. J. Phys. Opt.* **13**(2), 54–66 (2012).
47. S. Rana and A. Gupta, "A novel security enhanced decoder based on XOR detection for optical code division multiple access system using multi-diagonal code," *Indian J. Sci. Technol.* **9**(36), 1–9 (2016).
48. M. Z. Norazimah et al., "Analytical comparison of various SAC-OCDMA detection techniques," in *2nd Int. Conf. on Photonics* (2011).
49. S. A. Aljunid et al., "Development of modified double-weight code and its implementation in multi-rate transmissions," in *13th IEEE Int. Conf. on Networks Jointly held with the 2005 IEEE 7th Malaysia Int. Conf. on Communication*, Malaysia (2005).
50. A. R. Arief et al., "Enhanced performance of new family modified double weight codes spectral amplitude coding optical CDMA system network," in *IEEE Int. Conf. on Control System, Computing and Engineering* (2011).

51. Z. Wang et al., "Optical encryption with OCDMA code swapping using all-optical xor logic gate," *IEEE Photonics Technol. Lett.* **21**(7), 411–413 (2009).
52. R. M. Younis et al., "Fully integrated AND and OR optical logic gates," *IEEE Photonics Technol. Lett.* **26**(19), 1900–1903 (2014).
53. S. Singh et al., "Novel security enhancement technique against eavesdropper for OCDMA system using 2-D modulation format with code switching scheme," *Opt. Fiber Technol.* **22**, 84–89 (2015).
54. N. Ahmed et al., "Performance improvement of spectral amplitude coding-optical code division multiple access systems using NAND detection with enhanced double weight code," *Opt. Rev.* **19**(1), 1–6 (2012).
55. S. Kumawat and M. R. Kumar, "Design and analysis of different decoders for SAC-OCDMA systems," in *Proc. of the Int. Conf. on Recent Cognizance in Wireless Communication and Image Processing* (2016).
56. S. A. Nezamalhosseini et al., "Interference cancellation in optical CDMA systems via advanced binary optical logic gate elements," *IEEE Commun. Mag.* **50**(8), 96–101 (2012).
57. I. Glesk et al., "Increasing optical security with OCDMA using optical XOR," in *Photonics in Switching* (2007).
58. A. J. Jaye and G. B. Lakshmy, "A NAND subtraction detection technique for hybrid SCM SAC-OCDMA system," *Int. J. Innovative Res. Comput. Commun. Eng.* **4**(2), 1101–1106 (2016).
59. W. Li et al., "Cross-layer security based on optical CDMA and algorithmic cryptography," in *IEEE Optoelectronics Global Conf. (OGC)* (2016).
60. T. H. Shake, "Security performance of optical CDMA against eavesdropping," *J. Lightwave Technol.* **23**(2), 655–670 (2005).
61. G. Cincotti et al., "Physical layer security: all-optical cryptography in access networks," in *10th Anniversary Int. Conf. on Transparent Optical Networks* (2008).
62. M. L. F. Abbade et al., "All-optical cryptography through spectral amplitude and delay encoding," *J. Microwave Optoelectron. Electromagn. Appl.* **12**(2), 376–397 (2013).
63. W.-H. Chang et al., "Enhancing optical-CDMA confidentiality with multicode-keying encryption," *J. Lightwave Technol.* **33**, 1708–1718 (2015).
64. U. Kaur and H. Singh, "Security enhancement in OCDMA system using multicode keying and data randomisers," in *2nd Int. Conf. on Next Generation Computing Technologies* (2016).
65. C.-C. Yang, "Performance analysis of multi-code keying scheme for spectral-amplitude-coding optical CDMA network," *Int. J. Inf. Commun. Sci.* **2**(6), 100–103 (2017).
66. A. T. Reshma and V. R. Vipin, "Security enhancement of optical code division multiple access system using multicode-keying encryption," *Int. J. Innovative Res. Comput. Commun. Eng.* **4**(2), 1608–1613 (2016).
67. Y.-T. Chang, "Confidential enhancement with multi-code keying reconfiguration over TS/WH OCDMA networks," *Appl. Mech. Mater.* **284-287**, 2899–2903 (2013).
68. L. Qin et al., "Security performance analysis of an M-code keying OCDMA system," *Photonic Network Commun.* **15**, 19–24 (2008).
69. P. R. Prucnal et al., "Optical steganography for data hiding in optical networks," in *16th Int. Conf. on Digital Signal Processing* (2009).
70. H. Zhu et al., "Optical steganography of code-shift-keying OCDMA signal based on incoherent light source," *IEEE Photonics J.* **7**(3), 6801607 (2015).
71. P. Laka and L. Maksymiuk, "Steganographic transmission in optical networks with the use of direct spread spectrum technique," *Security Commun. Networks* **9**, 771–780 (2016).
72. S. Gupta and A. Goel, "New approach for performance and security enhancement in OCDMA networks," in *Proc. of Int. Conf. on Communication and Networks, Advances in Intelligent Systems and Computing*, Springer (2017).

Simarpreet Kaur received her Btech degree from Chandigarh Group of colleges, Landran, Mohali, in electronics and communication engineering in 2013 and her Mtech degree from Punjabi University, Patiala, in 2015. Currently she is pursuing, a PhD from Punjabi University itself.

Simranjit Singh is currently working as assistant professor in the Department of ECE in Punjabi University, Patiala. He has completed postdoctoral study at the University of Rochester in 2017 and has specialization in fiber-optic communication.