Analysis of the performance of a coherent SAC-OCDMA–OFDM–DWDM system using a flat optical frequency comb generator for multiservice networks

Abderraouf Fares1 · Kaddour Saouchi1 · Fatima Brik1 · Hanane Djellab2

Received: 28 November 2021 / Accepted: 4 July 2022 / Published online: 24 July 2022 © The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
This research proposes the architecture of a SAC-OCDMA–OFDM–DWDM system using a flat optical frequency comb generator and coherent communication. Its aim is to create a new OCDMA communication system that is specifically intended for multiservice networks. The suggested architectural design is numerically simulated and analyzed using OptiSystem and MATLAB. To quantify the performance of the proposed system, SNR, EVM, and BER were used as metrics. Furthermore, a comparison between the two codes, EDW and RD, has been presented. Thus, it has been revealed that the RD code system has better performance in terms of robustness and number of users than the EDW code. Besides, by analyzing the BER for several symbol rates and comparing it to the pre-FEC threshold, the proposed system demonstrates its effectiveness against linear and nonlinear effects. The results also show that optical noise affects signal quality; the mathematical analysis used allowed us to determine the impact of noise on the number of potential active users.

Keywords Spectral amplitude coding optical code-division multiple-access · Dense wavelength division multiplexing · Orthogonal frequency division multiplexing · Flat optical frequency comb · Coherent communication · Enhanced double weight · Random diagonal · Bit error rate

1 Introduction

In recent years, and due to the high demand for bandwidth, especially for 3D/4K/HD video streaming, e-learning, and cloud computing applications, optical code-division multiple-access (OCDMA) has emerged as one of the promising solutions as a multiple access technique for high-capacity passive optical networks (PONs) (Mrabet et al. 2020;
Kumawat and Maddila 2017; Kakaee et al. 2014; Seyedzadeh et al. 2017). OCDMA architectures are suitable for multiservice optical access networks due mainly to their features, such as full asynchronous multiple access capability, code design flexibility, low latency access, soft capacity on demand, high data confidentiality, and providing quality of service (QoS) differentiation at the physical layer (Tharek et al. 2016).

Furthermore, OCDMA has drawn interest as a robust and adaptable solution for free-space optical communications (FSO) that is appropriate for 5G networks and its applications (Farhgal 2019; Sarangal et al. 2017). Because of its simplicity and reduced cost of system components, spectral amplitude coding OCDMA (SAC-OCDMA) is one of the different techniques created for OCDMA systems (Upadhyay et al. 2019; Matem et al. 2019). In parallel, the combination of OCDMA with Wavelength Division Multiplexing (WDM) will mitigate the drawbacks of both techniques, such as low security for wavelength and data modulated flow (Cao and Gan 2012; Singh and Singh 2017), with the occurrence of inter-symbol interference (ISI), which also leads to multiple access interference (MAI), which considerably restricts the number of active users. The hybridization of OCDMA/WDM allows for the easy increment of channel capacity and their level of confidentiality.

In actuality, orthogonal frequency division multiplexing (OFDM) has dominated wireless communication systems such as long-term evolution (LTE) networks, and also represents a future solution for 5G (Cai et al. 2018), because of its high spectral efficiency, robustness against delay, and increasing transmission rate via M-ary modulation of subcarriers such as phase-shifted-keying (PSK) or quadrature amplitude modulation (QAM). In addition to the previously mentioned benefits of the OCDMA/WDM system, the use of OFDM in this system provides robustness to fading and multipath channels, as well as the ability to overcome the multi-access interface and multipath dispersion (Armstrong 2009), (Nawawi et al. 2018; Yousif et al. 2018), which reflect the specter efficiency.

Because of the rise in channel capacity, coherent optical communication is viewed as one of the potential alternatives for PONs; it provides the flexibility of wavelength selection and is particularly compatible and beneficial with long-range networks (Liu et al. 2010; Li and Dang 2017). By multiplexing numerous users on the transmitted optical spectrum in order to reduce the existence of MAIs in the asynchronous transmission mode, this approach in OCDMA systems will provide the same capacity as optical time-division multiple access (OTDMA).

In this paper, we proposed a new architecture for a SAC-OCDMA–OFDM system intended for multiservice systems. The architecture makes use of a flat optical frequency comb (OFC) generator and a coherent communication system (Fortier and Baumann 2019). OCDMA codes are created to be compatible and customized for multiservice networks; enhanced double weight (EDW) and random diagonal (RD) codes are primarily chosen due to their numerical properties, particularly their low cross correlation characteristics (Abdullah et al. 2008; Fadhil et al. 2009) and ease of implantation.

The paper also highlights the impact of noise on the number of potential active users. The bit error rate (BER), which is the primary metric used to examine and assess the performance of the proposed system in order to determine which code can provide the maximum number of users while also being the most resilient against linear and nonlinear impairments, is determined through a mathematical analysis.

The paper is organized as follows: the Sect. 2 provides a detailed description of the proposed system; the Sect. 3 shows a numerical analysis of EDW and RD codes for coherent detection, the Sect. 4 presents and discusses simulation results; and the Sect. 5 draws a conclusion.
2 Proposed system

Figure 1 depicts the block diagram of the proposed system, which is composed of a flat optical frequency comb OFC generator in order to generate the OCDMA codes. The frequency spacing between each frequency is the same as in a DWDM de-multiplexer. The latter is used to separate each frequency or wavelength so that the power combiners may easily create the OCDMA codes afterwards. The user signal is then modulated with each coded signal. After the transmission, a second flat OFC generator is utilized as a local oscillator, whose output is precisely the frequency where no interference is present, and it is mixed with the received signal before being detected using a balanced detector. The user data signal is the baseband of each received signal. This operation is charged to the low pass filter and OFDM demodulator in order to recover it.

Figure 2 shows the SAC-OCDMA encoder for this system, which consists of a flat OFC generator, DWDM de-multiplexer, and optical power combiners. The flat OFC signal is generated by a continuous wave (CW) laser modulated with a radio frequency (RF) signal using a dual-parallel Mach Zehnder modulator (DP-MZM) (Shang et al. 2015; Tran et al. 2019), where the CW laser’s electric field is expressed as:

\[
E_{\text{CW laser}} = E_0 \cos \left( \frac{2\pi C}{\lambda_0} t + \varphi_0 \right)
\]  

(1)

where \(E_0\) is the amplitude of the electric field, \(C\) is the speed of light, \(\lambda_0\) is the CW laser wavelength which is 1552.52 nm in this system and that is equivalent to \(f_0 = 193.1\) THz,
and $\varphi_0$ is the laser phase. Moreover, two RF signals are applied to the arms of the DP-MZM with the same frequency $f_1$ and with different voltages. Hence, the role of the DC bias voltages $V_{b_1}$, $V_{b_2}$ and $V_{b_3}$ is to control the transmission points of the DP-MZM. For the first arm, it is biased to the maximum transmission point by putting $V_{b_1} = 0\,\text{V}$ to suppress the odd sidebands. In the second arm, $V_{b_2}$ has the same voltage as the switching bias voltage of the DP-MZM, thus, the transmission point will be biased to the minimum transmission point in order to suppress the carrier and even sidebands. Thereafter, when $V_{b_3}$ is set to $0\,\text{V}$ this means that $\varphi_3$ will be zero and there will be no phase shifting at the output of the DP-MZM, in order to get seven frequencies or wavelengths with a spacing of $f_1$. The electric field of the DP-MZM output is:

$$E_{\text{out-flatOFC}}(t) = \frac{E_{\text{CW laser}}(t)}{\sqrt{2}} \left[ \sum_{l=-\infty}^{+\infty} J_2(lm_1) e^{i(2l\mu_1)(2\pi f_1)t} + \sum_{l=-\infty}^{+\infty} J_{2l-1}(lm_2) e^{i(2l-1)(2\pi f_1)t} e^{i\varphi_3} \right]$$

(2)

where $J_l$ denotes the Bessel function of $l$th order of the first kind, $m_1$ and $m_2$ are the modulation indexes of the first and second arm of the DP-MZM, and $\varphi_3$ is the bias angle. Hence, Fig. 3 represents the Bessel function of first kind. When the amplitude of the intersection between $J_0$ and $J_2$ is the same as the intersection between $J_1$ and $J_3$, these two points mean that the DP-MZM can generate multiple optical sidebands, creating a frequency comb, where $m_1 = 1.84$ and $m_2 = 3.05$, which means that six sidebands and the main career are all with the same amplitude, which is expressed by:

$$J_{-3}(m_2) = J_{-2}(m_1) = J_{-1}(m_2) = J_0(m_1) = J_1(m_2) = J_2(m_1) = J_3(m_2)$$

(3)

The modulation indexes are expressed as follows:

$$m_1 = \frac{\pi RF_1}{V_{\pi 1}}$$

(4)

$$m_2 = \frac{\pi RF_2}{V_{\pi 2}}$$

(5)
where $RF_1$ and $RF_2$ are the amplitudes of the RF signals, $V_{x1}$ and $V_{x2}$ are the half-wave voltages for each arm of the DP-MZM respectively. Figure 4 depicts the CW laser and the flat OFC spectrums (Shang et al. 2015). In this system, $f_1$ is going to be 25 GHz, which is the equivalent of $\lambda_1 = 0.2$ nm. In order to split each wavelength to construct the SAC-OCDMA codes, a DWDM de-multiplexer with a spacing of $\lambda_1$ is used for this purpose. Then a set of power combiners will be employed to combine the selected wavelengths to construct the SAC-OCDMA code for each user. Concerning the EDW and RD codes, the weight and the number of users have been fixed at three to get the same code length, which is six. As a result, the code length of the EDW code $N_{EDW}$ is defined as follows (Menon et al. 2012; Abd El-Mottaleb et al. 2020):

$$N_{EDW} = 2k + \frac{4}{3} \left[ \sin \left( \frac{k\pi}{3} \right) \right]^2 + \frac{8}{3} \left[ \sin \left( \frac{(k+1)\pi}{3} \right) \right]^2 + \frac{4}{3} \left[ \sin \left( \frac{(k+2)\pi}{3} \right) \right]^2$$

(6)

where $k$ is the number of users. The code length of the RD code is given by the next expression (Mostafa and Mohamed 2017; Upadhyay et al. 2019):

$$N_{RD} = k + 2W - 3$$

(7)

where $W$ denotes the code weight. Tables 1 and 2 show the EDW and RD codes for each user. The same number of users in this case leads to have the same MAI interferences, so the cross-phase modulation (XPM) (Tithi and Majumder 2020) has almost the same effect on both signals during the transmission. Figure 5 represents the EDW and the RD spectrums.

Since the length of both codes is six, just 6 successive sidebands will be selected for the coherent modulation. After the code construction, the code’s spectrum will be modulated with an OFDM signal using an optical coherent modulator as presented in Fig. 5. Hence, a pseudo random binary sequence generator is employed as a user data. Therefore, a mapping system is used to generate the in-phase and the quadrature component sequences. This system employs the QPSK and 16-QAM modulation will be employed.
Fig. 4  a Spectrum of the CW laser and b the flat OFC generator

Table 1  EDW codes for $W = 3$, $N_{EDW} = 6$

| User #1 | 0 | 0 | 1 | 1 | 0 | 1 |
|---------|---|---|---|---|---|---|
| User #2 | 0 | 1 | 0 | 0 | 1 | 1 |
| User #3 | 1 | 1 | 0 | 1 | 0 | 0 |

Table 2  RD codes for $W = 3$, $N_{RD} = 6$

| User #1 | 0 | 0 | 1 | 0 | 1 | 1 |
|---------|---|---|---|---|---|---|
| User #2 | 0 | 1 | 0 | 1 | 1 | 0 |
| User #3 | 1 | 0 | 0 | 1 | 0 | 1 |
After separating the I and the Q components, the OFDM modulator will be employed. After modulating the two components, the general electrical OFDM generated signal with $N_{sc}$ subcarriers in the $k_{th}$ symbol period can be expressed as (Chen et al. 2014):

$$s_k(t) = \sum_{n=0}^{N_u-1} C_{k,n} e^{j\frac{2\pi n}{T}}$$  \hspace{1cm} (8)

where $C_{k,n}$ designates the complex coefficient on the $n_{th}$ subcarrier in the $k_{th}$ symbol and $T$ is the OFDM symbol time. The OFDM modulator parameters are: The number of subcarriers is 512 and the IFFT points = 1024 with a cyclic prefix of the transmitted symbol. The $I(t)$ and $Q(t)$ of the electrical OFDM signal is modulated with the SAC-OCDMA user code, dual drive Mach–Zehnder modulators (DD-MZM) modulate each OFDM component.

Both of the DD-MZMs are biased towards the null transmission point due to minimization of the radio to optical up-converter nonlinearities (Shieh et al. 2008). $V_b/2$ is the bias voltage where $V_b$ is the switching bias voltage of the DD-MZMs. The optical $Q(t)$ component doesn’t require an optical phase shifter after modulation since the phase is shifted in the OFDM modulator (Sheetal and Singh 2018). As a result, a power combiner is used to combine both components. The output of the coherent optical OFDM modulator represents one user. Additional power combiners are utilized to combine all the users, which can be expressed by:

$$E_k(t) = \sum_{k=1}^{N_u} A_{Ik}(t)e^{j2\pi f_k t + j\varphi_k} + A_{Qk} Q_k(t)e^{j2\pi f_k t + \frac{\pi}{2} + j\varphi_k}$$  \hspace{1cm} (9)

where $N_u$ is the number of users, $A_{Ik}$ and $A_{Qk}$ are the amplitudes of each component for each user in OCDMA encoded signals, which are proportional to the I and Q components, respectively. Modulation indexes and the phase shifts of the DD-MZMs, $f_k(t)$ and $Q_k(t)$ are the OFDM I/Q components for each user (Shieh et al. 2008), $f_k$ and $\varphi_k$ are the set of

Fig. 5 Coherent Optical OFDM Modulator
frequencies and the phase that identify each user. The EDW and the RD output spectrums are shown in Fig. 6.

After the transmission of the combined signals, they will be decoded by splitting each wavelength alone using a DWDM de-multiplexer. Then an identical set of power combiners employed in the SAC-OCDMA encoder is used in order to construct each user spectrum for the second time. Figure 7 shows the SAC-OCDMA decoder. Coherent detection is the technique that is used to restore the OFDM signal. Furthermore, the local oscillator (LO) is mandatory for this technique. In this proposed system, the LO part is a second flat OFC generating seven wavelengths with a spacing of $\lambda_1$, followed by another DWDM de-multiplexer that splits wavelength, then a selection of wavelengths that are the same as the received signal that do not contain spectral interference, and finally, putting each selected wavelength, which represents the users and the received signal, into the inputs of the 90° hybrid coupler in the receiver of each user.

![Fig. 6](attachment:image.png)  
**Fig. 6**  
(a) Output spectrum of EDW and (b) RD code
Figure 8 shows the optical coherent detector including a $90^\circ$ hybrid coupler and two balanced detectors, for the recovery of $I(t)$ and $Q(t)$ components (Painchaud et al. 2009). After mixing the received signal with the LO signal, the output electric fields of the 90 degree hybrid coupler are written:

\[
E_1(t) = \frac{1}{\sqrt{2}} [E_s(t) + E_{LO}(t)]
\]  
(10)

\[
E_2(t) = \frac{1}{\sqrt{2}} [E_s(t) - E_{LO}(t)]
\]  
(11)

\[
E_3(t) = \frac{1}{\sqrt{2}} [E_s - jE_{LO}(t)]
\]  
(12)

Fig. 8 the receiver part for each user
where \( E_s(t) \) and \( E_{LO}(t) \) are the electric fields of the received signal and the LO signal, the received signal contains six modulated signals, three of them are the interference spectrums. The following expression can be used to infer it:

\[
E_s(t) = A_{s1}(t)e^{j(\omega_{s1}t+\phi_{s1})} + A_{s2}(t)e^{j(\omega_{s2}t+\phi_{s2})} + A_{s3}(t)e^{j(\omega_{s3}t+\phi_{s3})} + A_{s4}(t)e^{j(\omega_{s4}t+\phi_{s4})} + A_{s5}(t)e^{j(\omega_{s5}t+\phi_{s5})} + A_{s6}(t)e^{j(\omega_{s6}t+\phi_{s6})}
\]

And the LO signal can be expressed:

\[
E_{LO}(t) = A_{LO}e^{j(\omega_{LO}t+\phi_{LO})}
\]

where the square of \( A_{s1}(t), A_{s2}(t), A_{s3}(t), A_{s4}(t), A_{s5}(t) \) and \( A_{s6}(t) \) are the powers for each wavelength, and the square of \( A_{LO} \) is the power of the LO signal. After mixing the received signal with the LO signal and detecting the electric signal using a balanced detector, assuming the all phases are equal, the output photocurrents can be given by:

\[
\Delta i_I(t) = RA_{LO}[A_{s1}(t)\cos(\omega_{IF1}t) + A_{s2}(t)\cos(\omega_{IF2}t) + A_{s3}(t)\cos(\omega_{IF3}t) + A_{s4}(t)\cos(\omega_{IF4}t) + A_{s5}(t)\cos(\omega_{IF5}t) + A_{s6}(t)\cos(\omega_{IF6}t)]
\]

\[
\Delta i_Q(t) = RA_{LO}[A_{s1}(t)\sin(\omega_{IF1}t) + A_{s2}(t)\sin(\omega_{IF2}t) + A_{s3}(t)\sin(\omega_{IF3}t) + A_{s4}(t)\sin(\omega_{IF4}t) + A_{s5}(t)\sin(\omega_{IF5}t) + A_{s6}(t)\sin(\omega_{IF6}t)]
\]

where \( R \) is the photodetector responsivity, and \( \omega_{IF1} = \omega_1 - \omega_{LO}, \omega_{IF2} = \omega_2 - \omega_{LO}, \omega_{IF3} = \omega_3 - \omega_{LO}, \omega_{IF4} = \omega_4 - \omega_{LO}, \omega_{IF5} = \omega_5 - \omega_{LO}, \omega_{IF6} = \omega_6 - \omega_{LO}. \)

Knowing that \( \omega_{LO} \) is the same as one of the six wavelengths in the selected spectrum to be demodulated, \( \omega_{IF} \) is going to be zero, and the selected spectrum will be amplified and shifted to become a baseband signal as a result of mixing with the LO signal. Figure 9 shows the balanced detector output spectrums of both codes.

The received signal components is filtered using low pass cosine roll-off filters with a roll-off coefficient of 0.2 in order to maintain the baseband part of the received signal, and eliminate all the undesirable frequencies, and minimize the inter-symbol interferences in the OFDM signal. Next an OFDM demodulator, QPSK or 16-QAM decoder and digital signal processing (DSP) are used to restore the original transmitted signal, observe and study the system performance. The DSP is used generally with analog-to digital converters, its role is mainly to compensate for digitally the channel impairments such as chromatic dispersion (CD), polarization mode dispersion (PMD)(Amari et al. 2017), and all phase noises using adaptive equalizers by removing the rate of rotation of the constellation using finite impulse response filters. The DSP employs frequency offset estimator and career phase recovery algorithms for recovering the transmitted signal.
Theoretical performance of the EDW and RD codes of the optical coherent detection system are investigated. The signal to noise ratio (SNR) of the received signal determines the estimated BER value, the theoretical SNR is expressed by:

\[ \text{SNR} = \frac{I^2}{\sigma^2} \] (18)

where \( I^2 \) represents the power spectral density of the received photocurrent, and \( \sigma^2 \) is the variance of the noise sources in the transmission system. Thermal noise, shot noise, and amplified spontaneous emission noise (ASE noise) are the main sources of noise in optical systems.

![Received spectrums of the third user of EDW code, RD code](image)

**Fig. 9** Received spectrums of the third user of (a) EDW code, (b) and RD code

### 3 Mathematical analysis

The theoretical performance of the EDW and RD codes of the optical coherent detection system are investigated. The signal to noise ratio (SNR) of the received signal determines the estimated BER value, the theoretical SNR is expressed by:

\[ \text{SNR} = \frac{I^2}{\sigma^2} \] (18)

where \( I^2 \) represents the power spectral density of the received photocurrent, and \( \sigma^2 \) is the variance of the noise sources in the transmission system. Thermal noise, shot noise, and amplified spontaneous emission noise (ASE noise) are the main sources of noise in optical...
coherent detection. The intensity noise is neglected in this work because the intensity noise of the transmitted signal is eliminated by the transmission media high losses and the LO intensity noise is eliminated by balanced detection (Buscaino et al. 2019). Before detailing each noise, the transmitted signal average power should be detailed in order to determine the received photocurrent and the noise power. A 90° hybrid coupler is utilized in the optical coherent detection system to split the in-phase I and quadrature Q components of the transmitted signal, which is modulated by a coherent modulator. Knowing that the Q component is phase shifted by 90°, in order to simplify our analysis, the I component is considered because there is no phase shifting. The root mean square of the received photocurrent of the I component in the output of the 90° hybrid coupler is:

\[ I_I = R \sqrt{(P_rP_{LO}/4)} \]  (19)

where \( P_r \) and \( P_{LO} \) are the received power of the received signal and the LO power in the receiver. The received signal is an OCDMA encoded signal. In order to get the received electrical signal using coherent detection (90° hybrid coupler and balanced detector), the mathematical properties signal power of EDW and RD codes are defined by. From (Abdul-lah et al. 2008), the EDW code average power for spectral direct detection (SDD) is defined by the following expressions:

\[ P_{EDW} = PW/N \]  (20)

where \( P \) is the signal effective power at the receiver, \( W \) denotes the code weight, and \( N \) represents the code length. From (19) and (20), the photocurrent of the I component for EDW code is expressed by the next formula:

\[ I_{IEDW} = R \sqrt{WP_{EDW}P_{LO}/4N_{EDW}} \]  (21)

Concerning the RD code, according to (Fadhil et al. 2009), the following expression defines the RD code’s power for SDD detection:

\[ P_{RD} = 2PW/N \]  (22)

By replacing (22) in (19), the photocurrent of the RD code signal is:

\[ I_{IRD} = R \sqrt{WP_{RD}P_{LO}/2N_{RD}} \]  (23)

Consequently, the variance of the noise sources can be determined; we can express it by the next formula:

\[ \sigma^2 = \sigma^2_{shot} + \sigma^2_{ASE} + \sigma^2_{thermal} \]  (24)

where \( \sigma^2_{shot} \) is the shot noise, \( \sigma^2_{ASE} \) is the ASE noise and \( \sigma^2_{thermal} \) is the thermal noise. In this analysis, the shot noise of the LO in the receiver is the dominant noise, and as described in the previous section, the LO signal contains only the selected wavelength that will be recovered from the transmitted signal. This noise can be modeled by the next variance formula:
\[ \sigma_{\text{shot}}^2 = qP_{\text{LO}}RB \]  

(25)

where \( q \) is the electron’s charge and \( B \) is the effective bandwidth of the photodetector’s receiver. The use of inline optical amplifiers which generate noise that degrades the quality of the received signal is referred to as ASE noise. In this analysis, the local oscillator-ASE beating noise is the dominant ASE noise. It can be expressed by:

\[ \sigma_{\text{ASE}}^2 = R^2 P_{\text{LO}} n_{\text{sp}} (G - 1) hvB \]  

(26)

where \( n_{\text{sp}} \) is the spontaneous emission factor, \( G \) is the amplifier gain, \( h \) is the Planck’s constant, and \( v \) is the photon’s frequency. The thermal noise of EDW is the same as the RD code because it is always independent of the received photocurrent. The expression of the thermal noise is:

\[ \sigma_{\text{thermal}}^2 = \frac{4K_B T_n B}{R_L} \]  

(27)

\( K_B \) is Boltzmann’s constant, \( T_n \) is the absolute receiver noise temperature, and \( R_L \) is the receiver load resistor. After defining all the currents and the noise, the SNR for the EDW and RD codes can be calculated using the following expressions:

\[ \text{SNR}_{\text{EDW}} = \frac{\left( R \sqrt{\frac{WP_{\text{EDW}} P_{\text{LO}}}{4N_{\text{EDW}}}} \right)^2}{qP_{\text{LOEDW}}RB + R^2 P_{\text{LOEDW}} n_{\text{sp}} (G - 1) hvB + \frac{4K_B T_n B}{R_L}} \]  

(28)

\[ \text{SNR}_{\text{RD}} = \frac{\left( R \sqrt{\frac{WP_{\text{RD}} P_{\text{LO}}}{2N_{\text{RD}}}} \right)^2}{qP_{\text{LORD}}RB + R^2 P_{\text{LORD}} n_{\text{sp}} (G - 1) hvB + \frac{4K_B T_n B}{R_L}} \]  

(29)

Table 3 shows the main parameters used to calculate the SNR. To have the most direct measure that will aid in the analysis of the performance of both codes, the estimated BER is calculated by the following formula (Mrabet et al. 2018):

| Description                  | Parameters | Values                      |
|------------------------------|------------|-----------------------------|
| Electron charge              | \( q \)   | \( 1.602 \times 10^{-19} \text{ C} \) |
| Boltzmann’s constant         | \( K_B \) | \( 1.38 \times 10^{-23} \text{ J K}^{-1} \) |
| Absolute receiver noise      | \( T_n \) | 300 K                       |
| Load resistance              | \( R_L \) | 50 \( \Omega \)              |
| Spontaneous emission factor  | \( n_{\text{sp}} \) | 1.3                         |
| Quantum efficiency           | \( \eta \) | 0.6                         |
| Plank’s constant             | \( h \)   | \( 6.6260 \times 10^{-34} \text{ J s} \) |
| LO power                     | \( P_{\text{LO}} \) | 10 dBm                      |
| Received power               | \( P_{\text{REEDW}} \) or \( P_{\text{RD}} \) | \(-20 \text{ dBm}\)         |
| Central wavelength           | \( \lambda = \frac{1}{v} \) | 1550 nm                     |
\[ BER = \frac{2}{\log_2 M} \left( 1 - \frac{1}{\sqrt{M}} \right) \text{erfc} \left( \sqrt{\frac{3}{2}} \frac{\text{SNR}}{M - 1} \right) \]  

(30)

\( M \) is the high order of the advanced modulation format (M-PSK or M-QAM), since the transmitted data uses these mapping types to be employed in OFDM modulation.

Analytically, to compare the performance of the EDW and RD codes for optical coherent detection, the number of active users should be set, and it should be determined which code may provide the maximum number of users. The BER is the main parameter that can judge which code is the best. To compute the BER, the code length will be defined mainly as a function of the number of users \( k \). It is possible to calculate it using expressions (6) and (7).

The number of users is shown in Fig. 10 of the SAC-OCDMA coherent detection system for the EDW and RD codes using 16-QAM-OFDM modulation for different code weights and different bit rates in the presence of ASE noise. Clearly, the RD supports a larger number of active users for different code weights and different bit rates due to its low cross correlation characteristic. The MAI presence in the transmitted signal spectrum is reduced compared to the EDW code, which its suppression is simple and easier to implement. In addition, the presence of ASE noise decreases sharply the number of users due to its effects on the received signal, as a result, inline amplifiers are not recommended in this system.

However, in this system, the RD code cannot be considered better than the EDW code in terms of robustness against linear and nonlinear impairments, the performance should be studied when the number of users and the code weight are equal for each code, in order to find out which code is performing better.

![Fig. 10 Log(BER) versus number of users of optical coherent detection for different code weights and different bit rates in the presence of ASE noise](image-url)
4 Simulation results and discussion

A co-simulation technique is employed through the usage of OptiSystem and MATLAB. Furthermore, since the optical system is carried on the OptiSystem, MATLAB is in charge of executing the simulation, analyzing, processing, and presenting the results. The BER is calculated from the measured EVM from the constellation diagram. Moreover, the EVM provides an accurate measurement to evaluate multi-level and multi-phase modulation systems such as QPSK and 16-QAM modulations. Thus, it can be defined as the difference between the reference symbol vector and the measured symbol vector illustrated in the constellation, it can be expressed by (Schmogrow et al. 2012):

$$EVM = \sqrt{\frac{P_{err}}{\text{P}_{\text{ref}}}}$$

(31)

where $P_{err}$ is the average power of the error vector of the received data, including all the linear and nonlinear impairments, $\text{P}_{\text{ref}}$ is the average power of the reference symbol vector.

In this simulation, the optimum CW laser injected power into the transmitter and into the LO in the receiver for each user is defined by varying the injected power and determining which power corresponds to the minimum EVM in order to minimize the optical fiber nonlinear effects specifically the Kerr’s effect and the self-phase modulation (SPM), as well as get sufficient power for the transmission. Figure 11 shows that for both of codes, EDW and RD, the minimum EVM corresponds to an injected power of 10 dBm for symbol rate of 10 GBd using QPSK modulation over 60 Km including 50 Km of single-mode fiber (SMF), 10 Km of dispersion compensating fiber (DCF) and an erbium-doped fiber amplifier (EDFA) for attenuation compensation (Sheetal and Singh 2018). The figure also illustrates that when the injected power is adjusted, the RD code outperforms the EDW.

The influence of the noise presence is studied by adding ASE noise to the transmitted signal and evaluating the performance of the system for both codes. Moreover, the optical signal-to-noise ratio (OSNR) is the optical power divided by the ASE noise, the OSNR is measured over a reference OSNR where its ASE noise bandwidth is 0.1 nm at 1550 nm, by adjusting the ASE noise, the OSNR will also be also varied, which will influence
the performance of the EVM, the BER can be calculated using the following expression (Freude et al. 2012; Schmogrow et al. 2012):

\[
BER = \frac{1 - M^{-1/2}}{\sqrt{\frac{\log_2 M}{2}}} \text{erfc} \left( \sqrt{\frac{3/2}{(M - 1)r^2EVM^2}} \right)
\]

(32)

The constant \( r \) is depending on the modulation format, from (Freude et al. 2012), \( r_{QPSK} = 1 \) and \( r_{16-QAM} = \sqrt\frac{2}{3} \).

**Fig. 12** Log(BER) in function of OSNR for symbol rate of 10 GBd **a** using QPSK modulation, **b** using 16-QAM modulation
Figure 12 represents the log(BER) in function of the OSNR for symbol rate of 10 GBd for each user over several distances, which are: back-to-back (BtB) transmission, 50 km using SMF and 60 km which was described previously, and comparing its performance with pre-forward error correction (pre-FEC) threshold of $2.17 \times 10^{-3}$ in order to find out if the transmitted data can be recovered (Agrell and Secondini 2018). From Fig. 12a, all the curves are below the pre-FEC threshold when the QPSK modulation is employed when the OSNR starts from 5 dB. However for the performance of 16-QAM modulation shown in Fig. 12b, the threshold is respected after 9 dB for BtB transmission for both codes, 10 dB for 60 km for both codes too, almost 11 dB for RD code and EDW code for 50 km. Figure 13 shows the log(BER) versus the OSNR for the distance of 60 km described before, Fig. 13a shows that the symbol rate of 15 GBd for each user, starting from 7 dB the QPSK system, is also below the pre-FEC threshold for both codes. Concerning the 16-QAM
modulation, the EDW and RD codes verified the threshold at almost 12 dB. For the symbol rate of 20 GBD for each user shown in Fig. 13b, the pre-FEC threshold is verified for higher OSNR. Concerning the QPSK modulation, the EDW code respects the threshold at almost 7 dB, and the RD code is still below the pre-FEC threshold. The threshold is also respected for OSNR of 15 dB and 17 dB for the RD and EDW codes, respectively.

Concerning the discussion of the collected results, due to the DWDM system used in this proposed system, the XPM is induced from DWDM adjacent wavelengths, which specifically results in nonlinear phase noise due to the cumulative intensity dependence of the refractive index in the optical fiber, which heavily distorts the received signal. It is very clear from Figs. 11, 12 and 13 that the RD code system performs better than the EDW code for all the cases studied. Furthermore, as shown in Fig. 6b, wavelength interferences occur at the extremes of the RD code spectrum. On the other hand, for the EDW code, the interferences are located in the vicinity of the users wavelengths as shown in Fig. 6a. Moreover, the overlap of adjacent spectrums results in the XPM effect with interfered spectrums, which degrades the quality of detected signals. However, for the RD code, the overlap is limited to the interfered spectrums due to their positions at the extremity of the transmitted spectrums.

Figure 14 shows the constellation diagrams of both EDW and RD codes of the third user for a symbol rate of 20 GBD for BtB transmission, 120 km using twice the 60 km optical link which was described previously ((50 Km – SMF + 10 Km – DCF + EDFA) × 2), and 300 km using the same optical link five times ((50 Km – SMF + 10 Km – DCF + EDFA) × 5). The IQ skew is highly apparent in the BtB transmission due mainly to the electrical generation of the \( I(t) \) and \( Q(t) \) which are not separated exactly by 90\(^\circ\), which distorts the received signal. For 300 km QPSK system, the quality of the received signal constellation using RD code is better than the EDW. The same thing is observed for the constellation of 16-QAM system at a distance of about 120 km, where the received symbols are spread out clearly in the EDW code more than in the RD code because of the influence of overlapping discussed already.

The RD code outperforms the EDW thanks to the low cross-correlation feature, which provides the maximum number of users. The localization of the interferences in the received signal demonstrates the robustness of the RD against optoelectronic noise and the nonlinear effects of the optical fiber for coherent communication systems.

---

**Fig. 14** Constellation diagrams for different distances with symbol rate of 20 GBD
5 Conclusion

We have presented the simulation results of a coherent SAC-OCDMA–OFDM–DWDM system dedicated to multiservice networks. The architecture of the proposed system employs a flat OFC generator for code generation and DWDM system for code construction. Then, after applying the most known SAC-OCDMA codes, EDW and RD, to this proposed system to see the performance of its detection technique, the latter shows its effectiveness against linear and nonlinear effects by analyzing the BER for several symbol rates and comparing it with the pre-FEC threshold, mainly due to the conjunction of SAC-OCDMA–OFDM with the DWDM system despite the XPM and its influence on the performance of the transmitted signals. A comparison was established between the two codes, EDW and RD. The EDW code has been discovered to be faster than the RD code. The results also demonstrate the effect of optical noise on signal quality when transmitting some type of data over the proposed system. From this perspective, it is intended to complete this work with experimental data and also use new codes for further research, with mathematical features that take into account the positions of wavelength overlap in the code, the linear and nonlinear effects, particularly the XPM, which makes it possible to reduce the XPM as a result of the new codes’ design. These new codes will be used in 5G applications such as Radio-over-Fiber (RoF) and Free Space Optics (FSO) communications.

Funding The authors have not disclosed any funding.

Conflict of interest The authors have not disclosed any competing interests.

References

AbdEl-Mottaleb, S., et al.: MDW and EDW/DDW codes with AND subtraction/single photodiode detection for high performance hybrid. Opt. Quant. Electron. (2020). https://doi.org/10.1007/s11082-020-02357-x

Abdullah, M.K., Hasoon, M., Feras, N., Aljunid, S.A., Shaari, S.: Performance of OCDMA systems with new spectral direct detection (SDD) technique using enhanced double weight (EDW) code. Opt. Commun. 281, 4658–4662 (2008). https://doi.org/10.1016/j.optcom.2008.06.029

Agrell, E., Secondini, M.: Information-theoretic tools for optical communications engineers. In: 2018 IEEE Photonics Conference (IPC) (2018). https://doi.org/10.1109/IPCCon.2018.8527126

Amari, A., Octavia, A.D., Ramachandran, V., Sunish, K.O.S., Philippe, C., Yves, J.: A survey on fiber nonlinearity compensation for 400 Gbps and beyond optical communication systems. IEEE Commun. Surv. Tutor. 19(4), 1–17 (2017). https://doi.org/10.1109/COMST.2017.2719958

Armstrong, J.: OFDM for optical communications. J. Lightwave Technol. 27(3), 189–204 (2009). https://doi.org/10.1109/JLT.2008.2010061

Buscaino, B., Brian, D.T., Kahn, M.J.: Multi-Tb/S-per-fiber coherent co-packaged optical interfaces for data center switches. J. Lightwave Technol. 37(13), 3401–3412 (2019). https://doi.org/10.1109/JLT.2019.2916988

Cai, Y., Zhijin, Q., Fangyu, C., Li, G.Y., Mccann, J.A.: Modulation and multiple access for 5G networks. IEEE Commun. Surv. Tutor. 20(1), 629–646 (2018). https://doi.org/10.1109/COMST.2017.2766698

Cao, Y., Gan, C.: A scalable hybrid WDM/OCDMA-PON based on wavelength-locked RSOA technology. Optik Int. J. Light Electron Opt. 123(2), 176–180 (2012). https://doi.org/10.1016/j.ijleo.2011.03.015

Chen, C., Zhong, W.: MDPSK based non-equalization OFDM for coherent free-space optical communications. IEEE Photon. Technol. Lett. 1135(c), 1–4 (2014). https://doi.org/10.1109/LPT.2014.2329133
Fadhil, H.A., Aljunid, S.A., Ahmad, R.B.: Optical fiber technology performance of random diagonal code for OCDMA systems using new spectral direct detection technique. Opt. Fiber Technol. 15(3), 283–289 (2009). https://doi.org/10.1016/j.yofte.2008.12.005

Farghal, A.E.A.: On the performance of OCDMA/SDM PON based on FSO under atmospheric turbulence and pointing errors. Opt. Laser Technol. 114, 196–203 (2019). https://doi.org/10.1016/j.optlastec.2019.01.048

Fortier, T., Baumann, E.: 20 years of developments in optical frequency comb technology and applications. Commun. Phys. (2019). https://doi.org/10.1038/s42005-019-0249-y

Freude, W., René S., Bernd N., Marcus W., Arne J., David H., Swen K., et al.: Quality metrics for optical signals : eye diagram, Q-factor, OSNR, EVM and BER. In: 14th International Conference on Transparent Optical Networks ICTON 2012 (2012). https://doi.org/10.1109/ICTON.2012.6254380

Kakaee, M.H., Saleh, S., Fadhil, H.A., Siti, B.A.A., Makhfudzali, M.: Development of multi-service (MS) for SAC-OCDMA systems. Opt. Laser Technol. 60, 49–55 (2014). https://doi.org/10.1016/j.optlastec.2014.01.002

Kumawat, S., Maddila, R.K.: Optical fiber technology development of ZCCC for multimedia service using SAC-OCDMA systems. Opt. Fiber Technol. 39, 12–20 (2017). https://doi.org/10.1016/j.yofte.2017.09.015

Li, R., Dang, A.: A novel coherent OCDMA scheme over atmospheric turbulence channels. IEEE Photon. Technol. Lett. 1135(c), 1–4 (2017). https://doi.org/10.1109/LPT.2017.2652727

Liu, J., Lu, Y., Changjian, G.: Demonstration of low-cost uplink transmission in a coherent OCDMA PON using gain-switched fabry – pérot lasers with external injection. IEEE Photon. Technol. Lett. 22(8), 583–585 (2010). https://doi.org/10.1109/LPT.2010.2042948

Matem, R., Aljunid, S.A., Junita, M.N., Rashidi, C.B.M., ShihabAhmed, I.: Photodetector effects on the performance of 2D spectral/spatial code in OCDMA system. Optik J. Light Electron Opt. 178, 1051–1061 (2019). https://doi.org/10.1016/j.ijleo.2018.10.068

Menon, P.S., Ali, Z.G., Mandeep, J.S., Shaari, S.: Realization of 2-D OCDMA network using EDW code. Optik J. Light Electron Opt. 123(15), 1385–1389 (2012). https://doi.org/10.1016/j.ijleo.2011.07.073

Mostafa, S., Mohamed, A.A.: Performance evaluation of SAC-OCDMA system in free space optics and optical fiber system based on different types of codes. Wirel. Pers. Commun. 96, 2843–2861 (2017). https://doi.org/10.1007/s11277-017-4327-8

Mrabet, H., Mhatli, S., Dayoub, I., Giacoumidis, E.: Performance analysis of AO-OFDM-CDMA with advanced 2D-hybrid coding for amplifier- free LR-PONs. IET Optoelectron. 12(6), 293–298 (2018). https://doi.org/10.1049/iet-opt.2018.5042

Mrabet, H., Cherifi, A., Raddo, T., Dayoub, I.: A comparative study of asynchronous and synchronous OCDMA systems. IEEE Syst. J. (2020). https://doi.org/10.1109/JYSYST.2020.2991678

Nawawi, N.M., Anuar, M.S., Junita, M.N.: Cardinality improvement of zero cross correlation (ZCC) code for OCDMA visible light communication system utilizing catenated-OFDM modulation scheme. Optik J. Light Electron Opt. 170, 220–225 (2018). https://doi.org/10.1016/j.ijleo.2018.05.125

Painchaud, Y., Poulin, M., Morin, M., Têtu, M.: Performance of balanced detection in a coherent receiver. Opt. Express 17(5), 3659–3672 (2009). https://doi.org/10.1364/OE.17.003659

Sarangal, H., Singh, A., Malhotra, J., Chaudhary, S.: A cost effective 100 Gbps hybrid MDM–OCDMA–FSO transmission system under atmospheric turbulences. Opt. Quant. Electron. 49(5), 1–10 (2017). https://doi.org/10.1007/s11082-017-1019-2

Schmogrow, R., Nebendahl, B., Winter, M., Josten, A., Hillerkuss, D., Koenig, S., Meyer, J., et al.: Error vector magnitude as a performance measure for advanced modulation formats. IEEE Photon. Technol. Lett. 24(1), 2011–2013 (2012). https://doi.org/10.1109/LPT.2011.2172405

Seyedzadeh, S., Pour, F., Glesk, I., Kakaee, M.H.: Optical fiber technology variable weight spectral amplitude coding for multiservice OCDMA networks. Opt. Fiber Technol. 37, 53–60 (2017). https://doi.org/10.1016/j.yofte.2017.07.002

Shang, L., Li, Y., Ma, L., Chen, J.: A flexible and ultra- flat optical frequency comb generator using a parallel mach–zehnder modulator with a single DC bias. Opt. Commun. 356, 70–73 (2015). https://doi.org/10.1016/j.comcom.2015.07.065

Sheetal, A., Singh, H.: 5 × 10 Gbps WDM-CAP-PON based on frequency comb using OFDM with blue LD. Opt. Quant. Electron. 50, 446 (2018). https://doi.org/10.1007/s11082-018-1703-x

Shieh, W., Bao, H., Tang, Y.: Coherent optical OFDM : theory and design. Opt. Express 16(2), 841–859 (2008). https://doi.org/10.1364/OE.16.000841

Singh, S., Singh, S.: Performance analysis of spectrally encoded hybrid WDM-OCDMA. AEUE Int. J. Electron. Commun. (2017). https://doi.org/10.1016/j.aeue.2017.10.003
Tharek, A.O.A., Rahman, A., Aljunid, S.A.: A new model to enhance the QoS of spectral amplitude coding-optical code division multiple access system with OFDM technique. Opt. Quant. Electron. (2016). https://doi.org/10.1007/s11082-016-0750-4

Tithi, F.H., Majumder, S.P.: Analytical evaluation of combined influence of XPM, ASE and SRS in a Raman amplifier based WDM system. Optik Int. J. Light Electron Opt. 208, 164076 (2020). https://doi.org/10.1016/j.ijleo.2019.164076

Tran, T.T., Song, M., Song, M., Seo, D.: Highly flat optical comb generation based on DP-MZM and phase modulators. Electron. Lett. 55(1), 43–45 (2019). https://doi.org/10.1049/el.2018.6454

Upadhyay, K.K., Shukla, N.K., Chaudhary, S.: A high speed 100 Gbps MDM-SAC-OCDMA multimode transmission system for short haul communication. Optik Int. J. Light Electron Opt. 202, 163665 (2019). https://doi.org/10.1016/j.ijleo.2019.163665

Yousif, B., Ibrahim, E.M.A., Samra, S.: A modified topology achieved in OFDM/SAC-OCDMA-based multi-diagonal code for enhancing spectral efficiency. Photon Netw. Commun. (2018). https://doi.org/10.1007/s11107-018-0796-2

**Publisher’s Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.