Optical and Quantum Electronics (2022) 54:351
https://doi.org/10.1007/s11082-022-03714-8

An efficient algorithm to provide triple play services in passive optical network (PON)-OCDMA network

Hassan Yousif Ahmed[1] · Medien Zeghid[1,2] · Teena Sharma[3] · Akhtar Nawaz Khan[4] · Waqas A. Imtiaz[4] · Somia A. Abd El-Mottaleb[5]

Received: 19 July 2021 / Accepted: 28 March 2022 / Published online: 12 May 2022

Abstract

Adaptability of an effective access network in optical code division multiple access domain requires an efficient coding scheme which has the abilitiy to provide required communication capacity in terms of cardinality, reach, and data rates. In this paper, an extensive study and investigation has been carried out for adaptability study of a well-known coding scheme diagonal eigenvalue unity (DEU) code at various date rates in passive optical network (PON) environment. DEU code design is based on Jordan block matrix with ideal in-phase cross correlation (IPCC) properties. The numerical and simulation results show the ability of DEU code in supporting synchronized transmissions at different data rates that suits triple play services of video, audio and data (VAD). An algorithm is developed to determine the required chip duration that matches a particular service. It shows that data rate is more influential than code length on pulse duration especially for video applications. In support of the proposed algorithm, 5 Gb/s, 2.5 Gb/s, and 1.25 Gb/s data rate transmissions have been validated for various simultaneous users. In addition, a Poisson's distribution analysis is carried out aiming to study different bit rate scenarios with ad hoc population network. Results have concluded that higher value of average rate of simultaneous users (σ) is preferable for low data rate whereas the lower value of σ is suitable to the higher data rates in accordance with network population. In particular, for video streaming, the traffic running in a continuous fashion requires the highest transmission priority and small value of σ.

Keywords SAC OCDMA · Chip duration · VAD · Poisson distribution

✉ Hassan Yousif Ahmed
h.ahmed@psau.edu.sa

✉ Teena Sharma
teena.sharma1@uqac.ca

Extended author information available on the last page of the article

1 Introduction

In the age of social networking and e-government, the need for data transfer technologies has grown exponentially and the quality of service (QoS) has become affordable (Stok and Sargent 2000). The huge development of smart devices has led to increasing demand on the Internet by consumers of various applications which has resulted in a huge amount of bandwidth requirement (Salehi 1989; Salehi and Brackett 1989).

To fulfill the bandwidth and quality requirements of the diverse services, new technologies should be developed in order to meet the requirements and overcome challenges. In this regard, optical fiber communication is one of the main technologies to drive this revolution in information technology (Seyedzadeh et al. 2017a; Sharma and Maddila 2019).

OCDMA has been introduced as a highly efficient competitive technology in the field of fiber optics.

The success of the OCDMA technology in the field of optical communication has opened the way for reflection on the application of this technique in the field of fiber optic by experts in academic and industry (Ahmed and Nisar 2013a).

OCDMA technology provides simultaneous and asynchronous access to multiple subscribers with higher flexibility and simplicity of execution. In this technology, each subscriber uses OCDMA scheme to communicate fully through a unique coding approach, which distinguishes the intended information from the interference at the receiving end. This feature provides an effective mechanism to increase subscribers to transmit at high speed data rates and at a low cost when compared to other technologies (Ahmed and Nisar 2013b).

Several coding schemes such as time spreading, frequency hopping, and spectral amplitude coding (SAC) have been utilized to maximize the capacity of OCDMA system. However, SAC-OCDMA system received more attention due to their ability to mitigate multiple access interference (MAI) and inherited phase induced intensity noise (PIIN) phenomena at the receiving end by using codes with ideal in-phase cross correlation and detection techniques (Aljunid et al. 2383; Ahmed and Zeghid 2017; Ahmed et al. 2016; Sharma et al. 2019).

In addition, SAC-OCDMA system utilizes low-cost broadband non-coherent sources, which are most suitable for the required binary to spectral conversion and further provide desired capacity in terms of data, reach and cardinality (Ahmed et al. 2012). Various codes have been reported for SAC-OCDMA with property such as modified quadratic congruence code for prime weights (Wei et al. 2001), multi-weight unipolar code (Djordjevic et al. 2004), variable weight (VW) Khazani Syed (KS) code (Anas et al. 2009), random diagonal (RD) code (Fadhil et al. 2009a), multi service (MS) code (Kakaee et al. 2014a) and many others.

Service diversity and different data bit rates in optical networks are demanding and usually implemented through varying the code weight to support different services (Fadhil et al. 2012; Kakaee et al. 2015a). Application of multimedia is increasing which have a demand of varying transmission rate and quality of service (QoS) for different services such as voice, data, and image transmission (Kakaee et al. 2014b; Anas et al. 2016).

The coding techniques with the property of variable weight or variable length and both of them can suitable for these kinds of services. The code length refers to a transmission rate of the system. Longer code length carries data with a less transmission rate. The weight tells about a number of power sends by each code. Higher the code weight means higher the power and vice versa. VW OOC to support multimedia services with different QoS has been reported in Djordjevic et al. (2004).

VW Khazani-Syed (KS) code was reported in Nisar (2017). KS code is designed only for even weights. It uses mapping technique to obtain codes for higher number of users for same weight and VW. Experimental and simulation results of VW KS code have been shown for SAC–OCDMA system in Ahmad Anas et al. (2009).

In (Seyedzadeh et al. 2014), hybrid fixed-dynamic weight assignment technique is reported for VW KS code. Comparison of various detection techniques for KS code is reported in Seyedzadeh et al. (2016). VW random diagonal (RD) code is reported in Fadhil et al. 2009b for 'triple-play' service. In above techniques, the structure of encoder-decoder is subjected to change due to variation in code weight which is not practical and costly in implementation phase (Fadhil et al. 2009c).

A code construction is reported for multi-service (MS) code in Kakaee et al. 2015b for fixed weight, and variable QoS obtained by varying the number of codes in basic matrix. A VW-MS code is reported in Fadhil et al. 2009c; Seyedzadeh et al. 2017b; " Adaptive Transceiver Architecture With QoS Provision for OCDMA Network Based on Logic Gates," 2021), using the VWs to provide triple-play services.

One solution to overcome such problem is to use fixed weight for different QoS in a way that different chip length is achieved. In this paper, we have shown principally the implementation of fixed weight DEU code to support QoS diversity. Additionally, a new code algorithm is proposed for multimedia application using ideal cross correlation property without mapping. An algorithm is designed which takes any integer value of weight for any number of users.

Rest of this paper is organized as follows. Review of code construction and its properties are described in Sect. 2. Description of OCDMA systems along with Passive optical network (PON) network for triple play services and mechanism of triple play services in SAC-OCDMA systems is presented in Sect. 3. Section 4 presents mechanism of triple play services in SAC OCDMA and implementation of DEU code based OCDMA-PON architecture. Theoretical analysis as well as numerical and proof concept results are presented in Sect. 5. Finally, the conclusions are drawn in Sect. 6.

2 Diagonal eigenvalue unity (DEU) code family

DEU code was proposed by Ahmed et al. in Ahmed and Nisar 2013a; Ahmed and Nisar 2013b). It's construction is based on Jordan block matrix with variety of options for code weight (w) and number of users (*N*) selection such as combinations (w even, N even), (N even, w odd), (N odd, w odd) and (w odd, N even). The code length L is computed as L = N (w-1) + 1. For each user W = MD + SD (Number of element of MD = 1, Number of elements of SSD = 2 (i.e., 1, 1)). Where, MD and SD refers to main diagonal and super diagonal and SSD stands for successive super diagonal.

The code properties based on XOR subtraction technique can be written as (Kakaee et al. 2014a) where Eq. (1) and Eq. (2) represent autocorrelation and cross correlation respectively:

$$\sum_{i=1}^{L} C_f(i)C_g(i)\begin{cases} W, \ f = g \\ 1, \ \ f \neq g \\ 0, \ \ f \neq g \end{cases} \tag{1}$$

$$\sum_{i=1}^{L} C_f(i)\left(C_f(i) \oplus C_g(i) \cdot C_f(i)\right)\begin{cases} 0, & f = g \\ W-1, & f \neq g \\ 0, & f \neq g \end{cases} \tag{2}$$

Both equations describe upper and lower PIN photodiodes that alters and sends the electrical signal for subtraction operation. Zero and *W* are obtained as a product of subtraction operation for cross correlation and autocorrelation, respectively. The reason for using an XOR detection scheme is that it belongs to family of balanced detection schemes therefore achieves interference cancellation even for unfixed cross correlation while keeping strong signal to noise ratio (SNR) (Imtiaz et al. 2020). Thus, it makes sense to use it in DEU code sequence.

Figure 1 shows graphic representation for DEU code patterns when $W=3$ and $N=7$. The green colored block represents the MD and the corresponding blocks represents the elements of SSD.

The advantages of DEU code family are: 1) any positive integer number of weights can be used; 2) large flexibility in choosing the number of users (free cardinality); 3) simplicity of code construction; 4) maximum cross correlation is one.

3 Mechanism of triple play services in SAC-OCDMA systems

In this section, a diversity in service classes is provided through utilizing DEU code. An assumption is made to secure three different services required by every client. The principle idea of this assumption is to subgrouping the entire users with fixed weight resulting in different code lengths that match chip durations for a particular service.

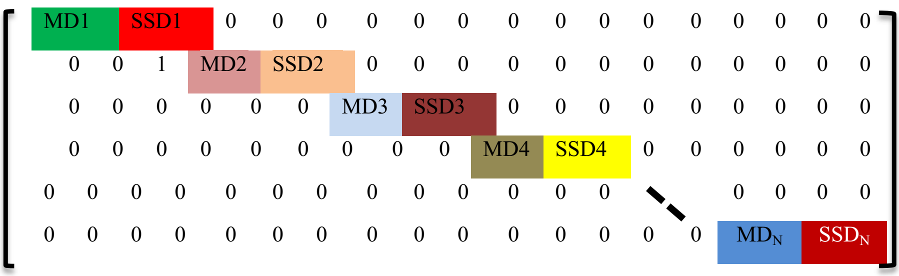

Fig. 1 Graphic representation of DEU code patterns

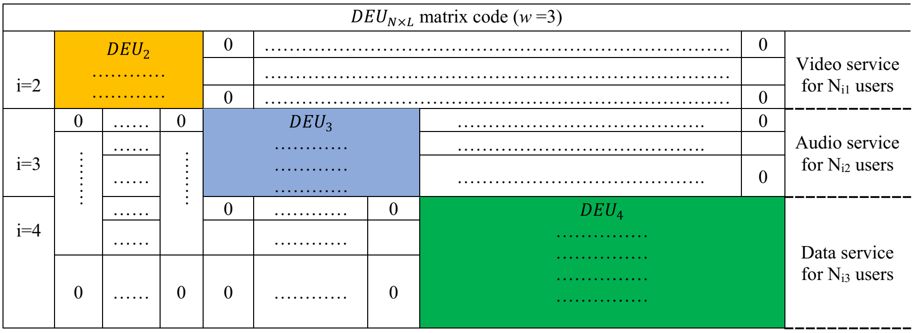

Fig. 2 Matrix representation of DEU code

Figure 2 shows a general representation for DEU matrix to support triple play services in which three different services satisfactory QoS level is provided in single system employing DEU code. Codes of different DEU_i is arranged in a fashion that maintains the cross correlation to minimum value.

Table 1 displays code sequences with w = 3 for different values of DEU_i which comprises 9 codes with three different i values ($i = 2, 3, 4$). The entire matrix is divided into three parts; the length of each part is $L_i = N_i(w - 1) + 1$. In this example, for video audio and data (VAD) services with w = 3, we assumed that 9 users are served where $i = 2, 3, 4$ respectively.

The code length L_i for DEU_2, DEU_3, DEU_4 users are 5, 7 and 9. Based on DEU flexible property, three different values of DEU_i are used to differentiate the services, where i represent number of users in every subgroup. As an example, for i = 2, 3 and 4, the services to be delivered are video, audio and data (VAD) respectively for code weight equals 3.

Encoding algorithms of SAC schemes are resulting from the combination of binary digits in order to make an efficient grouping of code length (L), weight (w) and correlation properties respectively. The basic working principle of SAC-OCDMA system is based on binary to spectral conversion, which is performed through encoder arrangement at the transmitter module (Ahmed et al. 2020). In this system, each user uses a unique DEU code where the transmitted signal appears as a product of data modulated by the given code.

Table 1 DEU code patterns for (w = 3 and N = 9)

i=2	1	1	1	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0
	0	0	1	1	1	0	0	0	0	0		0	0	0	0	0	0	0	0	0
i=3	0	0	0	0	1	1	1	0	0	0		0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	1	1	1	0		0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	1	1		1	0	0	0	0	0	0	0	0
i=4	0	0	0	0	0	0	0	0	0	0		1	1	1	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0		0	0	1	1	1	0	0	0	0
	0	0	0	0	0	0	0	0	0	0		0	0	0	0	1	1	1	0	0
	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	1	1	1

Furthermore, an OCDMA system permits simultaneously different users to use different data rate via to spectrum spreading.

Using DEU code, triple play services (VAD) is achieved for multimedia applications. For instance, in case of video transmission, the traffic pattern is continuous, which requires the highest transmission priority and signalling rate. Comparatively, the transmission of data is commonly given the lowest priority and signalling rate. Nevertheless, it can be assumed that as follows:

1. The video streaming rate $1/T_{Video}$ is a multiple of audio streaming rate service $1/T_{Audio}$ by integer number y which gives $T_{Video} = T_{Audio}/y$.
2. The audio streaming rate $1/T_{Audio}$ is a multiple of data streaming rate service $1/T_{Data}$ by integer number z which gives $T_{Audio} = T_{Data}/z$.
3. The video streaming rate T_{Video} is connected with DEU chip width (T_c) which gives $T_{Video} = xT_C$.

Then, the data rate service needs a DEU code length higher than the audio rate service in order to support the rate $\frac{1}{T_{Data}} = \frac{1}{xyzT_C}$. Likewise, the audio rate service requires a DEU code length higher than the video rate service in order to support the rate $\frac{1}{T_{audio}} = \frac{1}{xyT_C}$. However, video signalling requires a DEU code length less than data and audio services to secure the rate $T_{Video} = xT_C$.

Figure 2 shows the relation between each class of service bit duration and the length of the DEU sequence. Figure 2a, shows the bit of the data PRBS is modulated with DEU code by splitting it to chip duration (T_c). This pulse spreads to a DEU sequence of $xyzT_C \forall (x, y, z) \in Z$, i.e., x, y and z belong to the positive integer numbers (Z). Figure 2b and c depicts the pulses durations in the form of DEU sequences of xyT_c and xT_c for audio and video services respectively.

The scenario of triple play services process is shown as Algorithm 1. Algorithm 1 has five specified inputs: N, w, L, D and chip duration T_{ci}. While the output of the algorithm is the bit duration $PRBS_i$ that generated for i classes and DEU code sequences for $xyzT_C \forall (x, y, z) \in Z$. The proposed scenario of triple play services includes 4 steps to determine the type of service being delivered.

Determining the type of service (line 1) such that $T_{Ci} = \left\{T_{CD}, T_{CA}, T_{CV}\right\} where i \in \{1, 2, 3\}$

.

Generating T_{CD} chip duration for class "i = 1'' with data service (line 2).

Generating T_{CA} chip duration for class "i = 2'' with audio service (line 3).

Generating T_{CV} chip duration for class "i = 3'' with video service (line 4).

Algorithm: Encoding scenario for triple play services using DEU code

Input: D N, w, L, D
Input: service i : 1, 2, 3// *selection of data, audio and video services respectively*
Define : x, y, z //*integer numbers of DEU code sequence for video, audio and video services respectively*
Define : $T_{Ci} = \{T_{CD}, T_{CA}, T_{CV}\}$and x, y, z // *chip duration for data, audio and video services*
Output : $PRBS_i$ // $PRBS_i$ is the bit duration for *video, audio and data services*
Output : $DEUCodeSequence$;

1. Switch (i)
   2. Case ('1'):
      $T_{CD} = \frac{1}{L_1 D}$;
      $PRBS_1 = yzT_{CD}$
      $DEUcodeSequence = xyzT_{CD}$; break;
   3. Case ('2'):
      $T_{CA} = \frac{1}{L_2 D}$;
      $PRBS_2 = yT_{CA}$
      $DEUcodeSequence = xyT_{CA}$; break;
   4. Case ('3')
      $T_{CV} = \frac{1}{L_3 D}$;
      $PRBS_3 = T_{CV}$
      $DEUcodeSequence = xT_{CV}$; break;
5. Return $PRBS_i$;
6. Return $DEUcodeSequence$;

4 DEU based OCDMA-PON network for triple play services

In this section, we will examine the multi data rates implementation via adopting DEU code for multi services. DEU code has the potential to be implemented in last mile scenario to support different class of services with respect to their data rates due to its ability of supporting synchronized transmissions at different data rates.

Figure 3 shows PON topology based on OCDMA for uplink and downlink communications for multi services (Fadhil et al. 2009a). The proposed architecture is divided into three parts namely optical line terminal (OLT), optical distribution network (ODN), and ONT to mimic the conventional OCDMA-PON architecture. In this figure, PON is able to support diversity of multimedia transmissions where higher bitrate is dedicated to video applications as in ONU#1. Bit rate is the number of bits per second and it affects video quality in several ways. Firstly, it determines the video file size since high video bitrate gives high video quality and low bitrates result in poor video quality. ONU#2 supports voice with medium data rate whereas image was supported with low bitrate at ONU#N. At the OLT section, the received pseudo random bit sequence (PRBS) is converted to optical pulses and then encoded with optical code at the OCDMA transmitter (Fig. 4).

The combiner collects the OCDMA signal and broadcast them to several optical network units (ONUs) by splitting its power between all users. An inverse process takes place at ONU via OCDMA receiver to extract the original signal (Kakaee et al. 2014a). However, the utilization of PONs needs an effectual access scheme, which is able to provide a

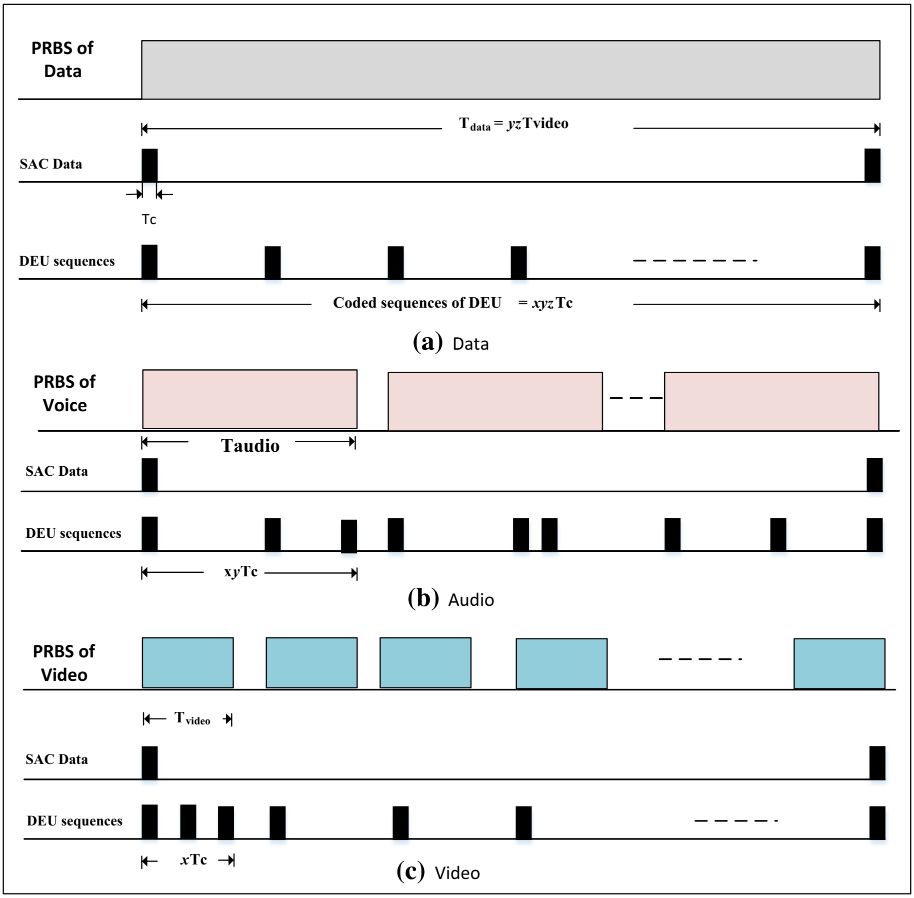

Fig. 3 Encoding mapping of triple play services using DEU coding: **a** data, **b** Audio, and **c** Video services

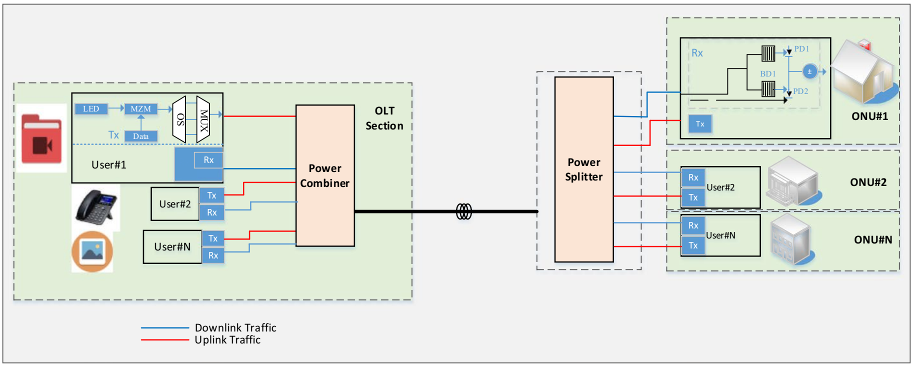

Fig. 4 DEU based OCDMA-PON system for triple play services

strong migration track towards next generation network capacity in terms of data rate and the number of users. The following section describes the utilization of PON to support VAD services.

5 Numerical analysis and results

5.1 Numerical results

Applying the derivation as (Ahmed and Nisar 2013b), the signal to noise ratio (SNR) for DEU code is calculated as in Eq. (3). All noises such phase induced intensity noise, the photodiode shot noise and the thermal noise are considered.

$$SNR = \frac{\frac{\Re^2 P_{sr}^2 (W-1)^2}{L^2}}{\frac{P_{sr} e B \Re}{L}[2(N-1)+W+1] + \frac{P_{sr}^2 B \Re^2 N}{2\Delta V L^2}\left[W+1+\frac{2(N-1)}{N-2}\right] + \frac{4K_b T_n B}{R_L}} \tag{3}$$

Psr is the effective power of a broad-band source at the receiver, e is an electronic charge, B is the electrical equivalent noise band-width of the receiver, KB is the Boltizmann's constant, Tr the absolute temperature of receiver noise, RL the load resistance, ΔV the optical source bandwidth. The bit error rate (BER) is computed from the SNR by the formula:

$$\text{BER} = P_e = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{\text{SNR}}{8}}\right) \tag{4}$$

erfc is a complementary error function.

Figure 5a shows the relation between BER and Q-factor for DEU code that have code weight w = 4 and at bit rate 1 Gbps. As cleared, when Q-factor increases, the BER decreases and at Q-factor = 5.7, the acceptable value of BER can be reached which is 10^{-9} which satisfies communication system. The relation between the number of users and Q-factor are studied and given in Fig. 5b at different bit rates. According to Fig. 5a, the best value of Q-factor is 5.77 which gives the acceptable BER that is 10^{-9}, so at bit rates 1 Gbps, 1.25 Gbps and 2.5 Gbps, respectively, the maximum allowable number of users that the system use DEU code with code weight = 4 can support at Q-factor is 5.77 is 36, 31 and 19, respectively.

Figure 6 shows pulse duration (Tc) versus code length at different data rate based on algorithm 1 where Tc = 1/(data rate × code length). In this figure, we examined the behaviour of the network in full load and partial load scenarios at different data rates.

The pulse duration decreases with increase in code length especially for partial network where a few numbers of users are involved. However, for highly populated network the Tc increases regardless of data rate values.

It is observed that data rate is more influential than code length on pulse duration. For VAD triple play services, a lower bit rate is associated to data bits with longer code length due to huge number of DEU chips to map a certain PRBS.

In particular, a video's PRBS requires higher bit rates with shortest code length to map a few DEU chips associated to video streaming; audio signals fall in between which is neither data bits nor video streaming.

Figure 7 plotted Tc versus data rate at full load scenario of network where 9 users were involved resulting in a code length of 19 based on algorithm 1 where, Tc = 1/(data

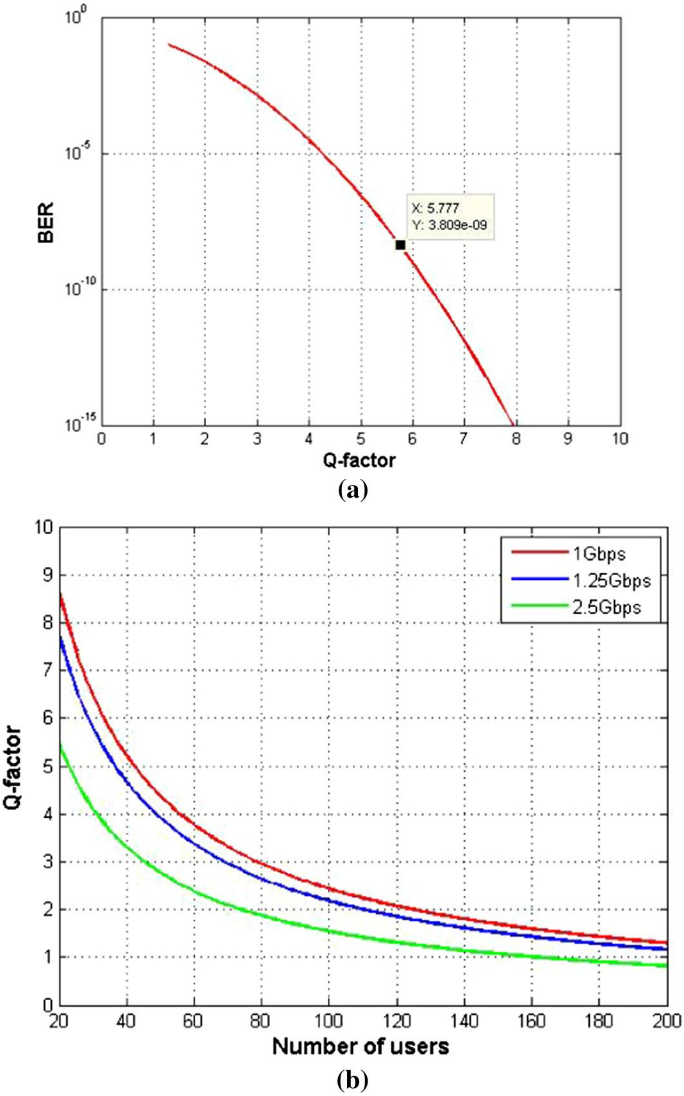

Fig. 5 **a** Q factor versus BER **b** Q-factor versus number of users

rate × code length). The pulse duration has inversely proportional relation with data rate for high-populated network scenario.

The impact of code length is minor at higher data rates especially for video streaming where shorten code length is required to maintain high rate demands by video applications.

For VAD triple play services, a lower bit rate is associated to data bits with long code length due to huge number of DEU chips to map a certain PRBS. In particular, a video's PRBS requires higher bit rates with shortest code length to map a few DEU chips associated to video streaming; audio signals fall in between which is neither data bits nor

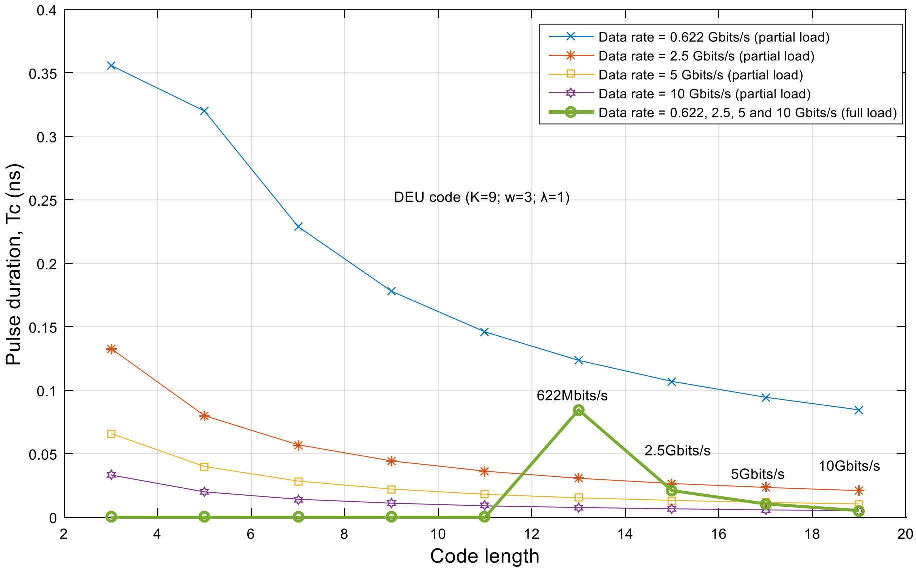

Fig. 6 Pulse duration (Tc) versus code length

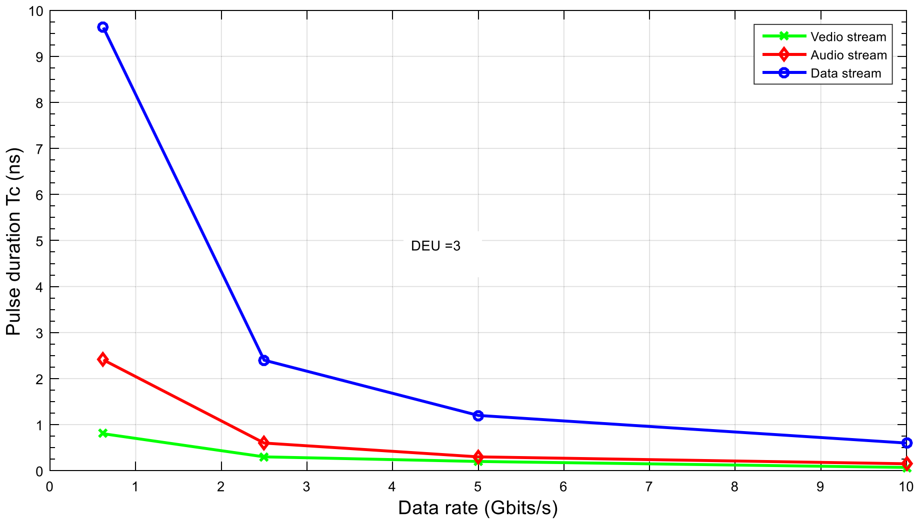

Fig. 7 Pulse duration (Tc) versus data rate to support triple services

video streaming. It is observed that data rate is more influential than code length on pulse duration.

In Fig. 8, the BER is drawn against the number of active users when Psr = -10 dBm at different data rate. It is noticed that the BER of DEU code is lower in comparison with MQC and MFH codes even for less value of weight is ($w = 4$ in this case). An acceptable

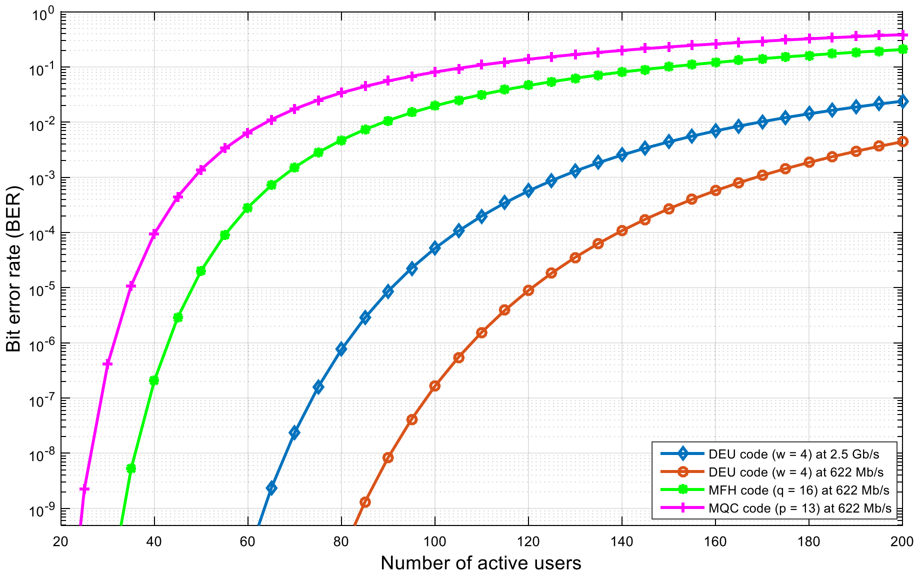

Fig. 8 BER versus number of active users when $P_{sr} = -10$ dBm at 622 Mb/s and 2.5 Gb/s

BER of 10^{-9} was attained by the DEU code with ≈82 active users versus 22 and 33 for MQC and MFH codes at 622 Mb/s.

In addition, 62 users were supported by DEU for data rate of 2.5 Gb/s which is higher than MQC and MFH codes despite their low data rate. This is evident from the fact that DEU code has an in-phase cross correlation property that strikes the MAI effects successfully. However, MQC and MFH used codes with a fixed in-phase cross correlation exactly equal to 1 for suppressing the effects of PIIN. Hence, this increases the probability of interference which leads to performance degradation.

5.2 Poisson's distribution

The probability of observing k events in a particular interval is given by:

$$P(k) = \frac{\sigma^k e^{-\sigma}}{k!} \tag{5}$$

e is representing exponential number, i.e., e = 2.71828, $k \in Z$ is representing a positive integer value, and k! is the factorial of k. In this paper, we perform a Poisson's distribution analysis to characterize full load and partial load analysis along with VAD scenarios. This analysis is carried out under the following assumptions (" Adaptive Transceiver Architecture With QoS Provision for OCDMA Network Based on Logic Gates," 2021):

- T is the number of times that a certain bit rate occurs in an interval and $T \in Z$
- The occurrence of a certain bit rate does not affect the probability that another bit rate will occur. Different data rates occur independently.
- Two different data rates cannot occur at exactly the same instant.

- The probability of data rate occurring is proportional to the length of the time period.

Table 2 tabulate the number of simultaneous users (NSU) accessing the network randomly between 2–12 min. This period has been divided into 5 time slots and each time slot period is 0.38 min as shown in Fig. 9. The average number of NSU (σ) accessing the network is varying in accordance with tfg where f is the number of interval and g is the number of subinterval. In addition, the minimum value of σ is dedicated for the highest data rate.

Figure 10 shows number of occurrences plotted against the probability of occurrences for different number of users accessing the network randomly at different time slots ranging from 1 to 5 min. The average number of users, σ (average event rate) is randomly setting where the highest value is almost 9 and lower value is almost 5.

The Fig. 10 proves that the highest probability of occurrence at 0.17 at interval#1 time whereas the lower probability of occurrence at 0.01 at interval#5. The highest value of σ is dedicated to low data rate of 622 Mbits/s and the lower value of σ is assigned to the highest data rate which is 20 Gbits/s. The remaining values of σ were distributed between these values as shown in Fig. 9. This assumption is made by the fact that less number of users increase the throughput, eventually allows the users to increase their data rate.

5.3 Proof of concept

An optical software simulator known as Optisystem, version 7.1 is utilized to perform multi services scenario in this section. Figure 2 is used as a core model to prepare the simulation setup. The implementation is performed for eight users $U_1, U_2, \ldots U_8$ as OLT#1 and OLT#2 racks based on Fig. 11 while up- and down-link traffic is observed by referring to eye diagrams at different data rate ranging from 0.622 Gbps to 5 Gbps. Each OLT section comprises four transmitters.

At each transmitter, the combination of light emitting diodes (LED), PRBS generator, non-return to zero (NRZ) pulse generator, Mach zehnder modulator (MZM) and 4:1 Multiplexer (MUX), form each single user (Fig. 12a). Construction of the transmitter module begins with an LED, which has wavelength ranging from 1490 to 1550 nm. Furthermore, a 30 nm bandwidth is set to the LED to achieve a relatively flat spectrum for binary to spectral alteration.

The LED end side is linked to a power splitter (PS) which splits the spectrum into four equal portions. These portions are injected into a 4:1 MUX arrangement, which comprises four band pass filters adjusted at particular wavelengths to reflect the spectrum in correspondence with the chip placement. Figure 12a and b shows the encoder structure and output of the DEU code [11110000] using 0.4 nm bandwidth filters centered at 1490 nm, 1490.4 nm, 1490.8 nm and 1491.2 nm respectively at 622 Mbits/s.

An optical modulator (MZM) is used to modulate the user information. It is further connected to an optical combiner which is utilized to inject the spectrum into single mode fiber (SMF). To achieve multi bit rate scenario the PRBS generator is adjusted in accordance with the targeted bit rate as follows:

1. *Set* $(x \times \mathit{Bitrate})$ *at PRBS of intended user where x is a positive real number*
2. *Set bit rate at public parameters in accordance with required data rate set by x*

Table 2 Number of simultaneous users accessing the network at different time slots

Time slot (t) in minutes/Number of simultaneous users (NSU)	Interval#1 [2–3.9]	Interval#2 [4–5.9]	Interval#3 [6–7.9]	Interval#4 [8–9.9]	Interval#5 [10–11.9]
	$t_{11}=2.38$ $NSU=4$	$t_{21}=4.38$ NSU = 7	$t_{61}=6.38$ NSU = 9	$t_{81}=8.38$ NSU = 3	$t_{101}=10.38$ NSU = 5
	$t_{12}=2.76$ $NSU=5$	$t_{22}=4.76$ NSU = 9	$t_{62}=6.76$ NSU = 8	$t_{82}=8.76$ NSU = 4	$t_{102}=10.76$ NSU = 8
	$t_{13}=3.14$ $NSU=7$	$t_{23}=5.14$ NSU = 3	$t_{63}=7.14$ NSU = 5	$t_{83}=9.14$ NSU = 7	$t_{103}=11.14$ NSU = 10
	$t_{14}=3.52$ $NSU=3$	$t_{24}=5.52$ NSU = 4	$t_{64}=7.52$ NSU = 7	$t_{84}=9.52$ NSU = 7	$t_{104}=11.52$ NSU = 7
	$t_{15}=3.9$ $NSU=2$	$t_{25}=5.9$ NSU = 6	$t_{65}=7.9$ NSU = 4	$t_{65}=9.9$ NSU = 7	$t_{105}=11.9$ NSU = 15
The average of NSU (σ)	$4.2 \approx 5$	$5.8 \approx 6$	$6.6 \approx 7$	$7.2 \approx 8$	9
Proposed data rate	20 Gbits/s	10 Gbits/s	5 Gbits/s	2.5 Gbits/s	622 Mbits/s

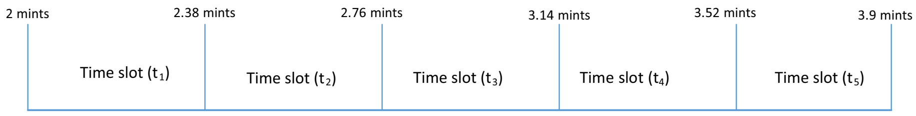

Fig. 9 Time slot distribution

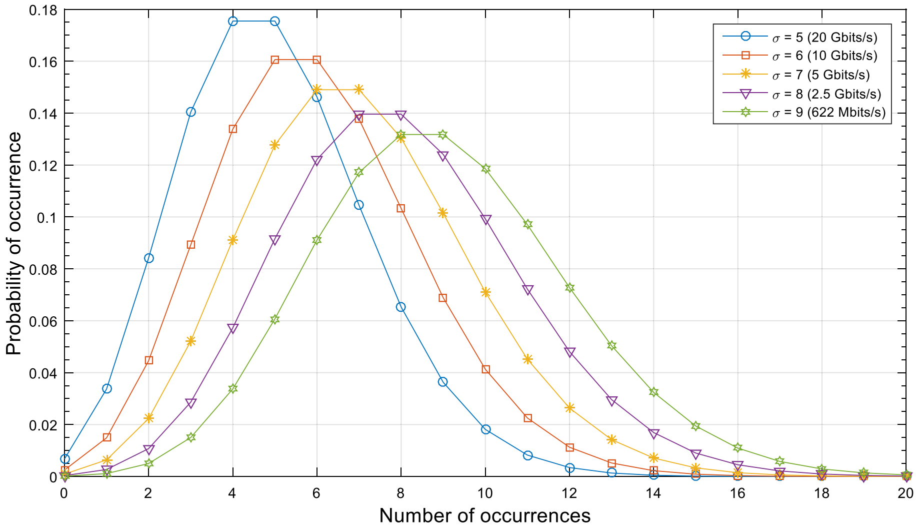

Fig. 10 Number of involving users vs. the probability of occurrences

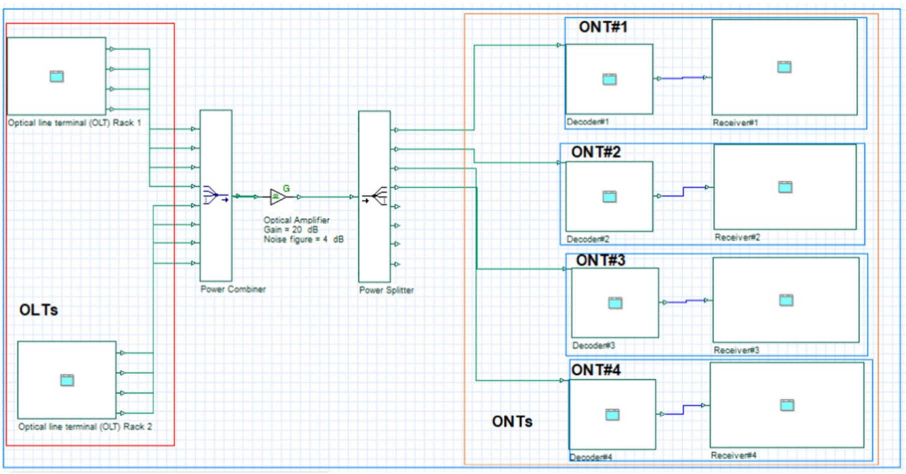

Fig. 11 Simulation setup for up- and down-link traffic analysis

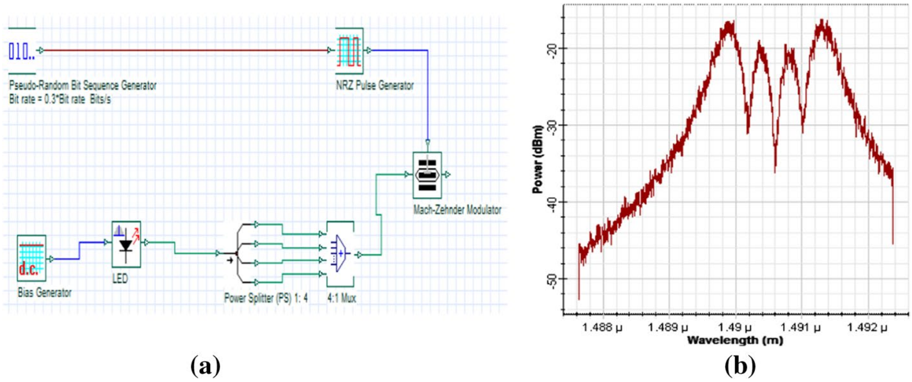

Fig. 12 **a**) Spectral encoder structure **b**) Output of the spectral encoder for 111,100 code sequence

For instance, if a 2.5 Gbits/s is needed for video streaming, x is set to 0.5 and bit rate is set to 5 Gbits/s in public parameter resulting in (0.5 × 5 Gbits/s) giving 2.5 Gbits/s.

At end side of SMF an optical splitter is connected to split the spectrum into N equivalent portions. These portions are connected to ONTs side, which is followed by special combination of optical adders, optical subtractors, PIN photodiode, uniform fiber-bragg grating (UFBG), low-pass filter, and decision-making circuit to extract the desired information via XOR detection scheme (Fig. 13).

Figure 14 shows the simulation output for the proposed multi bit rate scenario. Analysis is implemented for three users accessing the transmission medium at different data rates targeting diversity of applications. Since, cross correlation in DEU code exists between each three users, which makes sense to carry out the simulation for three users. All noise

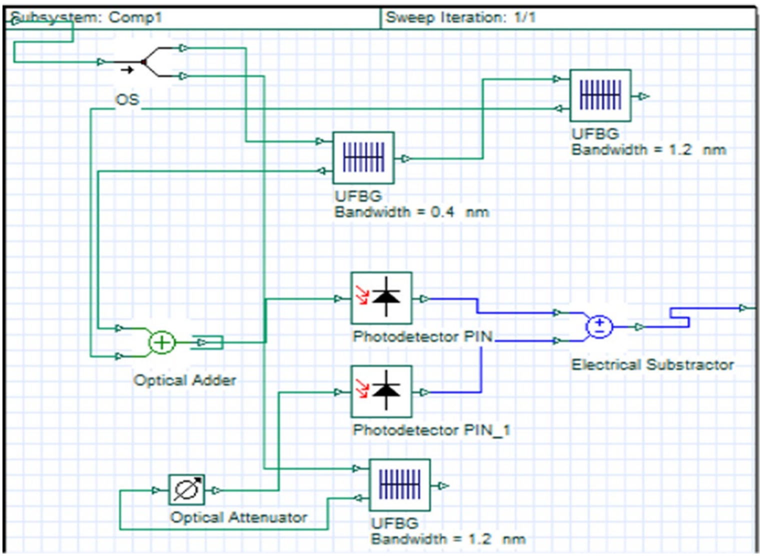

Fig. 13 Receiver structure using DEU code

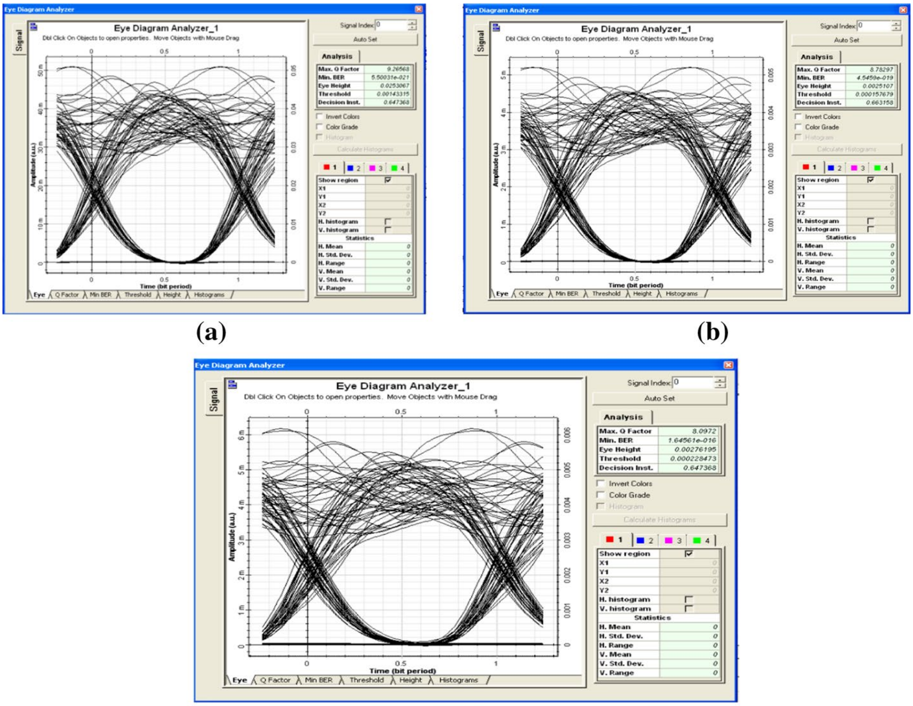

Fig. 14 The eye diagrams of the DEU after 10 km fiber span for three channels running simultaneously: **a** channel 1 at 1.25 Gbit/s with BER of 10^{-13}; **b** channel 2 at 2.5 Gbit/s with BER of 10^{-11}; **c** channel 3 at 5 Gbit/s with BER of 10^{-9}

sources such as shot, thermal, and dark noises are enabled to mimic the scenario to be close as much as possible to the reality. The receiver sensitivity is set to 0.75 A/W. The eye diagram patterns of three channels: channel#1 (1.25 Gbits/s), channel#2 (2.5 Gbits/s) and channel#3 (5 Gbits/s) running simultaneously for 10 km fiber span are shown in Fig. 14a–c respectively for DEU code. These three channels are designed to support data, voice and video respectively for different span links. The width of the eye opening defines the time interval over which the received signal can be sampled without error from intersymbol interference (ISI). When the height of the eye opening is large, this represents the best time to sample the received signal. The eye diagram patterns shown in Fig. 15a–c clearly showed that the DEU code system provides a noticeable performance in terms of BER. In addition, the figures reveal that DEU code can support multiple bit rate system fairly despite long distance. The eye pattern at 5 Gbits/s shows that even the effect of nonlinearities at high date rates is unavoidable, still desired signal can be detected with minor distortion. It can be observed that performance of DEU system deteriorates with increase in length of the fiber. In fact, when the fiber span reduces, the data rate must rise to regain a similar regression of the signal form. Therefore, to design and improve OCDMA network link parameters, the fiber span should be set as short as possible.

The eye diagram patterns of three channels: channel#1 (80 Mbits/s), channel#2 (622 Mbits/s) and channel#3 (750 Mbits/s) running simultaneously for 30 km fiber span are

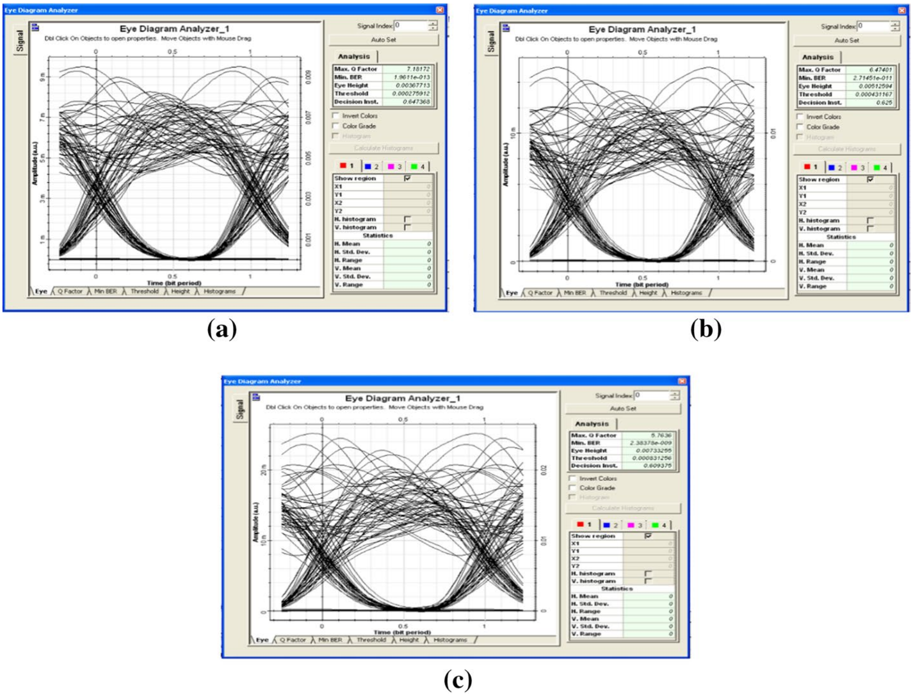

Fig. 15 The eye diagrams of the DEU after 30 km fiber span for three channels running simultaneously: **a** channel 1 at 80 Mbit/s with BER of 10^{-21}; **b** channel 2 at 622 Mbit/s with BER of 10^{-19}; channel 3 at 750 Mbit/s with BER of 10^{-16}

shown in Fig. 9a–c respectively for DEU code. The width of the eye opening defines the time interval over which the received signal can be sampled without error from intersymbol interference (ISI). When the height of the eye opening is large, this represents the best time to sample the received signal. The eye diagram patterns shown in Fig. 15a–c clearly showed that the DEU code system gave a noticeable performance in terms of BER. In addition, the figures reveal that DEU code can support multiple bit rate system fairly despite long distance. It is observed that BER increases as more data is transmitted across the medium. The eye pattern at 10 Gb/s shows that even the effect of nonlinearities at high date rates is unavoidable, still desired signal can be detected with minor distortion. Higher bit rate systems are limited by dispersion. As shown in the figure, for a 622 Mbits/s at 50 km, the system still works well with slightly high precision than 750 Mbits/s for the same distance. The eye diagram patterns of three channels: channel#1 (1.25 Gbits/s), channel#2 (2.5 Gbits/s) and channel#3 (5 Gbits/s) running simultaneously for 30 km fiber span are shown in Fig. 15a–c respectively for DEU code. These three channels are designed to support data, voice and video respectively for different span links. The width of the eye opening defines the time interval over which the received signal can be sampled without error from ISI. When the height of the eye opening is large, this represents the best time to sample the received signal.

It is clear from the results that to achieve efficient design and improve OCDMA network link parameters, the fiber span should be set as short as possible.

6 Conclusion

In this paper, we study and investigate the ability of DEU code in supporting synchronized transmissions at different data rates to support VAD services. Different type of data rate transmissions have been validated for various simultaneous users. The simulated results of five DEU coded channels running at data rates of 5 Gbits/s, 2.5 Gbits/s, and 1.25 Gbits/s over a communication-standard fiber showed a good quality of transmission even for long span. It is observed that for a 1.25 Gbits/s at 10 km, the system adopting DEU still work well with slightly high precision than 2.5 Gbits/s for the same distance. An algorithm for VAD application is developed which mapped VAD-PRBSs to chips durations. It is observed that data rate is more influential than code length on pulse duration especially for video applications. Moreover, a Poisson's distribution analysis is performed to characterize the bit rate scenarios. It is concluded that, highest value of σ is preferable for low data rate whereas the lower value of σ is assigned to the highest data rate in accordance with network population. For video streaming, the traffic running in a continuous fashion which requires the highest transmission priority and small value of σ. The numerical and simulation results proven the ability of DEU code in supporting synchronized transmissions at different data rates that suits triple play services (video, voice and data) at 20 Gb/s, 10 Gb/s, 5 Gb/s, 2.5 Gb/s, 750 Mb/s and 622 Mb/s data rate transmissions have been validated for various simultaneous users. It has been shown that the DEU code family can suppress intensity noise effectively and improve the system performance significantly for multiple bit rates scenario.

References

Ahmad Anas, S.B., Abdullah, M.K., Mokhtar, M., et al.: Optical domain service differentiation using spectral-amplitude coding. Opt. Fiber Technol. **15**(1), 26–32 (2009)

Ahmed, H.Y., Nisar, K.S.: Diagonal Eigenvalue Unity (DEU) code for spectral amplitude coding-optical code division multiple access. Opt. Fiber Technol. **19**, 335–347 (2013a)

Ahmed, H.Y., Nisar, K.S.: Reduction of the fiber dispersion effects on MAI for long span high-speed OCDMA networks using Diagonal Eigenvalue Unity (DEU) code. Optik **124**, 5765–5773 (2013b)

Ahmed, H.Y., Zeghid, M.: Numerical method for constructing fixed right shift (FRS) code for SAC-OCDMA systems. Int. J. Adv. Comput. Sci. Appl. **8**, 245–252 (2017)

Ahmed, H.Y., Elmaleeh, M.A., Fadhil, H.A., Aljunid, S.A., Saad, N.M.: Performance analysis of spectral-amplitude-coding optical CDMA systems with new subtract exclusive OR detection (SED) using vectors combinatorial (VC) code. Optik **123**(15), 1317–1410 (2012)

Ahmed, H.Y., Gharsseldien, Z.M., Aljunid, S.A.: An efficient method to construct diagonal permutation shift (DPS) codes for SAC OCDMA systems. J Theor. Appl. Inf. Technol. **94**(2), 475 (2016)

Ahmed, H.Y., Zeghid, M., Imtiaz, W.A., Sharma, T., Chehri, A., Fortier, P.: Two-dimensional permutation vectors (PV) code for optical code division multiple access systems. MDPI-Entropy. **22**(5), 576 (2020)

Aljunid, S.A., Ismail, M., Ramli, A.R., Abdullah, B.M.A.M.K.: A new family of optical code sequences for spectral-amplitude-coding optical CDMA systems. IEEE Photon. Technol. **16**(10), 2383–2385 (2004)

Anas, S.A., Abdullah, M., Mokhtar, M., Aljunid, S., Walker, S.: Optical domain service differentiation using spectral-amplitude-coding. Opt. Fiber Technol. **15**(1), 26–32 (2009)

Anas, S.B.A., Seyedzadeh, S., Mokhtar, M., et al.: Variable weight Khazani Syed code using hybrid fixed-dynamic technique for optical code division multiple access system. Opt. Eng. **55**, 106101 (2016)

Christian, W.: H and-Book on Statistical Distributions for Experimentalists. Springer, Berlin (2007)

Djordjevic, I.B., Vasic, B., Rorison, J.: Multi-weight unipolar codes for multimedia spectral-amplitude-coding optical cdma systems. IEEE Commun. Lett. **8**(4), 259–261 (2004)

Fadhil, H.A., Aljunid, S., Ahmad, R.: Performance of random diagonal code for OCDMA systems using new spectral direct detection technique. Opt. Fiber Technol. **15**(3), 283–289 (2009a)

Fadhil, H.A., Aljunid, S.A., Badlisha, R.: Triple-play services using random diagonal code for spectral amplitude coding OCDMA systems. J. Opt. Commun. **30**, 155–159 (2009b). https://doi.org/10.1515/JOC.2009.30.3.155

Fadhil, H.A., Aljunid, S.A., Badlisha, R.: Triple-play services using random diagonal code for spectral amplitude coding OCDMA systems. J. Opt. Commun. **30**(3), 155–159 (2009c)

Hassan, Y.A., Medien, Z., Waqas, A.I., Teena, S., Akhtar, N.K., Kottakkaran, S.N., Abelhaleem, A., Mona, M., Sultan, A.: Adaptive transceiver architecture with QoS provision for OCDMA network based on logic gates. IEEE Access **9**, 151089–151109 (2021)

Hilal, A.F., Syed, A.A., Hassan, Y.A., Hamza, M.R., Al Khafaji, M.: Variable cross-correlation code construction for spectral amplitude coding optical CDMA networks. Optik **123**(11), 956–963 (2012)

Imtiaz, W.A., Ahmed, H.Y., Zeghid, M., Sharma, T., Mirza, J.: Techno-economic analysis of two dimensional optical code division multiple access systems. Opt. Quantum Electron. **53**(1), (2021)

Kakaee, M.H., Seyedzadeh, S., Fadhil, H.A., Anas, S.B.A., Mokhtar, M.: Development of multi-service (ms) for sac-ocdma systems. Opt. Laser Technol. **60**, 49–55 (2014a)

Kakaee, M.H., Essa, S.I., Abd, T.H., Seyedzadeh, S.: Dynamic quality of service differentiation using fixed code weight in Optical CDMA networks. Opt. Commun. **355**(15), 342–351 (2015a)

Kakaee, M.H., Essa, S.I., Abd, T.H., et al.: Dynamic quality of service differentiation using fixed code weight in optical CDMA networks. Opt. Commun. **355**, 342–351 (2015b)

Kakaee, M.H., Essa, S.I., Seyedzadeh, S., Mokhtar, M., Anas, S.B., Sahbudin, R.K.: Proposal of multi-service (ms) code to differentiate quality of services for ocdma systems. In: 2014b IEEE 5th International Conference on Photonics (ICP), pp. 176–178 (2014b)

Sharma, T., Chehri, A., Fortier, P., Ahmed, H.Y., Zeghid, M. and Imtiaz, W.A.: Optical code construction of 2D spectral/spatial BIBD codes for SAC-OCDMA systems. Appl. Sci. **11**(2), p.783.

Salehi, J.A.: Code division multiple access techniques in optical fiber network—Par I: fundamental principles. IEEE Trans. Commun. **37**(8), 824–833 (1989)

Salehi, J.A., Brackett, C.A.: Code division multiple access techniques in optical fiber network—Part II: system performance analysis. IEEE Trans. Commun. **37**(8), 834–842 (1989)

Seyedzadeh, S., Mahdiraji, G.A., Sahbudin, R.K.Z., et al.: Experimental demonstration of variable weight SAC–OCDMA system for QoS differentiation. Opt. Fiber Technol. **20**(5), 495–500 (2014)

Seyedzadeh, S., Moghaddasi, M., Anas, S.B.A.: Variable-weight optical code division multiple access system using different detection schemes. J. Telecommun. Inf. Technol. **3**, 50–59 (2016)

Nisar, K.S., Ahmed, H.Y., Zeghid, M., Imtiaz, W.A., Sarangal, H. and Thapar, S.S.: The multi-service schemes for SAC-OCDMA systems with variable code weight. Opt. Quant. Electron. **53**(6), 1–18.

Seyedzadeh, S., Rahimian, F.P., Glesk, I., et al.: Variable weight spectral amplitude coding for multiservice OCDMA networks. Opt. Fiber Technol. **37**, 53–60 (2017b)

Sharma, T., Maddila, R.K.: Performance characteristics of the spectral amplitude-coding optical CDMA system based on one-dimensional optical codes and a multi-array laser. Ukr. J. Phys. Opt. **20**(2), 81–90 (2019)

Sharma, T., Maddila, R.K., Aljunid, S.A.: Simulative investigation of spectral amplitude coding based OCDMA system using quantum logic gate code with NAND and direct detection techniques. Curr. Opt. Photon. **3**(6), 531–540 (2019)

Stok, A., Sargent, E.H.: Lighting the local network: optical code division multiple access and quality of service provisioning. IEEE Netw. **14**(6), 42–46 (2000)

Wei, Z., Shalaby, H., Ghafouri-Shiraz, H.: Modified quadratic congruence codes for fiber bragg-grating-based spectral-amplitude-coding optical cdma systems. J. Lightwave Technol. **19**(9), 1274–1281 (2001)

Authors and Affiliations

Hassan Yousif Ahmed[1] · **Medien Zeghid**[1,2] · **Teena Sharma**[3] · **Akhtar Nawaz Khan**[4] · **Waqas A. Imtiaz**[4] · **Somia A. Abd El-Mottaleb**[5]

Medien Zeghid
medien.zeghid@fsm.rnu.tn

1 Electrical Engineering Department, College of Engineering at Wadi Aldwaseer, Prince Sattam Bin Abdulaziz University, Wadi Aldawaser 11991, Saudi Arabia

2 Electronics and Micro-Electronics Laboratory (E. μ. E. L), Faculty of Sciences, University of Monastir, Monastir 5000, Tunisia

3 Department of Applied Sciences, University of Quebec in Chicoutimi (UQAC), Chicoutimi Québec G7H2B1, Canada

4 Department of Electrical Engineering, University of Engineering and Technology, Jalozai Campus, Peshawar, Pakistan

5 Alexandria Higher Institute of Engineering and Technology, Alexandria 21311, Egypt