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Performance Analysis of 2D-OCDMA System in Long-Reach Passive Optical Network

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16 Abstract-In this paper, a performance analysis is reported for optical code division multiplexing (OCDM) system for long-reach passive optical network (LR-PON) systems by taking into account multiple 17 access interference (MAI), single-mode fiber (SMF) channel effects and receiver noise. 18 The mathematical model representing the 2-D optical code parameters for different receiver structures used 19 in optical code division multiplexing access (OCDMA) are developed, optimized and implemented using 20 Matlab simulations, where channel imperfections, such as attenuation losses and chromatic dispersion 21 22 have been considered. In the proposed system configuration, we have investigated the probability of error for Back-to-Back (B2B) with conventional correlation receiver (CCR), SMF with CCR receiver and 23 24 SMF channel with successive interference cancelation (SIC) receiver. Additionally, SMF channel with 25 SIC receiver system performance has been addressed by taking into account two key metrics, such as BER 26 and Q-factor as function of simultaneous users, and fiber length, respectively. We have managed to 27 substantially improve simultaneous multiuser data transmission over significant fiber lengths without use of amplification, where Q-factor of 6 at fiber length of 190 and 120 km, while a SIC receiver 28 29 using 5 stages cancelation is employed for 2D prime hop system (2D-PHS) and for 2D hybrid codes (2D-30 HC), respectively.

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32 Index Terms-LR-PON; Optical Transmitters; Optical receivers; Code division multiplexing.

- 34 I. INTRODUCTION
- 35

Multiplexing techniques play an important role in channel optimization and multimedia carrying data. 36 There are several multiplexing techniques in the literature, such as time division multiplexing (TDM), 37 wavelength division multiplexing (WDM), code division multiplexing (CDM) [1] and orthogonal 38 frequency division multiplexing (OFDM) [2]. In optical context, the primary multiplexing techniques 39 deployed are WDM and Optical CDM (OCDM). WDM techniques have their advantages due to its 40 network security and good scalability. However, they suffer from power consumption and floor space 41 availability in central office (CO). On the other hand, OCDM techniques have their benefits due to the fact 42

that no synchronization is required in the network and they can offer a high data security in order to satisfy customer data integrity [3,4]. Equally, optical code division multiplexing access (OCDMA) techniques are attractive solutions that offer simple network management and a great capacity to support multi-rate bursty traffic, low latency access and multi-class of quality of service (QoS) with variation in transmitted level power [5-7].

In our previous work Ref. [8], we have reported optimization of two-dimensional (2-D) optical code 48 parameters for different receiver structures used in OCDMA system. We have shown that the studied code 49 is determined by the prime number (P) and in the case when the prime number increases, the probability of 50 error decreases. In order to increase the number of simultaneous users in OCDMA network, we have 51 investigated the system performance using an OCDMA successive interference cancelation (SIC) receiver 52 with multistage interference cancellations in comparison to the conventional correlation receiver (CCR). 53 We have demonstrated that the number of stages and as well the value of threshold on each stage of the 54 OCDMA SIC receiver used in a system are the key system parameters which have a significant impact on 55 the OCDMA system performance. In addition, it is shown that we can reach a higher system performance 56 57 by employing an OCDMA SIC receiver instead of an OCDMA CCR receiver, in which the probability of error is decreased and the network subscriber is increased. By using advanced 2-D OCDMA codes, system 58 performance can have more flexibility by means of a full asynchronous communication, a higher user 59 capacity (i.e., cardinality), good correlation properties and enhanced spectral efficiency[6,9]. Additionally, 60 it should be noted that when the bit rate is increased above 40 Gb/s, the interplay between nonlinearity and 61 chromatic dispersion causes interference among users in OCDMA system (i.e., namely multiple access 62 interference (MAI)) resulting in significant system degradation. So, in order to reduce the system 63 64 degradation due to the channel nonlinearity, we limit the system performance bit rate at 40 Gb/s [10, 16]. Furthermore, for 40 Gb/s we consider that linear effects (i.e., chromatic dispersion) is more relevant when 65 compared to fiber nonlinearity that should be considered for higher data bit rate (>40 Gb/s) and in long-66 haul communications system (i.e., more than several thousands of kilometer). In the latter case, various 67 nonlinear physical impairments over OCDMA system should be considered, involving Kerr effect (i.e., 68 self-phase modulation (SPM), four waving mixing (FWM) and cross-phase modulation (CPM)), the 69 70 stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS).

In this work, we are focused on the investigations of the most important impact, such as MAI, optical 71 channel effects and photo-detector noise on the OCDMA system performance in PON context. Single mode 72 fibers (SMF)s, due to their small core size (less than 10 µm) allow only one mode to be transmitted with 73 74 low fiber attenuation, are used to develop communication networks, such as 2D-OCDMA-WDM passive optical network (PON) [9], ultra-dense WDM PON (UDWDM-PON) network [11], cable access network 75 using hybrid fiber-coaxial (HFC) networks [12] and cable access network using hybrid fiber-coaxial (HFC) 76 networks [13]. Furthermore, SMF can support metropolitan, long haul access, premises applications in 77 telecommunications, Cable TV (CATV), RoF Mach-Zehnder (MZ) based link [14], inter-data center 78 application [15] and long-reach PON (LR-PON) [16]. Likewise, LR-PON is a very interesting case of PON 79 that provides low cost and energy consumption by reducing the number of active nodes and by adding a 80 redundant link to ensure a higher availability connection between the different Metro and core nodes [17]. 81 The proposed OCDMA technique would be practical in LR-PON context applications while the 82 transmission distance can reach more than 100 km. Additionally, 16 simultaneous users at 40 Gb/s data 83 transmission is realized which is leading to a BER value less than 10-9 after 100 km SMF transmission 84 system. On the other hand, by employing advanced 2D-OCDMA codes, such as 2D prime hop system (2D-85 PHS) and 2D hybrid codes (2D-HC) the system performance can be increased in terms of security and 86 spectral efficiency. Various optical OCDMA receivers are employed in our proposed configurations, such 87 as SIC receiver with multistage interference cancellations and CCR. It is shown, that by using a SIC 88 receiver, simultaneous users can be enhanced significantly in the network and fiber length can be extensible 89

to 120 km and 190 km, leading to Q-factor of 6 for 2D-HC and 2D-PHS codes, respectively. Finally,
complexity study is performed in terms of CPU time for different OCDMA receivers, such as CCR, SIC
and parallel interference cancellation (PIC) for various 2D-OCDMA codes as function of simultaneous
users.

94 This paper is organized as follows; Section 2 presents the proposed OCDMA system architecture. Section 3 95 deals with the system model including encoder model, channel model and decoder model. Section 4 96 discusses the system performance in terms of probability of error in the case B2B with CCR, SMF with 97 CCR receiver and SMF with SIC receiver, respectively. Simulation results as function of BER and Q-98 Factor are discussed against simultaneous users and SMF fiber length, respectively. Section 6 presents the 99 complexity study of MATALB programs in terms of processing power for CCR, SIC and PIC OCDMA 100 receivers. Finally, conclusions are drawing in the last section.

101 II. System Architecture



Fig. 1. Proposed system architecture

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In this study, we consider a direct sequence-optical code division multiplexing access (DS-OCDMA) system where primary limitation is the MAI. Other impairments caused by the optical fiber and receiver noise are also considered. In the proposed DS-OCDMA system, illustrated in Fig. 1, the information bits that have been transmitted have been spread using the code signature generated by the encoder and then modulated by an optical modulator. For the optical modulation, we propose an OFDM modulation technique based on quadrature amplitude modulation (QAM) harnessing higher-order modulation formats and using cost-effective intensity-modulation and direct-detection (IM/DD).

The contribution of each user is then summed using an optical coupler (i.e., splitter) and then the optical signal is propagating along the SMF optical fiber link, reaching the reception part (receiver section). In this end, a photo-detector can convert the optical signal to the electrical one. Then, with the help of the OCDMA decoder, the estimated bit is being sent to the end user.

116 III. System Model

117 The proposed optical system configuration model involves the following device models; encoder model, 118 the channel model and the decoder model. The model for each device has been designed individually by 119 taking into account key model parameters and their effects into the overall system's performance.

120 A. Encoder model

121 At the output coupler, the transmitted signal is defined by s(t) which is the sum of all coded signals which 122 are transmitted through the SMF and can be expressed as:

124
$$s(t) = P_T \sum_{k=1}^{N} b_i^{(k)} c_k(t)$$
(1)

where $b_i^{(k)}$ represents the ith information bit of the user k and $c_k(t)$ represents the optical code assigned to 125 the user k. In the case, when a basic OCDMA CCR receiver is deployed, the optical demodulator provides 126 a signal, which is proportional to the received optical power. This signal is recovered by multiplying it with 127 128 the desired user's code $(c_k(t))$, integrated over a delay of one bit with a duration T. Then, we obtain a variable decision $Z_{i}^{(k)}$ which is compared with the decision threshold value (Th) in order to determine the 129 estimated bit sent by the user k $(\hat{b}_i^{(k)})$ [18]. We should mention also that P_T represents the chip power of the 130 transmitted signal (i.e., the amplitude of code weight equal to 1). Subsequently, we investigate the 131 generation of selected codes in this study, such as one-dimensional prime code (1D-PC), 2D-PHS and 2D-132 HC. The 1D-PC is generated by using Galois-field GF(P) for a given prime number P (i.e., time spreading 133 for each chip is used). In addition, 2D-PHS is generated with P time spreading and (P-1) wavelength 134 hopping. The 2D-HC is built as follows: maximum-length (ML) sequence is employed for the wavelength 135 hopping and the prime number is used for temporal spreading (i.e., an example of seven 2D-HC codes are 136 described in table 1, where $\{1, 2, 3, 4, 5, 6, 7\}$ symbolizing the wavelength $\{\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7\}$ [8]). 137

138

Table 1.Seven 2D-HC sequences with P=	=7
---------------------------------------	----

S_0H_1	30000000	20000000	70000000	00000000	00000000	10000000	00000000
S_2H_1	50000000	4000000	20000000	00000000	00000000	30000000	00000000
S_4H_1	20000000	10000000	6000000	00000000	0000000	7000000	00000000
S_1H_2	10000000	7000000	50000000	00000000	00000000	6000000	00000000
S_3H_2	4000000	3000000	1000000	0000000	0000000	20000000	00000000
S_0H_3	6000000	50000000	3000000	0000000	0000000	4000000	0000000
S_2H_3	70000000	6000000	4000000	00000000	00000000	50000000	00000000

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140 B. Channel Model

141 Next, the impulse response of the SMF used in the third optical transmission windows (i.e., 1550nm), is 142 given by [19]:

143

144

 $h_f(t) = \sqrt{\left(1 - j\right) \frac{c}{2\lambda^2 D_c L}} \exp\left(-j\frac{\pi c t^2}{\lambda^2 D_c L}\right)$ (2)

where c is the light velocity in vacuum, D_c is the chromatic fiber dispersion coefficient, L is the fiber 145 length and λ is the operating wavelength. The developed model has been implemented using MATLAB 146 147 simulations where in Fig. 2 we present the variation of the SMF transfer function as function of frequency in the range of [0,10] GHz. It is a highly important to represent the SMF transfer function as function of the 148 frequency due to simplifying the numerical simulation when fiber impairments are taken into 149 considerations in the OCDMA system performance. Additionally, the transfer function versus time need 150 convolution operator compared to a simple multiplication operator when dealing with transfer function in 151 terms of frequency. 152

153 The normalized SMF transfer function in dB is given by [20]:

154

155

$$Hf_{dB} = 10\log_{10}(\frac{H_{out}}{H_{in}})$$
⁽³⁾

where H_{out} and H_{in} are the Fourier transforms of the impulse response and back-to-back (B2B) system response, respectively.







Fig. 2. SMF normalized transfer function as a function of frequency.

As can be seen from Fig.2, the 100 km SMF normalized transfer function is inversely proportional to the 161 frequency, which shows that the SMF normalized transfer function decreases when the frequency increases. 162 Additionally, the normalized transfer function value is in the range of [0,-6] dB. In addition, we observe a 163 164 normalized SMF transfer function below -3 dB in the range of [0,2] GHz which can be potentially useful in the system physical implementation, in which the signal can be easily detected in the receiver side (i.e., 165 corresponding to the half of the transmitted signal). 166

C. Decoder Model 167

168 At the photo-detector output, the decision variable can be described mathematically with the following expression [21]: 169

170 171

$$Z_{i}(t) = \frac{RP_{R}}{2} \int_{0}^{T_{b}} \sum_{k=1}^{K} \sum_{l=0}^{N-1} B_{k}(t)C_{k}(t-lT_{c})h_{f}(t)dt + \phi$$
(4)

where R, P_R , T_b and \emptyset is the receiver responsivity, the optical received power, the bit period and the 172 noise caused by the photo-detector, respectively. 173

The decision variable $Z_i(t)$ is suitable in OCDMA receiver system, since it represents the electrical 174 OCDMA received signal that is compared to the receiver threshold which can be used to make a decision 175 on the received user bit. In fact, if the value presented by the decision variable is less than the threshold the 176 177 received bit is estimated as zero otherwise, the received bit is estimated as one.

The optical received power is related with the optical transmitted power (P_{τ}) by [22]: 178 ŀ

179

$$P_R = P_T - \alpha L \tag{5}$$

where α and Lare the attenuation coefficient and the length of the optical fiber, respectively. 180

The time bit is related to the time chip (T_c) with $T_b = FT_c$, where F is the number of chips in the user 181 signature. The decoder model architecture is illustrated in Fig.3. 182

- 183
- 184



Fig. 3. Decoder model architecture.

(6)

(8)

In the proposed decoder model, the following two structures of receiver are employed. Initially, a SIC receiver is employed to eliminate the contribution of the undesired users. Then, an arrayed waveguide grating (AWG) decoder is used to detect the desired user bit. At the input of the decoder model, the received signal taking into account the impulse response of the SMF, can be expressed as follows [23]:

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$$r(t) = s(t) * h_f(t)$$

where * denote the convolution operator. The photo-detector receiver converts the optical signal toelectrical signal and generates the following signal [23]:

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198
$$r(t) = \frac{RP_R}{2} \sum_{k=1}^{N} h_f(t) b_k c_k(t-\varphi) + n(t)$$
(7)

199 where n(t) is the photo-detector noise and φ is used to symbolize the delay over time of the received 200 code.

Knowing the desired code user $c_k(t)$ the CCR or SIC receiver give the estimated bit user $\hat{b}_k(t)$.

In order to reduce the effect of MAI, several multi-user detectors have been introduced in the literature. Among these detectors, the hard limiter (HL) [23], the parallel interference cancellation (PIC) [24] and Successive Interference Cancelation (SIC) receivers have shown to be promising [8].

- 205 IV. OCDMA System Performance
- 206 The probability of error can be expressed as follows [25]:
 - $P_e = \frac{1}{2} [P(0/1) + P(0/1)]$

where P(0/1) and P(0/1) are the probability of transmitting 0 and 1 while receiving 1 and 0, respectively.

In this study, the probability of error investigation in the case of an ideal channel, SMF with CCR receiver and SMF with SIC receiver, respectively. Next, after we have developed the model for each component used in the OCDMA system including their associated losses and degrading factors, we will investigate the overall OCDMA system performance consisted of the above stated components. However, initially we will consider the system's performance without the presence of the above components in order to compare the performance when realistic case is considered.

216 *A. Case of B2B*

We consider the number of interfering users as a binomial distribution with parameter N-1 and Pr_I the average probability of hits. Consequently, the probability of error can be expressed as [8]:

$$Pe \le \frac{1}{2} \sum_{i=Th}^{N-l} {\binom{N-l}{i}} (Pr_I)^i (1-Pr_I)^{N-l-i}$$
(9)

where *Th* is the receiver threshold value. In fact, the number of active users in OCDMA system depends on OCDMA code parameters known as the prime number P. At a given prime number P, the OCDMA system can support P, P(P-1) and P(P+1) users for the 1D-PC, 2D-PHS and 2D-HC, respectively. In the case when the prime number is equal to 31, the maximum theoretical number of users considering only MAI is equal to 31, 31×30 and 31×32 for 1D-PC, 2D-PHS and 2D-HC, respectively. As a result, the number of active users corresponding to the theoretical study is equal to 31, 930 and 992 users for 1D-PC, 2D-PHS and 2D-HC, respectively.

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Fig. 4. Probability of error as function of simultaneous users for CCR receiver.

On the other hand, as it is demonstrated in Fig.4 in order to reach a BER value between 10^{-9} and 10^{-10} when a CCR is used with P equal to 31, the maximum number of network subscribers (i.e. users) for both 2D-PHS and 2D-HC codes is equal to 520 users.

237 In order to further investigate the OCDMA system performance, we have employed the SIC receiver with 5 stages cancellation leading to Fig.5.Our OCDMA simulation results of the probability of error as a 238 function of simultaneous users when the SIC receiver is deployed are illustrated in Fig. 5[8]. It can be 239 shown from Fig.5 that OCDMA system can reach more than P² users at a BER value less than 10⁻¹⁰ when 240 the 2D-HC is used to encode data and P=31(i.e., OCDMA system can reach the theoretical number of 241 users). As a result, the OCDMA system performance is enhanced by means of SIC receiver with 5 stages 242 cancellation. Additionally, the SIC receiver can compensate the MAI to reach the theoretical user number 243 in the network as function of the code features while B2B system is considered. 244



Fig. 5. Probability of error (Pe) versus simultaneous users for SIC receiver.

248

249 The low probability of error is generated by a simulation program based on a probability approach using a combination of interference (i.e., symbolized with i in the equation (9), causing the MAI) among the 250 maximum number of simultaneous users (N). So, if N increases the combination will decrease and leading 251 to a low probability of error (in the order of 10^{-20} for N around 500 users). As a conclusion, in our previous 252 work [8] for a high number of simultaneous users corresponding to the theoretical numbers our target is to 253 reach a very good BER value less than 10^{-9} leading to a high bit rate proportional to ~Gb/s. Likewise, for P 254 equal to 31, our study shows that the OCDMA system can reach P(P-1) and P(P+1) equal to 930 and 992 255 simultaneous users with a low BER less than 10⁻⁹ when a harnessed SIC receiver with optimized 256 parameters is fitted for 2D-PHS and 2D-HC, respectively. 257

258 B. Case of SMF channel and CCR receiver

When considering a realistic channel model such as the SMF, both MAI and chromatic dispersion need to be taken into consideration and scrutinize their impact on the system performance. Here, we examine the impact of chromatic dispersion on the system performance affected by the propagation of the optical signal at different wavelengths end at different speeds over the SMF core. The probability of error of the OCDMA system considering the SMF channel can be expressed as [27]:

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$$P_{e} = \frac{1}{2} \int_{H} \sum_{i=Th}^{N-I} {\binom{N-I}{i}}^{l} (Pr_{I})^{i} (1-Pr_{I})^{N-l-i} H_{f} dH$$

(10)

266

where H_f is the Fourier Transform of $h_f(t)$. In this paper, we use the same approach in Ref. [27] to incorporate the fading phenomena in wireless OCDMA network. Additionally, we use the analogy between fading and dispersion in wireless and optical communication to introduce the chromatic dispersion in OCDMA system performance study.

- 271 C. Case of SMF channel with SIC receiver
- In the next section, we explore system performance of OCDMA SIC receiver using two-dimensional
- (2D) optical code. The CCR N (characterized by threshold ThN) estimated the bit sent by the user N ($\hat{b}_i^{(N)}$)
-) is multiplied by the undesired code user $(c_N(t))$ then subtracted from the entry signal (r(t)).
- The schematics of the SIC receiver architecture is illustrated in Fig. 6.

 $(t) \rightarrow (t) \rightarrow (t)$

Fig. 6. OCDMA SIC model architecture.

280 The input signal of the desired user in the receiver (user 1 characterized by 281 threshold Th1) can be expressed as:

$$r_{I}(t) = r(t) - c_{N}(t) \otimes \hat{b}_{i}^{(N)}$$

$$\tag{11}$$

283 The variable decision obtained at the OCDMA CCR 1 (desired user) can be expressed as

$$Z_{i}^{(1)} = \frac{RP_{R}}{2}Wb_{i}^{(1)} + I_{I} + A_{I}^{\prime}$$
⁽¹²⁾

(16)

where $I_1 = \sum_{k=2}^{N-1} I_k$ represents the interference caused by the (N-2) other undesired users. The cancellation

term of first stage of the OCDMA SIC receiver taking into account chromatic dispersion due to the SMF
 channel can be expressed by

288
$$A'_{I} = (b_{i}^{(N)} - \hat{b}_{i}^{(N)}) \int_{o}^{T} c_{N}(t) \otimes c_{I}(t) \otimes h_{f}(t) dt$$
(13)

We assume that the channel transfer function is independent of code signature and can be expressed as function of frequency using Fourier Transform Function (i.e., *Hf*=Fourier Transform ($h_f(t)$), then the cancellation term of the first stage of the OCDMA SIC can be expressed:

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$$A'_{I} = H_{f} \left(b_{i}^{(N)} - \hat{b}_{i}^{(N)} \right) \int_{o}^{I} c_{N}(t) \otimes c_{I}(t) dt$$
(14)

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We employ A'_{1} instead of A_{1} used in the case of the ideal channel calculation [8].

Next, the probability of error at the OCDMA CCR1 (desired user) can be expressed with two terms [8]:

$$P_{e1} = Pr(Z_i^{(1)} \ge Th_1 / b_i^{(1)} = 0).Pr(b_i^{(1)} = 0) + Pr(Z_i^{(1)} < Th_1 / b_i^{(1)} = 1).Pr(b_i^{(1)} = 1)$$
(15)

300 301

We know, the fact that $b_i^{(1)}$ has the same probability value to be equal to zero or one: 303

304
$$Pr(b_i^{(1)}=0) = Pr(b_i^{(1)}=1) = \frac{1}{2}$$

When we substitute the value of variable decision $Z_i^{(1)}$ and replace $b_i^{(1)}$ with corresponding value, we get for the first term:

$$P_{e10} = Pr(I_1 + A'_1 \ge Th_1 / b_i^{(1)} = 0) Pr(b_i^{(1)} = 0) = \frac{1}{2} Pr(I_1 + A'_1 \ge Th_1 / b_i^{(1)} = 0)$$
(17)



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We replace the value of interference caused by the (N-2) other undesired users (I1) and the cancellation term of first stage of the OCDMA SIC receiver (A'_I), we get the following expression:

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$$P_{e_{I0}} = \frac{1}{2} H_f \left[Pr_I \sum_{i=Th_N}^{N-2} {\binom{N-2}{i}} (Pr_I)^i (1-Pr_I)^{N-2-i} \sum_{i=Th_I+I}^{N-2} {\binom{N-2}{i}} (Pr_I)^i (1-Pr_I)^{N-2-i} \right] + (1-Pr_I \sum_{i=Th_N}^{N-2} {\binom{N-2}{i}} (Pr_I)^i (1-Pr_I)^{N-2-i} \sum_{i=Th_I}^{N-2} {\binom{N-2}{i}} (Pr_I)^i (1-Pr_I)^{N-2-i} \right]$$

$$(18)$$

313

315

Now, the second term of equation (8) can be deduced by:

316
$$P_{e1l} = Pr(I_l + A'_l < Th_l / b_i^{(1)} = 1) Pr(b_l^{(1)} = 1) = \frac{1}{2} Pr(I_l + A'_l < Th_l / b_i^{(1)} = 1)$$
(19)

317

We replace the value (I1) and the value (A'_1) in equation (19), we get the following expression:

319

$$P_{e_{II}} = \frac{1}{2} H_f Pr_I \sum_{i=TH_N-1}^{N-2} {\binom{N-2}{i}} (Pr_I)^i (1-Pr_I)^{N-2-i} \sum_{i=0}^{TH_I-W} {\binom{N-2}{i}} (Pr_I)^i (1-Pr_I)^{N-2-i}$$
(20)

321 322

where W is the weight of the 2D-OCDMA codes corresponding to the number of chips equal to 1.

323 V. OCDMA System Simulation Results

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We have used MATLAB to calculate the main system performance parameters. Table 2 presents the simulation parameters used for the numerical results of BER and Q-factor calculation, in particular for Laser DFB transmitter (wavelength, emitted power and spectral width) [28], SMF specification G.652 (length, attenuation loss and chromatic dispersion coefficient) [29], APD specification and code properties, respectively.

330 331 332

 Table 2.Numerical simulations parameters.

Symbol	DESCRIPTION	VALUE
λ	wavelength	1550 nm
P_{T}	Emitted power	10 dBm
$\Delta\lambda$	DFB spectral width	0.01nm
L	SMF length	100 km
α	SMF attenuation loss	0.2 dB/km
D_c	SMF Chromatic dispersion	17ps/(nm.km)
	coefficient	
R	APD Responsivity	0.9A/W
Р	Prime number	7
Th	Threshold for CCR receiver	W
Th1	Threshold for SIC receiver	W-2
k	Simultaneous users	16
D	Bit rate	40Gb/s

333

In this work, the system performance is firstly investigated as function of BER. The BER as a function of the minimum probability of error is given by [26]:

338

 $BER_{db} = 10 \log_{10} Pe_{min}$ (21)

339 where Pe_{min} is the minimum probability of error.

Additionally, the OCDMA system performance is given as function of Q-factor to simplify the calculation when performing the comparison of system performance for different codes. The Q-factor in dB is deduced from BER expression (21), as follows [11]:

343

344

$$Q_{dB} = 20 \log_1(\sqrt{2} erfc^{-1}(2BER))$$

In Fig.7, we illustrate the OCDMA BER system performance against simultaneous users for the case of
 B2B and 100 km SMF channel with CCR receiver. In addition, we present the system performance for 2D PHS and 2D-HC, respectively.



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Fig. 7. BER as a function of simultaneous users when CCR receiver is used.

As depicted from Fig.7, for CCR receiver and 25 simultaneous user the BER value is equal to 1.02×10^{-3} and 1.35×10^{-3} for PHS and HC, respectively. Likewise, while considering 100 km SMF channel the system performance is equal to 8.79×10^{-2} and 2.56×10^{-2} for 2D-PHS and 2D-HC, respectively.

From our systems modeling of the 2D-OCDMA when considering main factors that cause the degradation of the system, we have found that the 2D-OCDMA system degradation due to chromatic dispersion and fiber attenuation is about 9.1×10^{-4} and 2.42×10^{-2} for 2D-PHS and 2D-HC, respectively.



Fig. 8. Variation of BER as a function of the simultaneous users for PHS codes with SIC.

In Fig.8 and 9, we illustrate the 2D-OCDMA system BER for 100 km and SIC based receiver as a function of the simultaneous users for 2D-PHS and 2D-HC, respectively.

As depicted from Fig.8, BER of 2D-OCDMA system is presented as function of simultaneous users for B2B with 3 stages SIC receiver, SMF channel with 3 stages SIC receiver, B2B with 5 stages SIC receiver and SMF channel with 5 stages SIC receiver, respectively.

As shown from Fig.8, SIC receiver can enhance the 2D-OCDMA system performance using 2D-PHS 366 codes with 3 and 5 stages leading to a BER value less than 10⁻⁹ for 18 and 27 simultaneous, respectively. 367 While 100 km SMF is considered, 2D-OCDMA system performance is degraded from 1.18×10⁻⁸ to 368 6.26×10⁻⁸ for 25 simultaneous users using PHS codes with 3 stages SIC receiver compared to B2B system. 369 Also, for 25 simultaneous users 2D-OCDMA system performance is degraded from 2×10⁻⁹ to 1.79×10⁻⁹ 370 using PHS codes with 5 stages SIC receiver compared to B2B system. We conclude that, 2D-PHS 371 OCDMA system degradation is about 0.58×10⁻¹ and 0.21×10⁻¹ for the SMF with 3 stages SIC and SMF 372 with 5 stages SIC, respectively. 373



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Fig. 9. BER as a function of the simultaneous users for HC codes with SIC.

As depicted from Fig.9, 2D-HC codes upgrade 2D-OCDMA system performance for both B2B with 3 stages and 5 stages SIC receiver leading to a BER value less than 10^{-9} for 16 and 45 simultaneous, respectively. Likewise, for 40 simultaneous users and when considering 100 km SMF channel the system performance is decreased from 8.79×10^{-9} to 2.07×10^{-8} corresponding to B2B and SMF with 3 stages SIC, respectively. In addition, the system performance is decreased from 8.21×10^{-10} to 1.89×10^{-9} corresponding to B2B and SMF with 5 stages SIC, respectively. We conclude that, 2D-HC OCDMA system degradation is about 6.72×10^{-1} and 6.32×10^{-1} for the SMF with 3 stages SIC and SMF with 5 stages SIC, respectively.

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Table3. Number of simultaneous users leading to BER equal to 10^{-9} .

	2D-PHS	2D-HC
B2B + 3 stages SIC	17	14
SMF + 3 stages SIC	14	10
B2B + 5 stages SIC	27	45
SMF + 5 stages SIC	18	30

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In Table 3, we present the number of active user at BER equal to 10⁻⁹ for the case of B2B with 3 stages SIC receiver, SMF channel with 3 stages SIC receiver, B2B with 5 stages SIC receiver and SMF channel with 5 stages based SIC receiver, respectively. It is shown that 2D-HC provide more simultaneous users when a SIC with 5 stages cancellation is used due to its good autocorrelation properties related to ML sequence construction. So, 2D-HC codes become more robust against MAI.

Fig. 10 and 11 present 16 simultaneous users OCDMA Q-Factor representation versus fiber length for 2D-PHS and 2D-HC, respectively.



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Fig. 10.Q-Factor versus the fiber length for 2D-PHS codes.

According to Fig.10, the OCDMA system performance provides a Q-Factor in the range of 0 and 13 dB for 16 simultaneous users and P equal to 7 while using 2D-PHS codes. For 16 simultaneous users and 100 km SMF, 2D-OCDMA system performance with 3 stages SIC receiver is degraded by about (7.23-5.86=1.37 dB) compared to B2B system with 3 stages SIC receiver. Also, for the same system setting 2D-OCDMA system performance with 5 stages SIC receiver is degraded by about (10.52-9.87=0.65 dB) compared to B2B system with 5 stages SIC receiver.



Fig. 11.Q-Factor as versus the fiber length for 2D-HC codes.

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According to Fig.11, the OCDMA system performance provides a Q-Factor in the range of 0 and 11 dB for 16 simultaneous users and P equal to 7 while using 2D-HC codes. For 16 simultaneous users and 50 km SMF, OCDMA system performance with 3 stages SIC receiver is degraded by about (6.56-4.96=1.6dB) compared to B2B system with 3 stages SIC receiver. Likewise, for the same system setting 2D-OCDMA system performance with 5 stages SIC receiver is degraded by about (9.67-8.8=0.87dB) compared to B2B system with 5 stages SIC receiver.

In Table 4, we present the fiber length (i.e., in km) leading to Q-Factor equal to 6 (corresponding to a BER of 10⁻⁹) for the case of B2B with 3 stages SIC receiver, SMF channel with 3 stages SIC receiver, B2B with 5 stages SIC receiver and SMF channel with 5 stages SIC receiver, respectively.

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Fable4. Fiber	length	(km)	leading	to (2-Factor	equal	to	6.
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	2D-PHS	2D-HC
B2B + 3 stages SIC	100	40
SMF + 3 stages SIC	120	60
B2B + 5 stages SIC	170	100
SMF + 5 stages SIC	190	120

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From the data obtained in Table 3 and Table 4, we confirm that 2D-OCDMA PHS codes exhibit better system performance compared to 2D-OCDMA HC codes in terms of simultaneous users when 3 stages SIC receiver is employed for P equal to 7. However, 2D-OCDMA HC codes accommodate more number of simultaneous users at BER equal to 10⁻⁹ compared to 2D-OCDMA PHS codes while using SIC receiver based on 5 stages cancellation.

427 Our research work reveals that MAI and chromatic dispersion are the main causes leading to 2D-428 OCDMA system performance degradation in terms of BER and Q-factor while 100 km of fiber length with 429 16 simultaneous network subscribers are investigated using a probability model (Figs. 7,8 and 9). On the 430 other hand, SMF length can be extended to 190 km and 120 km for 2D-PHS and 2D-HC leading to a Q-431 factor equal to 6 while a SIC receiver based on 5 stages cancellation with appropriate threshold is employed 432 in OCDMA receiver side (Figs. 10 and 11).

In order to highlight the different 2D-OCDMA system features and to make a comparison between our proposed system and the other previous work in PON context in the recent years, we summarize the

different 2D-OCDMA system features as function of coding schema, reachability, number of users andperformance in Table 5.

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Table 5. 2D OCDMA system features in PON context.					
System	Coding Schema	Reachability (km)	Number of users	Performance	
2D-Optical Coding monitoring	MW-OOC	20	64	SNIR≥10dB	
Hybrid WDM/OOC based OCDMA	WDM-OOC	20	72	BER ≤10 ⁻⁹	
Multiclass OCDMA	ML-Generalized OOC	20	60	BER ≤10 ⁻⁷	
2D-OCDMA- WDM	НС	41	524	BER ≤10 ⁻¹⁰	
AO-OFDM- CDMA	НС	108	45	BER ≤FEC limit	
2D-OCDMA for LR-PON	HC,PHS	120, 190	16	Q-factor=6	

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As shown in Table. 5, various 2D-OCDMA signatures are proposed in PON context, such as multiwavelengths optical orthogonal codes (MW-OOC) [30], WDM-OOC codes [31], multi-length generalized OOC (ML G-OOC) codes [32] and HC codes [11,33]. In addition, the most important feature of PON reachability is extended to 41 km and 108 km to become a LR-PON for 2D-OCDMA-WDM and AO-OFDM-CDMA system, respectively. To the best of our knowledge, it is shown that our 2D-OCDMA for LR-PON system can reach a long distance equal to 120 km and 190 km for 2D-HC and 2D-PHS which has not been reported in similar system literature.

446 VI. COMPLEXITY STUDY

In order to explain the tradeoffs between the increasing costs in terms of processing power, when the number of stage are increased, we have addressed the total CPU Time (in seconds) performed by the different OCDMA receiver program as function of the number of cancellation stage and the simultaneous user via the "cputime" Matlab function. As shown in Fig.12, the CPU time performed for the different OCDMA receiver (i.e., CCR, PIC with one stage cancellation, SIC with 3 cancellation stages and SIC with 5 cancellation stages) is reported as function of increasing the number of simultaneous users in the range of [16-100] and a prime number equal to 7.



Fig. 12 Complexity of OCDMA receiver using 2D-PHS.

As shown from Fig.12, the complexity of the OCDMA receiver is increased while increasing the number of stage cancellation as well as the number of simultaneous user in the network.

In order to make a comparison of the complexity for different studied codes, in occurrence 2D-PHS and 2D-HC as function of the different OCDMA receiver structures in Fig.13, the CPU time performed for PIC with one stage cancellation and SIC with 5 cancellation stages is reported versus the increasing number of simultaneous users in the range of [16-100] and a prime number equal to 7.



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Fig. 13 Comparison of Complexity between 2D-PHS and 2D-HC.

As shown from Fig.13, the 2D-PHS outperforms 2D-HC in terms of complexity for a simultaneous user number less than 50 while a PIC or SIC receiver is employed. On the other hand, when the simultaneous user is greater than 55, the 2D-HC outperforms the 2D-PHS in terms of complexity for either OCDMA PIC or SIC receiver.

469 VII. CONCLUSION

In this paper, we have developed 2D-OCDMA mathematical model, implemented and
 investigated system performance using MATLAB simulations. Investigation of advanced
 2D-OCDMA system performance model is developed and implemented for B2B with CCR

receiver, SMF with CCR receiver and SMF channel with SIC receiver. In order to determine 473 the BER and O-factor, we have proposed and demonstrated a 2D-OCDMA system based on a probability 474 approach by incorporating the main key system limitations, such as MAI, attenuation loss and chromatic 475 dispersion. Our study shows that there is a tradeoff which is related to the number of 476 simultaneous users leading to BER equal to 10^{-9} for 2D-PHS codes and 2D-HC codes for 3 477 stages SIC receiver and 5 stages SIC receiver, respectively. Additionally, we have 478 demonstrated that 2D-PHS OCDMA system degradation in terms of Q-factor is increased by 479 means of 1.37 dB and 0.65 dB while chromatic dispersion and MAI are considered for 100 480 km SMF and 16 simultaneous users. Nonetheless, 2D-HC OCDMA system degradation due to 481 SMF is increased by about of 1.6 dB and 0.87 dB compared to B2B system with 3 stages 482 SIC receiver and B2B system with 5 stages SIC receiver, respectively. Finally, it was 483 shown that our 2D-OCDMA LR-PON system can extend the reachability of the PON by means of 120 km 484 485 and 190 km for 2D-HC and 2D-PHS codes, which to the best of our knowledge it has not been reported in literature in similar systems. Similarly, for a simultaneous user greater than 55, the 2D-HC outperforms the 486 2D-PHS in terms of complexity for either PIC or SIC OCDMA receiver. 487

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