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

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***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 Access Interference (MAI), Single-mode fiber (SMF) channel effects and receiver noise. The mathematical model representing the 2-D optical code parameters for different receiver structures used in Optical Code Division Multiplexing Access (OCDMA) are developed, optimized and implemented using Matlab simulations, where channel imperfections, such as attenuation losses and chromatic dispersion 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 SMF channel with Successive Interference Cancelation (SIC) receiver. Additionally, SMF channel with SIC receiver system performance has been addressed by taking into account two key metrics, such as BER and Q-Factor as function of simultaneous users, and fiber length, respectively. We have managed to 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 using 5 stages cancelation is employed for 2D Prime Hop System (2D-PHS) and for 2D Hybrid Codes (2D-HC), respectively.**

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

I. Introduction

Multiplexing techniques play an important role in channel optimization and multimedia carrying data. There are several multiplexing techniques in the literature, such as Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM), Code Division Multiplexing (CDM) [1] and Orthogonal Frequency Division Multiplexing (OFDM) [2]. In optical context, the primary multiplexing techniques deployed are WDM and Optical CDM (OCDM). WDM techniques have their advantages due to its network security and good scalability. However, they suffer from power consumption and floor space availability in Central Office (CO). On the other hand, OCDM techniques have their benefits due to the fact 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 parameters for different receiver structures used in OCDMA system. We have shown that the studied code is determined by the prime number (P) and in the case when the prime number increases, the error probability decreases. In order to increase the number of simultaneous users in OCDMA network, we have investigated the system performance using an OCDMA Successive Interference Cancelation (SIC) receiver with multistage interference cancellations in comparison to the Conventional Correlation Receiver (CCR). We have demonstrated that the number of stages and as well the value of threshold on each stage of the OCDMA SIC receiver used in a system are the key system parameters which have a significant impact on the OCDMA system performance. In addition, it is shown that we can reach a higher system performance by employing an OCDMA SIC receiver instead of an OCDMA CCR receiver, in which the error probability is decreased and the network subscriber is increased. By using advanced 2-D OCDMA codes, system performance can have more flexibility by means of a full asynchronous communication, a higher user capacity(i.e., cardinality), good correlation properties and enhanced spectral efficiency [6,9]. Additionally, it should be noted that when the bit rate is increased above 40 Gb/s, the interplay between nonlinearity and chromatic dispersion causes interference among users in OCDMA system (i.e., namely multiple access interference (MAI)) resulting in significant system degradation. So, in order to reduce the system 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 compared to fiber nonlinearity that should be considered for higher data bit rate (>40 Gb/s) and in long-haul communications system (i.e., more than several thousands of kilometer). In the latter case, various nonlinear physical impairments over OCDMA system should be considered, involving Kerr effect (i.e., self-phase modulation (SPM), four waving mixing (FWM) and cross-phase modulation (CPM)), the 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, the optical channel effects on the OCDMA system and photo-detector noise in PON context. Single Mode Fibers (SMF)s, due to their small core size (less than 10 µm) allow only one mode to be transmitted with low fiber attenuation, are used to develop communication networks, such as such as 2D-OCDMA-WDM Passive Optical Network (PON) [9], ultra-dense WDM PON (UDWDM-PON) network [11] and cable access network using hybrid fiber-coaxial (HFC) networks [12] and cable access network using hybrid fiber-coaxial (HFC) networks [13]. Furthermore, SMF can support metropolitan, long haul access, premises applications in telecommunications, Cable TV (CATV), RoF Mach-Zehnder (MZ) based link [14], inter-data center application [15] and long-reach PON (LR-PON) [16]. Likewise, LR-PON is a very interesting case of PON that provides low cost and energy consumption by reducing the number of active nodes and by adding a redundant link to ensure a higher availability connection between the different Metro and core nodes [17]. The proposed OCDMA technique would be practical in LR-PON context applications while the transmission distance can reach more than 100 km. Additionally, 16 simultaneous users at 40 Gb/s data transmission is realized which is leading to a BER value less than 10^{-9} after 100 km SMF transmission system. On the other hand, by employing advanced 2D-OCDMA codes, such as 2D Prime Hop System (2D-PHS) and 2D Hybrid Codes (2D-HC) the system performance can be increased in terms of security and spectral efficiency. Various optical OCDMA receivers are employed in our proposed configurations such as SIC receiver with multistage interference cancellations and CCR. It is shown, that by using a SIC receiver, simultaneous users can be enhanced significantly in the network and fiber length can be extensible 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.

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

II. System Architecture

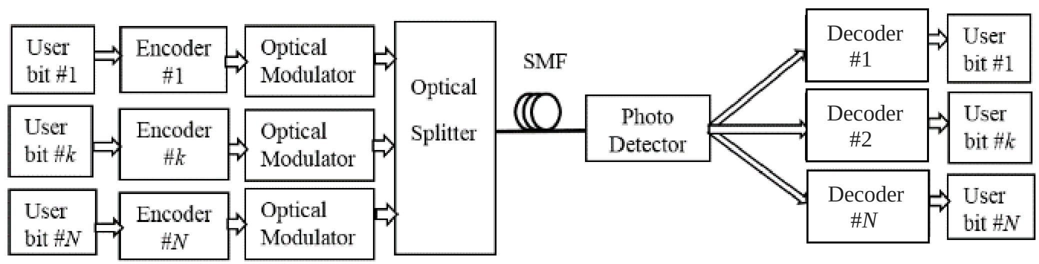

Fig. 1. Proposed system architecture

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.

III. System Model

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

A. Encoder model

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

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

where $b_i^{(k)}$ represents the ith information bit of the user k and $c_k(t)$ represents the optical code assigned to the user k. In the case, when a basic OCDMA CCR receiver is deployed, the optical demodulator provides a signal, which is proportional to the received optical power. This signal is recovered by multiplying it with 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 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 transmitted signal (i.e., the amplitude of code weight equal to 1). Subsequently, we investigate the generation of selected codes in this study, such as one-dimensional prime code (1D-PC), two-dimensional prime hop system (2D-PHS) and two-dimensional hybrid code (2D-HC). The 1D-PC is generated by using Galois-Field GF(P) for a given prime number P (i.e., time spreading for each chip is used). In addition, 2D-PHS is generated with P time spreading and (P-1) wavelength hopping. The 2D-HC is built as follows: maximum-length (ML) sequence is employed for the wavelength hopping and the prime number is used for temporal spreading (i.e., an example of seven 2D-HC codes are 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]).

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

S_0H_1	*30000000*	*20000000*	*70000000*	*00000000*	*00000000*	*10000000*	*00000000*
S_2H_1	50000000	40000000	20000000	00000000	00000000	30000000	00000000
S_4H_1	20000000	10000000	60000000	00000000	00000000	70000000	00000000
S_1H_2	10000000	70000000	50000000	00000000	00000000	60000000	00000000
S_3H_2	40000000	30000000	10000000	00000000	00000000	20000000	00000000
S_0H_3	60000000	50000000	30000000	00000000	00000000	40000000	00000000
S_2H_3	70000000	60000000	40000000	00000000	00000000	50000000	00000000

B. *Channel Model*

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

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

where c is the light velocity in vacuum, Dc is the chromatic fiber dispersion coefficient, L is the fiber length and λ is the operating wavelength. The developed model has been implemented using MATLAB 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 frequency due to simplifying the numerical simulation when fiber impairments are taken into considerations in the OCDMA system performance. Additionally, the transfer function as function of time need convolution operator compared to a simple multiplication operator when dealing with transfer function in terms of frequency.

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

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

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

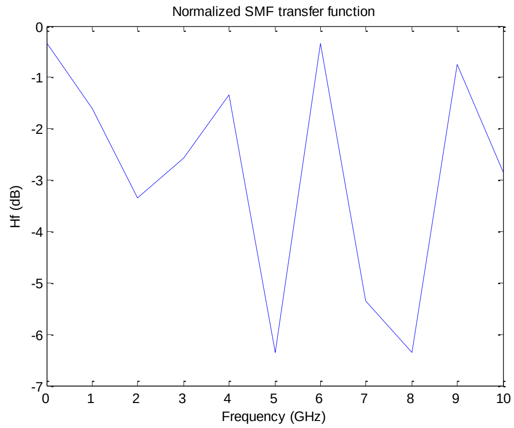

Fig. 2. SMF normalized transfer function as a function of frequency.

As can be seen from Fig.2, the 100 km SMF normalized transfer function is inversely proportional to the frequency, which shows that the SMF normalized transfer function decreases when the frequency increases. Additionally, the normalized transfer function value is in the range of [0,-6] dB. In addition, we observe a 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., corresponding to the half of the transmitted signal).

C. Decoder Model

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

$$Z_i(t) = \frac{RP_R}{2} \int_0^{T_b} \sum_{k=1}^{K} \sum_{l=0}^{N-1} B_k(t) C_k(t - lT_c) h_f(t) dt + \phi \quad (4)$$

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

The decision variable $Z_i(t)$ is suitable in OCDMA receiver system, since it represents the electrical OCDMA received signal that is compared to the receiver threshold which can be used to make a decision on the received user bit. In fact, if the value presented by the decision variable is less than the threshold the 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_T) by [22]:

$$P_R = P_T - \alpha L \quad (5)$$

where α and L are the attenuation coefficient and the length of the optical fiber, respectively.

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 signature. The decoder model architecture is illustrated in Fig. 3.

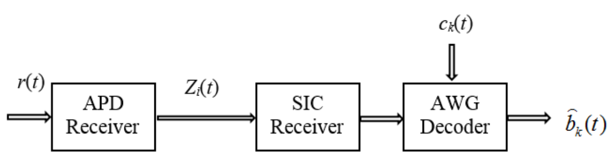

Fig. 3. Decoder model architecture.

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]:

$$r(t) = s(t) * h_f(t) \quad (6)$$

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

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

where $n(t)$ is the photo-detector noise and /psi is used to symbolize the delay over time of the received 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].

IV. OCDMA System Performance

The probability of error can be expressed as follows [25]:

$$P_e = \frac{1}{2}\left[P(0/1) + P(0/1)\right] \quad (8)$$

where $P(0/1)$ and $P(0/1)$ are the probability of transmitting 0 and 1while 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.

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]:

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

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.

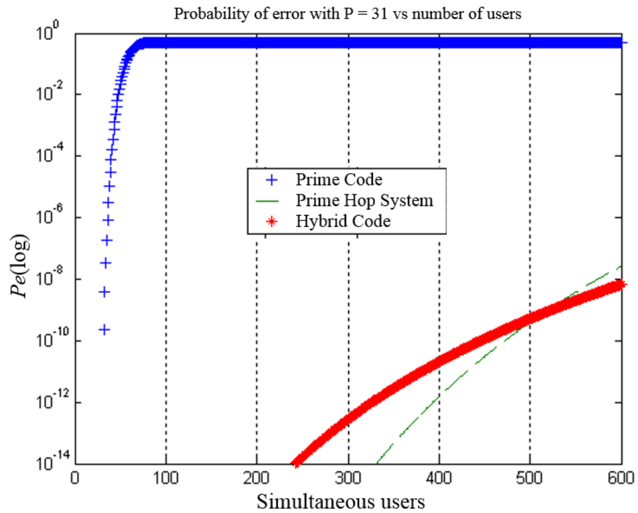

Fig. 4. Probability of error as function of simultaneous users for CCR receiver.

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.

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 function of simultaneous users when the SIC receiver is deployed are illustrated in Fig. 5[8]. It can be shown from Fig.5 that OCDMA system can reach more than P^2 users at a BER value less than 10^{-10} when the 2D-HC is used to encode data and P=31(i.e., OCDMA system can reach the theoretical number of users). As a result, the OCDMA system performance is enhanced by means of SIC receiver with 5 stages cancellation. Additionally, the SIC receiver can compensate the MAI to reach the theoretical user number in the network as function of the code features while B2B system is considered.

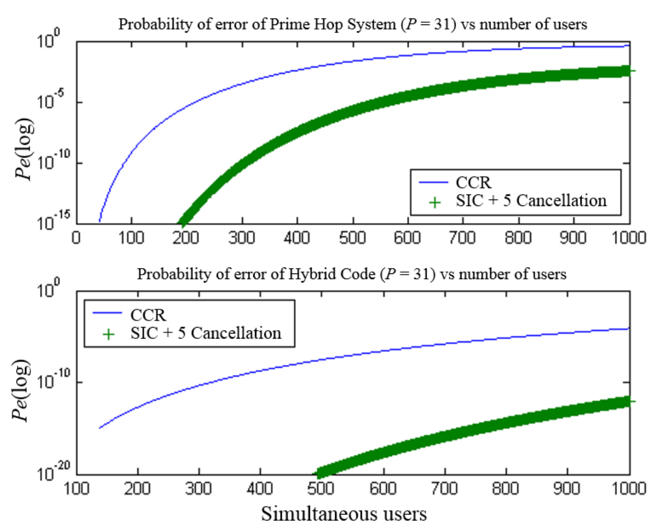

Fig. 5. Probability of error (Pe) vs. simultaneous users for SIC receiver.

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 maximum number of simultaneous users (N). So, if *N* increases the combination will decrease and leading to a low error probability (in the order of 10^{-20} for N around 500 users). As a conclusion, in our previous work [8] for a high number of simultaneous users corresponding to the theoretical numbers our target is to reach a very good BER value less than 10^{-9} leading to a high bit rate proportional to Gb/s. Likewise, for P equal to 31, our study shows that the OCDMA system can reach $P(P-1)$ and $P(P+1)$ equal to 930 and 992 simultaneous users with a low BER less than 10^{-9} when a harnessed SIC receiver with optimized parameters is fitted for 2D-PHS and 2D-HC, respectively.

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]:

$$P_e = \frac{1}{2} \int_H \sum_{i=Th}^{N-1} \binom{N-1}{i}^i (P r_I)^i (1-P r_I)^{N-1-i} H_f \, dH \qquad (10)$$

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.

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.

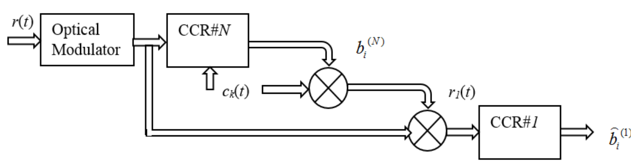

Fig. 6. OCDMA SIC model architecture.

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

$$r_1(t) = r(t) - c_N(t) \otimes \hat{b}_i^{(N)} \quad (11)$$

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

$$Z_i^{(1)} = \frac{RP_R}{2} W b_i^{(1)} + I_1 + A_1' \quad (12)$$

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

$$A'_1 = (b_i^{(N)} - \hat{b}_i^{(N)}) \int_o^T c_N(t) \otimes c_1(t) \otimes h_f(t) dt \qquad (13)$$

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:

$$A'_1 = H_f (b_i^{(N)} - \hat{b}_i^{(N)}) \int_o^T c_N(t) \otimes c_1(t) dt \qquad (14)$$

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]:

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

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

$$Pr(b_i^{(1)} = 0) = Pr(b_i^{(1)} = 1) = \frac{1}{2} \qquad (16)$$

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:

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

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'_1), we get the following expression:

$$\begin{aligned} P_{e_{10}} = \frac{1}{2} H_f [Pr_I \sum_{i=Th_N}^{N-2} \binom{N-2}{i} (Pr_I)^i (1-Pr_I)^{N-2-i} . \sum_{i=Th_1+1}^{N-2} \binom{N-2}{i} (Pr_I)^i (1-Pr_I)^{N-2-i} \\ + (1-Pr_I \sum_{i=Th_N}^{N-2} \binom{N-2}{i} (Pr_I)^i (1-Pr_I)^{N-2-i}). \sum_{i=Th_1}^{N-2} \binom{N-2}{i} (Pr_I)^i (1-Pr_I)^{N-2-i}] \end{aligned} \qquad (18)$$

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

$$P_{e11} = Pr(I_1 + A'_1 < Th_1 / b_i^{(1)} = 1).Pr(b_i^{(1)} = 1) = \frac{1}{2}.Pr(I_1 + A'_1 < Th_1 / b_i^{(1)} = 1) \quad (19)$$

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

$$P_{e_{11}} = \frac{1}{2} H_f Pr_I \sum_{i=TH_N-1}^{N-2} \binom{N-2}{i} (Pr_I)^i (1-Pr_I)^{N-2-i} . \sum_{i=0}^{TH_1-W} \binom{N-2}{i} (Pr_I)^i (1-Pr_I)^{N-2-i} \quad (20)$$

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

V. OCDMA SYSTEM SIMULATION RESULTS

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 [28], SMF specification G.652 [29], APD specification and code properties, respectively.

Table 2.Numerical simulations parameters.

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

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]:

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

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]:

$$Q_{dB} = 20\log_{10}(\sqrt{2}erfc^{-1}(2BER)) \qquad (22)$$

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.

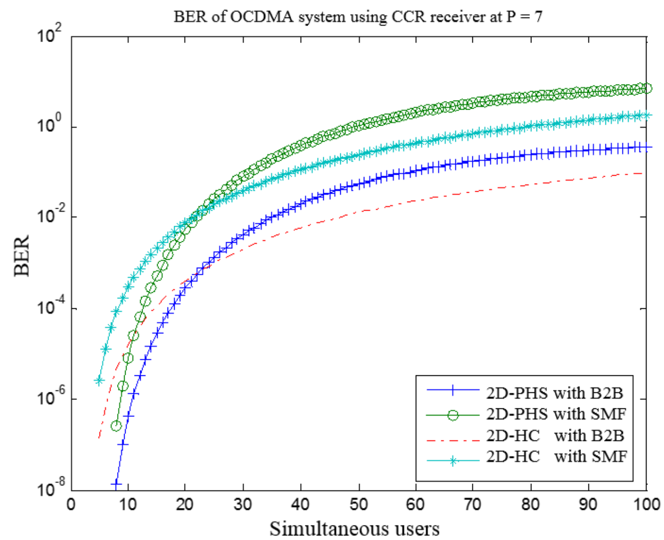

Fig. 7. BER as a function of simultaneous users when CCR receiver is used.

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.

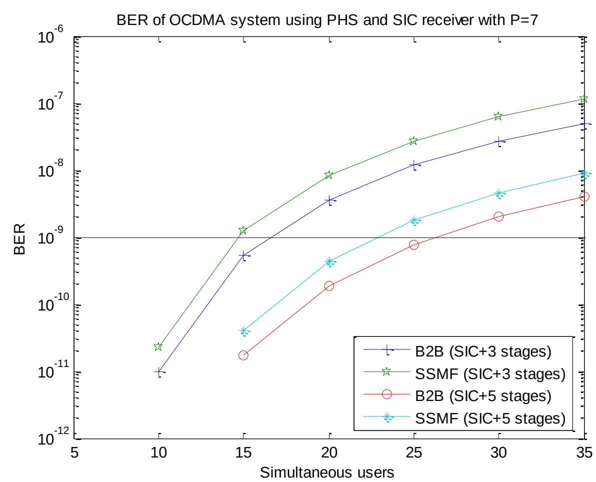

Fig. 8. Variation of BER as a function of the simultaneous users for PHS codes with SIC.

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 PHS and 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 codes with 3 and 5 stages leading to a BER value less than 10^{-9} for 18 and 27 simultaneous, respectively. While 100 km SMF is considered, 2D-OCDMA system performance is degraded from 1.18×10^{-8} to 6.26×10^{-8} for 25 simultaneous users using PHS codes with 3 stages SIC receiver compared to B2B system. Also, for 25 simultaneous users 2D-OCDMA system performance is degraded from 2×10^{-9} to 1.79×10^{-9} using PHS codes with 5 stages SIC receiver compared to B2B system. We conclude that, 2D-PHS OCDMA system degradation is about 0.58×10^{-1} and 0.21×10^{-1} for the SMF with 3 stages SIC and SMF with 5 stages SIC, respectively.

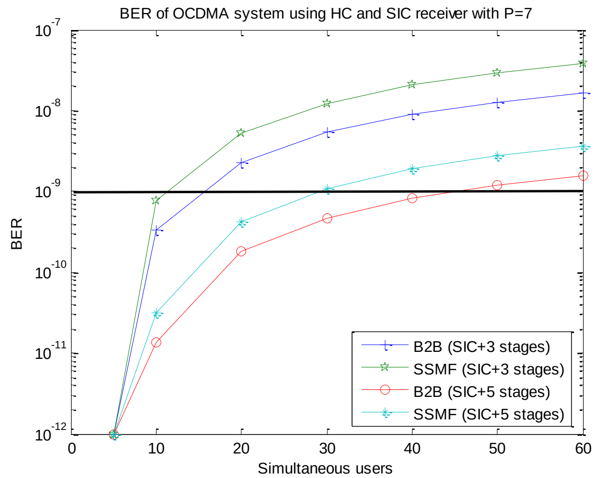

Fig. 9. BER as a function of the simultaneous users for HC codes with SIC.

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 3stages SIC and SMF with 5 stages SIC, respectively.

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

In Table 3, we present the number of active user at BER equal to10^{-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 his 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.

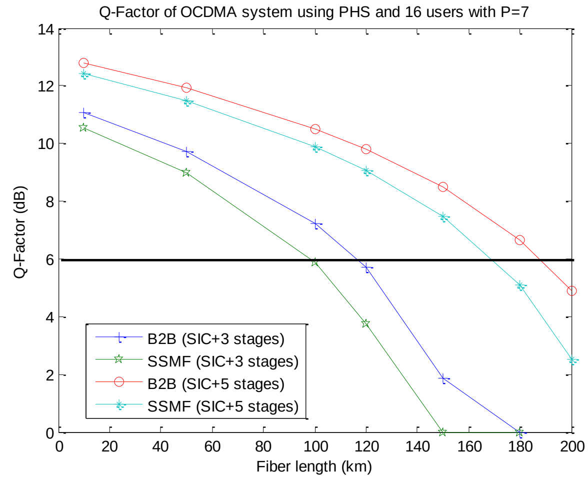

Fig. 10.Q-Factor vs. the fiber length for 2D-PHS codes.

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.

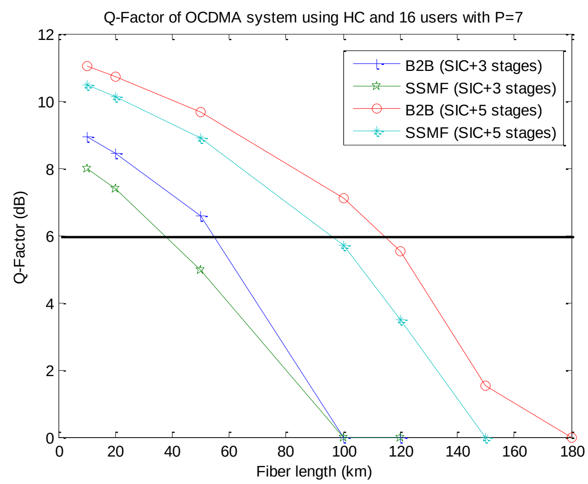

Fig. 11.Q-Factor as vs. the fiber length for HC codes.

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.

Table4. Fiber length (km) leading to Q-Factor equal to 6.

	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

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.

Our research work reveals that MAI and chromatic dispersion are the main causes leading to 2D-OCDMA system performance degradation in terms of BER and Q-factor while 100 km of fiber length with 16 simultaneous network subscribers are investigated using a probability model (Figs. 7,8 and 9). On the other hand, SMF length can be extended to 190 km and 120 km for 2D-PHS and 2D-HC leading to a Q-factor equal to 6 while a SIC receiver based on 5 stages cancellation with appropriate threshold is employed 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 year's, we summarize the different 2D-OCDMA system features as function of coding schema, reachability, number of users and performance in Table 5.

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 $\leq 10^{-9}$
Multiclass OCDMA	ML-Generalized OOC	20	60	BER $\leq 10^{-7}$
2D-OCDMA-WDM	HC	41	524	BER $\leq 10^{-10}$
AO-OFDM-CDMA	HC	108	45	BER ≤FEC limit
2D-OCDMA for LR-PON	HC,PHS	120, 190	16	Q-factor=6

As shown in Table. 5, various 2D-OCDMA signatures are proposed in PON context, such as multi-wavelengths 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.

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 "cpu time" 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.

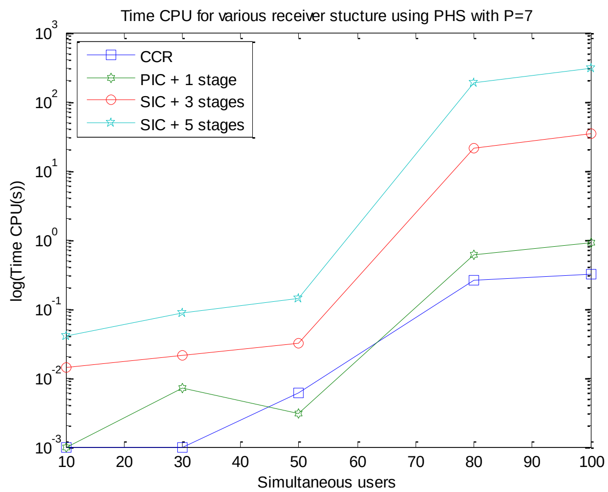

Fig. 12 Complexity of OCDMA receiver using 2D-PHS.

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.

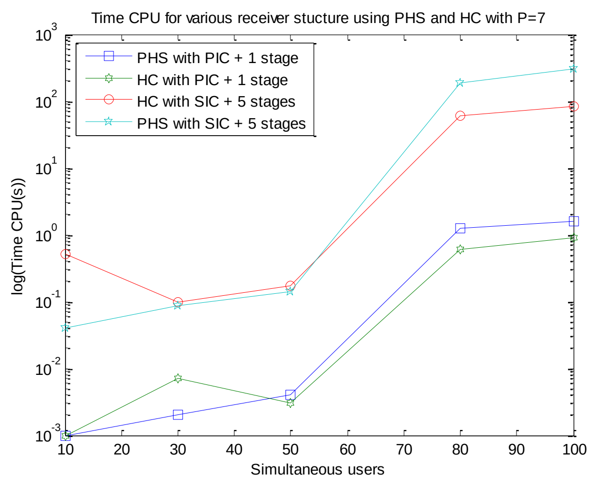

Fig. 13 Comparison of Complexity between 2D-PHS and HC.

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.

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 the BER and Q-Factor, we have proposed and demonstrated a 2D-OCDMA system based on a probability approach by incorporating the main key system limitations, such as MAI, attenuation loss and chromatic dispersion. Our study shows that there is a tradeoff which is related to the number of simultaneous users leading to BER equal to 10^{-9} for 2D-PHS codes and 2D-HC codes for 3 stages SIC receiver and 5 stages SIC receiver, respectively. Additionally, we have demonstrated that 2D-PHS OCDMA system degradation in terms of Q-factor is increased by means of 1.37 dB and 0.65 dB while chromatic dispersion and MAI are considered for 100 km SMF and 16 simultaneous users. Nonetheless, 2D-HC OCDMA system degradation due to SMF is increased by about of 1.6 dB and 0.87 dB compared to B2B system with 3 stages SIC receiver and B2B system with 5 stages SIC receiver, respectively. Finally, it was shown that our 2D-OCDMA LR-PON system can extend the reachability of the PON by means of 120 km 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 2D-PHS in terms of complexity for either PIC or SIC OCDMA receiver.

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