Performance Evaluation of an IMDD Optical OFDM-CDMA System

Sofien Mhatli[1,*], Hichem Mrabet[2,*], Elias Giacoumidis[3], Iyad Dayoub[4]

[1] SER'Com Lab., Tunisia Polytechnic School, Carthage University, Tunisia

[2] Saudi Electronic University, department of IT, College of Informatics and Computing, Medina, KSA

[3] Dublin City University (DCU), School of Electronic Engineering, Radio and Optical Laboratory, Glasnevin 9, Dublin, Ireland.

[4] Valenciennes University, IEMN/DOAE Laboratory–UMR CNRS 8520, University of Valenciennes and Hainaut-Cambresis, Valenciennes 59313, France

*Corresponding authors: sofien_mhatli@yahoo.fr, elias.giacoumidis@dcu.ie

In this paper, we propose a modulation technique for passive optical networks that harnesses two-dimensional prime hop system optical code division multiplexing access (OCDMA) and optical orthogonal frequency-division multiplexing (OFDM) for intensity modulation with direct-detection (IMDD) to enhance users' signal capacity in a cost-effective manner. The theoretical analysis is built from an analytical formula that takes into account both multiple-access interference and photodetector noise. Results show that OFDM-OCDMA with multiple users has similar performance to single-user conventional OOFDM for low transmitted powers.

1. Introduction

In order to achieve high data rates with effective cost in passive optical networks (PONs), researchers have employed many techniques, such as widespread innovation in network technologies, that serve to drive the growth of IPTV, HDTV, 3DTV, mobile media, and streaming video. On the other hand, to meet the corresponding explosion in bandwidth demand, 40G, 100G optical systems have been commercially deployed at the backbone layer and 400 G/1T systems have been investigated. The access layer must handle increased traffic and support more services [1, 2].

A long-term PON solution is next-generation (NG)-PON2 that has been discussed by the International Telecommunication Union—Telecommunications section (ITU-T) and the Full Service Access Network. Most operators expect this term to provide a higher bandwidth, increased split ratio, longer transmission distance, and greater access capacity, while making full use of existing optical distribution networks. Currently, access networks are PONs with a tree structure, in particular, time division multiplexing (TDM)-PON, which is widely applied, while Ethernet (E) PON and Giga (G) PON are suitable for fiber-to-the-x (FTTx) networks [3-5]. The 10G xPON standard and industry chain will be matured, and 10G xPON will become a mainstream technology for FTTx networks in the coming five years. Technology options for NG-PON2 [6] include wavelength-division multiplexing (WDM)-PON [7, 8], optical orthogonal frequency-division multiplexing (OFDM)-PON [9], time and wavelength division multiplexing (TWDM)-PON [10], and high-speed time division multiplexing access-passive optical network (TDMA-PON).

Indeed, optical orthogonal frequency-division multiplexing (OOFDM) is an attractive solution used in optical communication to achieve a highly spectral-efficient multicarrier transmission. Moreover, OOFDM subcarriers can be used to enable OFDM for access (OFDMA) and to allow flexible bandwidth allocation for multiple subscribers and services. The different subcarriers can be allocated to subscribers or services in the form of TDM, fiber-to-the-home (FTTH), fiber-to-the-building (FTTB), mobile station [1], Worldwide Interoperability for Microwave Access (WIMAX) repeater, and Wi-Fi hot spots.

This dynamic allocation of subcarriers depends on channel environments and application scenarios. While in OFDM PON, allocation of each subcarrier occurs in real time according to access distance, subscriber type, and access service within uncomplicated protocols that help optimize the access network. OFDM in PON makes effective use of spectral resources. This, in fact, lays a solid foundation for WDM-PON to be upgraded to dense (DWDM-PON) and ultra-dense (UDWDM-PON).

On the other hand, the OCDMA multiplexing technique is a very promising technique used to share all-fiber bandwidth and to reduce the effective cost and system complexity. In addition, with the help of OCDMA codes signature, network security becomes more effective and confident. Recently multiple-access systems based on OCDMA have been used and implemented in many optical networks [11–13], in which the proposed technique can offer higher data rates, better bandwidth efficiency, and a large number of simultaneous users.

In order to achieve privacy and security in transmission, we use optical code-division multiple-access (OCDMA), which provides several attractive features like asynchronous access, ability to support variable bit rates, bursty traffic, and scalability of the network [14]. Since CDMA systems can support asynchronous bursty traffic, transparency to overlaid protocols and decentralized operations are becoming suitable for local area networks (LANs).

Due to the all-optical processing-based optical code generation and recognition, the OCDMA exhibits unique features of allowing fully asynchronous transmission, low-latency access desirable for burst traffic environment, protocol transparency, high network flexibility, simplified network management, and so on [15]. Among all the other potential advantages, providing the information security is generally considered as an inherent benefit of OCDMA [16, 17].

In this work, we will combine CDMA and OFDM into one system called the OFDM-CDMA hybrid system, very appropriate for PON context. The primary benefit of this combination is to reduce chromatic and polarization-mode dispersion (PMD) effects in optical links, to get a free dispersion and PMD optical signal. Therefore, involving OFDM techniques in the hybrid system in PON can be used to smoothly evolve optical access networks to ultra-long-haul access networks. Due to the OFDM high-order modulation technique, the hybrid system also leverages the integration and low-cost advantages of high-speed digital signal processors and high-frequency microwave devices to develop access networks and make them more useful. Furthermore, the hybrid system can take advantage of eliminating inter-symbol interference caused by multipath and chromatic dispersion effects in transmission links. Moreover, by including OFDM high-order modulation, symbol length is increased using cyclic prefixes.

In this paper, we propose an analytical formula to carry out performance comparison between high-order modulation in PON systems based on hybrid OOFDM and OCDMA systems.

An OOFDM-OCDMA PON architecture is considered by employing 2D-OCDMA codes for the first time. Analytical calculations are performed using different modulation formats to evaluate the behavior of the proposed PON extension from 2D-OCDMA-WDM architecture [15]. Finally, transmission of 100 Gb/s OFDM-OCDMA PON over 80 km optical link is investigated as a function of the bit error rate (BER). Results show that five users can be covered with a 100 Gb/s peak data rate.

2. System model

In this section, the Optical OFDM-OCDMA system is presented with the encoder, the channel and the decoder model, as depicted in Fig. 1.
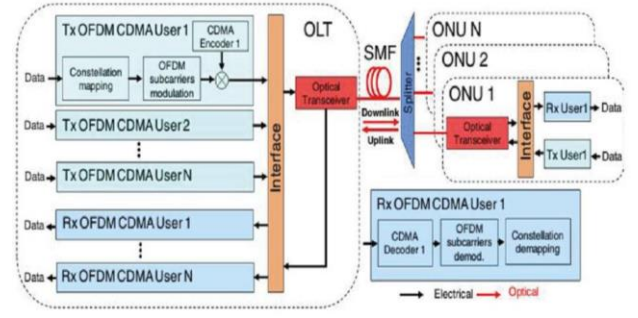

Fig. 1 Proposed architecture of hybrid OFDM-CDMA system for PON configuration.

Fig. 1 shows the proposed Optical OFDM-OCDMA PON architecture. We study the downlink direction which is comprised by the Optical Line Terminal (OLT) which generates unique encoded OFDM data streams with orthogonal codes for different users and these are simultaneously transmitted to the Optical Network Unit (ONUs). Each user has a corresponding unique CDMA receiver which decodes its own data, while the interference between multiple users can be eliminated through a code auto- and cross-correlation process in decoding. The decoded data is then demodulated using an OFDM demodulator.

The proposed architecture provides many benefits, including simple implementation, improved spectral efficiency, and security. In particular, it is possible to use a single standard source and detector at the central office to support all users as they share a single wavelength which allows optimization of existing infrastructure and simplifies network management. The correlation properties of the decoding process in a CDMA system also have the potential to improve receiver sensitivity and increase power budgets due to coding gain. This may allow the CDMA signal to be transmitted over longer distances than required in access networks without amplification, thus making possible the integration of access systems with Metropolitan Area Networks (MANs).

3. System architecture

The output of the OFDM modem block is mathematically described with:

$$S_m(t) = \frac{1}{\sqrt{N}} \sum_{k=1}^{N} X_k \exp\left(\frac{j2\pi f_c t}{N}\right) \qquad (1)$$

where N is the size of IFFT and X_k is the input symbol.

At the end of the kth user encoder, the signal can be described mathematically by the following expression:

$$s_k(t) = \sum_{l=0}^{F-1} P_T S_m(t) c_k(t - lT_c) \qquad (2)$$

Where P_T and C_k are the transmitted optical power and the kth signature code, respectively. In addition, F is the number of chips in each code signature. In this work, two-dimensional Prime Hop System (2D-PHS) codes are used as OCDMA signature code. An optical code is characterised by the following parameters (F, W, λ_a, λ_c), where F is the length of the code (number of total chip), W is the weight of the code (chips that have value 1), and (λ_a, λ_c) are the auto and cross correlation constraint, respectively.

In the OCDMA encoder, the optical code of the kth user is known as a code signature c_k (t) which can be expressed as [18]:

$$c_k(t) = \sum_{i=1}^{F} d_{k,i} P(t - iT_c) \tag{3}$$

Where $P(t - iT_c)$ is a unit rectangular pulse of duration T_c (chip duration) and $d_{k,i} \in \{0, 1\}$ is the ith value of the kth user signature.

The 2D-PHS sequences are generated with P equal to 5 and (P-1) wavelength hopping, where we obtain P (P-1) sequences of the length P^2 [18].

Table 1. 20 prime hop system sequence with P=5.

S_0H_1	10000	20000	30000	40000	50000	S_1H_1	10000	02000	00300	00040	00005
S_2H_1	10000	00200	00003	04000	05000	S_3H_1	10000	00020	03000	00004	00500
S_4H_1	10000	00002	00030	00400	05000	S_0H_2	10000	30000	50000	20000	40000
S_1H_2	10000	03000	00500	00020	00004	S_2H_2	10000	00300	00005	02000	00040
S_3H_2	10000	00030	05000	00002	00400	S_4H_2	10000	00003	00050	00200	04000
S_0H_3	10000	40000	20000	50000	30000	S_1H_3	10000	04000	00200	00050	00003
S_2H_3	10000	00400	00002	05000	00030	S_3H_3	10000	00040	02000	00005	00300
S_4H_3	10000	00004	00020	00500	03000	S_0H_4	10000	50000	40000	30000	20000
S_1H_4	10000	05000	00400	00030	00002	S_2H_4	10000	00500	00004	03000	00020
S_3H_4	10000	00050	04000	00003	00200	S_4H_4	10000	00005	00040	00300	02000

The number of active users in OCDMA depends on the code parameters (i.e., the prime number P). At a given prime number P, the OCDMA system can support, P(P-1) users for the 2D-PHS. As shown in Table 1, the selected prime number is equal to 5, so the maximum theoretical number of users considering only Multiple Access Interference (MAI) is equal to 5×4 2D-PHS codes. As a result, the number of active users corresponding to the theoretical study is equal to 20 users for 2D-PHS when P is selected to be 5.

Table 2. Number of users for 1D-PC and 2-PHS with P=31.

Code Technique	Theoretical number of users	Number of users with CCR receiver	Number of users with SIC receiver
1D-PC	31	25	30
2D-PHS	930	200	500

Table 2 provides the theoretical number of users, number of users with Conventional Correlation Receiver (CCR) receiver and the number of users with Serial Interference Cancellation (SIC) receiver at 10^{-9} BER for one-dimensional Prime Code (1D-PC) and 2-PHS with P equal to 31, respectively. To reach 200 users' sequences when a CCR is used in the OCDMA receiver, we should select the prime number P to equal to 15, which can generate 15×14=210 users' sequences [18]. Finally, to reach

210 users, it is a good practice to select P equal to 15 for the 2D-PHS construction sequences when a CCR is used at the receiver.

The electrical signal will be modulated by intensity modulation via a VCSEL, where the signal output of the laser can be described by the following expression:

$$S(t) = \sum_{k=1}^{K} s_k(t) \exp(j2\pi f_o t) \tag{4}$$

where K is the number of network subscribers (i.e., users). In addition f_o is the optical carrier of the VCSEL transmitter and $\exp(.)$ is the exponential function.

At the photo-detector output, the decision variable can be described mathematically by the following expression [19]:

$$Z_i(t) = \frac{RP_R}{2} \int_0^{T_b} \sum_{k=1}^{K} \sum_{l=0}^{N-1} S_m(t) C_k(t - lT_c) dt + \phi \tag{5}$$

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

4. System performance

The Signal-to-Noise Ratio (SNR) expression as function of simultaneous PON users is given by:

$$SNR_{eff} = \frac{S}{(K-1)\sigma^2 + N_0} \tag{6}$$

where S is the received signal corresponding to the transmitted symbol and σ^2 is variance of the noise (including MAI and subcarriers overlap). In this study, the noise variance is limited to MAI and photo-detector noise (N_0).These results help to estimate the average optical power that is required to achieve a specific BER. Then, we draw the BER versus the effective SNR at various QAM constellation size by using the well-known expression for BER given by:

$$BER_{M-QAM} = \frac{2}{\log_2 M} \left(1 - \frac{1}{\sqrt{M}}\right) erfc\left(\sqrt{\frac{3}{2} \frac{SNR_{eff}}{M-1}}\right) \tag{7}$$

where M is defined as the high order OFDM modulation parameter.

5. Simulation results and discussions

Recently, many researchers have focused on 100 Gb/s optical OFDM: In [20] authors propose a single sideband discrete multitone (SSB-DMT) with RF-up conversion (I & Q) and direct-detection for a signal capacity greater than 100 Gb/s that was successfully transmitted over 80 km SMF without chromatic

dispersion compensation. In [20] transmission performance was enhanced using a combination of bit-and-power loading (with different QAM levels), DSP-based Trellis coder modulation (TCM), and nonlinearity equalization (NLE) algorithms.

Also, in [22] authors propose an approach to reach 80 km optical transmission using IMDD OFDM with the maximum achievable bit rate to be equal to 122 Gb/s for up to 20 km. Moreover, 117 Gb/s is achieved at 40 km without optical amplifier and 101 Gb/s is transmitted over 80 km with single SOA. The capacity was maximized by the measured SNR by means of adaptive bit-and-power loading on each subcarrier [21].

To achieve a high bit rate, we employ a 20/40/80/100-Gb/s transmitter [20] using higher-order modulation formats, such as M-QAM (M>=4), which provide a higher spectral efficiency. Table 3 presents the simulation parameters deployed for the numerical results, where in particular the adopted VCSEL transmitter does not include laser nonlinearities or frequency roll-off, and therefore the inter-modulation nonlinear products upon direct-detection at the receiver are considered. It should be noted that since we use an APD instead of a PIN detector at the receiver, the nonlinear terms are removed and the receiver sensitivity is largely improved. This is why our proposed system can reach up to 80 km without an optical amplifier [23]. Finally, a standard SMF (SSMF) G.652 was adopted for fiber transmission in our simulated model.

Table 3. Simulation parameters

Parameter	Value
Operating wavelength	1550nm
Modulation format	4/16/32-QAM
Number of subcarriers	32
VCSEL spectral width($\Delta\lambda$)	0.5nm
SSMF length (L)	[20-80]km
Attenuation coefficient (α)	0.2dB/Km
Responsivity (R)	0.9A/W
Temperature (T)	300K
Load charge resistance (Rl)	10kΩ
Multiplication factor (M)	200
APD Gain (G)	15
APD Optical amplifier noise figure (Fn)	3
APD Electrical photo-detector bandwidth (ΔF)	40GHz
Bit-rate	[10-100] Gbit/s
PRBS Length	$5 \times 2^{31}-1$ bits
Prime number (P)	5

In Fig. 2, the BER against the LOP is depicted for 16/32-QAM OOFDM-OCDMA at different fiber length. It should be noted that the Back-to-Back (B2B) architecture has the best performance in both 16 and 32 QAM as mentioned in Fig. 2. Also, at the same modulation order, for example M=16, if there is increase in the fiber length from 20 km to 40 km, we observe a deterioration in the BER performance in the linear regime for LOP < 0 dBm. In the nonlinear regime we have a fixed BER because we consider only on this study the linear effects of the SMF and neglecting the nonlinearity since the distance is small. It is shown in Fig. 2 that the measured BERs can reach the Forward Error Correction (FEC)-limit.
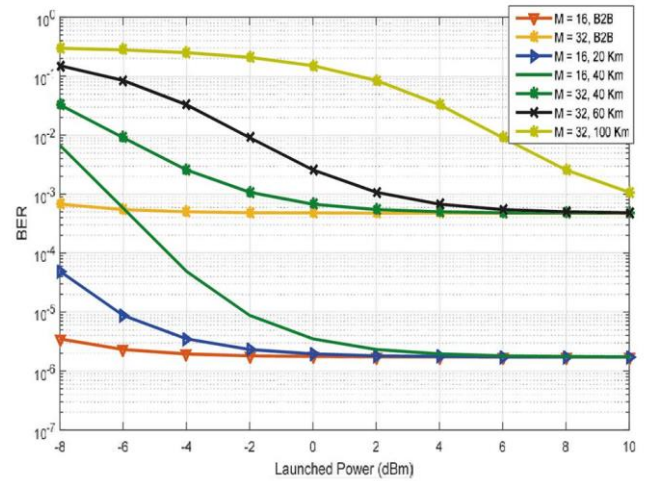

Fig.2 Comparison of high order modulation optical OFDM OCDMA, 10 Gb/s, at different fiber length B2B, 20, 40, 60 and 100 km.

In Fig. 3, the BER against the LOP is plotted for the 10/ 40/80 and 100 Gb/s OOFDM-OCDMA system at 80 km of transmission separating the OLT and the ONU. It is found that the BERs measured can reach the FEC-limit. There are increasing penalties of 2 dB, at a BER of 1×10^{-3}.
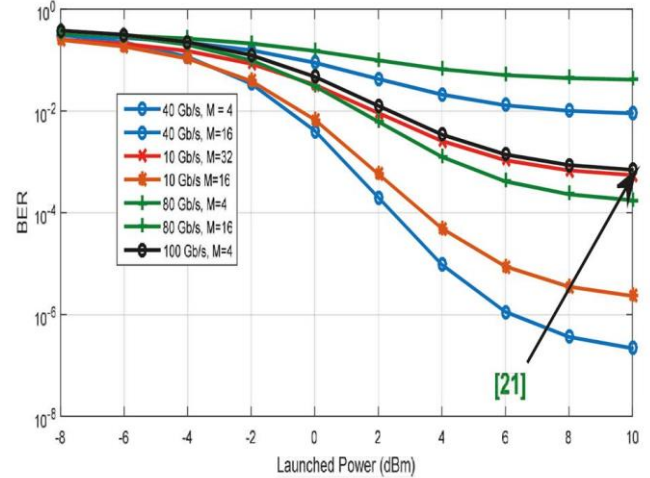

Fig. 3 Comparison of high order modulation optical OFDM OCDMA at different data rates: 10/40/80/100 Gb/s at 80 km.

In Fig. 4, the BER against the LOP is plotted for the 40 Gb/s OOFDM-OCDMA system at 80 km of transmission between the OLT and the ONU without using DCF, since chromatic dispersion is compensated with the cyclic prefix insertion. It is shown that the BERs measurements can reach the FEC-limit.
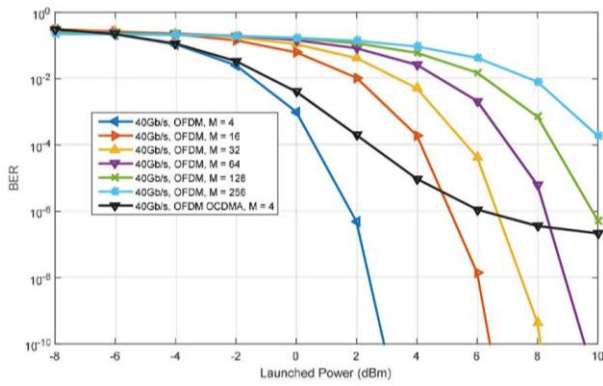
Fig. 4 Comparison of high order modulation optical pure OFDM and OFDM-OCDMA at 40 Gb/s, 80 km.

It is also shown from Fig. 4 while comparing pure OFDM-PON architecture and OFDM-CDMA, that there are increasing penalties of 2 dB, at a BER value of 1×10^{-5}. In addition, the hybrid system outperforms the pure OFDM system for high order modulation of 128 and 256 levels by achieving a BER value less than 10^{-5} at a LOP greater than 6 dBm. This degradation of high order modulation is due to the fact that the BER is inversely proportional to M. Hence, when M is increased the BER is decreased for high LOP and so the hybrid system maintains the same SNR value.
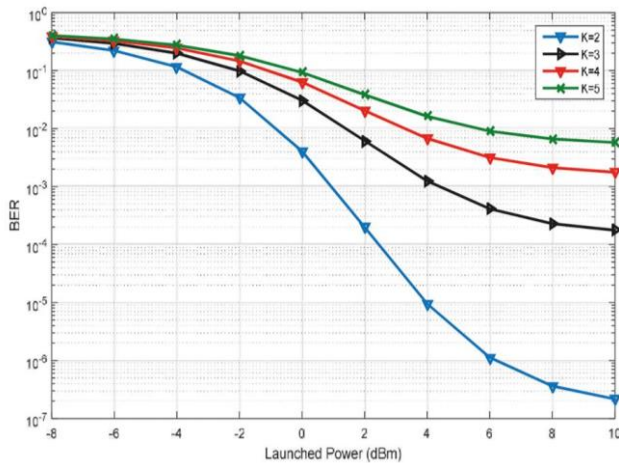

Fig. 5 BER versus LOP at 40 Gb/s for 80 km and 4 QAM OOFDM-OCDMA.

In Fig. 5, we plot the BER versus LOP of a 40-Gb/s 4QAM OOFDM-OCDMA system for 80 km. It is demonstrated that for 2D-PHS signatures the BER is equal to 10^{-5} for LOP equal to 4 dBm. Fig. 5 also shows that an increase in number of users will influent the system with a power penalty of 1.5 dB (i.e., for K=2 and K=3). This is due to fact that MAI is the most significant effect degrading the hybrid system performance.

6. Conclusion

A novel reformulation of hybrid OFDM-OCDMA was numerically demonstrated harnessing 2D-PHS codes in PON architecture for up to 100 Gb/s 16-QAM IMDD-OFDM and over 80 km of SMF transmission. Results indicated that OFDM-OCDMA with multiple users has similar performance to single-user conventional OOFDM for low transmitted powers.

Acknowledgements

References

[1] J. Zheng, "Efficient bandwidth allocation algorithm for Ethernet passive optical networks", IEEE proceeding, Vol. 153, pp. 464-468. 2006.

[2] S. F. Shaukat, U. Ibrahim and S. Nazir, "Monte Carlo Analysis of Broadband Passive Optical Networks", J. of World Applied Sciences, Vol. 12, No. 8, pp. 1156-1164, 2011.

[3] G. Kramer, B. Mukherjee, and G. Pesavento, "Ethernet PON (ePON): Design and Analysis of an Optical Access Network", Phot. Netw. Commun., Vol. 3, No.3, pp. 307-319. 2001.

[4] A. M. Ragheb, M. Elnamaky, H. Fathallah, and H. T. Mouftah, "Performance Evaluation of Standard IPACT for Future Long Reach Passive Optical Networks (LR-PON)", in proc. of International Conference on Communication Technologies, 2010.

[5] 10-Gigabit-Capable Passive Optical Network (XG-PON) systems, ITU-T Recommendation G987.

[6] T. Muciaccia, F. Gargano, and V. M. N. Passaro, "Passive optical access networks: state of the art and future evolution, IEEE Phot. J., Vol. 1, pp. 323-346, 2014.

[7] L. Xu, Qi Li, N. Ophir, K. Padmaraju, L. Luo, L. Chen, M. Lipson, and K. Bergman, "Colorless optical network unit based on silicon photonic components for WDM PON", IEEE Phot. Techn. Lett., Vol. 24, No. 16, pp. 1373-1374, 2012.

[8] H. Jung, N. Tran, C. Okonkwo, E. Tangdiongga, and T. Koonen, "10Gb/s bi-directional symmetric WDM-PON system based on polmux technique with polarization insensitive ONU", in proc. OFC 2010.

[9] S. Mhatli, M. Ghanbarisabagh, L. Tawade, B. Nsiri, M. A. Jarajreh, M. Channoufi, and R. Attia, "Long-reach OFDM WDM–PON delivering 100 Gb/s of data downstream and 2 Gb/s of data upstream using a continuous-wave laser and a reflective semiconductor optical amplifier", Opt. Lett., Vol. 39, no. 23, pp. 6711-6714 , 2014.

[10] C. Bhar, A. Mitra, G. Das, "Constrained Receiver Scheduling in Flexible Time and Wavelength Division Multiplexed Optical Access Networks", J. of Latex Class Files, Vol. 14, No. 8, 2015.

[11] C. Zhang, "Passive optical network based on optical-code-division multiple access", SPIE Optical Engineering, Vol. 45, No. 10, 2010.

[12] P. Prucnal, "Optical code division multiple access: fundamentals and applications", CRC press. 2006.

[13] S. R. Bhosale, S. L. Nalbalwar, S.B. Deosarkar, "Design and performance analysis of eight users 2-d and spectral phase encoding O-CDMA time domain systems", in proc. of IACSIT, Vol. 28, Singapore. 2012.

[14] J. S. Vardakas, I. D. Moscholios, M. D. Logothetis, V. G. Stylianakis, "Performance Analysis of OCDMA PONs supporting multi-rate bursty traffic", IEEE Trans. on Commun., Vol. 61, No. 8, pp. 3374-3384, 2013.

[15] H. Mrabet, I. Dayoub and R. Attia, "A Comparative Study of 2D-OCDMA-WDM System Performance in 40G-PON Context", IET Optoelectronics journal, Vol. 11, No. 4, pp. 141-147, 2017.

[16] X. Wang, Z. Gao, X. Wang, N. Kataoka, and N. Wada, "Bit-by-bit optical code scrambling technique for secure optical communication", Opt. Exp., Vol. 19, No. 4, pp. 3503–3512, 2011.

[17] S. Tseng, J. Wu, and W. Yang, "Two-dimensional spectral/spatial fiber-optic CDMA PON with EMS/EPD codes", IEEE Trans. on

Commun., Vol. 60, No. 11, pp. 3451-3460, 2012.

[18] H. Mrabet, I. Dayoub, R. Attia, and S. Haxha, "Performance improving of OCDMA system using 2-D optical codes with optical SIC receiver", IEEE J. of Lightw. Techn., Vol. 27, No. 21, pp. 4744–4753, 2009.

[19] S. Majumder, A. Azhari, and F. Abbou, "Impact of fiber chromatic dispersion on the BER performance of an Optical CDMA IM/DD transmission system", IEEE Phot. Techn. Lett., Vol. 17, No. 6, pp.1340-1342, 2005.

[20] L. Zhang, T. Zuo, Y. Mao, Q. Zhang, E. Zhou, G. N. Liu, and X. Xun Beyond, "100-Gb/s Transmission Over 80-km SMF Using Direct-Detection SSB-DMT at C-Band", IEEE J. of Lightw. Techn., vol. 34, no. 2, 2016.

[21] W. Yan, L. Li, B. Liu, H. Chen, Z. Tao, T. Ta, J. C. Rasmussen and T. Drenskin, "80 km IM-DD Transmission for 100 Gb/s per Lane Enabled by DMT and Nonlinearity Management", in OFC 2014, OSA, Anaheim, LOS Angeles, USA.

[22] H. Ji, L. Yi, Z. Li, L. Xue, X. Li, Q. Yang, S. Wang, Y. Yang, S. Yu, W. Hu, "Field Demonstration of a Real-Time 100-Gb/s PON Based on 10G-Class Optical Devices", J. of Lightw. Techn., pre-print, 2016.

[23] M. Tang and K. A. Shore, "30-Gb/s Signal Transmission Over 40-km Directly Modulated DFB-Laser-Based Single-Mode-Fiber Links Without Optical Amplification and Dispersion Compensation", IEEE J. of Lightw. Techn., Vol. 24, No. 6, 2006.