Optical Access Network based on OCDMA Systems: Transmission and Security Performance

Hesham A. Bakarman, T. Eltaif, P. S. Menon, M. Muqaibel, Shabudin Shaari

***Abstract*—** In this article we aim to investigate the theoretical and simulation analysis of the next-generation optical access network based on optical code division multiple access (OCDMA) technique. Hence, incorporating this technique with passive optical network (PON) will enable the system to support higher bandwidth compared to the standard PON. In this paper, an overview of optical OCDMA features such as increasing system capacity, physical layer network security, and improving the system performance were presented. The transmission performance of PON network based on OCDMA technique has been theoretically investigated using balanced detection scheme when modified quadratic congruence (MQC) codes were assigned as a signature sequence codes for the subscribers. Consequently, the effects of the contributed noises have been considered. These noises are phase-induced intensity noise (PIIN), shot noise and thermal noises. In addition, the system of 25 subscribers was simulated with MQC codes at the C band for the upstream signal with channel spacing 50 GHz. In addition, the system was simulated using modified prime code for multi premises network**.**Variation in the results was studied when fiber length and data rate were varied and different transmission power was applied. The system shows good results in terms of the bit error rate (BER), and suppression of multiple access interference (MAI). Furthermore, the security performance of the coding technique, at the physical layer, has been investigated based on the code properties for the MQC. As the code size is increased, both the complexity for the eavesdropper to detect high spectral chip pulse signal to noise ratio (SNR) and the system capacity are increased.

***Keywords*—**Passive optical network (PON), optical code division multiple access (OCDMA), modified quadratic congruence (MQC).

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I. Introduction

In recent years, optical CDMA (OCDMA) systems have attracted interest, due to their asynchronous access capability, user allocation flexibility, ability to support variable bit rate and security against eavesdroppers [1].
Nowadays, optical communication techniques are used in many applications. The access optical networks and the indoor optical wireless communications are among these applications. In both cases, OCDMA system based on spectral encoding using intensity modulation and direct detection (IM/DD) has been implemented [2].

The network between the optical line terminal (OLT) and the optical network units (ONU) is passive, i.e. it does not need any power supply. OCDMA technique and PON architecture shares the same technique, where both techniques are ‘a point to multipoint’ access technology with passive components, such as splitters, couplers, single fiber link and so forth where the cost can potentially be reduced. Hence, PON networks are recognized as an economic and future solution to alleviate the bandwidth bottleneck in the access network [3-4]. The OLT may contain all the encoder-decoder pairs required for communication with each ONU.

The PON network has been proposed to different multiplexing technologies, such as in Time Division Multiplexing (TDM) PON where simultaneous transmissions from several ONUs will collide when they reach the combiner. In order to avoid data collisions, each ONU must transmit in its own transmission window (time-slot based). The major advantage of a TDM PON is that all ONUs can operate on the same wavelength and are absolutely identical in design configuration. A transceiver in an ONU must operate at the full line rate, even though the bandwidth available to the ONU may be lower. In WDM-PON, each upstream channel (i.e., ONU) needs its own wavelength. Hence, the system cost will increase because each ONU would have to use a laser with narrow and controlled spectral width. It would also be more problematic for an unqualified user to replace a defective ONU because a unit with the wrong wavelength might interfere with some other ONUs in the PON. Using tunable lasers in ONUs may solve the inventory problem, but it is still expensive at the current state of technology. For these reasons, a wavelength division multiplexer WDM-PON network is not an attractive solution in today’s environment [5]. OCDMA-

PON, where each subscriber's channel is given its own code for spreading and de-spreading, is a good alternative in view of cost, simplicity, and noise reduction [6]. This technique combines the large bandwidth of the fiber medium with its flexibility to achieve high-speed connectivity [7]. OCDMA-PON has many features, where no synchronization is required between ONU and OLT units, and there is no need to upgrade the PON infrastructures (i.e., passive splitters). Also it has more features that are attractive such as bandwidth efficiency, soft capacity on demand, protocol transparency, simplified network control, and flexibility on controlling the quality of service (QoS) [7-9].

In this paper, an OCDMA-PON system using incoherent spectral amplitude coded (SAC) is presented. The system has been theoretically examined using MQC codes as a signature sequence for the users, with consideration of the noises contribution to the system SNR performance. The 25 subscribers encoded by the MQC code were simulated using OptiSystem (from Optiwave) commercial software. The C band was selected for the upstream signal with channel spacing of 50 GHz (0.4nm), because of the low attenuation over 35 km of transmission fiber between OLT and ONU at 1Gb/s and a minimum effective power of -22dBm. The measured Bit-error-rate (BER) curve shows error free data transmission. In addition, a multi premises network was simulated when the user's data encoding by modified prime code. In this section, 13 active users out of 25 subscribers were sent over single mode fiber and distributed by a splitter to 2 ONUs; each has 13 decoders to decode users' data.

Moreover, the security performance of incoherent spectral amplitude coded (SAC) OCDMA will be examined based on the code space size and its properties. The probability of correct detection of the encoded spectral chip pulses that represent the authorizer's signature code sequence is investigated. This probability is depending on detection and measuring the encoded spectral chip pulses SNRs.

II. Optical Access Networks

The access network domain plays an important role in next-generation network by connecting communications carriers and service providers with the individuals and businesses they serve. Carriers are also investing heavily in optical fiber as the transmission media of choice for fixed broadband access in the future due to its high-speed and stable transmission characteristics. Therefore, broadband optical access network is an ideal solution to alleviate the first/last mile bottleneck of current internet infrastructures [10].

A number of passive optical networks (PONs) have been standardized to provide broadband access services including ATM PON and broadband PON (APON and BPON, respectively; ITU G983), gigabit PON (GPON; ITU G984), and Ethernet PON (EPON; IEEE 802.3ah). These networks employ time-division multiplexing (TDM) to achieve cost effectiveness and have been widely accepted as the current-generation optical access solutions [11].

The wavelength division multiplexing (WDM) and subcarrier multiplexing (SCM) techniques can be also employed in PON. In WDM-PONs, each user can be assigned a dedicated wavelength and can enjoy the full bandwidth provisioned, while in SCM-PONs, a dedicated electrical subcarrier channel for each user which enables multiple users to share an optical channel and its associated optical components and, thus, may result in lower cost. In OCDMA PONs, users are assigned orthogonal codes, with which each user's data are encoded/decoded with an optical pulse sequence. OCDMA-PONs can, thus, provide asynchronous communications and security against unauthorized users [12].

III. PON based on OCDMA System

Since OCDMA systems have more advantages over the other access networks, it becomes the most attractive technique. These advantages include their flexibility of user allocation, asynchronous access capability, burst traffic, support of variable bit rates and security against unauthorized users [5]. In this paper, MQC codes will be tested for PON networking based on OCDMA technique by using SAC scheme as illustrated in Fig. 1. The fiber Bragg grating (FBG) has been used in our simulation to drop/reflect the specific wavelengths for each user at the transmitter and receiver sides. In this concept the encoded optical power pulse drives data only when the bit is ''1", otherwise no encoded optical pulse will be sent. At the user's transmitter encoder, the FBGs numbers should be equal to the weight number. The optical pulse passes through the first FBGs group, and then their corresponding spectral components will be reflected. At the receiver section, the SAC scheme was chosen to cancel the MAI between the users. The received signal will be reflected back from the FBGs, and its complementary signal will be propagated out from the other end of the grating group [13-18].

In this design, 25 subscribers using coding technique at 1Gb/s will be implemented using OptiSystem. The signal is modulated with both frame information and an address-code sequence, and continuous upstream in the C band has been chosen because of its low attenuation. Every user needs a specific wavelength, i.e., specific laser diode, and data generator where the transmitted signals are modulated by pseudorandom sequences of an external modulator. The receiver module consists of a positive-intrinsic-negative (PIN) photodetector and its accompanying electronics for signal recovery. Electronic parts, usually composed of amplifier, and clock and data recovery circuits (CDRs), depend on the protocol used on each wavelength.

IV. System Analysis

If In this section, the SAC-OCDMA has been proposed and implemented as a solution for PON systems. Therefore, MQC codes have been used as the signature sequence codes because of their good periodic auto/cross correlation properties.

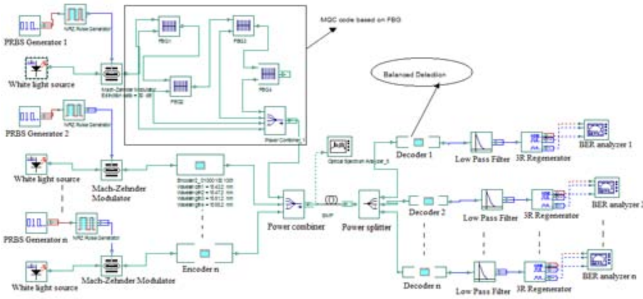


Fig. 1 OCDMA PON system

According to the MQC code properties we assume that N active users are equal to P2, code length of F =P2+P, and number of weights is equal to P+1. P is the prime number of the MQC codes. More details can be found in [13]. The MQC code properties based on balance detection is expressed as:

$$\sum_{i=1}^{F} c_k(i)c_l(i) = \begin{cases} P+1, & k=l \\ 1, & k \neq l \end{cases}. \quad (1a)$$

$$\sum_{i=1}^{F} c_k(i)\overline{c}_l(i) = \begin{cases} 0, & k=l \\ p, & k \neq l \end{cases}. \quad (1b)$$

The general equation of the received signal at the receiver is expressed as follows:

$$G^i(v) = \frac{P_{er}}{\Delta v}\sum_{n=1}^{N=P^2} b_n \sum_{i=1}^{F=P^2+P} c_n(i) . \begin{pmatrix} u\left[v - v_o - \dfrac{\Delta v}{2P^2}(-P^2+2i-2)\right] - \\ u\left[v - v_o - \dfrac{\Delta v}{2P^2}(-P^2+2i)\right] \end{pmatrix}. \quad (2)$$

Where P_{er}, b_n and c_n are the signal strength, bit sequence and spreading chip sequence of the nth user, respectively. N is the total number of users and $u(v)$ is the unit step function.

In this analysis, the effect of PIIN, shot and thermal noises have considered to the main contributed noises to the SNR performance. In addition, both the ideal synchronous case, i.e. $\tau_n = 0$ and ideal power for all the users were assumed [20]. The original prime code is analyzed using a Gaussian approximation. Therefore, the photocurrent variance can be expressed as follows [13-19]:

$$\langle i^2 \rangle = 2eIB + I^2 B\tau_c + 4K_b T_n B / R_L . \quad (3)$$

Where e is the electron's charge; I is the average current; B is the noise-equivalent electrical bandwidth of the receiver; Rl is the receiver load resistor; Kb is the Boltzmann's constant; T_n is the absolute receiver noise temperature.

In the above equation, the three terms are the representation of the shot noise, the PIIN noise and the thermal noise effect. The source coherent time τ_c can be expressed as [13-19]

$$\tau_c = \frac{\int_{v=0}^{\infty} G^2(v)dv}{\left[\int_{v=0}^{\infty} G(v)dv\right]^2}. \quad (4)$$

If the desired user is considered to be the first user, then the receiver output at the photo detectors during one bit period can be expressed as

$$G_1(v) = \frac{P_{er}}{P\Delta v}\sum_{n=1}^{N} b_n \sum_{i=1}^{F} c_n(i)\overline{c}_1(i). \begin{pmatrix} u\left[v - v_o - \dfrac{\Delta v}{2P^2}(-P^2+2i-2)\right] - \\ u\left[v - v_o - \dfrac{\Delta v}{2P^2}(-P^2+2i)\right] \end{pmatrix}. \quad (5a)$$

$$G_2(v) = \frac{P_{er}}{\Delta v}\sum_{n=1}^{N} b_n \sum_{i=1}^{F} c_n(i)c_1(i). \begin{pmatrix} u\left[v - v_o - \dfrac{\Delta v}{2P^2}(-P^2+2i-2)\right] - \\ u\left[v - v_o - \dfrac{\Delta v}{2P^2}(-P^2+2i)\right] \end{pmatrix}. \quad (5b)$$

The photocurrent at each photodiode, PD1 and PD2 in SAC scheme for the first user is given by (6(a, b))

$$I_1 = \int_0^{\infty} G_1(v)dv = \frac{P_{er}}{F}\sum_{n=2}^{N} b_n . \quad (6a)$$

$$I_2 = \int_0^{\infty} G_2(v)dv = \frac{P_{er}}{F}(P+1)b_1 + \frac{P_{er}}{F}\sum_{n=2}^{N} b_n . \quad (6b)$$

According to [13, 16-19], then the integral of $G_1^2(v)$ and $G_2^2(v)$, can be expressed as following:

$$\int_0^{\infty} G^2(v)dv = \frac{\Delta v}{F}\sum_{i=1}^{F} a^2(i) . \quad (7)$$

$$\int_0^{\infty} G_1^2(v)dv = \frac{P_{er}^2}{P^2\,\Delta v} . \sum_{i=1}^{F}\left\{\overline{c}_1(i) . \left[\sum_{n=1}^{N} b_n c_n(i)\right] . \left[\sum_{m=1}^{N} b_m c_m(i)\right]\right\} . \quad (8a)$$

$$\int_0^{\infty} G_2^2(v)dv = \frac{P_{er}^2}{F\,\Delta v} . \sum_{i=1}^{F}\left\{c_1(i) . \left[\sum_{n=1}^{N} b_n c_n(i)\right] . \left[\sum_{m=1}^{N} b_m c_m(i)\right]\right\} . \quad (8b)$$

From these results, we can calculate the signal from the desired user (i.e., first user) by the difference of the photodiode current outputs, which can be expressed as

$$I = I_1 - I_2 = \Re\frac{P_{er}}{P}b_1 . \quad (9)$$

The responsivity of the PD's is given by $\Re = \eta e / h v_c$. Here, η is the quantum efficiency, e is the electron's charge, h is the Plank's constant, and v_c is the central frequency of the original broadband optical pulse.

Now considering some of the correlation properties, the variance of the noise power according to (3) can be found as:

$$\left\langle i_1^2 \right\rangle = \frac{eB\Re P_{er}}{P^2+P}(P-1+2N)+\frac{B\Re^2 P_{er}^2 N}{2p^3\Delta v(P+1)}[P^2+N(1+P)-1]+4K_bT_nB/R_L \,. \quad (10)$$

From (9) and (10) the SNR is obtained as

$$SNR=\frac{\Re^2\frac{P_{er}^2}{P^2}}{\frac{eB\Re P_{er}}{P^2+P}(P-1+2N)+\frac{B\Re^2 P_{er}^2 N}{2p^3\Delta v(P+1)}[P^2+N(1+P)-1]+4K_bT_nB/R_L} \,. \quad (11)$$

Therefore, after the cancellation, the bit error rate (BER) can be estimated using the Gaussian approximation:

$$BER=\frac{1}{2}erfc\left(\sqrt{SNR/8}\right). \quad (12)$$

As a multiple access techniques, OCDMA is considered as a good candidate to provide physical layer network security. The security performance of incoherent spectral amplitude coded OCDMA has been investigated [21]. The probability that the eavesdropper can detect the authorized user's entire code word pulses with no errors will depend on the type of detection scheme and on the amount of time the eavesdropper observes the user's signal for each pulse detection. Based on classical detection analysis [21-22], this probability can be calculated from two quantities the probability of missing a transmitted pulse in a given time bin P_m, and the probability of falsely detecting a pulse in a bin where none was transmitted is P_F.

If the code interceptor makes a code word decision based on observing the transmitted signal for an encoded spectral amplitude coding OCDMA data bit interval, the overall probability of error-free code word detection is given by [21]:

$$P_{correct}=[Q(\sqrt{2E/N_o},\sqrt{2\gamma/N_o})^W[1-\exp(-\gamma/N_o)]^{(N-W)} \,. \quad (13)$$

where, E/N_o is the single pulse signal to noise ratio and γ is detection threshold. W and N represent code weight and code length of a spectral amplitude code OCDMA, respectively. Q is a function commonly called Marcum's Q function [23].

V. Numerical and simulation Results

In this section, the results of the theoretical analysis and simulation of OCDMA system using balanced detection scheme were presented. The signal to noise ratio and bit error rate versus the number of active users is presented in Fig 2 and Fig.3, when the prime number for MQC code is p=7, p=11, p=13 respectively, at -10dBm effective power. Clearly, the SAC scheme along with MQC code advantages auto/cross correlation properties, can suppress the MAI, reduce the effect of PIIN significantly, and hence, improve the system performance. The typical system parameters that used in this analysis are tabulated in table 1.

Table 1 System Parameters

Parameter	Value
Operation Wavelength	193.1 THz
PD quantum efficiency	0.6
Receiver noise temperature	300 k
Receiver load resistor	1030 Ω
Electrical equivalent bandwidth	80 MHz
Line-width of the thermal noise	Δv=3.75 THz

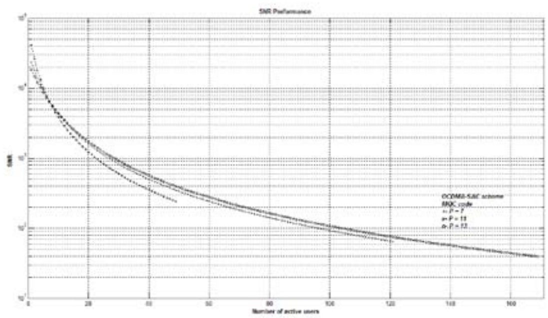


Fig. 2 SNR performance

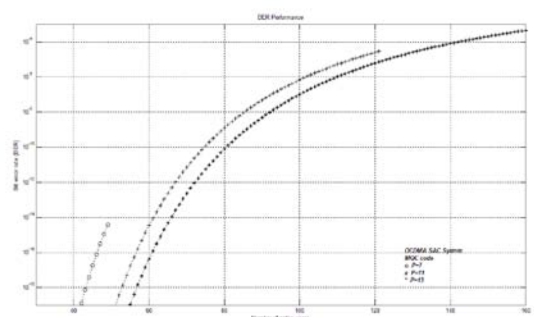


Fig. 3 BER performance

The simulation results have been investigated based on eye diagrams and spectral plots captured BER tester and OSA analyzer. The results obtained are shown on Figs. 4-10. The data is modulated using a Mazh-Zehnder modulator and pseudorandom bit sequence. Non-Return to Zero (NRZ) format was chosen for data coding because of its simplicity for this particular application. Therefore, 25 users based on OCDMA-PON technique were simulated, the signals encoded by MQC codes over a 35km SMF, and channel spacing of 50GHz (0.4nm) in C band. The spectrum of the first user code is presented in Fig. 4, where the data sent over MQC code with number of weights of 6. Fig. 5 shows the spectrum of all 25 users and the decoding spectrum of the first user using SAC scheme is presented in Fig. 6, where Fig. 6a shows the spectrum of the upper arm SAC scheme, where 6 pulses appear based on the number of weights 6, and Fig. 6b shows the spectrum of the lower arm of the SAC scheme, where 24 pulses appear based on the complementary of the upper part (30 – 6 = 24).

Fig. 7 shows the eye pattern of the first user. Obviously, it is found that the eye patterns of all other users are quite similar to the first user and have a BER of < 10^{-9}. For this particular MQC code size, Fig. 8 shows the ability of the OCDMA PON network to achieve BER of 10^{-9} at channel length of 35 km. The corresponding effective received power for simulation was shown in Fig. 9. It is obvious that the minimum effective power is -22 dBm to achieve BER of 10^{-9} at channel length of 35 km which is considered a suitable performance for fiber to the home (FTTH) applications. Fig. 10 illustrates the relation between the BER and the Q factor that has been measured from the first user performance. The higher the Q factor, the lower the BER values, consequently, the better the performance.

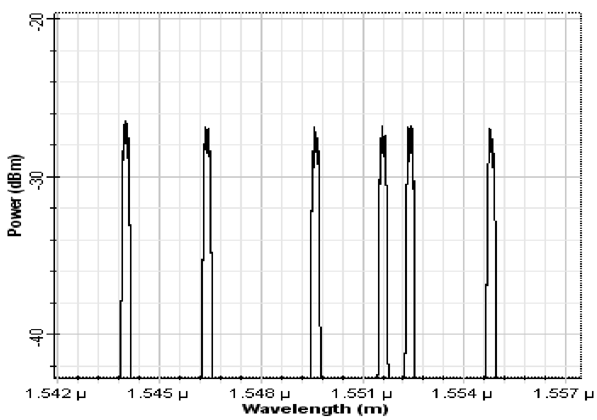


Fig. 4 First user spectrum showing the code weight is 6

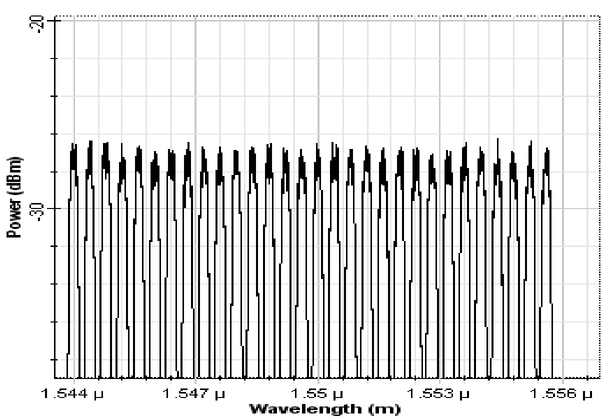
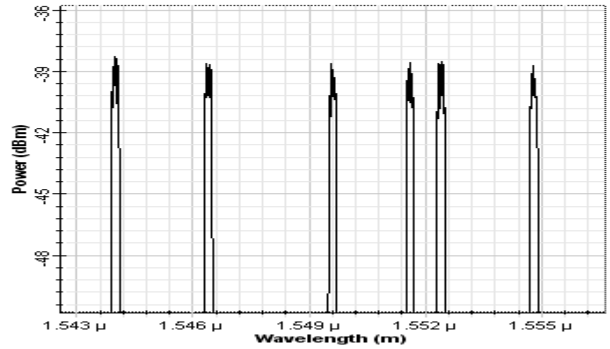
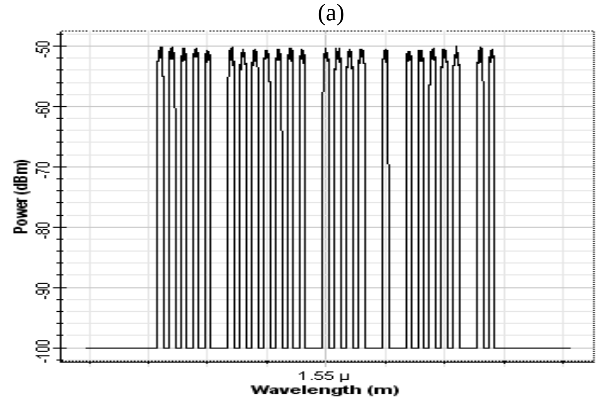


Fig. 5 Transmitted spectrum of all users



(a)



(b)

Fig. 6 SAC arms spectrum: a) first user decoded pulses, b) decoded pulses from other users

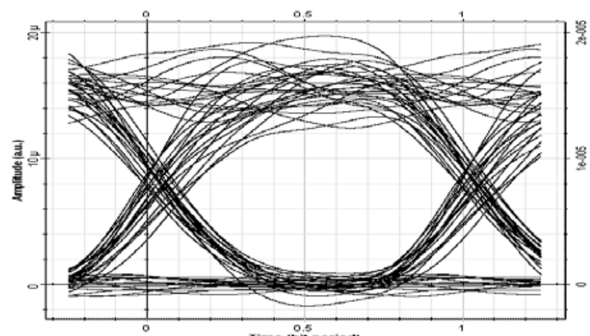


Fig. 7 Eye pattern of the first user after balanced detection

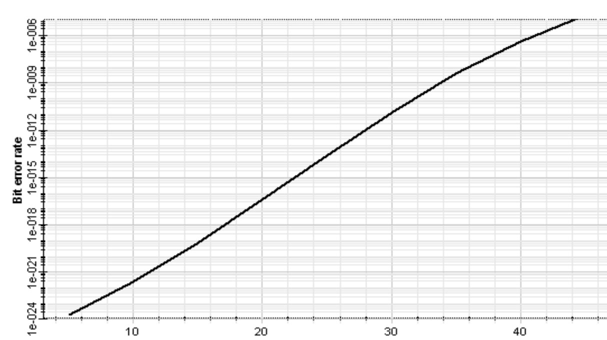


Fig. 8 BER vs channel length

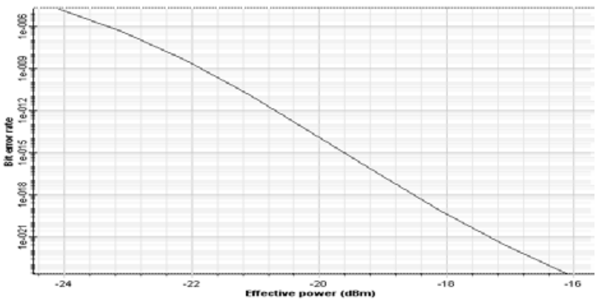


Fig. 9 BER vs effective power

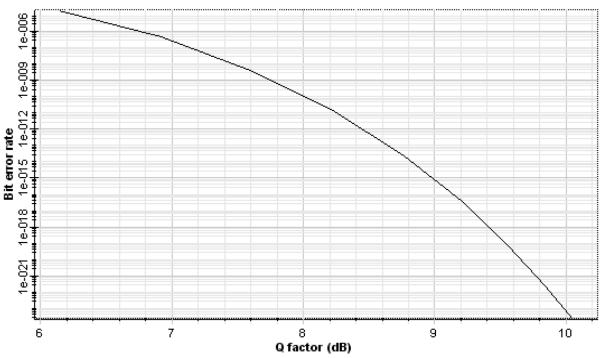


Fig. 10 BER vs Q factor

Fig.11-12. shows the results of multi premises optical network unit. A single OLT combing 13 active users, each encoded by modified prime code when the prime number is 5. 13 signals encoded and send over a single mode fiber to 2 ONU's with transmitted power 0 dBm and data rate of 6 Gbps, each one has 13 receivers. Hence, the system can support up to 26 users. The maximum channel length is 20Km as shown in Fig.11. The receiver sensitivity is affected by the multi premises system, where the best system performance can only be achieved when the effective power is -9 dBm as shown in Fig.12.

Employing the MQC code, Fig. 13 is obtained, which shows the eavesdropper probability of correct detection as a function of signal to noise ratio for a single detected code pulse. For probability of correct detection of 0.5, an eavesdropper receiver would need to detect SNR of 8dB. For probability of correct detection of 0.5, an eavesdropper receiver would need to detect SNR of 8dB. For probability of correct detection of 50 %, an eavesdropper receiver would need to detect SNR of

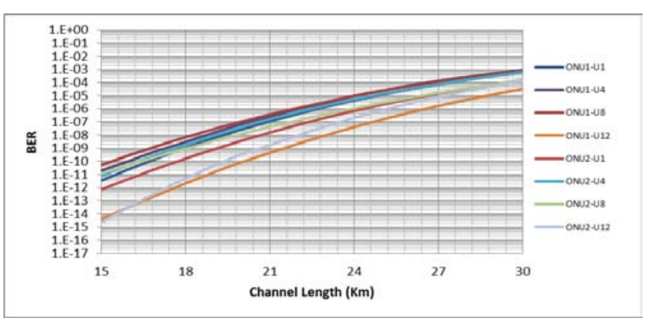


Fig. 11 BER vs channel length

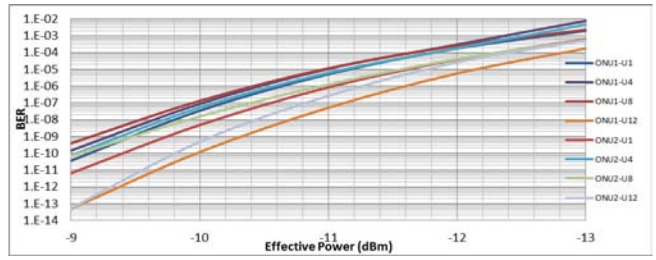


Fig.12 BER vs effective power

nearly 8 and 10.3 dB for MQC codes with prime number of 3 and 5, respectively. Therefore, high prime codes improve security of the PON networks.

Fig.14 shows the spectral chips bandwidth measured by the eavesdropper receiver. In this situation the eavesdropper is attacking the authorized user information in an isolated situation in which the other users are not communicated [21-22].

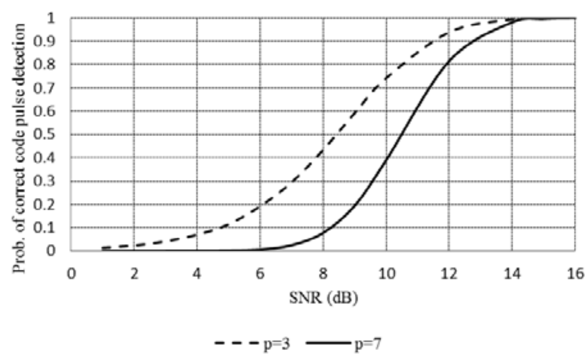


Fig. 13 Security performance of MQC codes

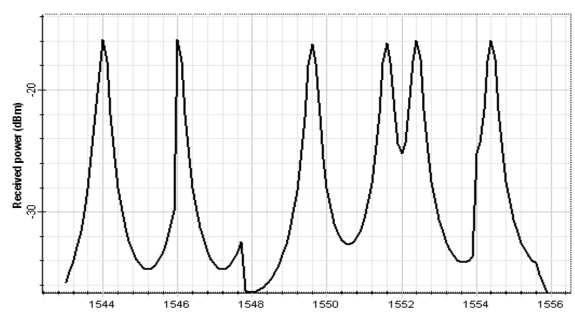


Fig. 14 Spectral chips bandwidth measured by the eavesdropper

Moreover, the use of OCDMA codes in PON systems can enhance the physical layer security in the transmitted optical channel. Fig. 15 shows some improvement for this security requirement. Therefore, by decreasing the encoded spectral chips bandwidth the eavesdropper will encounter complexity to obtain sufficient detected SNRs. Moreover, the eavesdropper would need to gain extra power to achieve the optimum BER (10^{-9}). For this part of the simulation, the eavesdropper would require an averaged power of almost -19 dBm as shown in Fig. 16.

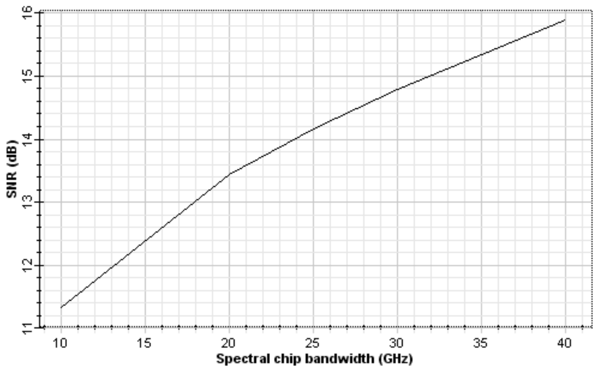


Fig. 15 Influence of the spectral chips bandwidth on the eavesdropper SNR

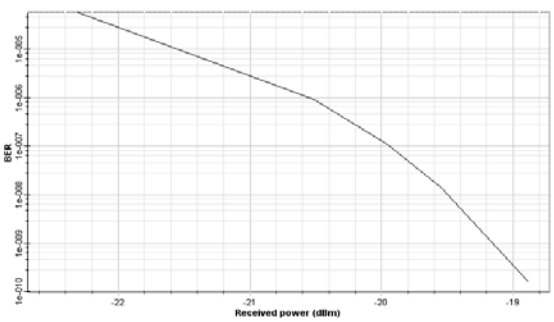


Fig. 16 Eavesdropper BER versus measured receiver sensitivity

VI. Conclusion

Passive optical networking based on optical CDMA technique was successfully simulated at 1Gb/s along 35km single mode channel, 0.4nm channel spacing and effective power -22 dBm in the C band using OptiSystem commercial software. The MQC code was chosen as a signature sequence code because of its good periodic auto/cross correlation properties. The results show that OCDMA PON system based on balanced detection method has high performance in terms of BER for 25 subscribers. A multi premises network was also simulated when the user's data encoding by modified prime code. In addition, the SAC OCDMA will increase the security performance of the PON networks. As the MQC code size increased, the complexity for the eavesdropper to detect high spectral chip pulse SNR is increased. Moreover, the use of OCDMA codes in PON systems can enhance the physical layer security in the transmitted optical channel.

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References

[1] M. Kulkarni, "A Modular Encoder Design Scheme for Turbo-encoded BPPM-OCDMA System," *International Journal of Communications* vol. 2, 2008.

[2] R. Lucaciu, A. Mihaescu, C. Vladeanu, "OCDMA Indoor Wireless Communications System with Mobile Receiver," *International Journal of Communications*," vol. 5, 2011.

[3] A. Girard, *FTTx PON Technology and Testing*, Quebec City, QC, Canada: Electro-Optical Engineering Inc., 2005.

[4] R. E.Wagner, J. R. Igel, R. Whitman, M. D. Vaughn, A. B. Ruffin, and S. Bickham, "Fiber-based broadband-access deployment in the United States, " *J. Lightw. Technol.*, vol. 24, pp. 4526–4540, 2006.

[5] K. Kitayama, X. Wang, and N. Wada, "OCDMA over WDM PON – solution path to gigabit symmetric FTTH," *J. Lightw. Technol.*, vol. 24, 1654–1662, 2006.

[6] F. Yamamoto, and T. Sugie, " Reduction of optical beat interference in passive optical networks using CDMA technique," *IEEE Photonics Tech. Letters*, vol. 12, pp. 1710–1712, 2000.

[7] P. R. Prucnal, *Optical Code Division Multiple Access: Fundamentals and Applications*, New York: Taylor & Francis, 2005.

[8] T. Hamanaka, X. Wang, N. Wada, A. Nishiki, and K.-I. Kitayama, "Ten-user truly asynchronous gigabit OCDMA transmission experiment with a 511-chip SSFBG en/decoder," *J. Lightw. Technol.*, vol. 24, pp. 95–102, 2006.

[9] P J. Penon, Z. A. El-Sahn, L. A. Rusch, and S. LaRochelle," Spectral amplitude coded OCDMA optimized for a realistic FBG frequency response," *J. Lightw. Technol.*, vol. 25, pp. 1256–1263, 2007.

[10] L. G. Kazovsky, N. Cheng, W.T. Shaw, D. Gutierrez, S. W. Wong, Broadband Optical Access Networks, John Wiley & Sons, 2011.

[11] L. G. Kazovsky, W. T. Shaw, D. G., N. C., and S. W. Wong, "Next-Generation Optical Access Networks," *J. Lightwave Technol*, vol. 25, pp.3428–3442, 2007.

[12] B. Ahn and Y. Park, "A symmetric-structure CDMA-PON system and its implementation," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 1381–1383, 2002.

[13] W. Zou, H. M. H. Shalaby, and H. G. Shiraz, "Modified quadratic congruence codes for fiber Bragg-grating-based spectral-amplitude coding optical CDMA systems," *J. Lightw. Tech.* LT-19, pp. 1274-1281, 2001.

[14] M. Kavehrad and D. Zaccarina," Optical code-division-multiplexed system based on spectral encoding of noncoherent sources," *J. Lightwave Technol.*, vol. 13, pp. 534–545, 1995.

[15] T. Eltaif, H. M. H. Shalaby, S. Shaari, & M. M. N. Hamarsheh, "Performance Analysis of a Hybrid Fiber Bragg-Grating Based Spectral-Amplitude Coding / Successive Interference Cancellation for Optical CDMA Systems," *Optics Communications*, vol. 282, pp. 1-6, 2009.

[16] T. Eltaif, H. M. H. Shalaby, S. Shaari, & M. M. N. Hamarsheh," Performance Enhancement of Successive Interference Cancellation Scheme Based on Spectral Amplitude Coding for Optical CDMA Systems Using Hadamard Codes," *Optic. Eng. SPIE.*, vol. 48, pp. 045002(1-7), 2009.

[17] T Eltaif, H M H Shalaby, S Shaari, & M. M. N. Hamarsheh. "Interference Mitigation Using Successive Interference Cancellation in Optical CDMA Systems," In Proceedings of the WSEAS conference. Turkey: 77-81. 2009.

[18] T. Eltaif,, H M H Shalaby, S. Shaari, & M. M. N. Hamarsheh, "Successive Interference Cancellation for Optical CDMA Systems: Fundamental Principles," WSEAS Transactions on Communications. Vol. 8(7), pp. 668-677. 2009.

[19] E. D. J. Smith, R. J. Blaikie, and D. P. Taylor, "Performance enhancement of spectral-amplitude-coding optical CDMA using pulse-position modulation," *IEEE Trans. Commun.*, vol. 46, pp. 1176–1185, 1998.

[20] J. A. Salehi, "Code division multiple-access techniques in optical fiber networks—Part I: Fundamental principles," *IEEE Trans. Commun.*, vol. 37, pp. 824–833, 1989.

[21] H. A. Bakarman, S Shaari, and M. Ismail, "Security Performance of Spectral Amplitude Coding OCDMA Systems," in *Proc. International Conference on Electronic Design, ICED 2008*, Dec. 2008, pp. 1-4.

[22] T. H. Shake, "Security performance of optical CDMA against eavesdropping," *J. Lightwave Technol*, vol. 23, pp. 655–670, 2005.

[23] H. L. Van Trees, *Detection, Estimation, and Modulation Theory*, Part I, John Wiley & Sons, 2001.