Enhanced Performance of SAC-OCDMA System based on SPD Detection Utilizing EDFA for Access Networks

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Abstract**—**In this paper, we present the impact of an EDFA (Erbium Doped Fibre Amplifier) for high data rate in Spectral Amplitude Coding Optical Code Division Multiple Access (SAC-OCDMA) networks. A Single photodiode (SPD) detection structure for SAC- OCDMA system is presented. The SPD detection can be flexibly constructed for any weight and number of users by using a single photodiode. Several advantages of using EDFA for simultaneous noise suppression and improved the signal quality. Thus, these features show the SPD combined with EDFA be a solution to enhance the overall system performance of SAC-OCDMA access networks. Based on the theoretical and simulation evaluation, Modified Double Weight (MDW) code is shown to provide a much better performance compared to existing SAC-OCDMA codes. The ability of the MDW code based SAC-OCDMA system utilizing EDFA to support simultaneous transmissions at different data rate has been successfully established through the simulated results of the (622 Mbps×3 users) at bit error rate of 10^{-10}.

Index Terms**—** SPD, EDFA, BER, PIIN, OCDMA

I. INTRODUCTION

Optical Code Division Multiple Access (OCDMA) is a method of sharing the bandwidth of optical fiber among a number of users in the local area network [1], [2]. While existing multiplexing techniques such as Wavelength Division Multiplexing (WDM) technique and optical Time Division Multiplexing (TDM) are ideally suited to long-haul networks, their requirement of high-accuracy wavelength-stabilization techniques and strict synchronization control limits their overall flexibility and scalability [3]. In contrast, OCDMA has several advantages for implementation of the local area network, such as capability to support asynchronous access networks, dynamic bandwidth assignment, all optical processing, and the ability to support multimedia services [3]-[5]. Generally, OCDMA system is limited by the Multi Access Interference (MAI) that results from the other users transmitting at the same time and on the same common channel [6]. Furthermore, there are other noises arising from the physical effect of the system design itself, such as Phase Induced Intensity Noise (PIIN), thermal noise, and shot noise [2], where the PIIN is related to the MAI due to the overlapping of the spectra from the different users [6]. The Spectral Amplitude Coding OCDMA (SAC-OCDMA) technique offers the ability to completely eliminate the MAI by spectral coding [7].

Codes for SAC-OCDMA systems employing intensity detection have to be unipolar, orthogonal (minimum cross-correlation) and constant weight value to obtain the low value of the probability of error due to MAI. Accordingly, a family of codes called Modified Double Weight (MDW) codes [8] has been designed. Recently, many detection techniques have been proposed for SAC-OCDMA systems such us a logic *gate* that simulates the function of the logical multiplication operator (AND)-detection technique, modified AND, and spectral direct detection techniques [9]-[11]. However, among all SAC-OCDMA detection techniques and based on the previously published papers at [9] and [10]. Single photodiode (SPD) detection technique has been proven as a good solution for ultra-high speed transmission, noise suppression and cost-effective [10]. Based on the previous studies presented in [12], [13], an Erbium Doped Fibre Amplifier (EDFA) operating in gain saturation can be used to suppress optical intensity noise and has been proposed for use in WDM systems [12]. In addition to, the EDFA has a positional to be used for simultaneous noise suppression and improved signal quality allowing a compact solution for access markets. We therefore proposed and investigated this technique as a mean to suppress the per-channel noise in SPD detection and improved the overall system performance in terms of bit-error rate (BER). Furthermore, we investigate the performance of our system numerically and by using optical simulator software "*OptiSystem*^{TM}" taking into the account the effect of different type of noises. The remainder of paper is organized as follows. In Section II, we review the system description based on MDW code and SPD detection. Section III is devoted to the system simulation model and performance analysis. Finally, conclusions are given in Section IV.

II. SYSTEM DESCRIPTION

A. *Modified Doubel Weight (MDW) code*

The code structure is based on Modified Double – Weight (MDW) code families for SAC-OCDMA systems. The MDW codes have a large number of weight can be developed based on double weight (DW) code of weight two, the MDW code is the modified version of DW code [7]. The MDW code possesses ideal cross-correlation

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properties and exists for every natural number [10][7]. However, the MDW code weight can be any even number that is greater than 2. Moreover, the MDW codes can also be represented by using the (K×N) matrix as shown in Fig. 1. The details of code structure and code parameters have been presented in [7].

$$\begin{vmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \end{vmatrix}$$

Fig. 1. The basic MDW code with code length 9, weight 4, and an ideal in-phase cross correlation

Fig. 1 shows that we can increase the number of user from 1 to 3 while the weight is still fixed at 4. An MDW code with weight of 4 denoted by (N, 4, 1) for any given code length N, can be related to the number of user K through:

$$N = 3K + \frac{3}{8}\left[\sin\left(\frac{k\pi}{3}\right)\right]^2 \tag{1}$$

Let $C_K(i)$ denote the i_{th} element of the K_{th} MDW code sequences, and according to the properties of MDW code, the direct detection technique can be written as:

$$\sum_{i=1}^{N} C_k(i)C_l(i) \quad = \begin{cases} W, & For \quad k = l \\ 1, & Else \end{cases} \tag{2}$$

To simplify our system analysis, the following assumptions are made [9], [10]:

- Each light source is ideally unpolarized and its spectrum is flat over the bandwidth [v_o-Δv/2, v_o+Δv/2] where v_o is the central optical frequency and Δv is the optical source bandwidth expressed in Hertz.
- Each power spectral component has an identical spectral width.
- Each user has an equal power (P_{sr}) at the transmitter.
- Each bit stream from each user is synchronized.

The above assumptions are important for mathematical straight for wardens. Devoid of these assumptions, it is difficult to analyze the system; for example, if the power for each spectral component is not identical and each user has a different power at the receiver. The power spectral density of the received optical signals can be written as [6]:

$$r(v) = \tfrac{P_{sr}}{\Delta v}\sum_{k=1}^{K} d_k \sum_{i=1}^{N} c_k(i)\ rect(i) \tag{3}$$

where P_{sr} is the effective power of a broadband source at the receiver, K is the active users and N is the MDW code length, d_k is the data bit of the Kth user that is “1” or “0”. The *rect(i)* is given by

$$rect(i) = u\left[\frac{\Delta v}{N}\right] \tag{4}$$

where *u(v)* is the unit step function.

B. Singal Photodiode Detection (SPD)

The proposed SAC-OCDMA receiver diagram of this technique is shown in Fig. 2. The received optical signal is decoded by the decoder, which has an identical spectral response to the intended encoder for the data to be received. The remainder of the signal from the decoder is then transmitted to the subtractive decoder (s-Decoder) to cancel out signals with mismatched signatures, i.e., interferers. The s-Decoder contains only frequency bins from different interferers represented logically in Table I. The output from the s-Decoder is either zero power unit for active user or cross-correlation power unit for interferers. The proposed technique can be performed using inexpensive ideal fiber Bragg-gratings (FBGs) dispersion to decode the received signal. After optical subtraction, the output is either code weight power unit for active user or zero power units for interferers. This implies that the interference signals are suppressed in the optical domain before the conversion of the signals to the electrical domain, as a result, the proposed SPD scheme alleviates both PIIN and MAI in the optical domain [5]. Moreover, the two interference signals at the optical subtractor are assumed to be equal and cancel each other out. However, practically, the interference signals differ slightly at the optical subtractor and results in a small amount of optical power to reach the photodiode. The main advantage of using the SPD is that the cancellation of the interference signals in the optical domain allows the use of only a single photodiode rather than two photodiodes as in typical subtraction detection schemes [6]. This reduces the amount of optical-to-electrical conversion and shot noise generated at the receiver part. The proposed detection technique can also be implemented with any fixed in-phase cross-correlation SAC codes with differ spectral chips distribution of the s-Decoder, depending on the structure of the SAC codes itself. Finally, after the desired signal is detected by a photodiode, the data-carrying electrical signal is low pass-filtered by a Bessel-Thompson filter. The band pass resulting from the filtering is assumed to be equivalent to 0.75 × DR, where DR is the data rate [14]

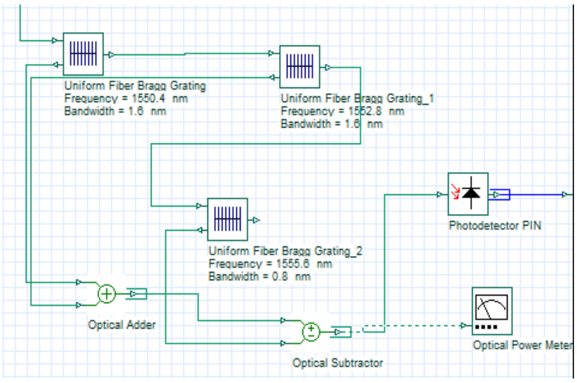


Fig. 2. SPD detection based on MWD code

The *SNR* for an electrical signal is defined as the average signal to noise power $SNR = \left[I^2/\sigma^2\right]$, where σ^2 is the variance of noise source (note: the effect of the receiver’s dark current and nonlinear noises are neglected in the analysis of the proposed system), given by

$$\sigma^2 = \left\langle i_{shot}^2 \right\rangle + \left\langle i_{PIIN}^2 \right\rangle + \left\langle i_{Thermal}^2 \right\rangle \tag{5}$$

Eq. (5) can be expressed as

$$\sigma^2 = 2eBI + I^2 B\tau_c + \frac{4K_b T_n B}{R_L} \tag{6}$$

where the symbols used in Eq. (6) bear the following meaning.

e	Electron charge;
I	Average photocurrent;
I^2	The power spectral density for I;
B	Electrical bandwidth;
K_b	Boltzmann Constant;
T_n	Absolute receiver noise temperature;
R_L	Receiver load resistor.

The formula used to calculate the bit-error-rate (BER) with Gaussian approximation can be expressed as [6],[16]

$$BER = P_e = \frac{1}{2} erfc\left(\sqrt{\frac{SNR}{8}} \right) \tag{7}$$

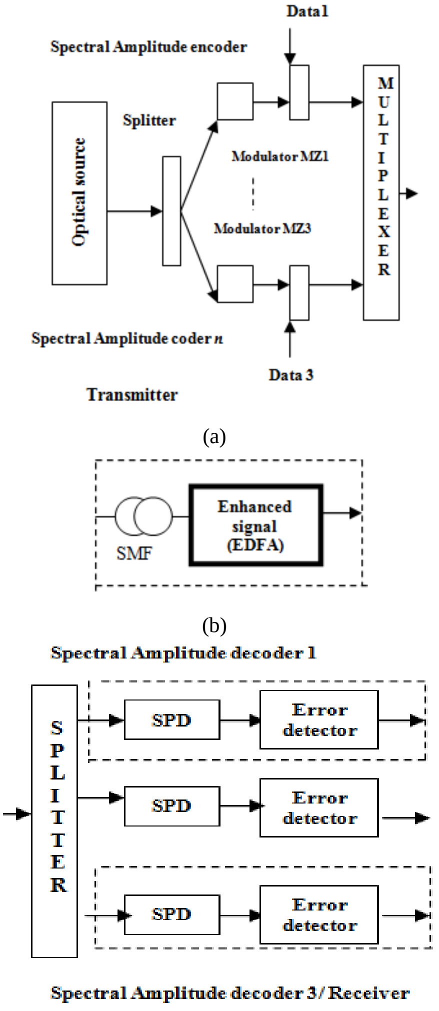
where *erfc* is the complementary error function.

TABLE I: LOGICAL REPRESENTATION OF INTERFERENCE CANCELLATION FOR MDW CODE

	Code Words
Main User (DES)	0 1 1 0 0 0 1 1 0
1^{st} Interfering User (I_1)	1 1 0 1 1 0 0 0 0
2^{nd} Interfering User (I_2)	0 0 0 0 1 1 0 1 1
(DEC *I_1)	0 1 0 0 0 0 0 0 0
Sum (I_1* DEC)	1
(DEC)''''	1 0 0 1 1 1 0 0 1
(I_1*I_2)	0 0 0 0 1 0 0 0 0
s-DEC = (DEC)'''' * (I_1*I_2)	0 0 0 0 1 0 0 0 0
(I_1*DEC)	0 0 0 0 1 0 0 0 0
Sum(I_1* s-DEC)	1
Sum(I_1*DEC) – Sum(I_1 *s-DEC)	1 – 1 = 0

C. SPD based EDFA Technique

The most common material for iong-haul telecommunication applications is a silica fiber doped with erbium, which is known as an erbium-doped fiber amplifier or EDFA originally the operation of an EDFA by itself was limited to the c-band (1530- to 1560-nm region), since the gain coefficient for erbium atoms is high in this region. This fact actually is the origin of the designation conventional band or C-band in our proposed system. Outside of this region the erbium gain peak drops off rapidly, and in the L-band it is only 20 percent of that in C-band [12]. Fig. 3 shows the setup of the proof-of-principle simulation for the proposed scheme. Each chip has a spectral width of 0.8 nm. The tests were carried out at a rate of 622 Mbps with the ITU-T G.652 standard single-mode fiber (SMF). All system parameters mentioned in Table I such us attenuation, dispersion, and nonlinear effects were activated and specified according to the typical industry values to simulate the real environment as close as possible. The performances of the system were characterized by referring to the bit-error rate (BER). After the SPD detection, the decoded signal were detected by a photo-detector (PD) followed by a 0.75 GHz low-pass-filter (LPF) and error detector respectively. The transmitted power is based on LED light source which is considered cost-effective approach for SAC-OCDMA system [15]. The proposed EDFA is placed directly before the SPD detector called “in line amplifier”. The line amplifier must have high gain and very low noise so that it does not degrade the signal-to-noise ratio of an already attenuated signal. The proper applicability of EDFA type and its parameters are described by ITU-T G662, so that nonlinaerlity, polarization, and other effects that affect the integrity of the channel and the quality of the transmitted signal are minimized. In addition, the more the EDFAs in our proposed system mean the more noise and the lower SNR ratio. Thus, one would be inclined to use higher gain to overcome this.



(a)

(b)

(c)

Fig. 3. The proposed system setup, a) Transmitter; b) Channel; c) Receiver.

The center wavelength and optical bandwidth for FBGs of each user are listed in Table II, where FBG1 and FBG2 representing the decoder, and FBG3 represents the s-Decoder. However, both FBGs with bandwidth twice the chip width and average adjacent center wavelengths are employed to decode the desired user's signal. Table III illustrates the typical parameters used for our simulation analysis

TABLE II: FBG$_S$ CHARACTERISTICS USED IN SIMULATIONS

USER	FBG	Center Wavelength (nm)	Optical bandwidth (nm)
User$_1$	FBG 1 FBG2 FBG3	1550.4 1552.8 1555.6	1.6 1.6 0.8
User$_2$	FBG1 FBG 2 FBG 3	1551.2 1555.2 1553.2	1.6 1.6 0.8
User$_3$	FBG 1 FBG2 FBG3	1553.6 1556 1550.8	1.6 1.6 0.8

TABLE III: SYSTEM PARAMETERS USED IN THE SIMULATION

Wavelength	1550nm
Thermal noise	1.8×10^{-23} W/Hz
Dark current	5 nA
Responsively	1 A /W
Optical bandwidth	B_0=3.75 THz
Attenuation	0.25 dB/km
No. of user,	3
code weight	4
EDFA gain	20 dB

III. SIMULATION RESULTS

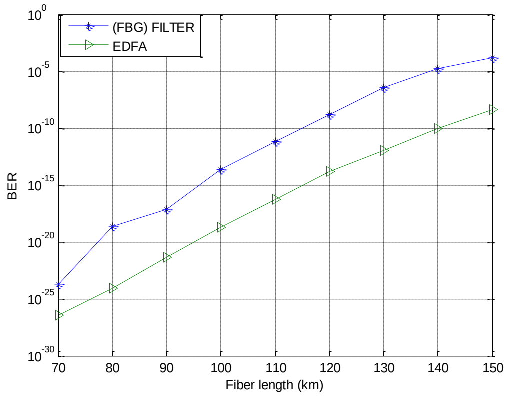


Fig. 4. BER versus fiber length at data rate of 622 Mbps

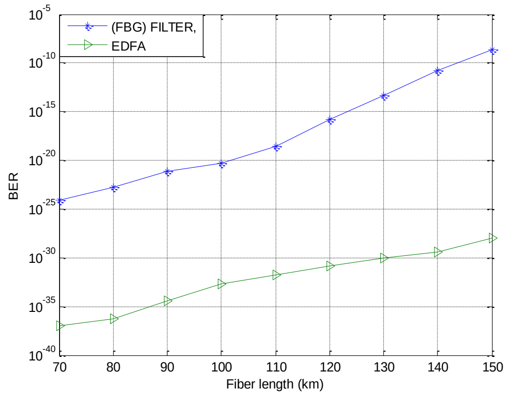


Fig. 5. BER versus fiber length at data rate of 400 Mbps

Fig. 4 and Fig. 5 show the average BER for three users against the fiber length at data rate of 622 Mbps and 400 Mbps. It can be seen that the average BER value increases with the increasing of the transmission length. Moreover, at BER of 10^{-10} the transmission distance are 115 km and 140 km for uniform FBG and EDFA, respectively. On the other hand, our simulation results indicate that the system performance is deteriorated by about more than one order of magnitude, when the dispersion effect is activated in the simulation model. Also, the results indicate that the system performance is deteriorated as the fiber length increases from 70 km to 150 km. In fact, when the fiber length increases, the data rate should decrease (Fig. 5) to recover a similar degradation of the signal form. Thus, in order to design and optimize link parameters, the maximum fiber length should be defined as short as possible, to obtain high data rate and to achieve a desired system performance without dispersion compensation device [15].

Fig. 6 shows average BER for three users against the data rate at fiber length of 70 km. It can be seen that the average BER value increases with the increasing of data rate for both techniques (uniform FBG and EDFA optical amplifier), for a given data rate the EDFA offers better performance in terms of BER than uniform FBG. This result indicates that there is a significant improvement in performance or, for a fixed BER, could accommodate a higher data rate for greater capacity.

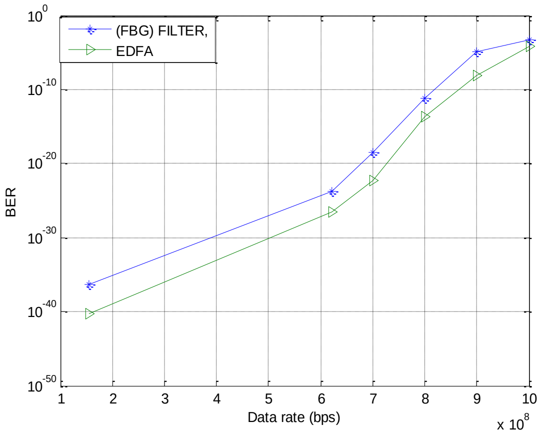
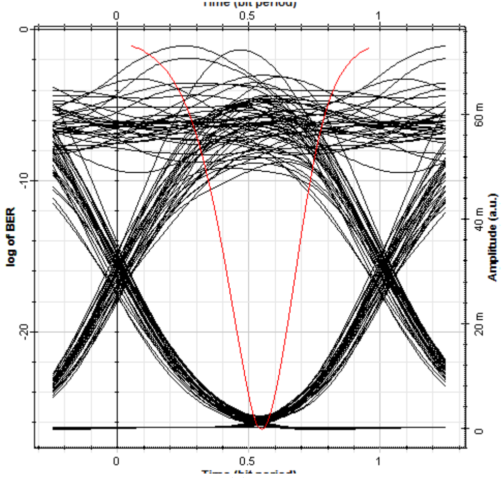


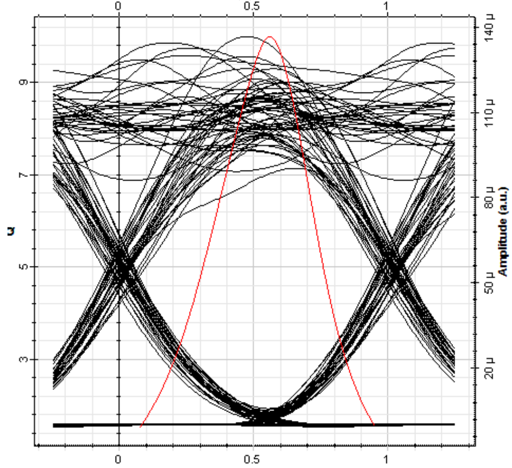
Fig. 6. BER versus data rate at fiber length 70 Km

Also, it can be seen from the simulation results shown in Fig. 7- Fig. 10, in the case of a long haul transmission distance of 130 km the BER performance is higher compared with 70 km transmission distance. The performance of the MDW code was tested and compared with a FGB filter without employing EDFA such as a uniform FBG filter. The MDW code test was carried out at 622Mps for 70 km, while the uniform FBG filter was evaluated with 622 Mbps at higher BER. The eye pattern shown in Fig. 7- Fig. 8 clearly shows that the MDW code network performs better with a large eye opening even though it was tested with a better BER performance and higher data rate. Although the BER of using EDFA is lower than a uniform FBG, it must be noted that an

EDFA is still performing better performance for a longer transmission distance and a higher data rate of 622 Mbps. That is achieved because of the properties of SPD detection such as no overlapping between the light spectra. The results in Fig. 7- Fig. 8 clearly show that an SAC-OCDMA network using SPD detection employing EDFA is suitable for the Wide Area Network (WAN) environment with a high data rate of 622 Mbps.

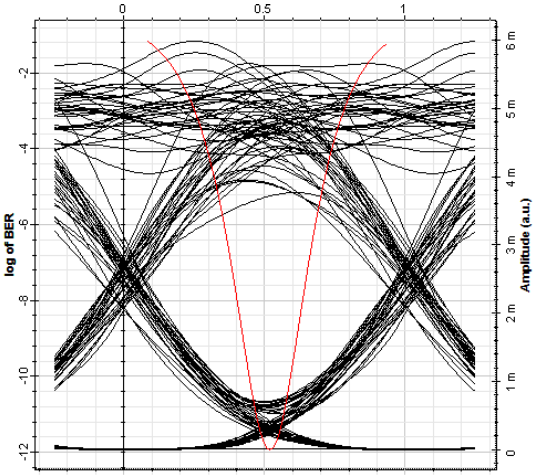


(a) EDFA

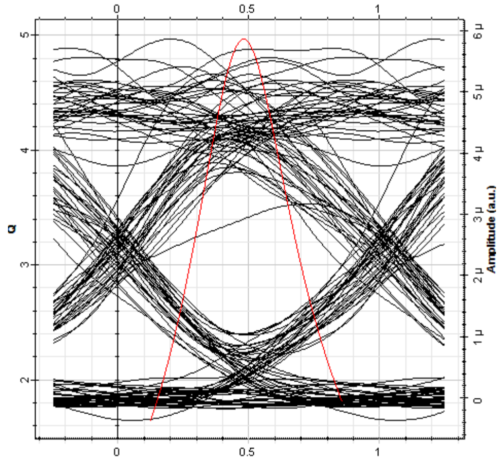


(b) Uniform FBG

Fig. 7. Eyes diagram for a fiber length of 70 km under 622 mbps data rate; a)EDFA: BER=3.3×10^{-27}; b) Uniform FBG: BER of 1.7×10^{-24}

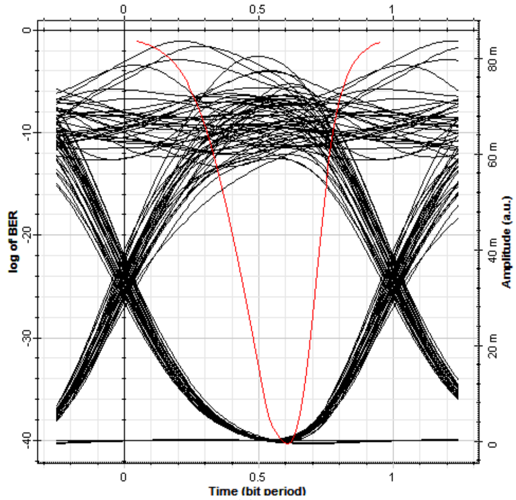


(a) EDFA

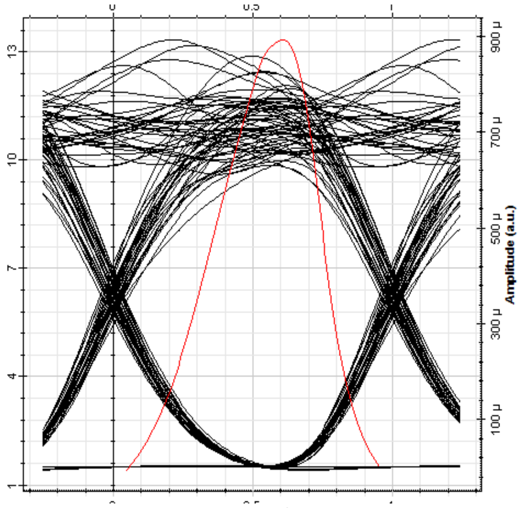


(b) Uuiform FBG

Fig. 8. Eyes diagram for a fiber length of 130 km under 622 mbps data rate; a)EDFA: BER = 1.1×10^{-12} ; b) Uniform FBG: BER =3.3×10^{-7}



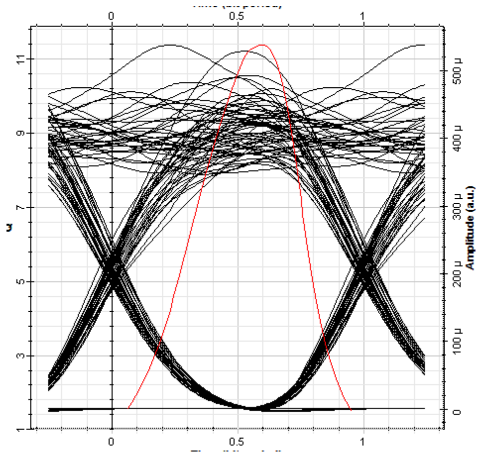
(a) EDFA



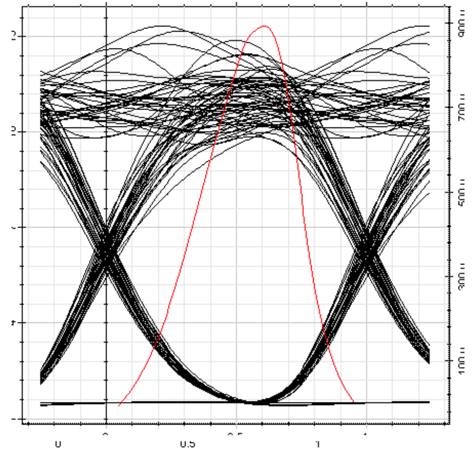
(b) Uniform FBG

Fig. 9. Eyes diagram for a fiber length of 70 km under 155 mbps data rate; a) EDFA: BER = 4.6×10^{-41}; b) Uniform FBG: BER = 3.4×10^{-37}

Fig. 11 shows the relationship between the received output signal power and transmitted power (LED input power) for various techniques (EDFA and FBG filter). It clearly shows that the output power increases with the increasing the input power. For example, at 0 dBm the received power are -28dBm, -4 dBm for FBG filter and EDFA respectively. Note that changing data rates have no significant changing in the output power. Moreover, it clearly shows that when the system operated at the different bit rates, the effect of distance on the output power is the same for both, for example, at the distance of 70 km with the input power of -10 dBm, the output power for 622 Mbps and 400 Mbps systems are both -12 dBm. However, the noise powers at 70 km for the uniform FBG and EDFA systems are -90 dBm and -101 dBm, respectively. The optical signal-to-noise ratio for the OCDMA system using EDFA is higher compared to the OCDMA system using FBG filter. Thus, the FBG filter system would have a lower noise power than an EDFA system.



(a) EDFA



(b) FBG Number

Fig. 10. Eyes diagram for a Fiber length of 130 km under 155 Mbps data rate; a)EDFA: BER = 7.2×10^{-30}; b) Uniform FBG: BER = 1.3×10^{-24}

TABLE IV. ENHANCED BER PERFORMANCE OF THE PROPOSED SYSTEM UTILIZING EDFA

DATA RATE	EDFA	FILTER FBG
155 Mbps (Voice)	4.6×10^{-41}	3.4×10^{-37}
622 Mbps (Video)	3.3×10^{-27}	1.7×10^{-24}
800 Mbps (Data)	8.4×10^{-14}	1.1×10^{-11}

Finally, Table IV shows the simulation results for the proposed system based on SPD detector utilizing EDFA at transmission distance of 70 km. However, the results clearly depict that at different applications (Voice, video, Data) specific BER is required in order to achieve different quality-of-service (QoS) requirements.

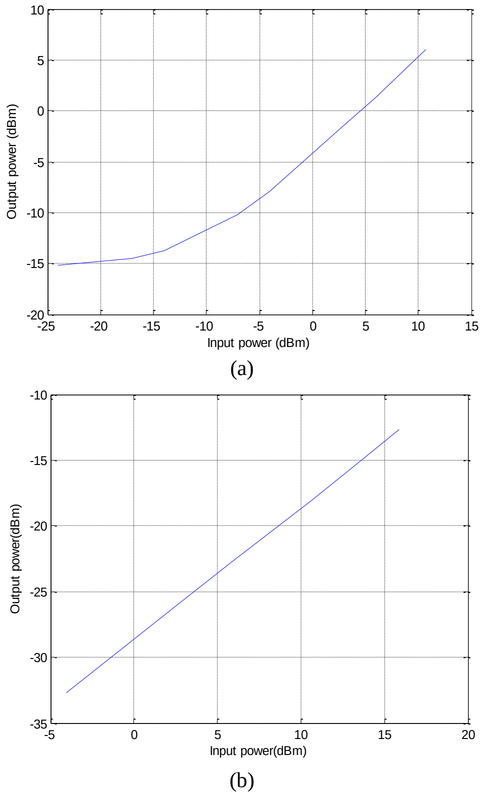


Fig. 11. Input power versus output power; a)EDFA; b)FBG filter

IV. PROPOSED SYSTEM FOR FTTH APPLICATIONS

The proposed system can be a promising candidate for Optical access networks which have been considered the networks of choice in recent years, especially in the Fiber to the Home (FTTH) applications, and OCDMA is fast becoming one of the main contenders for FTTH (Fig. 12). Fiber to the home (FTTH) is the installation and use of optical fiber from a central point directly to individual buildings such as residences, apartment buildings and businesses to provide unprecedented high-speed Internet access. The FTTH dramatically increases the connection speeds available to computer users compared with technologies now used in most places. In terms of cost, the proposed system is considered cost effective solution for FTTH networks as only single photodiode per user (Home) is employed, as previously mentioned in section II (subsection B).

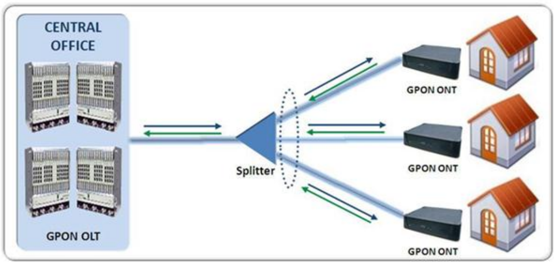


Fig. 12. The proposed system for FTTH solution

Fig. 13 depicts the variation of the SNR versus the number of homes (users) for the proposed system. The SNR of the proposed system decrease when the number of active users increases, mainly due to PIIN. Moreover, the proposed system gives the advantage of increasing the number of users without affecting the QoS at data rate of 622 Mbps.

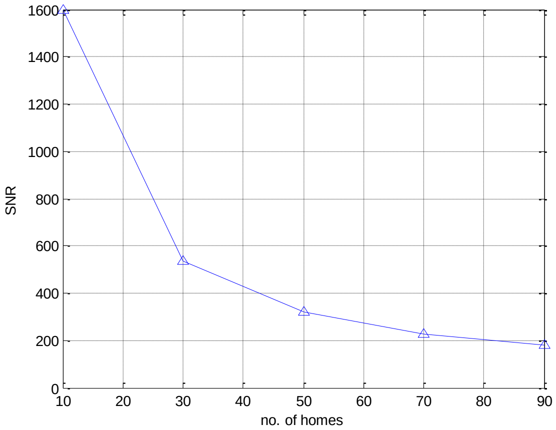


Fig. 13. SNR versus number of users (homes)

V. CONCLUSION

In this paper, the SPD detection is performed for spectral amplitude coding OCDMA system with single photodiode at the detection segment. It is shown that in order to achieve minimum BER of 10^{-10}. The ability of the proposed system to enhance the BER has been presented using EDFA, where three active users can be obtained with a proper choice of supportable code weight. The SPD detection with large weight (MDW code) always has smaller BER even when the code length is long. The PIIN is also an important system limitation which must be reduced. Thus, in an access optical network when the optical amplifier is used, the signal-to-noise ratio is enhanced significantly and the overall network performance can be improved. This proposed technique can be an excellent candidate for use in next generation OCDMA networks applications. The EDFA operates as a bidirectional amplifier in a single feeder fiber provides a sufficient total reach of 140 km for three channels using SPD OCDMA detection technique.

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