Impact of the Unipolar Family Codes on the Performances of DS-OCDMA System

Amel Farhat[a,d], Mourad Menif[b], Catherine Lepers[c], Houria Rezig[a], Philippe Gallion[d]
[a]Ecole Nationale d'Ingénieurs de Tunis, Laboratoire SYSCOM, BP. 37, Le Belvédère, 1020, Tunisia.
[b] Ecole Supérieure des Communications, U. R. CIRTACOM, Route de Raoued Km 3.5, 2083 El Ghazala - Ariana – Tunisia
[c]Laboratoire PhLAM, CNRS UMR 8523, Université de Lille, 59650 Villeneuve d'Ascq, France
[d]Institut TELECOM, TELECOM ParisTech, Ecole Nationale Supérieure des Télécommunications, 46 Rue Barrault 75013 Paris, France

ABSTRACT

This paper presents the Direct Sequence Optical Code Division Multiple Access (DS-OCDMA) system using two configurations of the optical source. To encode/decode transmitted data, we used Superstructured Fiber Bragg Grating (S-FBG) as encoders/decoders. We consider three unipolar family codes which are the Prime Sequence (PS), Quadratic Congruence (QC) and the Extended Quadratic Codes (EQC) codes. In order to evaluate the performances of our system in term of Bit Error Rate (BER), we implement the Importance Sampling (IS) technique, which is a variant of the well-known Monte-Carlo (MC) method. Our simulation results depict that EQC codes outperform QC and PS codes for the DS-OCDMA system using either coherent or incoherent source. We show also that using EQC codes with increasing the optical bandwidth and maintaining the electrical filter leads to improve the performance of incoherent system.

Keywords: DS-OCDMA, unipolar codes, coherent/incoherent source, beat noise, Bit Error Rate, Importance Sampling.

1. INTRODUCTION

Nowadays, the demand of high bit rate communication services such as telephone, high speed internet and high definition television is in exponential growth. As a result, high speed and large capacity systems are needed for access networks to serve the end-user. The optical fiber was presented as a solution due to its enormous bandwidth and low signal attenuation. Thus, many optical systems have been proposed such as Passive Optical Network (PON), Wavelength Division Multiple Access (WDMA) and Optical Code Division Multiple Access (OCDMA). The later system is one potential solution to assure multiple access in all-optical communication networks [1]. Indeed, OCDMA technique has many advantages as compared to Time Division Multiple Access (TDMA) and WDMA solutions. In fact, it provides for each user an access to the network without the need for traffic management or system synchronization as TDMA solution do. It also avoids sophisticated hardware such as wavelength-controlled tunable lasers as required in WDMA systems. Moreover, it offers many other advantages such as sharing of optical resources (source, fiber, etc…) and inherent data security.

The OCDMA systems can use either coherent or incoherent optical sources. In these systems, many technologies for encoding/decoding process including Fiber Optic Delay Line (FODL) and Fiber Bragg Gratings (FBG) have been considered. The OCDMA systems can be divided into different categories depending on the coding approach: Direct Sequence (DS) or temporal encoding [2], Frequency Encoding [3] and two-dimensional (2D) encoding [4]. Each coding approach can use either coherent or incoherent detection. The coherent detection manipulates the phase of the optical pulses in the encoding/decoding while the incoherent one is based on optical power through quadratic detection known as direct detection.

Depending on the detection process, two categories of codes can be used in coding/decoding transmitted data. Unipolar codes are needed for incoherent detection whereas bipolar codes are used in coherent processing. The choice of the family codes is based on its correlation properties. Indeed, bipolar codes, composed with '-1' and '1', present good correlation proprieties thus they reduce the Multiple Access Interferences (MAI) which lead to enhance system performance. But they are not largely used because of the complexity of the incoherent detection. Whereas, unipolar codes, which is a family of (0, 1) sequences, can be easily implemented but they present nonzero cross-correlation functions therefore they are quasi-orthogonal. The well-known families of unipolar codes designed for the Direct Sequence-OCDMA are the Orthogonal Optical Codes (OOC) [1], the Prime Sequence codes (PS) [2], the Quadratic Codes (QC) and the Extended Quadratic Codes (EQC).

The OOC have very long lengths and small weight and support few users resulting in a poor spectral efficiency while the PS codes have been shown to support many simultaneous users with shorter code length but, they suffer from high cross-correlation level [5]. The main property of QC and EQC codes of interest is their non-periodicity in fact the distance between '1' chips is never the same. However, the main disadvantage of EQC codes is that their length is twice as much as PS and QC ones [6].

The paper is organized as follows. In section 2, we present the Direct-Detection Direct Sequence OCDMA system using PS, QC and EQC family codes. Then we evaluate different receiver noises by given their variances. Next and in order to estimate the Bit Error Rate (BER), with taking into account all the receiver noises, we implement a new simulation technique which is the Importance Sampling (IS) method. Section 3 compares the performances of the three family codes. Simulation results depict that EQC codes outperform the PS and the QC ones for the two cases of optical sources. Using EQC codes, it was shown also that increasing their weight the multiplexing capacity can be improved. Moreover, using these codes, we demonstrate that increasing the optical bandwidth and maintaining the electrical filter enhance the BER for the incoherent source case. Conclusions are given in section 4.

2. DS-OCDMA SYSTEM

2.1 System description

The architecture of the DS-OCDMA system is giving in Fig. 1. Each transmitter is composed of a laser source for the coherent DS-OCDMA system or a broadband source followed by an external intensity modulator at the data repetition rate of 2.5 Gbps with low duty-cycle RZ signal in order to obtain a train of 50 ps short-pulses. The resulting pulse train is modulated afterward by the user's data, encoded by Superstructured FBGs (SFBGs) with a Full-Width at Half Maximum (FWHM) bandwidth 1.6 nm and transmitted through a three-port circulator.

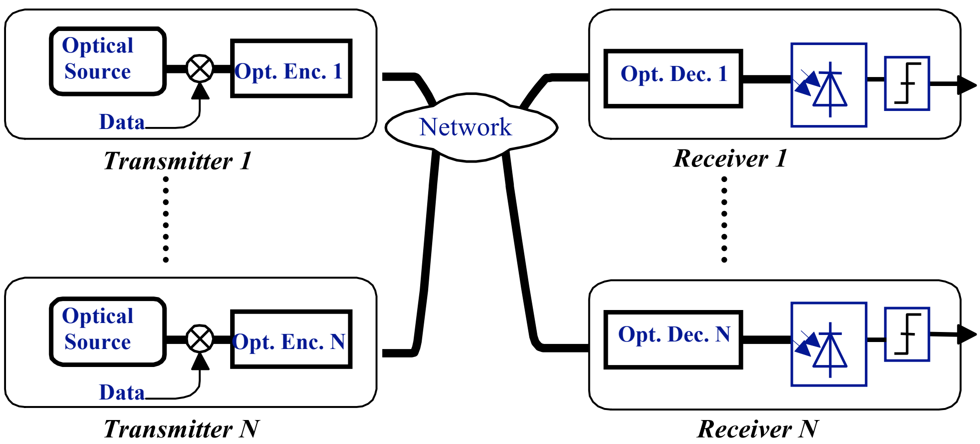

Fig. 1. DS-OCDMA system.

The encoder will temporally slice the incoming optical pulses into several chips where the positions of the chips are determined by the ON–OFF-keying spreading codeword assigned to each transmitter. The encoded pulse trains coming from different users are then combined, amplified and transmitted to the network.

Many optical codes could be implemented using such arrangement. Among them, unipolar codes characterized by 3 parameters (L, w, N) with L the code length, w its weight i.e. number of chips with '1' in the code and N is the multiplexing capacity. In our simulations, we have considered a quadratic detection DS-OCDMA system using PS, QC and EQC codes with $p = 3$, where p is a prime number. The length of PS and QC codes is p^2 while the EQC codes length is $p(2p-1)$.

At the receiver, the incoming data are decoded after removing the time spreading and summing all chip energy into a single pulse. The resulting pulses are converted into electrical signal. A decision circuit compares the received power to a threshold in order to extract the transmitted data.

2.2 Noises

We assume that all noise sources generated at the receiver such as thermal noise, dark current, shot and beat noise are present in the system. In our case, we considered that they are independent Gaussian noises represented by its variances. The thermal noise variance is given by:

$$\sigma_{th}^2 = \frac{4kT}{R} B_e, \tag{1}$$

with k is the Boltzmann's constant, T the temperature, R the electrical impedance and B_e refers to the electrical filter bandwidth.

Let B_o to the optical bandwidth, G to the optical amplifier gain and P_{in} to the optical signal power at the input of the optical amplifier. According to these parameters, the photo-currents generated by the signal and the spontaneous emission at the output of the optical amplifier will be respectively [7]:

$$I_s = RP_{in}, \tag{2}$$

$$I_{sp} = 2n_{sp}(G-1)eB_o, \tag{3}$$

where R is the responsivity of the photodiode, n_{sp} the inversion parameter, e the electron charge. Then the dark current noise variance is expressed as:

$$\sigma_d^2 = 2eI_d B_e. \tag{4}$$

For the shot noise case, the variance is given by:

$$\sigma_{sh}^2 = 2B_e(I_s + I_{sp})e. \tag{5}$$

The beat noise consists of a dc contribution arising from beating between the same optical frequency components and an ac contribution due to beating of different frequency components. To consider this noise generated by square law photo-detection we have to examine two cases [7].

For the coherent DS-OCDMA system, signal-spontaneous beat term (S-Sp) and the spontaneous-spontaneous beat term (Sp-Sp) are considered. The variance of signal-spontaneous beat noise (beating between the signal and the added amplifier spontaneous emissions) is given by:

$$\sigma_{s-sp}^2 = 2GI_s I_{sp} \frac{B_e}{B_o}. \tag{6}$$

The spontaneous-spontaneous beat noise (beating between the spectral components of the added amplifier ASE) is defined as:

$$\sigma_{sp-sp}^2 = \frac{1}{2} I_{sp}^2 \frac{B_e(2B_o - B_e)}{B_o^2}. \tag{7}$$

With the incoherent source, a third noise term, called signal-signal beat noise (S-S), must be included to represent the noise generated by beating of the Amplified Spontaneous Emissions (ASE) signal at different frequencies of the optical bandwidth [7]. The variance of this noise is defined by:

$$\sigma_{s-s}^2 = \frac{1}{2}\left(GI_{sp}\right)^2 \frac{B_e\left(2B_o - B_e\right)}{B_o^2}. \tag{8}$$

2.3 Simulation technique choice

In order to estimate BER performances of a DS-OCDMA system many techniques can be used such as Gaussian Approximation (GA), Monte-Carlo (MC) and Importance Sampling (IS) methods. To simplify the analysis, Gaussian Approximation (GA) is currently used. In fact this technique uses the noises variances to determine the probability of error. However this analysis is only valid if the weight of the codes is important [8].

To avoid the GA’s drawback, we can use Monte-Carlo (MC) technique. It is a statistical technique allowing the modeling of a real digital communication system in order to measure its performances [9]. The principle of the MC technique consists on comparing the emitted and received sequences and counting the number of errors. It achieves realistic estimations of optical communication system performances. However, this technique requires a large number of simulation trials to estimate the BER in a reasonable interval of confidence [10].

The computation of error probabilities via MC simulations require excessively large sample sizes and are not practical for estimating very low values of error probabilities [10], it is possible to use Importance Sampling (IS) method. The IS is a modified MC technique used to determine low probability events without needing a huge number of samples. The main idea of the method is to consider events from tailed regions more frequently [9]. The IS technique consists on modifying the statistics of the Probability Density Function (PDF) of the input random process. Various simulation approaches based on IS techniques have been introduced [9]. Indeed, the modification of the original PDF can be done by increasing the variance. This implementation is known as the Conventional Importance Sampling (CIS). While the Improved Importance Sampling (IIS) technique is based on optimized translations of the mean of the original PDF by a constant which will be chosen in order to minimize the variance of the IS estimator [9]. As the IIS technique become more significant with increasing the system memory size [9], which is not our case, we choose to implement the CIS technique.

2.4 Importance Sampling Validation

The implementation of IS technique, require the choice of the noise source. And then, we have to change its statistics by increasing its variance. In OCDMA system, MAI and beat noise are considered as the main sources of degradation of the performances of the system. As the number of interferers is small, for the case of PS code with small weight (w=3), we cannot implement IS for the MAI.

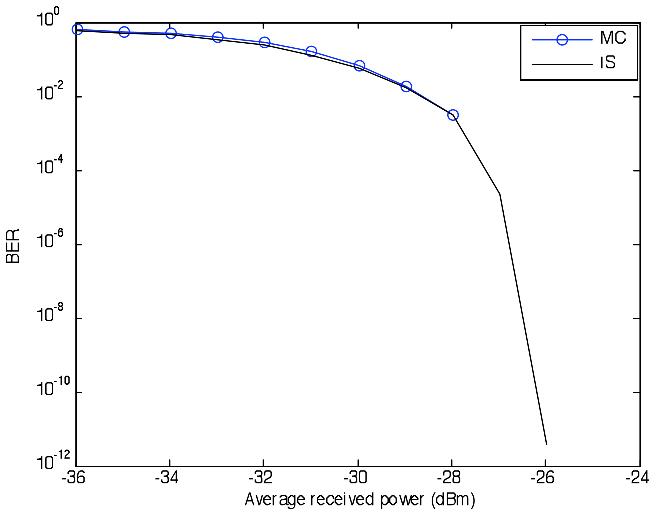

Fig. 2. Validation of Importance Sampling method versus Monte Carlo method for a DS-OCDMA system with PS codes.

Therefore, we have to generate the data of all users including the interferers. Thus, we apply the IS technique for the beat noise. The modified beat noise variance is [9]:

$$\sigma^{*2} = \frac{\sigma_{BN}^{2}}{1-\alpha}, \tag{9}$$

with σ^2_{BN} is the original beat noise variance and α is a IS parameter defined in [11].

To show the advantages of IS method versus MC method, it is possible to evaluate their performances for the same number of samples. Fig. 2 illustrates the BER performances versus the received power for the coherent DS-OCDMA system with the same parameters as above. Simulations result show that with MC simulations, we get a BER around 10^{-3} however IS method reaches a BER lower than 10^{-10}. This demonstrates that results obtained with IS technique are more relevant even with small length of bit sequence. MC technique is unable to deliver higher performances with a small number of samples.

3. PERFORMANCES OF DS-OCDMA SYSTEM

To evaluate the impact of the unipolar codes on the DS-OCDMA system, we will compare three family codes which are PS, QC and EQC codes for coherent and incoherent DS-OCDMA system. Then, we will consider the EQC codes family to study the capacity of multiplexing and the impact of the optical bandwidth of encoders for incoherent DS-OCDMA system.

3.1 Unipolar codes comparison

In our simulations, we have considered a mono-user configuration of DS-OCDMA system. The BER performances for such configuration using the PS, QC and EQC codes at 1.25 Gbps are depicted in Fig. 3. We have used encoders with FWHM bandwidth of 0.4 nm. The electrical filter is 0.7 times the bit rate.

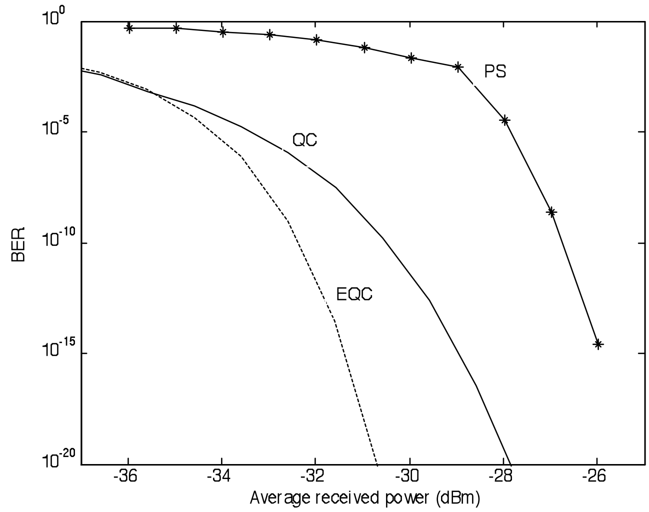

Fig. 3. BER performances of coherent DS-OCDMA system with PS, QC and EQC codes at 1.25Gbps and B_0=0.4 nm.

Firstly, we observe a power penalty of 2 dB at 10^{-10} for the QC as compared to the EQC codes. However, by comparing the EQC and PS codes, this power penalty is equal to 6 dB. Hence, the EQC codes offer better performances than the QC and PS codes for the coherent DS-OCDMA system. This can be explained by the fact that the EQC codes present the best correlation properties. Indeed, the auto and cross-correlation functions have values equal respectively to 1 and 2 for the EQC codes while they are equal respectively to 2 and 4 in the QC case and (p-1) and 2 for the PS codes. The impact of the family codes is clearly shown for the coherent DS-OCDMA system by comparing the three family codes. Then, we suggest evaluating this impact on the performance of the incoherent DS-OCDMA system.

In Fig. 4, we illustrate the BER performances of the incoherent DS-OCDMA system with PS, QC and EQC codes at 2.5 Gbps and B_0=1.6 nm. We depict that for the high-level of received power the incoherent system performances present a BER floor which is due to the beat noise. As for the coherent case, the EQC codes outperform the QC and the PS codes.

By comparing Fig. 3 and Fig. 4, we demonstrate that the coherent DS-OCDMA system offers better performances than the incoherent configuration.

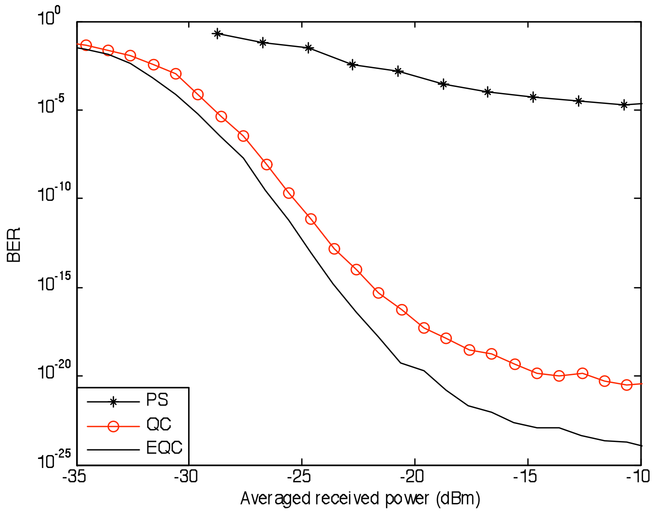

Fig. 4. BER performances of incoherent DS-OCDMA system with PS, QC and EQC codes at 2.5 Gbps and B_0=1.6 nm.

3.2 Multiplexing capacity of EQC codes

Using the EQC codes, we have considered two cases of DS-OCDMA system which are mono and two users. Fig. 5 shows BER performances of coherent DS-OCDMA system at 1.25 Gbps with optical bandwidth 0.4 nm for the single user and the two users' cases. We notice that increasing the number of users leads to decrease the BER performances. In fact, by increasing the number of users, more power is required to get the same value of BER. For the weight p=3, the multiplexing capacity is equal to p-1=2 users. For this case, the simulations results show a power penalty of 2 dB at 10^{-10} between mono and two users' configurations.

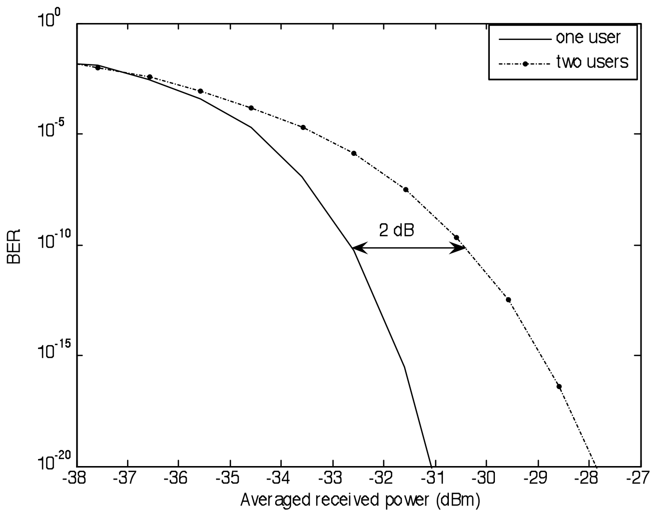

Fig. 5. BER performances of coherent DS-OCDMA system with EQC codes at 1.25 Gbps and B_0=0.4 nm.

This power penalty is explained by the MAI effects on the BER performances. Indeed, the intensity of this noise is proportional to the number of the interferers.

3.3 Impact of optical bandwidth for incoherent DS-OCDMA system using EQC codes

Now, we will consider the impact of encoder optical bandwidth in order to enhance the performances of the incoherent DS-OCDMA system. Fig. 6 gives the BER performances of the laser and the incoherent DS-OCDMA system with EQC codes at 1.25 Gbps. In the incoherent configuration different values of optical bandwidth are used. We notice that for low level of power, the BER performances are the same for both coherent and incoherent system. In fact in this case, the thermal noise is the major contributor [7]. But for higher level of power, coherent system outperforms the incoherent one. Indeed, the BER performances of the incoherent DS-OCDMA system are limited by beat noise due to the signal to signal beat noise caused by incoherent optical sources.

In addition, we demonstrate that increasing the optical bandwidth and maintaining the electrical bandwidth leads to increasing the performances of the system. We notice that even the incoherent source present a limitation at the higher received power caused by the beat noise, we get acceptable performances. For example, at B_0=0.8 nm, the BER is around 10^{-9} and if we increase this parameter the system performance can be more improved. The incoherent source presents a lower cost than the coherent one and it can also shared over many users. That's why, it is important to use this optical source and control the effect of the beat noise on such system configuration.

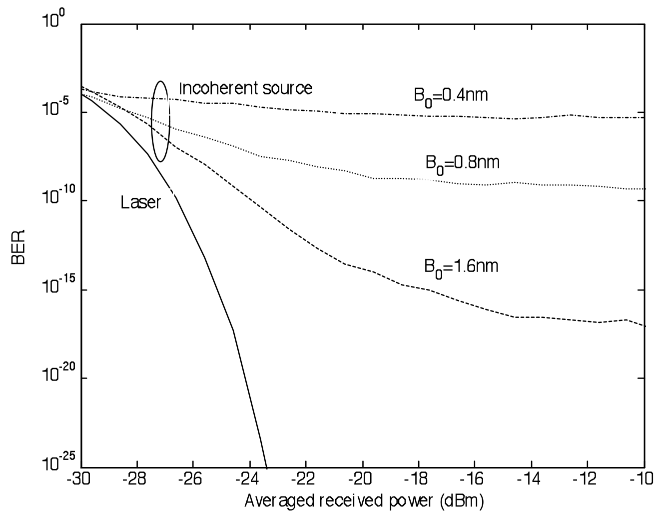

Fig. 6. BER performances of DS-OCDMA system with EQC codes at 1.25 Gbps for different optical bandwidth.

4. CONCLUSION

In this work, we have presented the direct detection DS-OCDMA system using three unipolar family codes PS, QC and EQC codes. Taking in consideration all receiver noises, we have evaluated the BER performances by implementing the Importance Sampling technique. The comparison of the three family codes, we have demonstrated that using EQC codes, both coherent and incoherent system offer better performances than with PS and QC codes. For the incoherent system, we show that the performance is limited by BER floor caused by the Beat Noise. With such system, we get acceptable performances even with the presence of a BER floor. Therefore, we need to optimize the ratio between optical and electrical bandwidth to overcome this limitation. Indeed, the incoherent source such as the spectrum-sliced source is more economical than the coherent one and it can be shared over many users.

REFERENCES

[1] Salehi J.A. "Code Division Multiple-Access Techniques in Optical Fiber Networks-Part I: Fundamental Principles," IEEE Trans. (37), 824-833 (1989).

[2] Prucnal P.R., Santoro M.A. and Fan T.R, "Spread Spectrum Fiber-Optic Local Area Network Using Optical Processing," J. Lightwave. Technol. 4(5), 547-554 (1986).

[3] Kavehrad M. and Zaccarin D., “Optical code-division-multiplexed systems based on spectral encoding of noncoherent sources,” J. Lightwave Technol. (13), 534-545 (1995).

[4] Fathallah H., Rusch L. A., "Robust Optical FFH-CDMA Communications: Coding in Place of Frequency and Temperature Controls," J. Lightwave Technol. 17(8), 1284-1293 (1999).

[5] Zhang, J.-G., Picchi, G., "Tunable prime-code encoder/decoder for all-optical CDMA applications," Elec. Lett. 29(13), 1211-1212 (1993).

[6] Fsaifes I., Lepers C., Lourdiane M., Gallion P., V. Beugin et P. Guignard, "Source coherence impairments in a direct detection direct sequence optical code division multiple access system," App. Opt. 46(4), 456-462 (2007).

[7] Mathlouthi W., Menif M., and Rusch L. A., "Beat noise effects on spectrum-sliced WDM," Proc. SPIE 5260, 44-54 (2003).

[8] Chen J. and Yang G., "CDMA Fiber-Optic Systems with Optical Hard Limiters," J. Lightwave Technol. 19(7), 950-958 (2001).

[9] Lu D. and Yao K., "Improved Importance sampling technique for efficient simulation of digital communication systems," IEEE Selected Areas in com. 6(1), 67-75 (1988).

[10] Mandayam N. B. and Aazhang B., "Importance Sampling for analysis of direct detection optical communications systems," IEEE Trans. 43(2/3/4), 229-239 (1995).

[11] Farhat A., Menif M., Lepers C., Rezig H., Gallion P., "Performance Comparison of Coherent versus Incoherent Direct Sequence Optical Code Division Multiple Access System," Proc. SPIE 7099, paper PDS -3-6-2, (2008).