Importance Sampling Applied to An Optical DS-CDMA System

Amel Farhat^{1,4}, Mourad Menif², Catherine Lepers³, Houria Rezig¹, Philippe Gallion⁴

^{1.} Ecole Nationale d'Ingénieurs de Tunis, SysCom, BP 37, Le Belvédère, 1012, Tunisie.

² Ecole Supérieure des Communications, CIRTACOM, Cité Technologique des Communications, El Ghazala, 2083, Tunisie.
³ Laboratoire PhLAM, CNRS UMR 8523, Université de Lille I, 59650 Villeneuve d'Ascq, France.

^{4.} Ecole Nationale Supérieure des Télécommunications (GET Télécom Paris), 46 Rue Barrault 75013 Paris, France.

(farhat@enst.fr, mourad.mnif@supcom.rnu.tn, lepers@enst.fr, houria.rezig@enit.rnu.tn, gallion@enst.fr)

Abstract—In this paper, we evaluate the performances of a Direct-Sequence Optical Code Division Multiple Access (DS-OCDMA) system. We estimate the bit error rate (BER) of the system using Importance Sampling (IS) technique by taking into account multiple access interferences (MAI) and noises from the receiver. Conventional Monte-Carlo method uses a great number of samples to derive BER evaluation but only a very small fraction of them contributes to error determination. By using IS method, we increase artificially the number of errors by biasing the input distribution, and therefore it is possible to reduce the number of simulations required for BER estimation. We validate the IS method and demonstrate a BER agreement between simulation results and experiments.

I. INTRODUCTION

Optical Code Division Multiple Access (OCDMA) systems are one potential solution to multiple access in alloptical communication networks [1]. Indeed, OCDMA technique has many advantages as compared to Time Division Multiple Access (TDMA) and Wavelength Division Multiple Access (WDMA) solutions. 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. In addition to random and simultaneous access capability, OCDMA technique offers robust information security which represents a serious request for the end-users. In fact only the authorized receiver will be able to receive the emitted signal by using appropriate codeword and corresponding hardware.

OCDMA systems can be classified as coherent or incoherent depending on the detection process. In coherent systems, the electrical field of the light pulses must be taken into account. Higher BER performances may be potentially achieved in such systems but high-precision control of the optical path within the encoder and decoder is required [2]. Incoherent systems are considered as more practical because the light sources and the encoding/decoding techniques have lower complexity and cost [3].

For such systems, sources like incoherent broadband sources (LED, ASE from EDFA and SOA, etc...) and coherent sources (SCL, MLL, etc...) and lately Supercontinuum sources have been used. In OCDMA systems, many technologies for encoding/decoding process including Fiber Optic Delay Line (FODL), Fiber Bragg Gratings (FBG) have been considered. The coding can be 1dimensional using time domain or frequency domain or 2dimensional using frequency and time domains simultaneously. Direct Sequence (DS) [1], Frequency Encoding (FE) [4] and Fast-Frequency Hopping (FFH) [5] OCDMA solutions have been studied.

In order to achieve an experimental setup, all those parameters and others such as Multiple Access Interferences (MAI) and noises from receiver have also to be considered. In this case, it is suitable to optimize the system parameters through simulations. Many simulation techniques could be used to determine system performances such as Gaussian Approximation (GA) and Monte-Carlo technique (MC). The last technique is a statistical method allowing the modeling of a real system in order to measure its performances. To obtain good performances, i.e. to achieve a low Bit Error Rate (BER), MC method requires a large number of samples corresponding to a huge calculation time. To decrease the number of simulations involved in BER simulation, it is possible to increase the number of errors in an invertible way by biasing the input distribution. Implementations known as Conventional Importance Sampling (CIS) or Improved Importance Sampling (IIS) are customarily used [6]. In [7], a special class of biased distributions based on large deviations theory was applied to simulate optical communication systems. IIS is more interesting over CIS when the system memory size increases [8].

In Section 2 of the paper, the DS-OCDMA system is presented. Section 3 presents and compares the Monte-Carlo and Importance Sampling techniques. In section 4, we show and comment simulation results in order to evaluate the performance of DS-OCDMA. Finally, conclusions are given in section 5.

II. DS-OCDMA SYSTEM

A block diagram of the considered DS-OCDMA system is shown in Fig. 1. At the transmitter, a short light pulse of 50 ps at the data repetition rate, is generated by an integrated laser/electro-absorption modulator (ILM) representing the chip time (T_c). The generated pulses are modulated afterward by the information data of each user and converted into a chip sequence by injection in the encoder, composed by a series of Fiber Bragg gratings (FBG) separated by sections of optical fiber with variable length, through a three-port circulator.



Figure 1. Block diagram of a DS-OCDMA system.

The FBGs will temporally slice the incoming optical signal into a pulse train where the positions of the pulses are determined by the spreading codeword assigned to each transmitter. To get the same reflected power from the different FBGs, each one will presents a different reflection rate, to compensate the incident wave depletion during its propagation through the FBGs [9]. The reflected pulse trains coming from different users are combined and transmitted through the network to the receivers.

Many optical codes could be been implemented using a such arrangement. Unipolar codes composed with '0' and '1' are largely used. An optical code is characterized by 3 parameters (L, ω, N) with L the length of code, ω its weight i.e. number of chips with '1' in the code and N is the capacity of multiplexing. The Prime Sequence (PS) codes have been shown to be significantly shorter codes than Optical Orthogonal Codes (OOC) [9]. Moreover, the use of non periodic Quadratic Codes (QC) and Extended Quadratic Codes (EQC) sparser and longer than PS shown that the shape of the auto-correlation function is less sensitive to interferometric effects than the PS codes [10].

Basically, the function of the receiver is to detect the presence of the pulse train from the desired transmitter and rejects the MAI contribution coming from other users. The decoder removes the time spreading of the pulse train and gathers all chip energy into a single pulse. More details on the experimental setup are reported in [10].

III. MONTE-CARLO/IMPORTANCE SAMPLING TECHNIQUES

Monte Carlo technique is a statistical technique allowing the modeling of a real system in order to measure its performances [11]. After encoding/decoding process, the binary data pass through a block decision and then the emitted and received sequences are compared. The simulation MC counts the number of errors. These simulations require a large number of samples to do BER estimation becoming a huge one to estimate very low values of error probability [8].

A. Principe

To do simulations more efficiently, it is possible to use CIS. The IS is a modified Monte Carlo technique used in simulation to determine low probability events without needing a huge number of samples [8]. The main idea of the method is to consider the events from important regions more frequently [8] [11]. Let

$$X_k = D_k + N_k,\tag{1}$$

with binary data D has equal probability of $\{0,1\}$ and the total Gaussian noise N with zero mean and variance σ^2 .

If D=0, then X is a Gaussian random variable of zero mean and variance σ^2 . The aim of IS is obtained by modifying the probability density function f of the input random process. The new PDF f^* is a Gaussian PDF with a zero mean and a new variance defined by [8]:

$$\sigma^{*2} = \frac{\sigma^2}{1 - \alpha} \tag{2}$$

For $0 \le \alpha < 1$, we note a variance increasing of the random variables *X**(as shown figure 2) so:

$$\sigma^{*2} > \sigma^2 \tag{3}$$

The modification in the distribution is later corrected by weighting the samples. The CIS weights are defined as the likelihood ratio [8]:

$$\omega_{CIS}(x) = \frac{f(x)}{f^*(x)} = \left(\frac{\sigma^*}{\sigma}\right) \exp\left[-\left(1 - \frac{\sigma^{*2}}{\sigma^2}\right)\left(\frac{x^2}{2\sigma^2}\right)\right], \quad (4)$$

B. Noises

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

$$\sigma_{ih} = \frac{4kT}{R} \tag{5}$$

k is the Boltzmann constant, T the temperature and R the resistance.

Let B_e refers to the electrical filter bandwidth, 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 [12]:

$$I_s = RP_{in},\tag{6}$$

$$I_{sp} = 2n_{sp}(G-1)eB_o, \tag{7}$$

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

$$\sigma_d = 2eI_d B_e, \tag{8}$$

The variance of signal-spontaneous beat noise (beating between the signal and the added amplifier spontaneous emissions) is given by:

$$\sigma_{s-sp} = 2GI_s I_{sp} \frac{B_e}{B_o},\tag{9}$$

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

$$\sigma_{sp-sp} = \frac{1}{2} I_{sp}^2 \frac{B_e(2B_o - B_e)}{B_o^2},$$
 (10)

The shot noise variance is given by:

$$\sigma_{sh} = 2B_e(I_s + I_{sp})e, \qquad (11)$$

The MAI and the beat noise are usually considered as the main degradation in OCDMA system [10]. In our application we choose to bias the beat noise (BN) and in the future we have to consider the MAI by determining its distribution. So the new variance of the BN is given by:

$$\sigma^* = \frac{\sigma_{BN}}{1 - \alpha},\tag{12}$$

$$\sigma_{BN} = \sigma_{sp-sp} + \sigma_{s-sp}, \qquad (13)$$

IV. SIMULATION AND RESULTS

We have considered a DS-OCDMA system with three different transmission rates: 1, 1.25 and 2.5 Gbps. The system uses two family of codes PS and EQC with the same weight (p = 3) where p is a prime number. For the PS codes, the length code will be $L=p^2$ whereas and with the same

weight, the EQC codes have a length L=p(2p-1). The FBGs used to implement the encoders/decoders are uniform with different reflectivity rate [10] and having a Full-Width at Half Maximum (FWHM) bandwidth $\Delta\lambda=1.6$ nm representing the optical bandwidth B_o used on our simulation.

We applied the CIS technique to the beat noise as mentioned before. We have considered a random sequence of only 1000 bits due to the gain achievable by considering the Importance Sampling techniques [8]. Indeed, we are able to reach a BER lower than 10^{-9} which is not possible to get with MC. We have chosen α equal to 0.6 in order to optimize the BER curves.



Figure 2. BER performances of the desired user with PS codes at various transmission rates in presense of one interferer.

Fig. 3 presents the results of simulations for a DS-OCDMA system using a PS codes for the three transmission rates (1 Gb/s, 1.25 Gb/s and 2.5 Gb/s) and compared with the experimental results obtained in [10] where only one interferer is active. We observe, with increasing the bit rate, the presence of a power penalty in the simulation results caused by a constant decoding duration as the bit duration decay with increasing the bit rate. The same phenomena are observed in the experimental curves with 'o' mark.

Fig. 3 depicts some discrepancy between simulation and experimental results (~1 dB for 1 Gb/s at 10^{-10}). This could be explained by the fact that we did not consider the multipath beat noise MBN related to the design of the encoder/decoder together with the coherence of the system. So the received pulses at the detector may beat together within a chip-time duration giving rise to MBN [10].



Figure 3. BER performances of the desired user with EQC codes at various transmission rates in mono-user configuration.



Figure 4. BER performances of the desired user for PS and EQC codes in with one interferer at 1Gb/s.

Fig. 4 shows the BER performances obtained through simulations and compared with experimental results for the mono-user configuration with EQC codes at different bit rates. We observe the same behavior, as in PS case, concerning the power penalty induced by raising the bit rate.

In order to compare the performance achieved by the two family codes (PS and EQC), we illustrate in Fig. 5 the obtained BER curves with 1 Gb/s rate transmission. The use of a non periodic EQC codes, longer than PS, gives an improvement in the BER performance due to the fact that EQC codes are less sensitive to MAI noise.

V. CONCLUSIONS

We evaluated the performance achievable by a DS-OCDMA system by applying Importance Sampling method. We used two family codes (PS and EQC) with the same weight. The results clearly demonstrates the importance of IS approach able to give us with only 1000 bits a BER estimation closely to the experimental results given in [10]. For the future, we have to include the multipath beat noise by taking into account the variable length separating the different FBGs and causing the phase fluctuation of the signal.

REFERENCES

- J.A. Salehi, "Code Division Multiple-Access Techniques in Optical Fiber Networks-Part I: Fundamental Principles," IEEE Trans., vol. 37, pp. 824-833, August 1989.
- [2] N. Karafolas and D. Uttamchandani, "Optical fiber code division multiple access networks: A review," Opt. Fiber Technol., vol. 2, pp.149–168, April 1996.
- [3] B. Ni and J. S. Lehnert, "Performance of an Incoherent Temporal-Spreading OCDMA System With Broadband Light Source," Journal Lightwave Technol., vol. 23, pp. 2206-2214, July 2005.
- [4] M. Kavehrad and D. Zaccarin, "Optical code-division-multiplexed systems based on spectral encoding of noncoherent sources," Journal Lightwave Technol., vol. 13, pp. 534-545, March 1995.
- [5] H. Fathallah, L. A. Rusch, "Robust Optical FFH-CDMA Communications: Coding in Place of Frequency and Temperature Controls," Journal Lightwave Technol., vol. 17, pp. 1284-1293, August 1999.
- [6] M.C. Jeruchim, P. Balaban and K. S. Shanmugan, Estimating the error probability of a digital system from Simulation of communication systems, Plenum Press, New York, 1992 section 5.6, pp. 492–531.
- [7] K. Ben Letaief, "Performance analysis of digital lightwave systems using efficient computer simulation techniques," IEEE Trans., vol. 43, pp. 240–251, 1995.
- [8] D. Lu and K. Yao, "Improved Importance sampling technique for efficient simulation of digital communication systems," IEEE Selected Areas in communication, vol. 6, pp.67-75, January 1988.
- [9] E.S. Shivaleela, K.N. Sivarajan and A. Selvarajan, "Design of a new family of two dimensional codes for fiber optic CDMA networks," Journal Lightwave Technol., vol. 16, pp.501-508, April 1998.
- [10] I. Fsaifes, C. Lepers, M. Lourdiane, P. Gallion, V. Beugin et P. Guignard, "Source coherence impairments in a direct detection direct sequence optical code division multiple access system," Appl. Opt., vol. 46, pp. 456-462, 2007.
- [11] K.S. Shanmugam and P. Balaban, "Modified Monte Carlo simulation technique for the evaluation of error rate in digital communication," IEEE Trans., vol. 28, pp.1916-1924, November 1980.
- [12] W. Mathlouthi, M. Menif, and L. A. Rusch "Beat noise effects on spectrum-sliced WDM," Proceedings of SPIE, vol.5260, pp. 44-54, December 2003.