Performance improvements of a VLC system, in a V2X context, using a different multiplexing technique

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ABSTRACT

This paper scrutinizes visible light communication (VLC) employing hybrid optical time division multiplexing (OTDM) wavelength division multiplexing (WDM). It also demonstrates the simulation of VLC using the direct sequence optical code division multiple access (DS-OCDMA) system developed by OptiSystem-Matlab Co-simulation. The profits of WDM and OTDM capacities have been combined using two levels of freedom to build up of the system. The performances are demonstrated in the simulated findings of the bit error rate (BER) in relationship with the data rate and the number of users. First, the simulated results display the usefulness of the system. Then, the number of users has been significantly enhanced. Besides, the OCDMA functions by appointing a specific code to each user and could provide asynchronous and simultaneous access to numerous users. One drawback is multiple access interference (MAI). The use of very long code sequences is crucial in order to lessen this effect. Hence, very large bandwidths are essential. This study aims at demonstrating, through system simulation, the practicability of an all-optical conventional correlation receiver dedicated to a DS-OCDMA access network link. Again, OptiSystem has been used to realize our blocks.

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1. INTRODUCTION

With the rapid expansion of smartphones, the radio frequency (RF) spectrum becomes a limited resource. Recently, much attention has been paid to visible light communication (VLC) as a new generation of wireless technology [1]. Our technology can utilize installed lighting infrastructure to serve both communication and lighting tasks simultaneously. In these systems, where the transmitters operate using light-emitting diodes (LEDs), data is sent by alternating the turning on and off of the light at a high rate. The communication channels of VLC systems are line-of-sight (LOS) links and broadcast lines. We find the photodetectors at the receivers to capture the data from the optical signal sent [2], [3].

Comparing it with conventional RF, the bandwidth used in the VLC is approximately 300 THz, much more remarkable than the RF, and licensing is not needed for VLC. Furthermore, VLC is safer as compared to RF communications since non-transparent objects, like walls, cannot be breached by the lights included in visible light communication. This sort of communication utilizes different frequency bands compared to RF. Hence, electromagnetic interference can’t be attained with classical communications. In this sense, it could be of great benefit if used in prohibited areas, such as hospitals and airports, which are highly affected by electromagnetic interference or security matters [4]. Additionally, VLC is rather not harmful to humans versus RF communications and provides a higher data rate connection. Having demonstrated the numerous benefits of VLC, it also has challenges, which must be considered before proceeding to large-scale applications. In external applications like vehicle-to-everything (V2X) systems, there are many challenges for the channel, as controlling the environmental conditions is difficult [5].

For VLC to function in these circumstances, they must use strong modulation with dynamic access. In most cases, like conference rooms and malls, the transmission of signals from multiple users at the same time is essential. Hence, there shall be a need to identify the most adequate multiple access methods for VLC. Meanwhile, outdoors environments within VLC communications may cause high multipath interferences, which must be adequately eased. Also, the multi-user interference (MUI) in VLC must be eliminated at the receiver. To solve the above issues, we shall investigate the ability of wavelength division multiplexing-visible light communication (WDM-VLC) with an red-green-blue-amber (RGBA) LED to support optical time-division multiplexing (OTDM) multiplexing. An OTDMA/WDM-VLC model using the RGBA LED transmitters is hence recommended. We study a four-wavelength operation with data transmission over red (675 nm), green (525 nm), blue (450 nm), and amber (589 nm). These LEDs are supplied with OTDM user data. Accordingly, code division multiple access (CDMA) technology has considered another cost-effective technique that is mostly utilized in VLC systems, in this study called VLC-CDMA.

VLC-CDMA offers many benefits compared to traditional CDMA. Signature code design is extremely crucial for CDMA communications. Therefore, optical orthogonal codes (OOC) are studied in this work to deliver multiple simultaneous access in a multi-user network.

2. METHOD

2.1. Vehicle-to-everything communication

V2X or vehicle to everything communication refers to a communication system among vehicles that allows the exchange of information from a vehicle to moving parts of the traffic system that might affect that vehicle. This communication system aims at ameliorating road safety, traffic issues, and energy saving on the roads [6]. Connected vehicles are rapidly gaining traction, primarily due to their cost effectiveness and convenience. However, few are aware of the potential for these vehicles to make driving safer and much more efficient by communicating directly with other vehicles, infrastructure and the cloud.

2.2. DS-OCDMA

Optical direct sequence optical code division multiple access system (DS-OCDMA) is a system where each user operates an on/off keying (OOK) modulation to send separate and equally probable binary data via an optical channel (Figure 1). The encoder impresses a sequence code on the binary data. The sequence code is attributed to each user in order to withdraw the data at the receiver level: the received signal will be contrasted with the sequence code to recover the data [7], [8].

Numerus unipolar orthogonal codes and their application on OCDMA have been studied since 1988. Two categories of those codes have attracted the most attention: OOC and prime codes (PC) [9], [10]. Optical orthogonal codes, described by [11], possess better properties of auto and inter-correlation than prime codes, as they require complex algorithms to generate [11]. Whatever the used code, the OCDMA system performances still depend on the compromise between the number of code sequences available and the correlation properties. The performances have been enhanced thanks to the different variants of OOC and PC that have been developed during recent decades. In our study, we have chosen OOC [12].

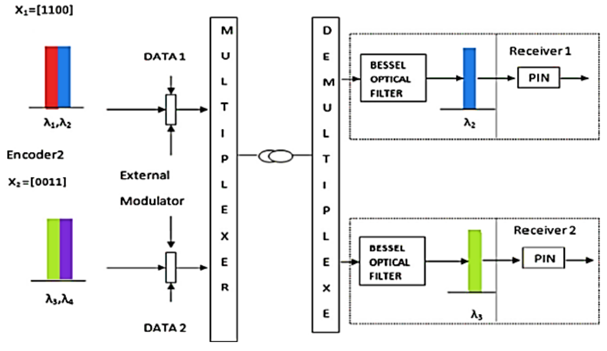

Figure 1. Architecture of a DS-OCDMA system

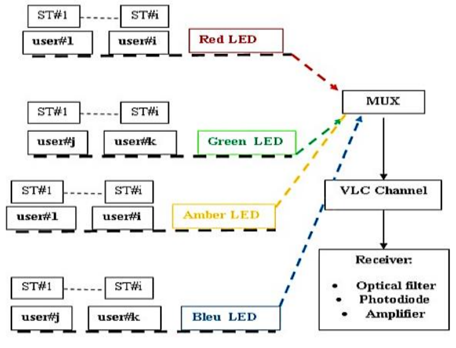

Figure 2. The hybrid OTDM/WDM VLC system

2.2.1. The optical orthogonal codes

For low multiple access interference (MAI) and error probability, the chosen codes must have good correlation characteristics. We consider OOC in this work [13]. A class of codes is defined by $(F, W, \lambda_a, \lambda_c)$ where F is the sequence length and W is the weight. λ_a and λ_c are the auto and cross-correlation constraints which we considered equal to one in this study. The maximum number of user's N in the OOC class is defined as:

$$N = \frac{(F-1)}{W(W-1)} \tag{1}$$

2.3. Outdoor VLC system

The hybrid OTDM/WDM VLC topology is made of N users (Figure 2). They are divided into "K" WDM groups. Within each group, N_i users share one wavelength in a time-division multiplexing (TDM) manner. Each wavelength of the WDM system will send a signal to TDM active users. The totality of users in the hybrid system is:

$$N = \sum N_i \tag{2}$$

In this work, the visible light band is separated into several communication channels using various single-color LEDs [14]. The light produced by all transmitters will be blended into white, or other defined colors in free space and reach the receiver after traveling a certain distance. At the receiver level, the corresponding detectors for each channel are used to detect signals of specific wavelengths through limited band-pass filters. In our proposed system, according to Figure 3, the example of the visible light channel used is the line of side channel model. The accepted optical power from the LED source can be defined as by:

$$P_r = h(0)P_i \tag{3}$$

Where:
- $h(0)$: is the channel DC gain
- P_i: is the transmitted optical power

In order to model as devotedly as possible, the VLC channel, we should correspondingly include the ambient light noise with the line of side channel model. The receiver noise is mainly considered by the particularities of the photo-detector and the electric pre-amplifier [15]. It is composed of several sources:
- The shot noise: it emerges from the statistical nature of the generation and collection of photoelectrons if an optical signal is an incident on a photo-detector.
- The thermal noise: it is introduced by the receiver circuit.
- The dark current noise: the photodiode dark current I_D is the current that continues to flow through the bias circuit of the device when no light is incident on the photodiode [16]. It arises from electrons and/or holes that are thermally generated in the PN junction of the photodiode:

$$\langle i_D^2 \rangle = 2qI_D\Delta f \tag{4}$$

2.4. The hybrid OTDM/WDM VLC system

The design establishment is shown in Figure 3. Concerning WDM, we can introduce N_i users by assigning each of them a time slot (TS) OTDMA (Figure 4). Each wavelength of the WDM system will send a signal for OTDMA mode active users [17]. The whole number of users in the hybrid system can be expressed as:

$$S_j = \sum_{n=1}^{N_i^{\lambda_j}} \sum_{k=-\infty}^{+\infty} a_k^{n_{\lambda_j}} P(t-(n-1)T_s - kT) \cos\left(\frac{2\pi c}{\lambda_j} t\right) \tag{5}$$

Where:
- $P(t)$ denotes a RZ-OOK pulse with a T_s duration.
- $a_k^{n_{\lambda_j}}$ is the k^{th} data bit of the n^{th} user transmitting on the wavelength λ_j and T_s is the time slot corresponding to n^{th} user.

At the output of the multiplexer, the total transmitted signal $S(t)$ is given by the following on the (6).

$$S(t) = \sum_i S_{k_i}(t) = \sum_i \sum_{k=1}^{N} b_k(t).c_k(t) \cos\left(\frac{2\pi c}{\lambda_i} t\right) \tag{6}$$

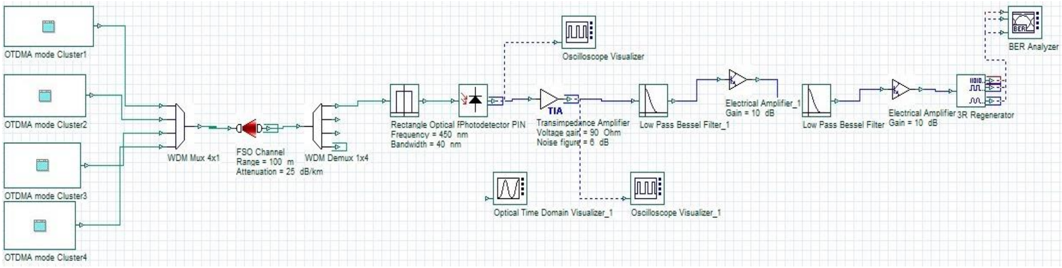

Figure 3. Simulation of the proposed OTDMA/WDM-VLC system using RZ-OOK modulation

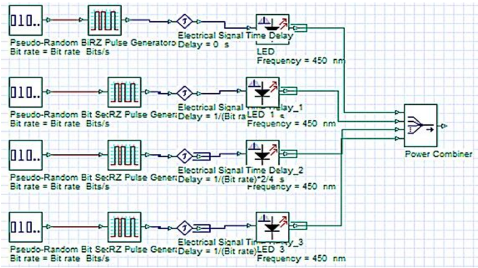

Figure 4. Block of four users OTDMA

2.5. The DS-OCDMA/VLC system

In this system (Figure 5), we have used the OOC that is developed by a Matlab block in co-simulation with OptiSystem in order to simulate the usefulness of the DS-OCDMA/VLC system for communication (V2X). The aim is to achieve the sequence codes corresponding to each user and apply them simultaneously in the OptiSystem system simulator by Matlab [18]. The coded data of each user will be synchronously transmitted in a single color by means of LEDs. The free space between the two ends represents the transmission channel, where the colors shall be united. At the receiver end, we can detect the data of the desired user that utilizes a conventional correlation receiver (CCR). In what follows we shall determine the different blocks the system is made of.

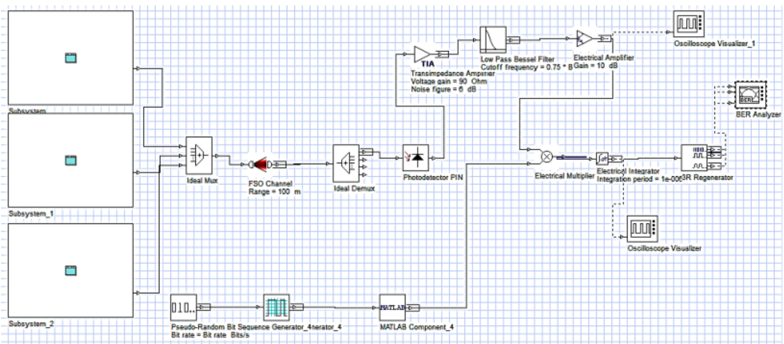

Figure 5. The proposed system for DS-OCDMA/VLC

2.5.1. Transmitter

At the level of the transmitter, the OOC codes that represent the user's signatures are generated by Matlab blocks. The code family (64.4.1.1) used in this simulation bears five users. Our proposed system depends on grouping N users, each sharing a wavelength, after having undergone an non return to zero (NRZ) coding [18]. The encoded data shall be transmitted by LEDs of different colors. The lights generated by the LEDs will be spread into the free space, which is the transmission channel in this case [19]. The transmitted signal $S_{k_i}(t)$ at the input of each cluster shown in Figure 6, can be expressed by:

$$S_{k_i}(t) = \sum_{k=1}^{N} b_k(t).c_k(t) \cos\left(\frac{2\pi c}{\lambda_i} t\right) \tag{7}$$

Where:

- $b_k(t) = \sum_{i=-\infty}^{+\infty} b_i^{(k)} P_{T_b}(t - iT_b)$ denotes the data of user k.
- $b_i^{(k)}$: is the i^{th} data bit of the k^{th}user. it takes the values 0 or 1.
- $c_k(t) = \sum_{j=-\infty}^{\infty} c_j^{(k)} P_{T_c}(t - jT_c)$ is the code sequence of user k that represents the signature of each user. This makes it easy to distinguish the desired user from other users.
- At the output of the multiplexer, the total transmitted signal $S(t)$ is given by the following on the (8).

$$S(t) = \sum_i S_{k_i}(t) = \sum_i \sum_{k=1}^{N} b_k(t).c_k(t) \cos\left(\frac{2\pi c}{\lambda_i} t\right) \quad (8)$$

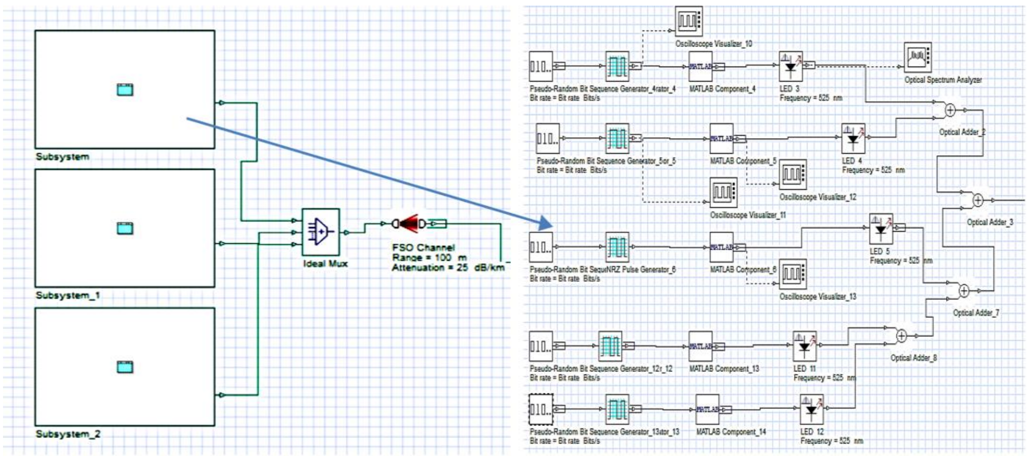

Figure 6. Transmitter bloc VLC

2.6. Receiver

2.6.1. The photodiode

There are various techniques available for converting an optical signal into electrical ones [20]. In the study at hand, we use a rather direct detection method by the means of a component called photodiode, which might be either photodiode intrinsic negative (PIN) or avalanche photodiode (PDA). We utilize a PIN diode model available at OptiSystem libraries. The characteristics of the photodiode are displayed in the Table 1.

Table 1. Characteristics of the photodiode

Name	Value	Units
Responsivity	0.22	A/W
Dark current	10	nA

At the block output, the expression of the electrical current detected is:

$$i(t) = i_s(t) + i_{th}(t) + i_d + i_{sh}(t) \quad (9)$$

- $i_s(t) = r.P_s(t)$: is the optical signal calculated from the responsivity r.
- $i_{th}(t)$: is the thermal noise current calculated from the power spectral density defined by the parameter thermal noise.
- i_d: is the dark current.
- The shot noise current $i_{sh}(t)$ is calculated according to the power spectral density.

2.6.2. Reception concept

At the level of the receiver, the photodiode detects the light emitted by the transmitter and converts the signal from optical to electrical, which necessitates amplification and filtering for the conditioning [21]. The received signal is correlated with the code of the targeted user. At this level, an integrator (Figure 7), reformats the multiplier output signal to calculate the total power per bit. The decision variable is presented by the output signal. Then, in order to make the estimated data, the decision variable will be compared with the value of the threshold S of the decision-making.

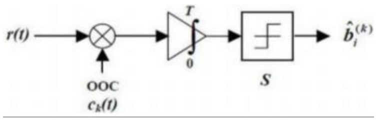

Figure 7. The conventional correlation receiver

At the output of the integration block, we shall obtain the decision variable value $Z_1^{(i)}$ for the i^{th} data bit of the desired user [22]:

$$Z_1^{(i)} = \int_0^{T_b} b_i^{(1)}.c_1(t)dt + \sum_{k=2}^{N} b_i^{(k)} \int_0^{T_b} c_k(t).c_1(t)dt == W.b_i^{(1)} + \sum_{k=2}^{N} b_i^{(k)} \int_0^{T_b} c_k(t).c_1(t)dt \quad (10)$$

The second concept in (12) represents the interference due to other users (IAM): its value depends simultaneously on all the emitted data $b_i^{(k)}$ of undesired users as well as on the inter-correlation among the desired users' codes $c_1(t)$ and those of undesired users $c_k(t)$ [23]. If the targeted user sends a data bit $b_i^{(1)} = 1$, the decision variable $Z_1^{(i)} = W + I_1$ with:

$$I_1 = \sum_{k=2}^{N} b_i^{(k)} \int_0^{T_b} c_k(t).c_1(t)dt \quad (11)$$

The IAM concept I_1 takes any positive or equal to zero value depending on the data of the other users $b_i^{(k)}$ and that of the inter-correlation $\int_0^{T_b} c_k(t).c_1(t)dt$. In that case, we can come to the conclusion that: $Z_1^{(i)} \geq W$ taking an encoding rule such as:

$$\begin{cases} \text{if } Z_1^{(i)} \geq S \Rightarrow \hat{b}_i^{(1)} = 1 \\ \text{if } Z_1^{(i)} < S \Rightarrow \hat{b}_i^{(1)} = 0 \end{cases} \quad (12)$$

– We cannot make a decision error over $\hat{b}_i^{(1)}$ when $\hat{b}_i^{(1)} = 1$ if we have $W \geq S$.
– If the user sends a data bit $\hat{b}_i^{(1)} = 0$ the decision variable $Z_1^{(i)} = I_1 \geq 0$.

According to the encoding rule (12), we can in that case make an error in $\hat{b}_i^{(1)}$ if $Z_i^{(1)} = I_1 \geq S$. As S is limited to the maximum by the weight W, we can deduce that the optimal conventional receiver threshold is $S = W$ [24], [25].

We consider that the degradation of a user's performance is only due to MAI. The data transmission is equiprobable:

$$P_e = \frac{1}{2} prob\left(\hat{b}_i^{(1)} = \frac{0}{\hat{b}_i^{(1)}} = 1\right) + \frac{1}{2} prob\left(\hat{b}_i^{(1)} = \frac{1}{\hat{b}_i^{(1)}} = 0\right) \quad (13)$$

$\hat{b}_i^{(1)}$ is the i^{th} data bit of the desired user. According to the previously defined encoding rule (14), we can write:

$$P_e = \frac{1}{2} prob\left(Z_1^{(i)} < \frac{S}{\hat{b}_i^{(1)}} = 1\right) + \frac{1}{2} prob\left(Z_1^{(i)} \geq \frac{S}{\hat{b}_i^{(1)}} = 0\right) \quad (14)$$

The decision variable $Z_1^{(i)}$ is defined as:

$$Z_1^{(i)} = W.\hat{b}_i^{(1)} + I_1 \quad (15)$$

Where I_1 represents the interference concept:

$$I_1 = \sum_{k=2}^{N} b_i^{(k)} \int_0^{T_b} c_k(t).c_1(t)dt \quad (16)$$

So:

$$P_e = \frac{1}{2} prob(W + I_1 < S) + \frac{1}{2} prob(I_1 \geq S) \quad (17)$$

The optimal threshold of a comparator corresponds to: $S = W$.

Which means that the interference concept I_1 is the summation of $(N-1)$ random variables identically distributed $I_k^{(1)}$ such as :

$$I_k^{(1)} = b_i^{(k)} \int_0^{T_b} c_k(t).c_1(t)dt \tag{18}$$

- Concerning OOC codes, $(L, W, 1,1)$ the concept $I_k^{(1)}$ may not take but two values: 0 or 1.
- Thus, the concept I_1 may take values between 0 and $(N-1)$.
- In that case: $prob(W + I_1 < S) = 0$ even if $S = W$.
- So, the error probability calculation is reduced to: $P_e = \frac{1}{2} prob(I_1 \geq S)$.

The OOC codes $c_k(t)$ and $c_1(t)$ of a length L contain W chips of 1. So the probability that:

$$\int_0^{T_b} c_k(t).c_1(t)dt = 1 \text{ is : } \frac{W^2}{L} \tag{19}$$

The probability density of $I_k^{(1)}$ may be written as:

$$dp\left(I_k^{(1)}\right) = \frac{1}{2}.\frac{W^2}{L}.\delta\left(I_k^{(1)} - 1\right) + \left(1 - \frac{1}{2}.\frac{W^2}{L}\right).\delta\left(I_k^{(1)}\right) \tag{20}$$

We deduce the expression if the probability density of I_1:

$$dp(I_1) = \sum_{i=0}^{N-1} C_{N-1}^{i} \left(\frac{W^2}{2L}\right)\left(1 - \frac{W^2}{2L}\right)^{N-1-i} \delta(I_1 - i) \tag{21}$$

So:

$$prob(I_1 \geq S) = \int_S^{\infty} dp(I_1)dI_1 = \sum_{i=0}^{N-1} C_{N-1}^{i} \left(\frac{W^2}{2L}\right)\left(1 - \frac{W^2}{2L}\right)^{N-1-i} \tag{22}$$

We then obtain the error probability of a conventional receiver of a synchronous DS-OCDMA system:

$$P_e = \frac{1}{2} \sum_{i=0}^{N-1} C_{N-1}^{i} \left(\frac{W^2}{2L}\right)\left(1 - \frac{W^2}{2L}\right)^{N-1-i} \tag{23}$$

3. RESULTS AND DISCUSSION

We have operated two simulations in this study. One by the use of OptiSystem and the other using Matlab and OptiSystem in co-simulation for V2X communication. In the following we will highlight the details of these simulations and the performance results.

3.1. Hybrid OTDM/WDM VLC system

We simulated our VLC system using four colors on each one we have N_i TDMA users (Table 2). We employed an optical filter at the input of the photodiode in order to reduce the effect of noise of the ambient light. A bassel filter is placed at the output of the amplifier.

Table 2. List of the main OptiSystem components used for simulating hybrid OTDM/WDMA VLC systems

Parameter	Value
Bitrate	250 Mb/s
Modulation	NRZ-OOK
Optical sources (LED)	Wavelengths: 450 nm, 525 nm, 589 nm, 675 nm
Distance	100 m
Rectangular optical filter	Wavelength: 450 nm
PIN photodiode	Responsivity: 0.22 A/W
Amplifier (TIA)	Voltage gain: 90 Ohm
Low pass Bessel filter	Cut off frequency: 0.75×Bitrate
Electrical amplifier	Gain: 10 dB

Initially, we simulated our system with 4 colors: red, green, blue and amber (RGBA). Figure 8 displays the eye diagram for 250 Mb/s. We can see that the diagram is relatively open and that the minimum BER is $1.68.10^{-7}$ is obtained for a distance of 10 m. Next, we simulated the main system for several data rates.

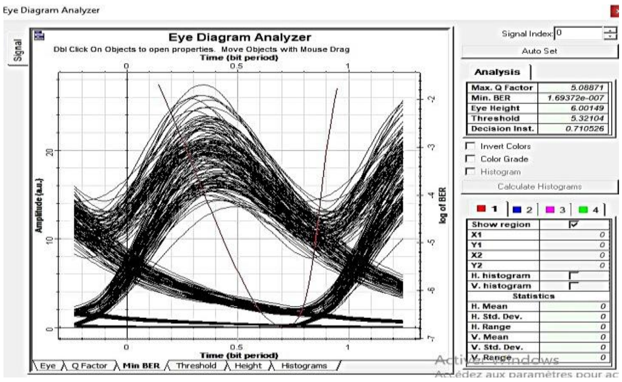

Figure 8. Eye diagram analyser for 250 Mbit/s

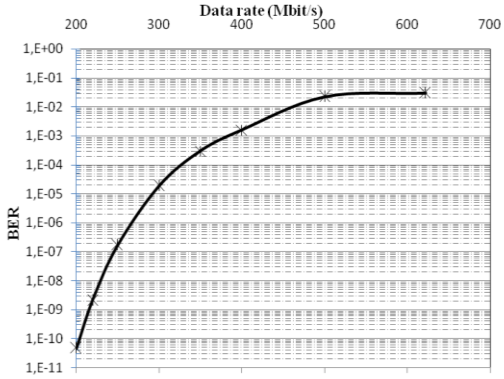

Figure 9. BER versus data rate

Figure 9 shows the BER variations as a function of the data rates. We can see that the performances decrease when the data rate increases. We can conclude that there is a compromise between performances and data rate.

3.2. The DS-OCDMA/VLC system

With the purpose of studying the feasibility of a VLC/OCDMA system using uni-polar OOC codes, we have simulated a system taking the real physical parameters of the components by different threshold values into account. We designed the VLC system using a DS-OCDMA system by NRZ-OOK modulation (Table 3). The transmitted signal of NRZ-OOK inputs is modulated with the LEDs. For the generation of the OOC codes, we were required to use a co-simulation with Matlab. The oscilloscope visualizer of the OOC code generated by Matlab blocks is shown in Figure 10. The optical signal transmitted through the LOS channel over a distance of 100 m is detected by the photo-diode which converts the optical signal into an electrical signal, and the received signal is weak. So an electrical amplifier is used to amplify the signal. The received signal is reconstructed and recovered at the receiver level, a multiplication of the signal by the code of our desired user was necessary in order to maintain that the power present in the chips unit of the code $'b_i^k = 1'$.

Table 3. List of the main OptiSystem components used for simulating DS-OCDMA VLC systems

Parameter	Value
Bitrate	1 Mb/s
Modulation	NRZ-OOK
Optical sources (LED)	Wavelengths: 450 nm, 525 nm, 675 nm
Users per LED	5
Distance	100 m
Rectangular optical filter	Wavelength: 450 nm
PIN photodiode	Responsivity: 0.22 A/W
Amplifier (TIA)	Voltage gain: 90 Ohm
Low pass Bessel filter	Cut off frequency: 0.75×Bitrate
Electrical amplifier	Gain: 10 dB
Matlab component	Sequence length: 256
	Samples per bit: 2048
	Number of sampels: 524288

Then the signal is reformatted by an integrator to evaluate the total power per bit. The oscilloscope visualizer of the integrated signal on a temp bit is shown in Figure 11. The signal at the output of the integrator represents the decision variable that will be compared to the threshold value.

3.2.1. Bit error rate

Our system has been simulated for different possible values of thresholds, Figure 12 shows the variation of BER according to the threshold. We can see that the performance increases when the threshold increases. There is a trade-off between the threshold and the system performance. The results show that our system has nearly the same performance as the theory.

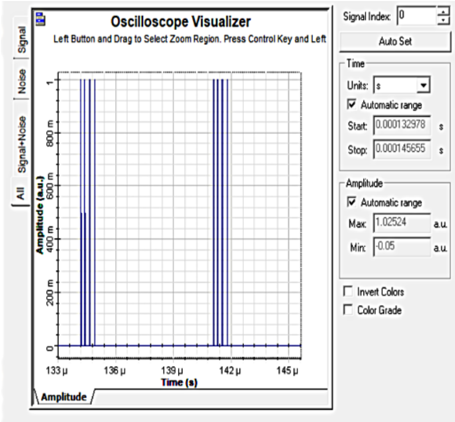

Figure 10. Signal of the Matlab code

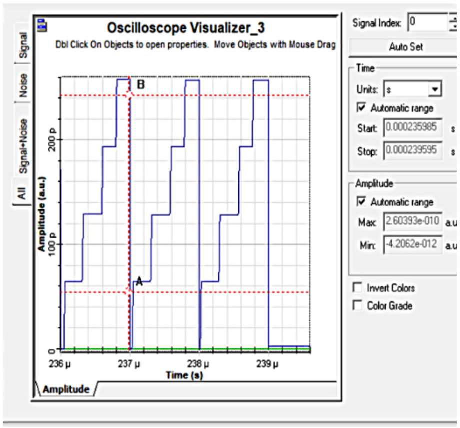

Figure 11. The integrated signal on a temp bit

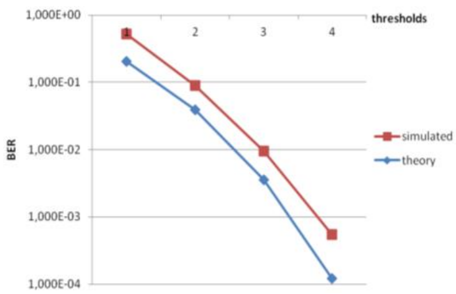

Figure 12. BER variation with a function of the threshold

4. CONCLUSION

A simulation of a hybrid TDM/WDM as well as a study of OCDMA VLC systems have been presented in this paper. The results have demonstrated the feasibility of our systems and that they allow us to remarkably enlarge the number of users. Also, to improve the performances in terms of coverage, data rate, and lighting quality, the number of users over each channel must be taken into account. Our proposed outdoor VLC system consists of the application of NRZ-OOK modulation using filtering techniques in both systems. We used an electrical low-pass Bessel filter to reduce the shot and thermal noises. The results have shown that the BER performance has proven to be relatively the same as the theory. Accordingly, the NRZ-OOK modulation is best with the influence of optical noise background. The suggested method with OptiSystem helps us to set up the VLC system and then can be materialized for implementation to achieve good performance with minimum effort and in a short time.

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