Cascaded PLC-VLC Channel Using OFDM and CSK Techniques

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***Abstract*—This paper puts in Cascade the power line communications (PLC) channel and the visible light communications (VLC) channel, in order to use the PLC channel as backbone for the VLC channel. This combination is suitable for applications in which hybrid PLC-VLC systems are needed. We investigate the behaviour of the cascaded channels for a full link transmission. Quadrature phase shift keying combined with orthogonal frequency division multiplexing (QPSK-OFDM) is used over the PLC channel and color shift keying (CSK) is deployed over the VLC channel to convey the information. Cascaded channel variances are analyzed. Complete simulated bit error rate (BER) is analyzed and presented for multiple scenarii that could occur in the two channels.**

***Index Terms*—PLC-OFDM, VLC, Hybrid systems, Cascaded channels, PLC-VLC interface. CSK scheme, RGB colors space.**

I. Introduction

Research on power line communications (PLC) technology has shown that the PLC channel can be used to transmit high and low data rate information [1]. PLC technology is deployed in low mobility applications. In those type of applications, the main causes of impairment that degrade the performance of the transmission are noise, attenuation and inter-symbol interference. The solution to mitigate inter-symbol interference (ISI) is the design and implementation of an anti-multipath which is practically the equalization technique [2]. Nowadays, Orthogonal frequency division multiplexing (OFDM) is the most used method in communication systems to overcome the effects of multipath fading and delay dispersion. The PLC channel is a frequency selective and multipath channel. It requires the use of OFDM to mitigate the problem caused by the delay dispersion. OFDM has been proposed in many PLC systems including broadband PLC (NBPLC) [3] and narrowband PLC (NBPLC) [4].

Visible light communications (VLC) technology can be used as a contact-less and wireless solution for the efficient deployment and successful connection of the PLC technology to the end user. VLC uses the visible spectrum to transmit data, and is regulated by the standard for short range wireless optical communication using the visible spectrum (IEEE 802.15.7). It gives to the compliant three operating modes on the physical layer; PHY I, PHY II and PHY III [5], [6], each having corresponding proposed modulation schemes. Color shift keying (CSK), indicated for PHY III, is suitable for high data rate transmission. CSK presents some advantages in comparison to other modulation schemes such as on-off keying (OOK), pulse position modulation (PPM) and variable PPM (VPPM): CSK does not modulate the intensity of the resulting luminous flux, and at large scale LEDs, CSK scheme provides no in-rush current [7].

A few attention was accorded to hybrid systems including PLC and VLC channels. In [8], a hybrid system is presented using VLC to supplement a radio frequency wireless system. In [9], an integrated system of white LED-VLC and PLC using a single carrier binary phase shift keying (SC-BPSK) is proposed. [10] proposes a system combining orthogonal binary frequency shift keying (BFSK) and OOK for interfacing between PLC and VLC channels. In [11], the authors focused on the integration of indoor visible light and the PLC systems. OFDM is highlighted with an emphasis on multiple inputs and multiple outputs (MIMO). To the best of the authors' knowledge, combining OFDM and CSK for a cascaded PLC-VLC system has never been investigated. In this paper, we focus on matching the OFDM constellation from the PLC channel to the CSK constellation on the VLC channel. The channels are coupled in cascade to predict the behaviour of the entire system and its variance is analyzed through simulation. The bit error rate is also analyzed through simulations for multiple combinations of the variances of the two channels.

The rest of the paper is organized as follows: The system model is presented in Section II. The PLC and VLC channels are briefly presented and an overview of both OFDM and CSK modulation techniques is given. Section III discusses the OFDM to CSK mapping method, and, introduces the lighting constraint and the communication objective. Simulation results are presented in Section IV and concluding remarks are provided in Section V.

II. Cascaded PLC-VLC Model

The incoming data is modulated using quadrature phase shift keying (QPSK) scheme combined with the OFDM technique. The modulated signal is sent through the PLC channel where it is corrupted by the PLC noise. From the PLC channel, the signal is demodulated and the detected constellation is mapped into a CSK constellation for retransmission over the VLC channel. The VLC receiver performs a CSK

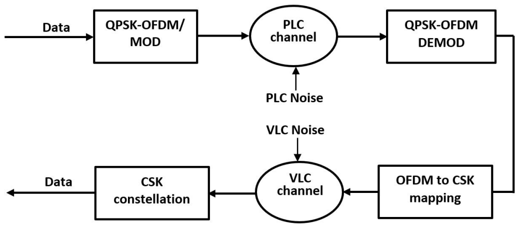

Figure 1. Cascaded PLC-VLC communication system model using QPSK-OFDM over the PLC channel and CSK over the VLC channel

demodulation and the information bit is recovered. Fig. 1 depicts the communication model under study.

A. The PLC and VLC channels

The PLC channel, made of the conductors that are also used for electric power transmission, is an exceedingly harsh channel [1]. This is due to the types and magnitudes of the noise present over the channel and the attenuation related to its low impedance. The main types of noise identified over the PLC channel: Impulsive noise, modelled using Poisson distribution [12]; cyclo-stationary noise, which is a periodic impulsive noise [13]; Narrowband interference, originated from many sources, varies with the time of the day and background noise grouping the remaining noise [12].

The VLC channel is the space between the light emitting diodes (LEDs) used as transmit antenna and the photodetector (PD) used as receive antenna [14]. The noise sources include sunlight, incandescent and fluorescent light. In addition to the noise present in the channel, the receiver in its operation produces noise. This is due to the impact of the photons on the surface of the receiver. Two main types of noise are inventoried: shot noise, modelled using Poisson distribution, and thermal noise.

B. PLC-OFDM

The PLC channel is presented as an echo-based channel due to the various reflections that happen in the power line [1]. The structure of the channel is then presented as a finite impulse response filter (FIR), showing that the channel is a sum of M pieces of a bandwidth B. Then, we have B/M Hz of bandwidth per sub-channel. OFDM is a multi-carrier modulation obtained by using orthogonal sub-carriers in a frequency division multiplexing (FDM) system. It divides the total data rate to be transmitted into the number of sub-carriers [15]. Cyclic prefixes (CP) are used in OFDM to combat multipath by converting an ISI channel into a fix number of ISI-free parallel sub-channels. Each of those sub-channels is affected by an additive white Gaussian noise (AWGN) of zero mean and variance equal to the number of sub-channels divided by 2 [16]. OFDM systems transmit M data symbols represented by $\mathbf{X} = [X_0, X_1, \ldots, X_{M-1}]$ in an OFDM block through M sub-carriers. The CP is added before the parallel to serial (P/S) block. The input data modulated using quadrature amplitude modulation (QAM) or PSK is grouped in blocks of M parallel symbols, each of them representing a coefficient of an inverse fast Fourier transform (IFFT) of matrix F_M^{-1}. The IFFT operation is performed on the transmitter side to yield the OFDM time domain vector $\mathbf{s}(t) = [s_0(t), s_1(t), \ldots, s_{M-1}(t)]$, then, a cyclic extension of duration d is appended on each block to obtain $[s_d, s_{1+d}, \ldots, s_{M+d-1}]$. The frequency domain representation of the data sequence is summed by the P/S block. That sum passes through a digital to analogue converter and the resulting signal is sent over the PLC channel. The equivalent system affected by AWGN is modelled as [1]

$$\mathbf{Y} = \mathbf{H}_p \mathbf{X} + \mathbf{n}_p, \tag{1}$$

where $\mathbf{X}$, $\mathbf{Y}$ are the transmitted and the received alphabets respectively. $\mathbf{H}_p$ is the PLC channel impulse response and $\mathbf{n}_p$ is the noise vector. At the receiver, after the CP has been removed, the received sequence passes through the serial to parallel (S/P) block and the resulting data sequence is multiplied by the matrix F_M to perform the FFT operation. The FFT operation restores the frequency domain signal ready to be demodulated by the QAM or PSK system [1], [4]. The upper part of Fig. 2 depicts a PLC-OFDM system.

C. The CSK scheme

Nowadays, a new generation of light bulbs made of LEDs is available to be used in lighting. They provide more flexibility in terms of current intensity modulation. They absorb less energy, and provide better visual comfort with respect to their counterparts incandescent and luminescent light bulbs. One distinguishes two main types: single color LEDs and multi-color LEDs. Multi-color LEDs contain more than one color LED in one package. The most used multi-color LED is the RGB-LEDs. It contains precisely three color LEDs (red, green and blue) in the package and can produce the maximum number of colors of the visible spectrum. This is obtained by modulating the current intensities of the three included LEDs.

- The CSK modulation method

CSK is a communication modulation scheme that maps symbols to colors. RGB-LEDs are used in CSK to couple the message to the channel. The color corresponding to a symbol is produced by combining the three lights emitted by the three LEDs included in the package. In 1931, the International Commission on Illumination (CIE) defined seven bands of original colors from red (700 nm) to violet (420 nm) including orange (620 nm), yellow (580 nm), green (530 nm), and blue (470 nm). The three primary colors used represent three bands chosen among the seven provided by CIE [7]. IEEE 802.15.7 gives rules and guidelines for designing CSK constellations. CSK design methods and examples are provided in the literature. In [17], constellation design for CSK is proposed for VLC technology using billiards algorithm to produce the constellation polygon. [18] and [19] propose a design based on the convex optimization methods. [20] proposes the design of a CSK system including many light sources, taking into account multi-color LEDs containing more than three color in a package. An enhanced CSK technique for high speed wireless VLC based on four color LEDs is presented in [21]. In general, to construct the CSK constellation, the three primary colors are represented by the three vertices of a triangle delimited by the red, green and blue colors. The rest of symbols are inserted in the triangle following a distribution proposed in [7].

- Constraints in designing a CSK system

Due to the double function of the LEDs, both lighting and communication should be optimized. Two main constraints are to be met while designing a constellation for CSK: Firstly, the average optical power must remain constant during data transmission. Practically, colors must be created with a constant light intensity. Secondly, in order to offer a lighting system with balance colors, an average color is required. Both constraints are grouped in the following equations.

$$\begin{cases} P_{avg} = p_{r,k} + p_{g,k} + p_{b,k} & \text{(a)}, \\ C_{avg} = \sum_{\alpha} \gamma_k S_k & \text{(b)}, \end{cases} \tag{2}$$

where $p_{r,k}$, $p_{g,k}$ and $p_{b,k}$ related to the k^{th} symbol, are the light intensities produced by the red, green and blue LEDs respectively. $\alpha = \{red, green, blue\}$ and γ_k corresponds to the probability of transmitting the k^{th} symbol.

- The CSK channel

The CSK channel is a multi-stream VLC channel that can be represented by an impulse response $\mathbf{H}_v$ given by

$$\mathbf{H}_v = \begin{pmatrix} h_{rr} & h_{rg} & h_{rb} \\ h_{gr} & h_{gg} & h_{gb} \\ h_{br} & h_{bg} & h_{bb} \end{pmatrix}, \tag{3}$$

where h_{ij} represents the front-end gain between each sent color i and received color j. $\mathbf{H}_v$ describes the environment of the transmission, in which, cross-talk, Shot, thermal and Fano noise can happen [22]. In general, the system tracks the channel at the beginning of the transmission so that $\mathbf{H}_v$ is well known by the receiver. For a system corrupted by AWGN, the observed symbol set $\mathbf{Z}$ is extracted from the general transmission equation, given by

$$\mathbf{Z} = \mathbf{H}_v \mathbf{Y} + \mathbf{n}_v, \tag{4}$$

where $\mathbf{Y}$ and $\mathbf{n}_v$ are the input symbol set and the VLC channel noise respectively. The received optical signal compared to the noise signal is given by [9]

$$SNR = \frac{\theta^2 P_r^2}{N_0 B}, \tag{5}$$

where SNR is the signal to noise ratio, θ is the responsitivity of the photodetector, P_r the received optical power, N_0 being a double-sided power-spectral density of the noise and B the desired bandwidth.

- CSK constellation design

We consider a CSK constellation of size M. The incoming symbols alphabet is mapped into the color constellation $\mathbf{C}$ = $\{C_0, C_1, C_2, \ldots, C_{M-1}\}$. Each C_k, (k = 0, 1, 2, . . ., $M-1$) is a number of the CIE 1931 xy chromaticity gamut, hence, can be represented by its xy coordinates. Nevertheless, to calibrate the current intensities of the LEDs, C_k is represented by its color coordinates R_k, G_k and B_k; R_k, G_k and B_k sum up to 1 [18] and [19]. The xy coordinates of the color C_k can be found by combining its RGB color coordinates with the xy coordinates of the primary colors red , green and and blue lights according to

$$\begin{cases} x_k = R_k x_r + G_k x_g + B_k x_b, \\ y_k = R_k y_r + G_k y_g + B_k y_b, \end{cases} \tag{6}$$

where (x_r, y_r), (x_g, y_g) and (x_b, y_b) are the xy coordinates of the original red, green and blue colors respectively.

- The CSK receiver

The CSK receiver is a color sensor. It is made of multiple detectors that are sensitive to specific wavelengths and convert the light chromaticity and its intensity into signals. The CSK receiver uses the threshold selection technique to detect the information concealed in the lights. In general, a concentrator is used to concentrate the maximum of the light on a very small detector area, and, three optical filters are used to reduce crosstalk and interference.

III. OFDM to CSK Mapping

The OFDM signal received from the PLC channel is characterized by: a probably non-uniform power gain, a non linear phase across frequencies and a non-uniform power spectrum. The vector set $\mathbf{Y}$ measured at the output of the PLC channel is retransmitted over a non-negative and incoherent signal transmission involving incoherent LEDs. OFDM physical layer offsets are: the symbol, frequency and clock offsets. Added to the delay dispersion, these offsets considerably affect the transmitted message. This implies that the OFDM compensation parameters such as the CP and the peak to average power ratio (PAPR) compensation will affect the lighting parameters. In order to map the OFDM signalling to the CSK constellation, both systems must have the same constellation size (M in our case). As presented in Section II, an efficient FFT operation is needed to recover the frequency domain message from the PLC channel. Let $\mathbf{Y}$ = $\{Y_0, Y_1, Y_2, \ldots, Y_{M-1}\}$ be the OFDM symbol alphabet received from the PLC channel, $\mathbf{Y}$ is mapped to the color constellation $\mathbf{C}$ in such a way that (7) is satisfied.

$$\begin{cases} Y_0 \Rightarrow C_0(x_0, y_0), \\ Y_1 \Rightarrow C_1(x_1, y_1), \\ . \quad\quad . \\ Y_{M-1} \Rightarrow C_{M-1}(x_{M-1}, y_{M-1}). \end{cases} \tag{7}$$

Each C_k is represented using its xy coordinates (6) and the RGB representation gives the current intensities to be applied to the three color LEDs. The principle of OFDM to CSK mapping technique is also described in Fig. 2. The incoming temporal signal $y(t)$, obtained after the P/S block at the OFDM receiver, is used to control the LEDs. Let $a(t)$ be the transmitted signal at the VLC antenna. $a(t)$ is the optical chromaticity function derived from the temporal signal $y(t)$. The expression of $a(t)$ is given in (8) and represents the sum of colors in the xy plan.

$$a(t) = \sum_{k=0}^{M-1} \begin{pmatrix} R_k x_r + G_k x_g + B_k x_b \\ \\ R_k y_r + G_k y_g + B_k y_b \end{pmatrix} \tag{8}$$

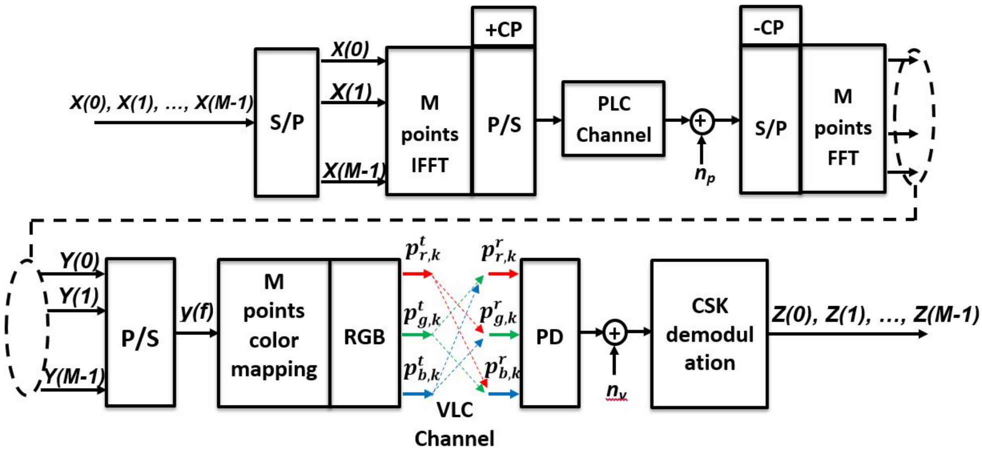

Figure 2. Block schematic describing the principle of OFDM-CSK

The received temporal signal over the VLC channel $z(t)$ is expressed as [9]

$$z(t) = \theta a(t) \otimes h_v(t) + n_v(t), \tag{9}$$

where $p \otimes q$ is the convolution operation of p by q, $n_v(t)$ the AWGN noise, and θ the responsivity of the photo detector.

A. Illumination constraints

The colors are selected in accordance with the CSK constellation design proposed in [7]. Dimming technique, based on amplitude control, is used to control the brightness of a color by modulating the corresponding forward current. The design must meet the lighting constraints defined earlier (see 2-a), while conveying the information with acceptable throughput. The optical power necessary to achieve this is defined from the desired average luminous flux and is given by

$$P_{avg} = \frac{\Phi_{avg}}{\eta}. \tag{10}$$

Here η represents the luminous efficacy and Φ_{avg} = (Φ_{max} + Φ_{min})/2 represents the average luminous flux required. P_{avg} imposes a constant value to the total current $i_t = i_{r,k}+i_{g,k}+i_{b,k}$ within the transmitted alphabet $\mathbf{Y}$, imposing bounds to the baseband signal $a(t)$ ($A_{min} \leq a(t) \leq A_{max}$). Consequently the luminous flux produced during the transmission of $\mathbf{Y}$ satisfies

$$\Phi_{avg} - \Delta\Phi \leq \Phi_k \leq \Phi_{avg} + \Delta\Phi, \tag{11}$$

where $\Delta\Phi$ = $|\Phi_{max}$ - $\Phi_{avg}|$ = $|\Phi_{min}$ - $\Phi_{avg}|$. Under this condition, the average color condition defined in (2-b) must be respected. Hence, in our case, (2-b) is re-written as [19], [23]

$$C_{avg} = \frac{1}{M} \sum_{k}^{M-1} [\langle \overline{g}, Y_k \rangle], \tag{12}$$

where $\langle u, v \rangle$ is the inner product of u and v. Using the general weighted inner product form in a finite-dimensional space, we can write the double lighting constraints on the OFDM to VLC transmission system as

$$\begin{cases} P_{avg} = \frac{1}{\eta} \overline{g}^T \mathbf{W}_m Y_k, \\ C_{avg} = \frac{1}{M} \sum \overline{g}^T \mathbf{W}_m Y_k, \end{cases} \tag{13}$$

where $\langle \overline{g}, Y_k \rangle$ = $\overline{g}^T \mathbf{W}_m Y_k$ is the matrix decomposition of the inner product (12), $\overline{g}$ = $[g_r,\ g_g,\ g_b]^T$ represents the optical gain of the LEDs [19], and Y_k is the k^{th} symbol recovered from the PLC channel (Y_k = $\mathbf{H}_p X_k$ + $\mathbf{n}_p$). $\mathbf{W}_m$ is a 3×3 diagonal positive-finite weight matrix expressed as

$$\mathbf{W}_m = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}, \tag{14}$$

where λ_1, λ_2 and λ_3 are all positive. The power and color constraints are met when the quantity ($g_r \lambda_1 R_k$ + $g_g \lambda_2 G_k$ + $g_b \lambda_3 B_k$) remains constant $\forall k \in \{0, 1, 2, \ldots, M-1\}$. This is made possible by processing the balancing factors λ_1, λ_2 and λ_3. A color stabilisation module is still necessary in the system to ensure the average color is constant.

B. Design objectives

$\mathbf{H}_v$ filters both $\mathbf{Y}$ and $\mathbf{n}_p$ from the PLC channel. Considering the general transmission equation over a channel affected by AWGN, the transmission over the double-channel is given by

$$\mathbf{Z} = \mathbf{H}_T \mathbf{X} + \mathbf{N}_T, \tag{15}$$

where $\mathbf{Z}$ and $\mathbf{X}$ represent the received alphabet at the VLC channel output and the original symbol set at the input of the PLC channel, respectively. $\mathbf{H}_T$ = $\mathbf{H}_v \mathbf{H}_p$ represents the two channels mounted in cascade and $\mathbf{N}_T$ = $\mathbf{H}_v \mathbf{n}_p$+$\mathbf{n}_v$ is the noise combination from the cascaded channels. The objective is to realize a system that will bound the luminous flux (16-a), keeps constant the average color (16-b) and maximizes the minimum distance for a given SNR [19], [24](16-c).

$$\begin{cases} \Phi_{min} \leq \overline{g}^T \mathbf{W}_m Y_k \leq \Phi_{max},\ (j \neq k) & \text{(a)} \\ C_{avg} = \frac{1}{M} \sum \overline{g}^T \mathbf{W}_m Y_k & \text{(b)} \\ min \|\mathbf{H}_T (X_j - X_k)\|_2 & \text{(c).} \end{cases} \tag{16}$$

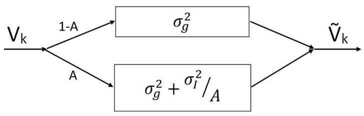

Figure 3. Two-state Class A noise model

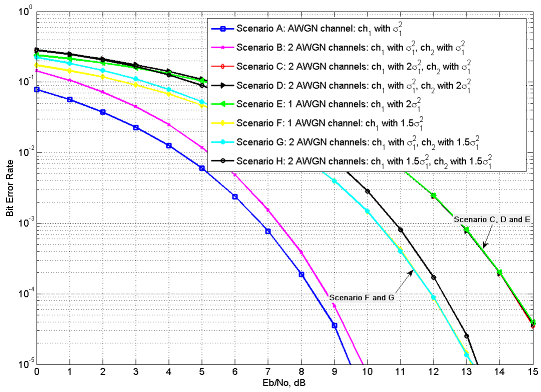

Figure 4. BER performance for 2 cascaded AWGN channels with different variances.

The objective given in (16-c) takes into account the cascaded channel matrix $\mathbf{H}_T$, while the lighting constraints (16-a, 16-b) are related to the observed k^{th} vector Y_k.

IV. Simulation and Results

For the PLC channel, a two-state Middleton Class A noise model is used which takes into account impulsive noise. Such a model is shown in Fig. 3. The k^{th} data sample V_k experiences AWGN only with probability $1 - A$, and experiences both AWGN and impulsive noise with probability A. $\tilde{V}_k$ is the noisy version of V_k. In the noise model in Fig. 3, the parameters are defined as follows: A is the probability of impulsive noise, σ_g^2 and σ_I^2 are the variances of AWGN and impulsive noise, respectively. The ratio of both variances is given by $T = \sigma_g^2/\sigma_I^2$. The impulsive noise is therefore completely defined by A and T. For all simulations where there is impulsive noise, we used $A = 0.1$. There is no need to do simulations for various values of A as this factor does not influence the bit error rate performance of OFDM [25], [26]. The simulation is performed by sending 10^5 data bits through the cascaded (PLC-VLC) channel.

Firstly we analyze the behaviour of a system including two distinct channels in cascade. Let σ_1^2 and σ_2^2 be the noise variances on the first and second channels respectively, we simulate the two different channels in eight scenarii. The scenarii are selected according to the ratio σ_1^2/σ_2^2 of the two channels. Hence, the system performance is analyzed for three cases: $\sigma_1^2/\sigma_2^2 = 1$, $\sigma_1^2 < \sigma_2^2$ and $\sigma_1^2 > \sigma_2^2$. This preliminary test gives an idea on the behaviour of our system. The results are shown in Fig. 4, giving the bit error rate as function of the ratio of energy per bit to the spectral noise density (E_b/N_0). Scenarii A, E and F show the system performance

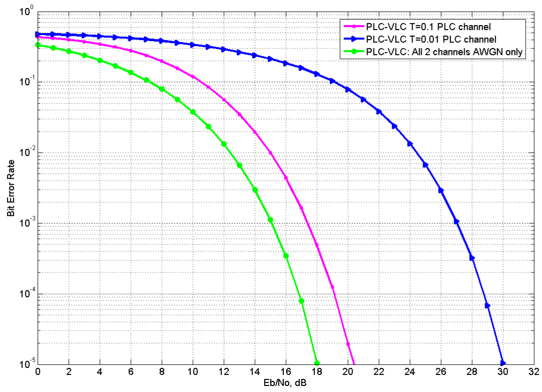

Figure 5. BER performance for 2 cascaded AWGN and inpulsive channels using QCSK-256 OFDM and 4-CSK.

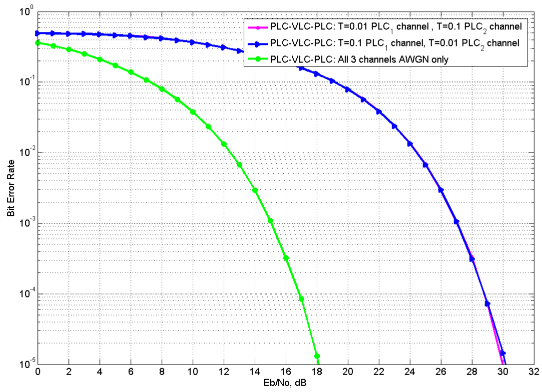

Figure 6. BER performance for 3 cascaded AWGN and inpulsive channels using QCSK-256 OFDM and 4-CSK.

over AWGN channels with variances σ_1^2, $1.5\sigma_1^2$, and $2\sigma_1^2$ respectively. They show that as the variance increases, the system offers poor performance. In scenarii B, C, D, G and H, we investigate the system over two channels in cascade. In B, the two channels have the same variance ($\sigma_1^2 = \sigma_2^2$), the system performs better than the case of a single channel with variance $2\sigma_1^2$. In C and D, the variance of the first channel is twice the one of the second and vice-versa, respectively. The system has almost the same performance in both cases and is equivalent to the performance of the system over a channel with variance $2\sigma_1^2$. In G, the variance of the second channel is 1.5 times greater than the one of the first channel. The performance of the system is the same as in the case of one channel with variance $1.5\sigma_1^2$. In H, both channels have the same variance $1.5\sigma_1^2$. The performance is close to the one of a single channel with variance $1.5\sigma_1^2$.

Three simulations were performed to analyze our interfacing. They all consider QPSK-OFDM and 4CSK techniques over PLC and VLC channels respectively. They are performed under the assumption that there is no cross-talk between channels over the VLC channel. Furthermore, no reflection, no multipath and no delay are considered. In the first simulation, we look at the performances of a combined 256 OFDM-

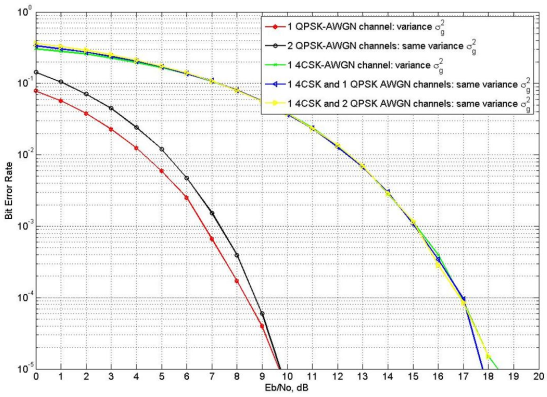

Figure 7. BER performance for 2 cascaded AWGN channels using QPSK-256OFDM and 4-CSK

4CSK. The results for various values of T are shown in Fig. 5. The second simulation continues the investigation started previously. We consider three channels. A 256 OFDM is deployed over the PLC channel and a 4CSK over the VLC channel. The results for various values of T are shown in Fig. 6. In the last case analyzed, we assume that there is no impulsive noise in both channels. Fig. 7 depicts the results of this last analysis. It can be seen from Figs. 5, 6 and 7 that the bad channel (between the two channels in cascade) determines the overall performance of the cascaded PLC-VLC and PLC-VLC-PLC channels. From the bit error rate versus SNR curves in Figs. 5, 6 and 7 we conclude that communication between the PLC and VLC channels is feasible. Even though not applied in this paper, conventional error control coding techniques can easily be applied in the cascaded channels to improve performance.

V. Conclusion

This paper investigates a hybrid system including PLC and VLC technologies. Both PLC and VLC channels are subject to impulses and AWGN. On the PLC side, QPSK is considered and 256 OFDM technique is used. On the VLC side, a 4CSK is used to convey the information through the channel. A system in cascade including two channels with two different noise variances was studied to predict the behaviour of our system. Concrete analysis of our interfacing technique was performed in three steps. We considered different scenarii that could happen over the two channels. QPSK$-$256 OFDM/4CSK over AWGN and impulsive channels were included. The same configuration was investigated including three channels. The ratio T between the variance of AWGN and the one of the impulsive noise was varied to analyze the performance of the system. The last configuration was QPSK/4CSK. The BER was presented in each case and the results commented.

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