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Effects of LED Non-linear Response and Waveform Settings on Multi-Cell VLC System Deployments

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Abstract—Visible light communication (VLC) offers the opportunity to provide services with new requirements, when compared to the ones offered so far by radio wireless technologies almost exclusively. The idea behind VLC is to re-use the light signal, currently utilized for illumination purposes only, to transfer information wirelessly. *Light-emitting diodes* (LEDs), which are the natural sources of light for VLC due to their fast time response and high energy-efficiency, are devices with a notable non-linear response. A current trend to improve the achievable data rate of the VLC links relies on the use of linear waveforms, instead of just using On-Off Keying, which is robust against LED non-linearities but difficult to adapt to the variable VLC link conditions. Since having a linear transfer function is important when using efficient waveforms such as *orthogonal frequency division multiplexing* (OFDM), this paper starts by modelling the voltage-versus-current response of commercial LEDs. Then, the derived model is used to identify the guidelines that new VLC prototypes should fulfill. In particular, this paper focuses on the strength of the communication signal, compared to the light source optical power, and shows the way in which these parameters affect the coverage range of a multi-cell VLC system. The effect that these key design parameters have on the VLC link are identified, based on a real experimental setting, as they are difficult to model accurately due to the complex non-linear nature of LEDs when working in highly energy-efficient regimes.

Index Terms—Visible-light communications; LEDs; nonlinear response; linear modulation; OFDM; prototype implementation.

I. INTRODUCTION

The demand of wireless communication services has been continuously growing during the last few decades. Moreover, since most of these wireless systems have relied almost exclusively on the use of radio frequency (RF) bands, there is practically no portion of the electromagnetic spectrum that has been left unused (reserved) to provide future wireless services. In parallel, during the last decade, there have been some standardization initiatives that proposed to use light signals as a new mean to carry information wirelessly. The first approach towards the implementation of a *visible light communication* (VLC) waveform, engineered by contemporary available technology, was to use digital signal modulations, which are robust against the non-linear effects introduced by *light-emitting diodes* (LEDs) [1]. Later on, more advanced waveforms based on *orthogonal frequency division multiplexing* (OFDM) were proposed to modulate the intensity

of the LED light beam [2]. Unfortunately, the successful development of RF-based communication systems has delayed the the massive adoption of VLC technology up to now, where new use cases have emerged in which State-of-the-Art (SotA) wireless technologies based on radio signals cannot provide a feasible solution [3].

Though light-based wireless communications have not been massively adopted by consumers so far, the radio spectrum scarcity that we currently have, as well as the recent development that has existed on the desing of optical waveforms based on OFDM, offer new opportunities to explore the effect that non-linear effects that LED would have on the transmitted linear signals (beyond baseline On-Off Keying ones) [1], [4]. Moreover, the ultra-dense deployment of lighting fixture in most indoor environments, particularly in large-sized office buildings and public places such as hotel lobbies, offers the possibility to enable a multi-cell VLC system, in which the frequency-reuse concept can be exploited in the same way as in conventional RF-based communication systems.

In this paper, we consider a multi-cell scenario in which the different luminaires of the room are able to transmit an independent VLC data-carrying signal towards different mobile terminals. In this context, our aim is to study the coverage area of each independent VLC transmitter in this multi-cell scenario that is configured. The classical concept that states that the desired communication signal power vanishes below the noise-plus-interference signal power in cell-edge users is valid in this context. Then, to enable the reliable coexistence of parallel VLC links, the reliable power control of the optical signal power per cell is mandatory. Moreover, since the VLC signal that is emitted is placed on a portion of the spectrum that is sensitive to the human eye, the illumination level that is generated should be also controlled. This way, the user of the VLC system would not experience any undesirable visual effects, such as the light flickering, when the VLC data is transmitted in bursts by the LED transmitter. Based on this, the careful adjustment of the DC-bias point of the LED device must be also carefully controlled in a real VLC system.

According to the non-linear response that was observed our commercial LED model under study, which would be deployed in every VLC transmitter of the multi-cell VLC scenario, we observed that it is very challenging to establish the effect that that optical transmit power of each LED has on the received signal quality at the output of the Photodetector. We studied

Fig. 1. LED response. Modelling of the I/V relationships with $I_S = 10$ nA, $T = 273 + 25$ [K], and $n = 8$. Four reference points are indicated.

these effects by means of numerical simulation first, and then by the measurement of relevant key performance indicators, such as the Bit Error Rate (BER), of an actual software-defined VLC link based on OFDM. Thanks to these observations, we identified key guiding rules to design the power control mechanism of a VLC link, when used in a multi-cell scenario like the one that is configured in most indoor environments.

The rest of the paper is organized as follows: Section II presents the system model, whereas Section III studies the signal strength that is observed in the proposed scenario. Numerical results are presented in Section IV, and the actual VLC experimental setting that was build is described in Section V. Finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

The classical LED models are summarized here, to have the fundamental background that is needed to anticipate the observations that are later made with our experimental platform.

A. Theoretical model for the electrical response of an LED

We start our analysis considering that as any diode, an LED tends to follow a relationship between the DC current (i.e. I_d) and the voltage in its terminals (i.e. anode-cathode voltage V_{ak}) given by [5], [6]

$$I_d = I_S \left(\exp \left\{ V_{ak} / (n V_T) \right\} - 1 \right), \quad (1)$$

where

$$V_T = \frac{k T}{q}, \quad (2)$$

k is the Boltzmann constant, T is the absolute temperature, q is the electron charge, and n is an ideality factor. The model in (1) is stated as our main *I/V model*. Since an LED is an specific kind of diode, this compact model results interesting to anticipate some the electrical characteristics that will be later on observed in practice. As expected, the commercial LEDs used in our experimental setup tend to follow this model. The modelling in (1) is shown in Fig. 1. To simplify the observation of certain characteristics of the problem, we start by supposing the current that is fed into the LED attains the form

$$I_d = I_{DC} + i(t). \quad (3)$$

Fig. 2. Voltage waveform to achieve a sine-like current across the LED. The model assumes $I_{DC} = 210$ mA and $m = 1$

Then, as the current signal in (3) contains a DC component (i.e. I_{DC}), it is possible to see that

$$i(t) = m I_{DC} \sin(\omega t). \quad (4)$$

It is important to highlight that in a real communication system, $i(t)$ is intended as the signal that embeds the information bits. In this starting point, we simplify $i(t)$ as a sinusoidal waveform. Note that these statements rely on the assumption that it is valid to express $I_d = f\{V_{ak}\}$. Since (1) is a bijective function, it is valid to express

$$V_{ak} = f^{-1}\{I_d\}. \quad (5)$$

Now, the model in (4) is related to (5) to observe that V_{ak} has two components, i.e. a DC component and a time-varying signal, which are explicitly observed in the following equation:

$$V_{ak} = V_{AK} + v_{ak}. \quad (6)$$

B. Non-linear effects on voltage that is applied on the LED

It is important to emphasize that so far, we have focused on the transmitter side. In particular, it makes sense to consider the working principle of a so-called *LED driver*, which must be used to feed the data carrying signal into the LED device that takes the role of VLC transmitter. Clearly, in a convenient VLC transmitter design, it is desirable to have a collection of LEDs working simultaneously, in order to increase the total transmission power of the VLC link. However, and without any loss of generality, we consider that a single LED is used as VLC transmitter to simplify the analysis.

The time-varying voltage signal v_{ak} depends on $i(t)$. Meanwhile, although a simplified sinusoidal model was set for $i(t)$ as in (4), the non-linear I/V function that models the electrical transfer function of the LED modifies the shape of the voltage data-carrying signal in a very special way. A special case is presented in Fig. 2. Up to this point, we can observe that the continuous line in Fig. 2 has a waveform very different to that expected for sinusoidal signals. This observation shows that the bandwidth required in the driver circuit of the set of LEDs is higher than that established by the communication signal, which is referenced here as $i(t)$. This is an important

observation that a particular model, such as the one presented in (1), is able to anticipate successfully ¹.

III. SIGNAL STRENGTH AND OPTICAL POWER

The electrical power that an LED consumes is directly related to optical power that it irradiates [5], [7]. In addition, since manufactures expect that the designers of drivers use DC levels to feed the LED devices, it is frequent to find directly current intensity as the input to analyze the optical power. Due to that, in this paper we model the instantaneous electrical power that is dissipated in the LED as

$$P_{DC,AC} = V_{ak}I_d. \quad (7)$$

Then, the illumination level that the LED light source provides in the target room is expected to be proportional to the average power that is dissipated. Consequently, $\bar{P}_{DC,AC}$ stands for the mean value of $P_{DC,AC}$. As expressed before, the light devices in conventional infrastructure can be enabled to communicate across its optical radiated energy. It is important to analyze that, besides the non-linear model in (1), a second non-linear relationship appears here, to indicate the available optical power (or luminous intensity) [7] as the output LED signal.

Meanwhile, a new analysis is necessary at this point since the signal $i(t)$ that is enabled by the VLC technology, which is not present in LED-based illumination artifacts used solely for illumination, may affect the luminous intensity according to the status of the data transmission. The presence of the AC data-carrying signal, which is added on top of the DC level, allows us to model the instantaneous power of the communication signal as

$$p_{AC} = v_{ak}i(t). \quad (8)$$

Note that in this context, terminology $\bar{p}_{AC}$ stands for the mean value of p_{AC} in the time domain.

A. Linearized small-signal model for an LED response for low intensity modulation indexes

We now recall a classical approach used in the so-called *small-signal analysis* of non-linear electronic components, which is usually used in presence of transistors but can be also used in presence of diodes. In the latter case, a dynamic resistor value

$$r_d = \left. \frac{dV_{ak}}{dI_d} \right|_{V_{ak}=V_{DC}} \quad (9)$$

is defined, which can be seen as a coefficient that models the linear relationship that exists between current and voltages signals in the LED device. Then, we can express the interaction that exists between the time-varying input voltage component v_{ak} and output communication signal current $i(t)$ with the aid of the linear approximation

$$\hat{v}_{ak} \approx r_d i(t). \quad (10)$$

¹Note that there are well-known principles to analyze diodes (and LEDs in particular) if the I/V response in a particular device does not follow this mathematical setting. However, the exponential-like response is broadly accepted.

Fig. 3. Global power consumed by the LED in the VLC link. It is observed a convenient lack of sensitivity between m and $P_{DC,AC}$.

In this context, $\hat{v}_{ak}$ is an estimated value of the actual value that v_{ak} takes, which is represented by the dashed line in Fig. 1. Then, according to this analysis, the AC power in the VLC transmitter can be approximated as

$$\hat{p}_{AC} = \hat{v}_{ak}i(t), \quad (11)$$

where $\mathbb{E}\{\hat{p}_{AC}\}$ is used to represent the mean value of $\hat{p}_{AC}$. We emphasize that in a multi-cell VLC scenario, the adjustment of the optical transmission power per link is of major importance, in order to ensure the coexistence of parallel transmission links in adjacent cells [8]. Then, approximation presented in (10) provides a simplified calculation that can be used in the VLC-enabled devices (hotspots) with limited resources.

B. Error estimation when using the linearized LED model

Let us assume that the relevant variable to be optimized in the multi-cell VLC scenario is p_{AC} . Then, by setting the following error measurement to analyze the effectiveness of the simplified calculation in (11), i.e.

$$\eta = \frac{\mathbb{E}\{\hat{p}_{AC}\} - \bar{p}_{AC}}{\bar{p}_{AC}} \times 100, \quad (12)$$

can be used to analyze the relative error as a percentage.

IV. NUMERICAL RESULTS

Some numerical results are illustrated in this section, in order to visualize in an intuitive way the most important relationships that have been found. The model in (1) is analyzed with the parameters $I_S = 10$ nA, $T = 273 + 25$ [K], and $n = 8$. Four specific values are selected for the DC current that is applied in the LED under study, namely $I_{DC} = 90, 130, 170$, and 210 mA. These precise values of DC current were selected to be aligned with parameters reported in the data sheet of the three LED models used in our experiments². The geometric positions of this specific settings are presented in Fig. 1. The global power, modelled by (7), is shown in Fig. 3.

²To analyze the performance of few commercial LED devices, three generic LED part numbers were selected, namely: 3228 (similar SAMSUNG), 2835_4065A ("Macroled" local label), and a specific CREE model.

Fig. 4. AC power in the LED as function of m . A convenient effective sensitivity of $\hat{p}_{AC}$ according to m is observed in the presented curves.

A specific behavior is highlighted here, since it can be shown that different values were set for m in this experimental setting, namely: $m = 0.2, 0.4, 0.6, 0.8$. The constant current I_{DC} stands for the previously reported values. In spite of the changes in m , and the nonlinear current versus voltage model that is underlying for the LED, the mean power $P_{DC,AC}$ remains approximately constant. It allows us to infer that a multi-cell VLC deployment [9] can adjust the value m to optimize coverage area, without varying the light intensity in the room [10]. Note that $P_{DC,AC}$ is a variable that stands for the measured electrical power that is dissipated in the LED. The luminous intensity should be obtained from the data sheet of the LED manufacturer, which is a relationship that is expected to be nonlinear, as shown in [7]. The symbol $\Phi(P_{DC,AC})$ is used to model this transfer function.

The value $\bar{p}_{AC}$, which can be obtained from (8)), is now analyzed in detail. The chosen values for m and I_{DC} are kept as indicated previously. In Fig. 4, it is observed that the mean power $\bar{p}_{AC}$ is effectively influenced by the value in m .

Note that the power measurements in $\hat{p}_{AC}$ can be analyzed by means of the (nonlinear) transformation, which is frequently reported in the datasheets of LEDs, to indicate the luminous intensity. However, the transformation referred is frequently characterized by means of static measurements. Based on the complexity that lies behind the accurate modeling of LEDs, it is not straightforward to assume that this linearized model is accurate. In other words, although $\Phi(P_{DC,AC})$ can be found in complete data sheets, accepting also that a statement dependant on the current can be found, a similar relationship like $\Phi(\bar{p}_{AC})$ presents some uncertainties, and is not currently being published to the best knowledge of the authors.

As illustrated later, the $\bar{p}_{AC}$ power can vary the coverage range [11], as well as the nonlinear distortion in the VLC communication signal. Then, it is expected to manipulate the value of m , possibly in a closed-loop fashion with the aid of a feedback link, to optimize the coverage area and the density of VLC mobile terminals. Based on this assumptions, a simplified observation, such as the one presented in (11), seems to be useful to deal with limited resources in cost-effective devices. The error in (12) is analyzed by means of Fig. 5, which shows that this simplified estimation gives an accurate results for moderate values in m . As a rule of thumb, we can interpret that an adequate criterion is to use values of $m < 0.5$.

To sum up, it is important to emphasize that the observations

Fig. 5. Percentage of error in the simplified estimation of AC power.

Fig. 6. Experimental setup used in the practical evaluation. The deployment includes: Laptop computers to run the software-defined processing, FPGA device, DAC device, driver circuit, array of LEDs, photodiode with Transimpedance Amplifier, an SDR-based device acting as VLC receiver.

made are especially justified by relationships in the electrical domain. The transformation from electrical power to luminous intensity, not frequently informed by manufacturers so far, simply states that additional effects appear in the setting that is used to assess the performance of a VLC system.

V. EXPERIMENT WITH A REAL IMPLEMENTATION

To address a more realistic characterization of the effects involved in this application, a *software-defined* approach has been followed to implement a VLC link based on an OFDM waveform. The scenario employed an Altera(R) FPGA device with 65K logic gates and a Texas Instruments(R) DAC904 interface to implement the transmitter. A specific driver circuit was built to feed a set of LED modules connected in series. The performance of the driver achieved a bandwidth closer to 10 MHz, and DC currents up to 150 mA, along with AC amplitudes of 80 mA peak-to-peak. In addition, a PIN Photodiode Vishay(R) BPW34 was used, in connection with a SDRPlay-RSP1 device which acts as receiver. A specific Transimpedance Amplifier (TIA) has been also built, to amplify the weak current that comes at the output of the photodiode. GNUradio with special C++/Python blocks were used to drive the tests. A picture of the actual experimental setup, which was used to carry out the experiment, can be appreciated in Fig. 6.

In the OFDM setting, 64 subcarriers were included in the IFFT/FFT blocks in the transmitter/receiver. From them, only 52 subcarriers were activated, using 4 subcarriers to

Fig. 7. BER performance as function of the signal-to-noise-plus-distortion ratio (SNDR) for an uncoded OFDM-based VLC link.

Fig. 8. BER performance as function of the relative amplitude of the communications signal.

transport pilot signals to estimate the Channel State Information (CSI) in reception for equalization. An effective bitrate of 1.2 Mbps was reached when considering the payload bits. BPSK symbols were used in preamble of the OFDM frames, and QPSK symbols were used to embed the payload. Cyclic prefix extension was set to 25%. Preamble was adapted to implement Schmidl & Cox synchronization. An Intermediate Frequency (IF) carrier of 500 kHz was used to feed the LED with a real-valued signal, as the complex-valued signal at the output of the IFFT block in transmission cannot be fed directly to the intensity-modulated VLC link. The energy of the OFDM signal was concentrated around the 0.15–0.85 MHz passband.

In Fig. 7, the *bit error rate* (BER) performance is presented for an uncoded OFDM link as function of the Signal-to-Noise-plus-Distortion Ratio (SNDR). The adjustment of the transmitter pursued an increasing value in m . The observed effect is a degradation in the BER performance, since the distortion that was introduced on the VLC signal was increased as the intensity modulation index m was made stronger. Note that the higher is the intensity modulation index m , the longer is the expected coverage range of the VLC system. Then, by measuring the spectral power leakage, the nonlinear distortion was also analyzed. The labels in Fig. 7 show these measurements; however, the *power spectral density* curves of the different received OFDM signals were not included in this paper for the sake of brevity. Since the noise power in the receiver is related to the relative distance to the transmitter, Fig. 7 suggests that it is possible to find a tradeoff between noise power and (in-band) distortion power, to accommodate coverage areas of each LED in a multi-cell VLC deployment.

Figure 8 shows the BER performance of the test link against different values of relative amplitude for the communications signal. It is shown that the performance can be limited by

noise (if the amplitude of the signal is low, which in turn favors the reduction of interference to other receivers that may be nearby). In turn, the distortion significantly increases the BER when high amplitudes favor the non-linear response of the LED. Based on this statements, sophisticated control techniques, such as the ones based on machine learning which were reported in references such as [12], [13], can find the most convenient working point to minimize the impact of the non-linear LED effects that were identified in this paper.

VI. CONCLUSIONS

We used classical tools to derive the key requirements that govern the performance of a driver circuit that feeds the LED of a VLC transmitter. We also presented some novel ideas regarding to control the power in the LEDs, such that the signal at the output of the photodiode is suitable for VLC reception. The coverage area was taken into consideration and its dependence on the communications signal amplitude was analyzed. Moreover, the BER of an actual software-defined VLC link based on OFDM was measured. Complex relationships seem to be subjacent, and the convenience of efficient control techniques, such as those enabled by machine learning algorithms, are expected to be a good solution to deal with the non-linear effects in VLC systems, particularly when LEDs are configured to work at high illumination levels.

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