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Modulation Schemes Effect on the Driver Efficiency and the Global VLC Transmitter Energy Consumption

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***Abstract*—Visible Light Communications (VLC) make the most of the fast switching times of LEDs to transmit information. High transmission rates have been achieved with different modulation schemes as CSK or OFDM. However, the main asset of LED lamps, which is energy efficiency, has been overlooked. In this paper we analye how the modulation schemes affect the energy efficiency of LED lamps. We compare the effect of switched waveform (OOK, VPPM) and continuous waveform (OFDM) modulation schemes. Switched waveform signals present energy efficiency results between 15% and 30% better than continuous waveform signals.**

Keywords—VLC; Driver; Energy Efficency

I. Introduction

Over the last decade, traditional incandescent lamps have been progressively replaced by white light emitting diodes (WLED). This replacement is motivated by LED long lifetime and low heat generation, but mainly because of LED high energy efficiency. A commercial WLED is currently able to emit more than 180 lm/W [1,2], although the overall efficiency falls to 75-100 lm/W including the power supply. In order to assure a high electrical-optical conversion efficiency, a well-adapted power supply or driver is required. LED drivers should supply a constant current or voltage to the LED (or LED array) and are usually based on switched voltage sources, as they require efficiencies of more than 90% [3]. Dimming capability, which is necessary in illumination, may be accomplished with a pulse width modulation (PWM) modulated bias current using a switching metal oxide semiconductor (MOS) transistor. PWM signal controls the emitted light power so as to provide a desired mean value while its switching frequency should be high enough to avoid flickering effects.

Visible light communication (VLC) makes use of the LED short switching times to transmit information. The VLC IEEE 802.15.7 standard [4] defines three physical layers (PHY) and their related modulation schemes depending on the channel interface. PHY1 is intended for low data rate communications (<267 Kbit/s), indicating the use of On-Off keying (OOK) and variable pulse position modulation (VPPM). PHY2 and PHY3 are designed for indoor applications with moderate and high data rates (<96 Mbit/s), using OOK and VPPM and color shift keying (CSK) respectively. CSK can be used when white illumination is produced through the combination of red, green and blue (RGB) LEDs. Dimming can be achieved either by adding an extension to the transmission frame to adjust the average bias level (OOK, CSK) or by changing the pulse duty cycle (VPPM).

For OOK and VPPM modulation schemes, the transmission rate is restricted by the switching time of a WLED, determined by its phosphor layer, which is about several hundred nanoseconds, i.e. a bandwidth of a few megahertz (typically 2-3 MHz) [5]. In order to overcome this limitation, the phosphor delay can be removed at the receiver using a blue filter, which increases the bandwidth up to 20 MHz [6]. A 175 MHz bandwidth could be reached using high-frequency driver circuits [7-9]. On the other hand, when using RGB sources, the bandwidth can be increased by enabling the modulation of each color independently, known as wavelength-division multiplexing (WDM) or CSK [10-12].

High spectrally efficient techniques such as orthogonal frequency-division multiplexing (OFDM) and discrete multitone (DMT) can be used to further increase the transmission bandwidth. Due to the available signal power of VLC systems, the tradeoff between the data rate and SNR can be used. OFDM is based on the generation of a multicarrier signal, whereas each sub-carrier is independently modulated (M-QAM, MPSK) to create several parallel communications channels. Considering illumination is a unipolar signal, the traditional RF bipolar OFDM has to be adjusted. Optical OFDM can be achieved either by adding a dc-bias signal, known as DC biased optical OFDM (DCO-OFDM) [13] or by removing all the negative values at the original bipolar modulating signal, known as asymmetrically clipped OFDM

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(ACO-OFDM) [14]. ACO-OFDM is more efficient for low symbol constellations, while DCO-OFDM produces a better performance for larger constellations. Asymmetrically clipped DC biased optical OFDM (ADO-OFDM) combines both techniques to achieve greater optical power efficiency [15]. The Short-Range Optical Wireless Communications Task Group (TG 7r1) is preparing the revision of the IEEE 802.15.7r1 standard [16] and includes OFDM for high data rate communications. IEEE 802.15.7r1 proposes the use of OFDM in combination with adaptive mechanisms to adjust the system to channel variations brought about by multipath effects (e.g. wall reflections) and receiver mobility [17-19]. Many theoretical works and experiments show the applicability of OFDM and DMT schemes, reaching data rates over 1 Gbps [20-23].

The most part of research efforts have focused on increasing the transmission rate, achieving remarkable results. However, the main function of LED lamps, which is lighting, and their most relevant advantage over traditional lamps, which is energy efficiency, have been overlooked.

In this work, we study how the VLC modulation schemes affect the overall energy efficiency of an LED lamp. To illustrate how the signal waveform affects the energy efficiency of the lamp, first we analyse basic switched and sinusoidal signals. Afterwards, we compare the effect of three modulation techniques: OOK, VPPM and OFDM. Results show that when using continuous waveform (CW) signals instead of switched waveform (SW) signals, the energy efficiency of LED lamps becomes a significant issue.

II. THEORICAL MODEL

To clarify the effect of the signal waveform on the energy efficiency of an LED lamp, we consider a simplified model of an LED modulating driver circuit (see Fig. 1). For this work a single LED has been considered, though results with LED arrays are similar according to our simulations and experiments. An efficient power supply produces the bias voltage V_{DD}. This voltage is applied to the LED (or LED array) and the current (I_{LED}) is controlled by the driver.

An LED driver, in its basic setup, is formed by a MOS transistor, which controls the current applied to the LED. How this control is achieved while securing an optimal energy performance, has been the subject of many research works [24-30]. The best method for driving an LED for illumination is using a current constant source configuration. However, due to

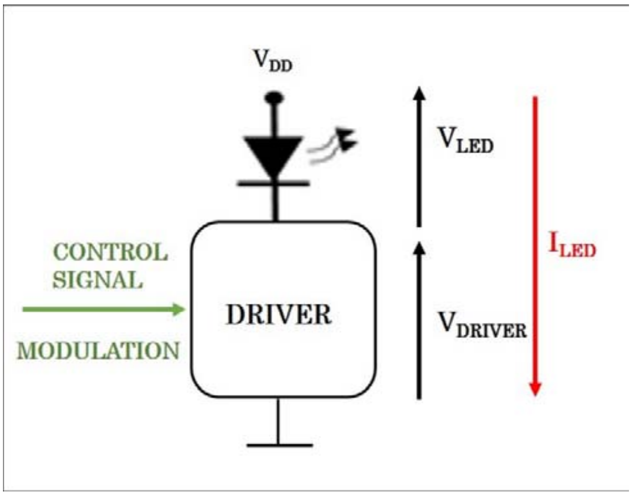

Fig. 1. Model of an LED modulating circuit.

its high impedance, it is not fast enough for the modulation function. In this work, we use a voltage constant configuration, where the MOS incorporates both VLC functions (control and modulation) in a single device. Control and modulation may be implemented using separated devices, e.g. a bias-T [31,32]. Concerning the scope of this work, i.e. the energy efficiency of drivers, would be the same for a single and two devices configuration, where it would be necessary to add the power dissipation from both the illumination and the modulation devices.

We define η, the ratio between the power dissipated by the LED and the total dissipated power, in order to analyse the energy efficiency of the driver:

$$\eta = \frac{P_{LED}}{P_{TOTAL}} \qquad (1)$$

Equation (1) defines the amount of power wasted in the driver, reducing the lamp's efficiency. As $I_{LED}=I_{DRIVER}$, η can be calculated as:

$$\eta = \frac{< v_{LED}(t) \times i_{LED}(t) >}{< v_{LED}(t) \times i_{LED}(t) > + < v_{Driver}(t) \times i_{LED}(t) >} \qquad (2)$$

Equation (2) shows that η depends on the current waveform (I_{LED}) and both LED and MOS voltages (V_{LED} and V_{DRIVER}). Both instantaneous current and voltages depend on the signal waveform. The energy efficiency ratio η can vary from between 0 (completely inefficient) to 1 (ideally efficient). V_{LED} and V_{DRIVER} are determined by the LED and MOS I-V characteristic curves including transition effects. The I-V curves of the used commercial LED (HP803WW) and MOS (MGSF1N03LT1G) have been measured experimentally for this study.

For a first analysis, we have considered square and sinusoidal signals, as examples of SW and CW signals. In Fig. 2 we represent the joint I-V curves of the LED and MOS. For the correct comparison of the signals, we establish the next two

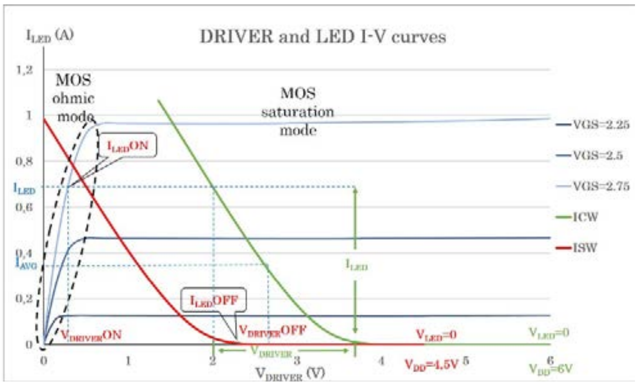

Fig. 2. I-V joint curves for the MOS (blue) and LED (red and green). The vertical axe represents the current $I_{LED}=I_{DRIVER}$. The horizontal axe represents the MOS voltage (V_{DRIVER}) starting at the origin (V_{DRIVER}=0V). Starting at V_{DRIVER}=6V and going backwards, the horizontal axe represents the LED voltage (V_{LED}). Notice that $V_{DD}=V_{DRIVER}+V_{LED}$.

constraints: current average (I_{AVG}), which sets the level of illumination and must be the same for both SW and CW; and current peak (I_{MAX}), which is limited by the LED characteristics (I_{MAX} =1A).

The MOS curves for different gate voltages (V_{GS}) are printed in blue. The red and green lines represent the I-V curves of an LED, drawn from the right hand side, i.e. V_{LED}=0V for V_{DD}=4.5V and 6V respectively.

The red line corresponds to a square (SW) signal, where the driver switches between the low state (OFF) and the high state (ON). For these V_{GS} values, the MOS changes between the cutoff mode ($V_{GS} < V_{th}$), where the MOS acts as an open circuit and there is no current; and the ohmic mode ($V_{GS} > V_{th}$ and $V_{DRIVER} < (V_{GS} - V_{th})$), where the MOS acts as a resistor controlled by the gate voltage (V_{GS}) relative to both the source and drain voltages, i.e. it depends on V_{DRIVER}. This switching is efficient because there is no power consumption in the cutoff mode, and at the ohmic mode, V_{DRIVER} is very low, so the power dissipated at the driver is low. The level of illumination (I_{AVG}) can be dimmed by varying the higher level of the SW signal or even V_{DD}, although the optimal methods change the duty cycle of the signal or add an extension to adjust the level of illumination.

On the other hand, to obtain a CW signal at the LED (green line in Fig. 2), the driver must be modulated with a sinusoidal signal. The level of illumination (I_{AVG}) is determined by the signal offset. To avoid signal distortion or clipping, the MOS must be at the saturation or conduction mode ($V_{GS} > V_{th}$ and $V_{DRIVER} > (V_{GS} - V_{th})$), where the current depends directly on V_{GS}, which is independent of V_{DRIVER}. In this mode, power dissipation at the driver is increased since there is always current (I_{LED}>0) and V_{DRIVER} is higher than in the ohmic mode.

Fig. 3 shows the effect of the signal waveform on the power dissipation over time, specifically during a signal period. Red colored lines represent a SW (square) signal. When the driver signal (V_{GS}) is set to a low value, it causes the MOS to be at the cutoff mode, where the voltage at the driver V_{DRIVER} is high, but there is not current (I_{LED}=0), and consequently there is not power dissipation (P_{DRIVER}=0). On the other hand, when V_{GS} is set to value so the MOS is in the ohmic mode, there is I_{LED} and V_{DRIVER} is low, resulting in a low P_{DRIVER}. Green colored lines represent a CW (sinusoidal) signal. In order to avoid clipping and signal distortion, V_{GS} values move within a range where the MOS is at saturation mode. As a result, P_{DRIVER} is higher, since there always happen to exist simultaneously both V_{DRIVER} and I_{LED}.

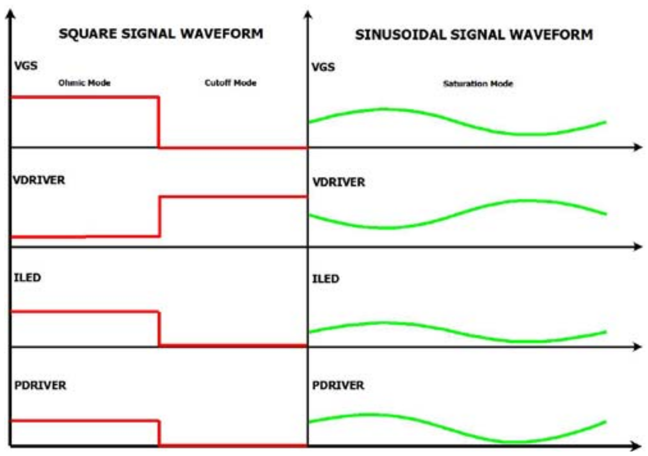

Fig. 3. Driver signals during a period time: SW (square) signal in red and CW (sinusoidal) in green).

III. Experimental results

We have modeled and simulated an LED driver circuit and calculated the driver efficiency ratio η for different illumination values (I_{AVG}). Table I shows the efficiency ratio for the square signal. The signal modulating the driver is set to an On-Off 200 KHz switching with a constant high value. The level of illumination is determined by the duty cycle (dc) and the supply voltage V_{DD}. Generally, V_{DD} will have a constant value, though it could be regulated to compensate the thermal effects. As can be seen in Table 1, above V_{DD}=5.3V, the driver (MOS) changes into the saturation mode and is no longer efficient (I_{AVG} does not further increase).

Table II shows the efficiency ratio η calculation for the sinusoidal signal. The driver modulating signal is a 200 KHz sinusoidal wave with an offset, which determines the level of illumination, and an amplitude, which is limited to avoid clipping. It can be seen how η improves when V_{DD} is reduced down to 5.4V, the limit to avoid distorting the optical signal for the given amplitude. Lower V_{DD} could be used by decreasing the signal amplitude, although it would mean a critical drop in the optical signal amplitude and consequently the SNR. It is also important to point out the η deterioration for low illumination signals (low I_{AVG}).

Looking at the energy efficiency ratio η of the two waveforms, we can see that the square signal presents much better values (≥0.88) than the sinusoidal signal (≤0.73). The difference increases for low illumination values (≥0.87) versus (≤0.58).

TABLE I. EFFICIENCY RATIO H FOR A SQUARE (SWITCHED) SIGNAL

V_{DD}	dc=25%		dc=50%		dc=75%	
(V)	*I_{AVG} (A)*	*η*	*I_{AVG} (A)*	*η*	*I_{AVG} (A)*	*η*
4	0.099	0.938	0.199	0.946	0.299	0.949
4.25	0.126	0.927	0.252	0.935	0.379	0.938
4.5	0.153	0.916	0.306	0.924	0.46	0.926
4.75	0.18	0.903	0.36	0.911	0.54	0.914
5	0.205	0.89	0.410	0.897	0.615	0.900
5.25	0.227	0.873	0.454	0.881	0.682	0.883
≥5.3	Driver (MOS) in saturation mode (I_{AVG} does not increase)					

TABLE II. EFFICIENCY RATIO H FOR A SINUSOIDAL SIGNAL

V_{DD}	offset=25%		offset=50%		offset=75%	
(V)	*I_{AVG} (A)*	*η*	*I_{AVG} (A)*	*η*	*I_{AVG} (A)*	*η*
≤5.4	Driver (MOS) in ohmic mode, clipping.					
5.5	0.242	0.582	0.481	0.666	0.721	0.732
5.75	0.242	0.551	0.481	0.648	0.721	0.708
6	0.242	0.525	0.481	0.631	0.721	0.686

After evaluating the effect of basic SW and CW signals, for the next step we consider actual VLC modulation signals: OOK, VPPM and OFDM. We study the effect for the transmission of a 128 bit data packet. As for the basic waveforms, the constraints are the level of illumination and current peaks.

First, we study the effect of an OOK modulation signal, with the parameters established by the IEEE 802.15.7 standard: 200 KHz clock frequency, Manchester encoded. Table III shows the results. As expected, we can see that the OOK signal presents a similar behavior (and η) compared to the basic SW (square) signal.

Secondly, we analyze the effect of a VPPM signal. We adjust it to the parameters of the IEEE 802.15.7 standard while maintaining the illumination level and the transmission rate: 400 KHz clock frequency, 4B6B encoded. Table IV shows the results. VPPM and OOK results are very similar, being the small differences caused by the change of clock frequency.

Finally, we study the effect of an OFDM signal. We consider a signal with 4 sub-carriers. Each sub-carrier uses a binary phase shift keying (BPSK) modulation. In order to match the OOK transmission rate, we use a 50 KHz BPSK modulated sinusoidal signal. Table V shows the energy efficiency ratio η results for the 128 bit data packet transmission.

TABLE III. EFFICIENCY RATIO H FOR AN OOK SIGNAL

V_{DD} (V)	dc=25%		dc=50%		dc=75%	
	I_{AVG} (A)	*η*	*I_{AVG} (A)*	*η*	*I_{AVG} (A)*	*η*
4	0.100	0.930	0.201	0.943	0.301	0.947
4.25	0.127	0.919	0.254	0.932	0.381	0.936
4.5	0.154	0.908	0.308	0.920	0.463	0.924
4.75	0.181	0.895	0.362	0.908	0.543	0.912
5	0.206	0.882	0.422	0.894	0.619	0.898
5.25	0.229	0.865	0.457	0.877	0.686	0.881
≥5.3	Driver (MOS) in saturation mode (I_{AVG} does not increase)					

TABLE IV. EFFICIENCY RATIO H FOR A VPPM SIGNAL

V_{DD} (V)	dc=25%		dc=50%		dc=75%	
	I_{AVG} (A)	*η*	*I_{AVG} (A)*	*η*	*I_{AVG} (A)*	*η*
4	0.100	0.928	0.201	0.942	0.301	0.949
4.25	0.127	0.917	0.254	0.931	0.381	0.937
4.5	0.154	0.905	0.308	0.919	0.462	0.926
4.75	0.180	0.893	0.362	0.907	0.542	0.913
5	0.205	0.879	0.413	0.893	0.618	0.899
5.25	0.228	0.863	0.457	0.876	0.685	0.883
≥5.3	Driver (MOS) in saturation mode (I_{AVG} does not increase)					

TABLE V. EFFICIENCY RATIO H FOR AN OFDM SIGNAL

V_{DD} (V)	offset=25%		offset=50%		offset=75%	
	I_{AVG} (A)	*η*	*I_{AVG} (A)*	*η*	*I_{AVG} (A)*	*η*
≤5.4	Driver (MOS) in ohmic mode, clipping.					
5.5	0.248	0.644	0.489	0.727	0.714	0.795
5.75	0.248	0.616	0.489	0.696	0.714	0.760
6	0.248	0.591	0.489	0.667	0.714	0.727

Although the behavior is similar to that achieved for the sinusoidal signal, η presents improved values (around 6% better). This performance is caused by the multi-carrier nature of the OFDM signal which leads to an average lower amplitude compared to the simple sinusoidal waveform, i.e. higher optical power efficiency. Energy efficiency could be improved by further reducing the signal amplitude, giving rise to SNR reduction and transmission degradation.

Fig. 4 summarizes the energy efficiency ratio η results: (a) for SW signals with the driver in the ohmic mode; (b) for CW signals with the driver in the saturation mode. Notice the different x-axis ranges in both figures.

There is a clear difference between SW signals (square, OOK and VPPM) versus CW signals (sinusoidal and OFDM). This difference is brought about by the waveform shape and the driver (MOS) working mode dependency. As we can see in Fig. 4(a), SW signals allow the driver to be in the ohmic mode, keeping a high efficiency. By adjusting the power supply V_{DD} to the optimal value (4V for this circuit), η can reach values of close to 0.95. As it can be observed, driver energy efficiency for SW signals is virtually independent of the level of illumination, which is determined by the duty cycle. On the

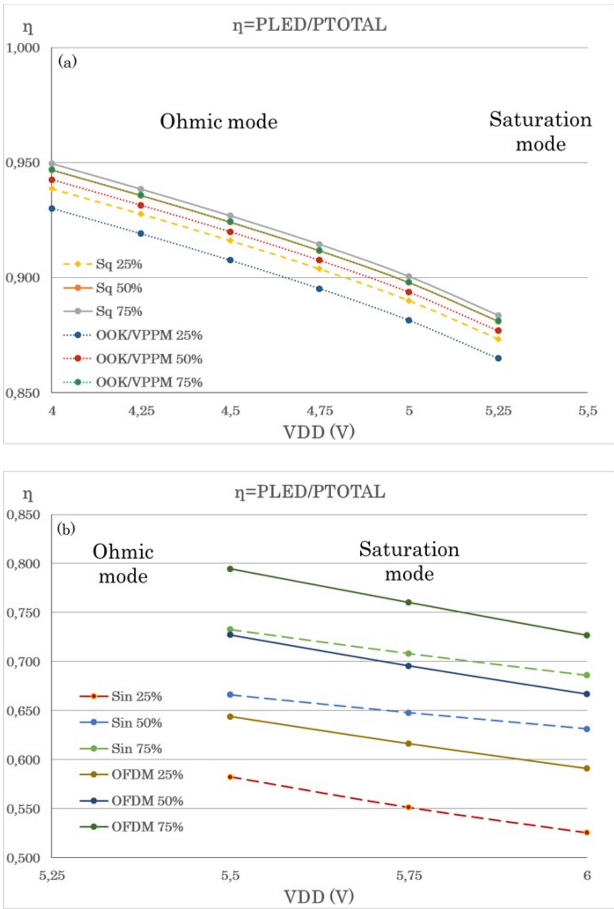

Fig. 4. Summary of results for the energy efficiency ratio η. (a) ohmic mode (switched, OOK and VPPM signals) and (b) saturation mode (sinusoidal and OFDM signals). It can be seen how η drops when increasing the power supply VDD. Furthermore, the CW signals energy efficiency ratio radically decreases for low illumination values.

other hand (see Fig. 4(b)), the CW signals force the MOS to be in the saturation mode to avoid clipping, where the efficiency drops significantly. By regulating the power supply V_{DD} to the lower value without signal distortion (5.5V for this circuit), η cannot reach the 0.8 mark, for the best case, which is the high illumination level OFDM signal. Since for CW signals η is illumination-dependent, it drastically degenerates for low levels of illumination.

In summary, the energy efficiency ratio η is higher for SW signals than for CW signals: $\eta \leq 0.95$ vs $\eta \geq 0.795$ for high levels of illumination; and $\eta \geq 0.865$ vs $\eta \leq 0.644$ for low levels of illumination.

VLC emitters are LED lamps, generally formed by and an array of high power LEDs, resulting in a high emitted optical power. Therefore, the SNR, and consequently the Bit Error Rate (BER) and the Channel Capacity (C), depend directly on the optical signal amplitude. For SW signals, the signals amplitude is constant and equals to I_{MAX}. For CW, the amplitude is affected by dimming: it is I_{MAX} for the 50% illumination level signal, but is limited to $2(I_{MAX}-I_{AVG})$ for dimming>50% and $2I_{AVG}$ for dimming<50%. Reducing signal amplitude below these values could improve the energy efficiency of CW signals (enabling V_{DD} reduction without distortion). However, amplitude reduction would cause SNR degradation, minimizing the spectral efficiency.

For SW signals the SNR remains almost constant for different energy efficiency ratios, while for CW signals, SNR is inversely proportional to η. In order to compare the tradeoff between the energy efficiency and the achievable data rates of the modulation techniques, schemes with comparable data rates, as CSK and OFDM should be analysed. This analysis will be presented in future works.

IV. Conclusions

In conclusion, this work shows, that the waveform shape strongly influences the overall energy efficiency of an LED lamp. SW signal-based modulations (such as OOK or VPPM) have a high energy performance ($0.86 \leq \eta \leq 0.95$), while CW signal-based modulations (such as OFDM) reduce energy efficiency ($0.59 \leq \eta \leq 0.79$), mainly constrained by the signal amplitude and the level of illumination.

It is important to remember that the primary lamp function is lighting, and that the main reason why LED lamps are replacing traditional lighting sources is their energy efficiency. Therefore, when using LED lamps as VLC transmission devices, a balance between energy efficiency and binary rates should be achieved.

We think this work should help to raise awareness on the energy efficiency of VLC drivers and boost research community to find solutions to this issue.

The effect on the emitter efficiency of the other modulation scheme proposed in the IEEE 802.15.7 standard (CSK) is currently being researched and will be presented in future works. High energy efficiency results are expected as CSK use signals with similar characteristics to OOK and VPPM, i.e. SW signals.

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