Constraints on drivers for visible light communications emitters based on energy efficiency

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Abstract: In this work we analyze the energy efficiency constraints on drivers for Visible light communication (VLC) emitters. This is the main reason why LED is becoming the main source of illumination. We study the effect of the waveform shape and the modulation techniques on the overall energy efficiency of an LED lamp. For a similar level of illumination, we calculate the emitter energy efficiency ratio η (P_{LED}/P_{TOTAL}) for different signals. We compare switched and sinusoidal signals and analyze the effect of both OOK and OFDM modulation techniques depending on the power supply adjustment, level of illumination and signal amplitude distortion. Switched and OOK signals present higher energy efficiency behaviors ($0.86 \leq \eta \leq 0.95$) than sinusoidal and OFDM signals ($0.53 \leq \eta \leq 0.79$).

OCIS codes: (060.4510) Optical communications; (060.2605) Free-space optical communication; (230.3670) Light-emitting diodes.

References and links

1. S. Nizamoglu, G. Zengin, and H. V. Demir, "Color-converting combinations of nanocrystal emitters for warm-white light generation with high color rendering index," Appl. Phys. Lett. **92**(3), 031102 (2008).
2. H. Chiu, Y. Lo, J. Chen, S. Cheng, C. Lin, and S. Mou, "A high efficiency dimmable LED driver for low-power lighting applications," IEEE Trans. Ind. Electron. **57**(2), 735–743 (2010).
3. "IEEE Standard for Local and Metropolitan Area Networks–Part 15.7: Short-Range Wireless Optical Communication Using Visible Light," (2011).
4. O. Gonzalez, R. Perez-Jimenez, S. Rodriguez, J. Rabadan, and A. Ayala, "OFDM over indoor wireless optical channel," IEE Proc., Optoelectron. **152**(4), 199–204 (2005).
5. J. Armstrong and A. J. Lowery, "Power efficient optical OFDM," Electron. Lett. **42**(6), 370–372 (2006).
6. S. D. Dissanayake and J. Armstrong, "Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD systems," J. Lightwave Technol. **31**(7), 1063–1072 (2013).
7. A. H. Azhar, T. A. Tran, and D. O'brien, "A gigabit/s indoor wireless transmission using MIMO-OFDM visible-light communications," IEEE Photonics Technol. Lett. **25**(2), 171–174 (2013).
8. G. Cossu, R. Corsini, and E. Ciaramella, "High-speed bi-directional optical wireless system in non-directed line-of-sight configuration," J. Lightwave Technol. **32**(10), 2035–2040 (2014).
9. A. Tsiatmas, C. P. M. J. Baggen, F. M. J. Willems, J.-P. M. G. Linnartz, and J. W. M. Bergmans, "An illumination perspective on visible light communications," IEEE Commun. Mag. **52**(7), 64–71 (2014).
10. M. Arias, A. Vázquez, and J. Sebastián, "An overview of the AC-DC and DC-DC converters for LED lighting applications," Automatika (Zagreb) **53**(2), 156–172 (2012).
11. J. M. Alonso, J. Vina, D. G. Vaquero, G. Martinez, and R. Osorio, "Analysis and design of the integrated double buck–boost converter as a high-power-factor driver for power-LED lamps," IEEE Trans. Ind. Electron. **59**(4), 1689–1697 (2012).

1. Introduction

Over the last decade, white light emitting diodes (WLED) have been increasingly replacing traditional incandescent lamps, due to their long lifetime and low heat generation, but mainly because of their high energy efficiency. A commercial WLED is currently able to emit more than 180 lm/W [1]. Nevertheless, high electrical-optical conversion efficiencies require well-adapted power supplies (drivers). These devices should supply a constant current or voltage to

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the LED (or LED array) while maintaining robustness against aging, temperature changes or voltage fluctuations. They are usually based on switched voltage sources, as they require efficiencies of more than 90% [2]. In order to include a dimming capability, as required in illumination, a switching metal oxide semiconductor (MOS) transistor and a pulse width modulation (PWM) modulated bias current can be used. Its switching frequency should be high enough to avoid flickering effects, while controlling the emitted light power so as to provide a desired mean value.

Visible light communication (VLC) is based on the dual use of LED lamps for illumination and communication. VLC makes use of the LED short switching times to transmit information. The VLC IEEE 802.15.7 [3] standard defines three physical layers (PHY): PHY1 is intended for low data rate communications (<267 Kbit/s) using 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 both previous modulations and color shift keying (CSK) respectively. For OOK and VPPM modulation schemes, the transmission rate is limited by the switching time of a conventional PhB WLED, brought about by its phosphor layer.

In order to further increase the transmission bandwidth, high spectrally efficient techniques such as orthogonal frequency-division multiplexing (OFDM) and discrete multitone (DMT) can be used. The VLC field is a good candidate for applying these techniques, because of its intrinsic large signal power, so the tradeoff between the data rate and SNR can be used. The working group preparing the revision of the IEEE 802.15.7r1 standard identifies 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. OFDM generates a multicarrier signal, whereas each sub-carrier is independently modulated (M-QAM, MPSK) to create several parallel communications channels. Bearing in mind that illumination is a unipolar signal, the traditional bipolar OFDM has to be adapted. Optical OFDM can be achieved either by adding a dc-bias signal, known as DC biased optical OFDM (DCO-OFDM) [4] or by removing all the negative values at the original bipolar modulating signal, known as asymmetrically clipped OFDM (ACO-OFDM) [5]. 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 [6]. Many theoretical works and experiments show the applicability of OFDM and DMT techniques, reaching data rates over 1 Gbps [7,8]. However, as all the research efforts have focused on increasing the transmission rate, the main function of LED lamps, which is lighting, and their most relevant advantage over traditional lamps, which is energy efficiency, has been overlooked.

In this work, we study how the waveform shape and the modulation techniques affect the overall energy efficiency of an LED lamp. When using continuous waveform (CW) signals instead of switched waveform (SW) signals, the energy efficiency of LED lamps becomes a problem. To clarify how the signal waveform affects the energy efficiency of the lamp, first we analyze basic switched and sinusoidal signals. After that, we compare the effect of two modulation techniques: OOK and OFDM.

2. Theorical model

Figure 1 shows a simplified model of an LED modulating driver circuit. 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. For this work a single LED has been considered, though results with LED arrays are similar according to our simulations.

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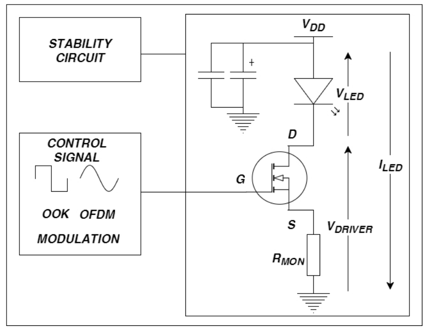

Fig. 1. Model of a LED modulating circuit.

The most extended method for driving an LED for illumination is using a current constant source. Manufacturers as Osram and Cree, and electronic component designers as Texas Instruments use it for power control purposes. For high-speed switching it is usually employed a constant-voltage configuration, based on a MOS transistor, which controls the current applied to the LED as depicted in Fig. 1. The MOS integrates both VLC functions (control and modulation) in a single device and its behavior in terms of energy performance has been the subject of many research works [9–11]. See Fig. 7 in Ref [11] for an example of an efficient LED driver with the MOS as the control element. Regarding energy efficiency considerations, the effect of the stability circuit can be neglected. In order to analyze the effect of the waveform shape, we define η as the ratio between the power dissipated by the LED and the total dissipated power:

$$\eta = \frac{P_{LED}}{P_{TOTAL}} = \frac{< v_{LED}(t) \times i_{LED}(t) >}{< v_{LED}(t) \times i_{LED}(t) > + < v_{DRIVER}(t) \times i_{LED}(t) >} \tag{1}$$

Equation (1) defines the amount of power budget in the driver and considers $I_{LED} = I_{DRIVER}$. It is clear that η depends on the current waveform (I_{LED}) and both V_{LED} and V_{DRIVER}. Both instantaneous current and voltages depend on the signal waveform. The energy efficiency ratio η can vary from 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. Figure 2 shows the joint I-V curves. For a first analysis, we have considered square and sinusoidal signals, as examples of SW and CW signals. For the correct comparison of the signals, the two main constraints are: 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 (I_D vs. V_{DS}) 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). 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 the 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 frame extension to adjust the level of illumination [3].

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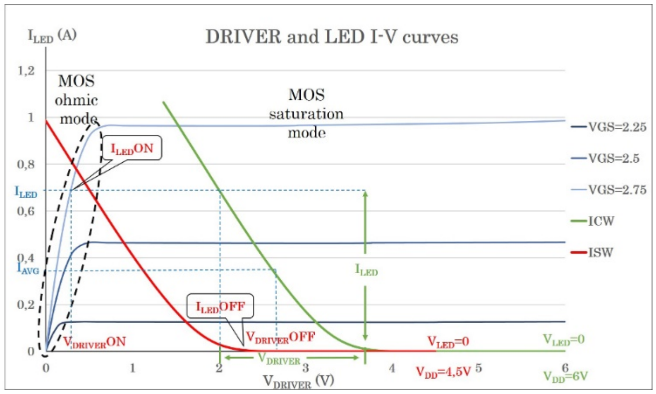

Fig. 2. I-V joint curves for the MOS (blue) and LED (red and green). The vertical axe represents the current $I_{LED} = I_{DRIVER}$. The horizontal axe represents the MOS voltage (V_{DRIVER}) starting at the origin ($V_{DRIVER} = 0V$). Starting at $V_{DRIVER} = 6V$ and going backwards, the horizontal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

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>0) and V_{DRIVER} is higher than in the ohmic mode.

3. Experimental results and discussion

We have modeled and simulated an LED driver circuit and calculated the driver efficiency ratio η for different illumination values (I_{AVG}). Table 1 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 can be slowly changed to compensate the thermal drifts. 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.

Table 1. Efficiency ratio η for a square (switched) signal.

	dc = 25%		dc = 50%		dc = 75%	
V_{DD} (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	0.460	0.926
4.75	0.180	0.903	0.360	0.911	0.540	0.914
5	0.205	0.890	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					

Table 2 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. It is also important to point out the η deterioration for low illumination signals, i.e. low I_{AVG}.

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Table 2. Efficiency ratio η for a sinusoidal signal.

	offset = 25%		offset = 50%		offset = 75%	
V_{DD} (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

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). After studying the effect of basic SW and CW signals, for the next step we consider actual VLC modulation signals: OOK and OFDM. We study the effect for the transmission of a 128 bit data packet. As for the basic waveforms, the level of illumination and current peaks are the used constraints. First, we consider an OOK modulation signal, with the parameters established by the IEEE 802.15.7 standard [3]: 200 KHz clock frequency, Manchester encoded. Table 3 shows the results.

Table 3. Efficiency ratio η for an OOK signal.

	dc = 25%		dc = 50%		dc = 75%	
V_{DD} (V)	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					

As expected, we can see that the OOK signal presents a similar behavior (and η) compared to the basic SW signal. 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 4 shows the energy efficiency ratio η results for the 128 bit data packet transmission. Although the behavior is similar to that achieved for the sinusoidal signal, η presents improved values (around 6% better). This performance change 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. Regarding SNR, in SW, the signal amplitude is constant, and equals I_{MAX}. On CW the amplitude is limited to the minimum value of $2(I_{MAX}-I_{AVG})$ or $2I_{AVG}$ due to distortion avoidance. Thus, CW dimming affects the receiver SNR.

Table 4. Efficiency ratio η for an OFDM signal.

	offset = 25%		offset = 50%		offset = 75%	
V_{DD} (V)	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

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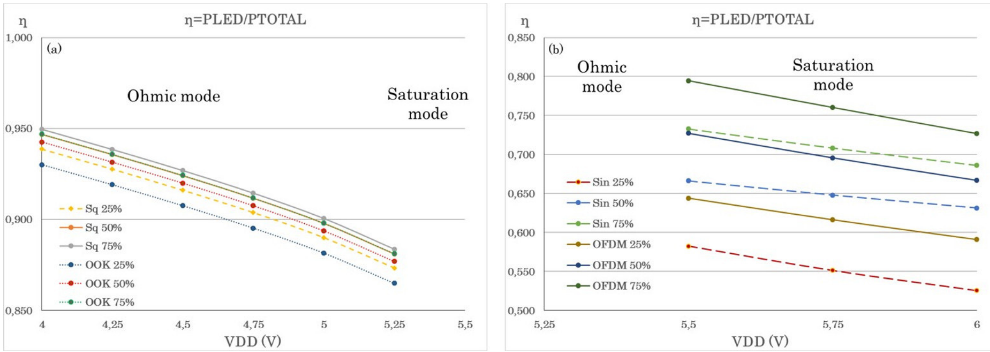

Fig. 3. Summary of results for the energy efficiency ratio η. (a) ohmic mode (switched and OOK signals) and (b) saturation mode (sinusoidal and OFDM signals). It can be seen how η drops when increasing the power supply V_{DD}. Furthermore, the CW signals energy efficiency ratio radically decreases for low illumination values.

Figure 3 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 and OOK) 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. 3(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), η can reach values of close to 0.95, which is virtually independent of the level of illumination, which is determined by the duty cycle. On the other hand [see Fig. 3(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), 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.

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

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