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A Review of Visible Light Communication LED Drivers

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***Abstract*—This paper presents a survey of LED drivers for Visible light communication by making a systematization of the most relevant published research. The modulator circuits were classified according to four types. To match the solutions with potential applications, power and efficiency ratings of conventional lighting and data rate of typical multimedia streaming are used as reference values. In conclusion, Linear Mode Modulators (LMMs) lead the number of publications and Switching Mode-based Modulators (SMMs) are a recent trend. SMMs can provide a good efficiency supporting power levels for indoor and outdoor luminaries and data rate for audio streaming. LMMs support video streaming given the higher data rates; however, the power rating corresponds to, at most, indoor illumination with significant lower efficiency.**

***Index Terms*—Visible light communication (VLC), LED Drivers, Efficiency, Illumination, Data Rate, Digital Communication.**

I. Introduction

Visible light communication (VLC) can be considered as a green technology [1] because it can save energy by using the light for both lighting and communication purposes. To achieve this goal, it must be assured that the communication functionality does not significantly degrade the system efficacy compared to conventional LED luminaries. Energy focused solutions of circuits capable of controlling the power provided to LEDs, simultaneously addressing illumination aspects and communication concerns, are called VLC LED drivers [2].The LED efficacy under VLC modulation and the selected electronic driver circuitry are critical aspects for the system global efficiency [3], [4] .

A great number of different approaches of VLC LED drivers have been presented in the literature, which will be reviewed and classified in this paper. There are several investigation approaches that concern the implementation of a VLC LED driver, Fig. 1a systematises research in four distinct wide areas, namely: i) channel and applications, ii) codes and methods, iii) communication stack and integration, and iv) hardware and methods. Among these, the hardware and methods concern circuits, physical devices and its technologies. In the context of the electronic circuits, this paper aims at reviewing the current solutions for energy conversion and data transmission in VLC applications.

The features concerning energy conversion and data transmission in a VLC LED driver are in the physical layer of the communication stack; these relations are systematised in Fig. 1b. The implementation of light modulation depends on the LED current control capability. This function is performed by an electronic circuit that is the target of the current study.

The main focus is made on organizing the available information to guide future works, identifying opportunities and exposing advantages and limitations of the presented solutions. The references included in this survey were selected according to the following criteria:

- **Inclusion Criteria**: Published works aiming at VLC applications that present circuits or test electronic drivers in which the modulator type was clearly specified [2], [3], [5], [6], [8]–[47] .
- **Exclusion Criteria**: i) References focused only on LED characterization, VLC channel analysis, receiver design or modulation schemes, without driver specification, and ii) proposed topologies without mathematical support or without simulation or experimental results.

There are previous papers in the literature that have presented reviews about VLC LED drivers [1], [5]–[10], [37], [39]. However, none of these works have a surveying approach, nor proposed any systematization of the literature based on the presented data. This work is an improved version of a previous manuscript [49] in which the whole

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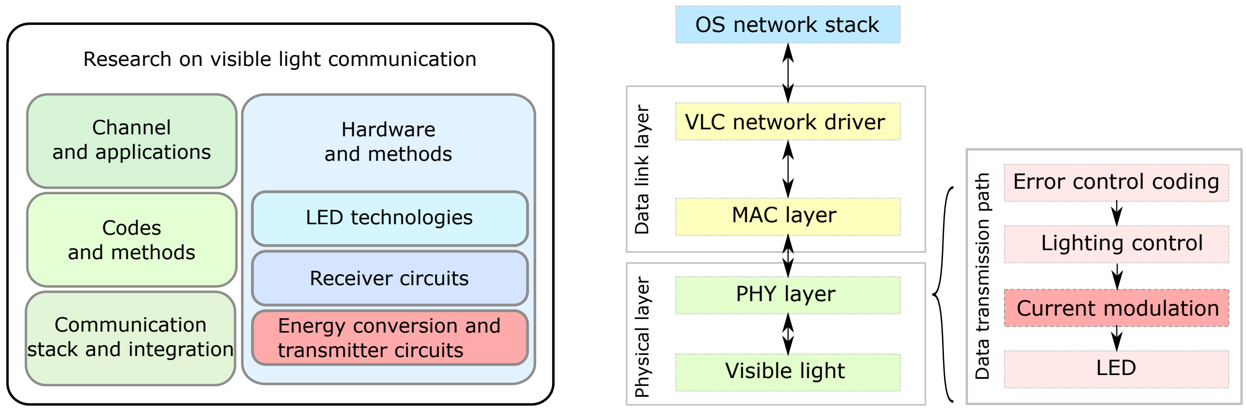


(a) Current work context on VLC research.

(b) VLC communication stack based on [48].

Fig. 1. Research context and application in a communication stack.

analysis has been reviewed and new information related to modulation schemes, circuit topologies and signal amplitude has been included. Furthermore, this survey was updated with recently published works and a summary table of the features of the modulators was included as a general easy-guide for the reader.

This work is organized as follows. First, an overview of modulation strategies commonly used for VLC is presented in Section II. Second, the structure of a VLC LED driver is presented in Section III. Third, the proposed modulator classification is described in Section IV. Fourth, the state of the art of VLC LED drivers including the most relevant performance figures is presented in Section V. Finally, Section VI summarizes the conclusions of this review.

II. Modulation Strategies for VLC Applications

In a VLC application, the communication signal is carried by the LED irradiated light. It is unipolar because the light is modulated in intensity; therefore, the common passband modulation schemes can only be used with a superimposed dc level or other modification. Most literature assumes that the light intensity of an LED is proportional to its current, both of them keeping the same waveform because of the quasi-linear relationship between them [50]. For VLC, the average light level is used to provide the visual perception, in which the communication signal must not take part. For this purpose, the communication signal must be allocated in a band free of harmful flicker effects, known as flicker-safe band [51], [52]. In this review, bandwidth, bit load and spectral efficiency will be addressed from a communication perspective.

The selection of the modulation strategy represents a very important aspect of the VLC system since it defines the features and possible topologies of the modulator. Fig. 2 illustrates the waveforms of the most common VLC modulation schemes. In the following a brief description of the main aspects of modulation schemes that are pertinent to this work is presented.

Baseband modulation schemes use a predefined sets of pulse shapes, usually rectangular pulses, which are also known as line codes. Examples include binary pulse modulation schemes as on-off keying (OOK), variable pulse-position modulation (VPPM), 2-level pulse amplitude modulation (PAM), and multiple level PAM, as for example 4-level PAM and 8-level PAM. Manchester is a line code that has no components at low frequencies other than the dc parcel; it ensures no flicker if a high enough carrier frequency is thus selected. However, the other line codes cannot ensure a flicker-safe communication in VLC, since the corresponding spectrum of the signal is dependent on the pulse harmonic components and symbol rate. Hence, to avoid harmful flicker, commonly an encoding method is applied before the line code generation, e. g. 4B6B, 8B10B or other run-length limited codes [53]. Other strategies to compensate the average light level and avoid flicker can be implemented in the time interval between frames (inter-frame) [54]. However, these line codes and inter-frame strategies also affect the

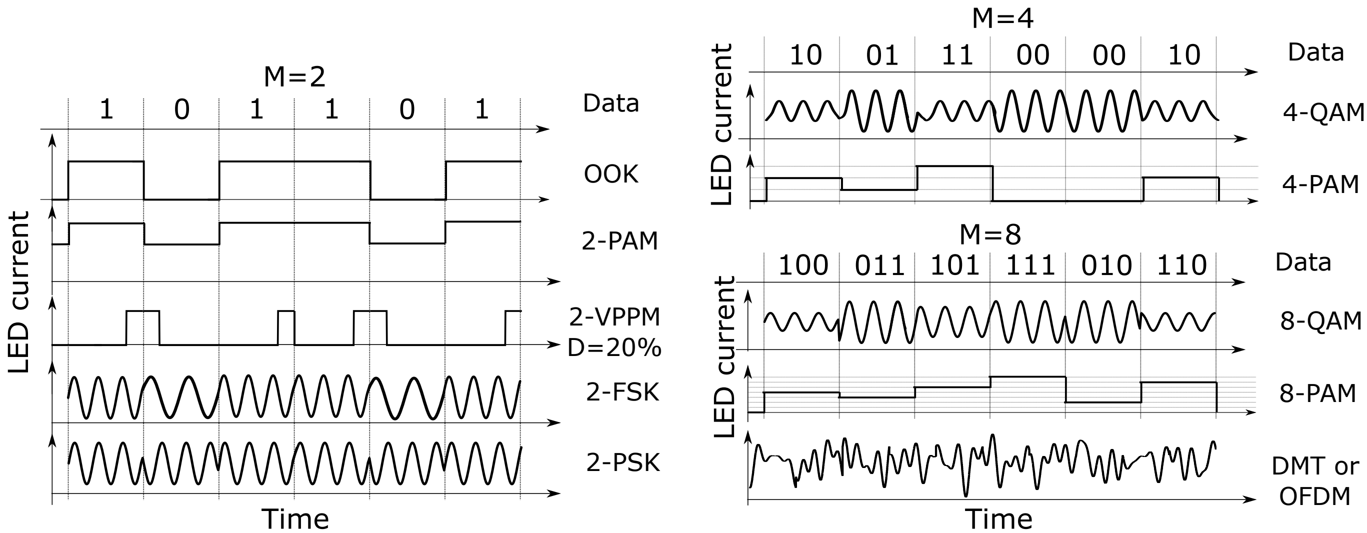


Fig. 2. VLC modulation waveforms.

bandwidth to data rate trade-off, harming the overall communication performance.

Passband modulation schemes are generated by shifting the frequency of a baseband signal into a higher band. In VLC, common passband schemes are usually modified for unipolar signaling or biased with enough dc level to avoid negative signal value. One or more carriers can be used in the modulated signal, known as single carrier modulation scheme (SCM) or multiple carrier modulation scheme (MCM), respectively. Examples of SCM are phase-shift keying (PSK), frequency-shift keying (FSK) and quadrature amplitude modulation (QAM). An example of MCM is the orthogonal frequency-division multiplexing (OFDM). Several different OFDM schemes are used in VLC because of the non-negative signal restriction, for example, Direct Current-Offset OFDM (DCO-OFDM) [55], Asymmetrically Clipped Optical OFDM (ACO-OFDM) [56], Flip-OFDM [57] and Unipolar OFDM (U-OFDM) [58].

From the driver design point of view, this wide sort of modulation schemes can be separated into two groups. Firstly, binary pulse modulation schemes, more generally called OOK-based, as OOK and VPPM, can be generated by simply interrupting or shunting the LED current and can be implemented by simple circuits. Secondly, the other modulation schemes demand more sophisticated drivers that are able to fine modulate the current at several instantaneous values in a continuous fashion. These schemes usually provide advantages such as easily increasing the spectral efficiency and handling channel distortions.

Therefore, frequency spectrum of binary pulse modulation schemes includes less signal power inside the essential bandwidth when compared to other more complex modulation schemes. Particularly, phosphor-covered white LEDs exhibit a characteristic cutoff frequency in the range from 3 to 3.8 MHz, which limits signal bandwidth and data rate in VLC applications [11] if no equalization or pre-emphasis is applied. In this sense, modulation schemes with a narrower spectral power distribution take more advantage of this technology.

In this paper, when referring all sort of modulation schemes, the prefix of the modulation names (M) represents the number of the different symbols provided by the scheme, e.g. 4-PAM and 64-QAM. Therefore, the bit load of this modulation can be calculated as $log_2(M)$ bit/symbol. The spectral efficiency is the quotient between the modulation data rate and its bandwidth, measured in bps/Hz. The higher this quotient, the higher the maximum data rate a given modulation scheme can achieve using a fixed signal bandwidth. In this sense, also the signal amplitude shall be accordingly scaled to allow the receiver to detect the transmitted symbols correctly. For this reason, LED's forward current standard deviation is used to represent the amplitude of the communication signal in a more general fashion than only peak or peak-to-peak measurement. Since a large number of samples is used, this metric is

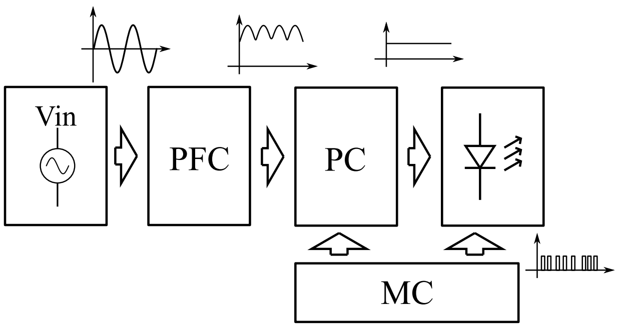


Fig. 3. VLC LED driver structure.

equivalent to the calculation of the root mean square of this variable after removing its dc parcel.

III. VLC Driver Structure

The block diagram of a VLC LED driver is illustrated in Fig. 3, which consists on the three following stages:

1) Power Factor Correction (PFC) stage: This first block rectifies the ac grid voltage while assuring a low distortion of the current drained from the grid to satisfy energy quality standards. This requirement is very restrictive in illumination devices with power above 5 W.

2) Power Control (PC) stage: This block is used to generate a regulated dc voltage or current to supply the LED at its nominal operating point. Moreover, dimming may be accomplished by this block. This converter must be able to regulate the output voltage of the PFC stage, filtering any residual low frequency ripple.

3) Modulator for Communication (MC) stage: This is the extra block that adds the VLC functionality to a conventional LED driver. It is dedicated to generate the VLC LED stimuli, which can be obtained by a voltage or current shaping process. The circuit topology of this block is defined according to the type of modulation and bandwidth requirements, among other aspects like cost, circuit complexity, efficiency, etc.

However, not all of these blocks are required in every VLC system. For example, a battery-operated LED driver will omit the PFC stage. Likewise, the separation among circuit blocks is not mandatory, e.g. integrated power stages may perform two functions simultaneously in a single stage [59]. Next section presents the proposed classification of the circuit topologies used as modulator for VLC.

IV. Modulator Types

In this section, a classification of the different modulators is presented. This classification will be used in Section V to sort the works published in the literature and to explore their most relevant features. Four types of circuits are defined according to their operating principles:

A. Linear Mode Modulator (LMM)

These topologies are based on transistors operating within their linear region. Common types are class A, B, AB and C amplifiers. Particularly, class C amplifiers can also be used as narrowband amplifiers. Thus, they operate based on a dissipative principle because there is a considerable voltage across the transistors power terminals simultaneously to the main current flow in order to keep the desired operating point. Therefore, the energy efficiency of this class of modulator is usually lower than the efficiency achieved by other modulator types. This type of circuit is used as radio frequency (RF) amplifier and in a wide variety of applications because they allow for fine shaping of output signal without pronounced distortions or shape limitations other than the characteristic bandwidth.

B. Switching Mode Modulator (SMM)

These converters are based on transistors operating in saturation or cut-off regions to generate a square waveform that is afterward applied to an LC band-pass filter or low-pass filter. In this sense, the low-pass filter-based modulator, as the class D circuit, fits better for VLC application because it can provide the constant bias current together with the current modulation capability. The low-pass-filter based modulator is designed so that it allows the communication signal to be applied to the LED while attenuating the higher switching frequency harmonics. Its operating principle provides higher efficiency because both conduction and switching losses are low.

The choice of switching frequency directly affects the filter passband bandwidth while the dc level is employed to provide the average illumination. SMMs can be operated in two different ways:

1) Average Current Control: It consists of shaping the LED average current by modulating the duty cycle (D) [6], [8], [24], [38] to track the reference of the VLC signal whose harmonic content remains within the filter passband.

2) Ripple Modulation (RM): It takes advantage of the converter inherent residual frequency content that remains after filtering. This can be implemented either by controlling the frequency [18] or the phase (ϕ) [2], [36], [41], [47] of the switching signal according to the information to be transmitted. Hence, this scheme allows the signal band to exceed the filter bandwidth. However, in this case, the resulting signal shape is directly dependent on the filter parameters.

C. Series Switch Modulator (SSM)

This modulator is based on turning on and off the LED by using a series switch. This circuit cannot control the instantaneous current level, which is regulated through the PC stage. As the actuator, a single transistor, e.g. a BJT or MOSFET, is usually employed. This type of modulator differs from LMM in that there is no transistor bias current to operate the transistor in linear region. On the contrary, the transistor is operated in cut-off and saturation regions, as an open and closed switch, respectively. Therefore, this circuit is only able to generate rectangular pulses, which reduces the possible signal modulation space. An alternative implementation of this circuit consists of using one additional switch to sweep out the remaining electrical carriers from the LED P-N junction during the turn-off process. This decreases the turn-off time and helps in enlarging the modulation bandwidth [5], [16].

D. Parallel Switch Modulator (PSM)

This modulator is based on supplying the LED by a constant current source, which can be shunted by a switch connected in parallel with the LED. When the switch is turned on, the current through the LED is interrupted. Therefore, it can reproduce binary pulse modulation schemes that require only on and off levels, similarly as in the case of the SSM. However, this solution presents lower efficiency due to the power losses in the switch during shunting [6].

E. Possible modulation schemes

The previously presented modulator types have specific limitations regarding the modulation schemes that can be generated. Table I depicts the modulator types with the corresponding possible modulation schemes.

V. Review of VLC LED Drivers

In order to compare the performance of the different solutions investigated in this review, commercial performance metrics used for conventional lighting are used as reference levels [60]. These levels are employed when comparing i) power rating: decorative spot light (84 lm @ 1.1 W), T8 2ft and 5ft LED retrofit (800 lm @ 7.6 W and 2000 lm @ 19.1 W, respectively) and outdoor (8000 lm @ 50 W); ii) efficiency rating: outdoor high power (92% @ 250 W), outdoor intermediary power (87% @ 50 W) and compact indoor (82% @ 8 W). Similarly, the data rate used in common applications of wireless local area network communications and in multimedia streaming are used as a reference [61]:

i) Wi-Fi 4 (IEEE 802.11n, 600 Mbps), Wi-Fi 5 (IEEE 802.11ac, 3.47 Gbps), and Wi-Fi 6 (IEEE 802.11ax, 9.61 Gbps); ii) audio: mobile phone (8 kbps), digital broadcasting (192 kbps) and high fidelity (1 Mbps); iii) MPEG-4 encoded video: 1080p HDTV (20 Mbps), 4k UHDTV (240 Mbps) and 8k UHDTV (480 Mbps). However, some of the publications do not provide information on these specific metrics and therefore they could not be included in the comparison.

The VLC drivers are classified following 4 key aspects that are present in any analysis, namely: i) power level, ii) energy efficiency, iii) data rate and iv) circuit type, as is summarized in Fig. 4. Those aspects comprehend the lighting, the application in communications and the implementation of the modulators for VLC.

A. Publication Chronology

Fig. 5 depicts the accumulated number of publications of each year from 2008 to 2019 classified according to the modulator type. Those publications that presented more than one modulator type were considered multiple times. This is the reason why the total accumulated number of publication in 2019 (49) exceeds the number of references included in this review (44).

TABLE I
MODULATOR TYPES WITH POSSIBLE MODULATION SCHEMES.

Modulator type	**Modulation scheme**			
	Baseband		**Passband**	
	Binary pulse based [a]	**Multiple-level pulse based** [b]	**Single carrier** [c]	**Multiple carrier** [d]
LMM	X	X	X	X
SMM	X	X	X	X
SSM	X [e]			
PSM	X [e]			

[a] Examples: OOK, VPPM, PWM.
[b] Example: M-PAM.
[c] Examples: dc-biased ASK, PSK and QAM.
[d] Examples: DCO-OFDM, ACO-OFDM, Flip-OFDM, U-OFDM, dc-biased DMT.
[e] One of the light levels is zero, therefore the signal amplitude is associated with the average signal value.

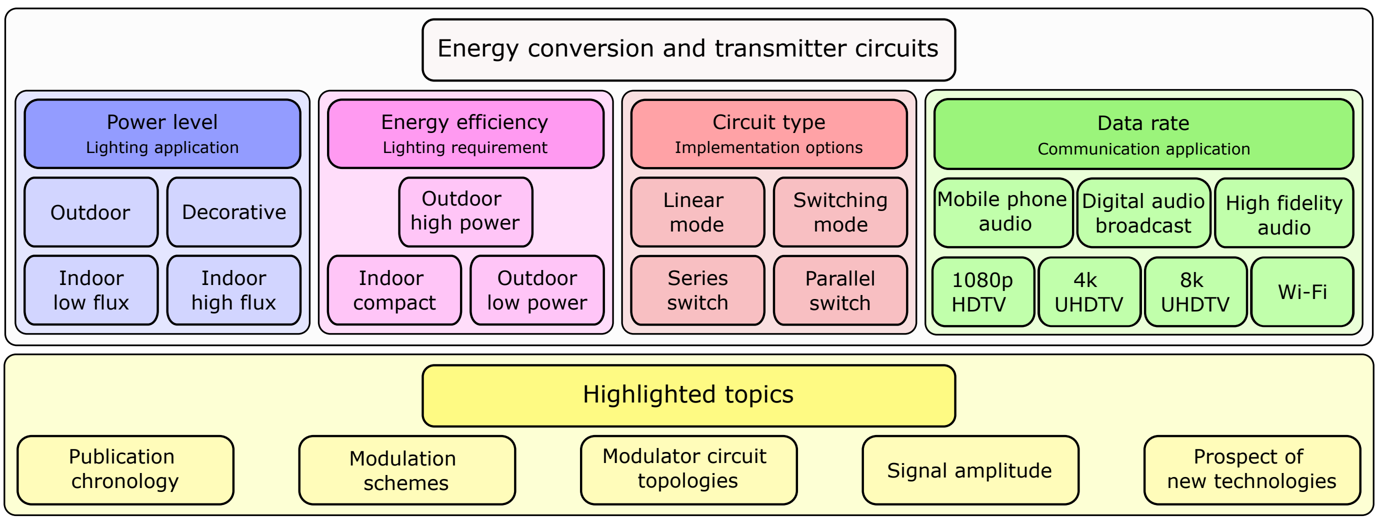


Fig. 4. Key aspects of the review on energy conversion and transmitter circuits.

The first conclusion based on this data is that LMM-based converters lead the number of published works. However, it can be seen that SMMs have experienced a great increase since 2016, overcoming the number of published works based on SSM in 2018. A second conclusion is that the research about VLC trends to the same circuit types as used in conventional LED drivers, most of them based on SMM. This suggests that such design trend is motivated by the fact that designers are pursuing higher efficiency and lower circuit complexity, both of them attainable by reducing the number of power processing stages.

B. Modulation Schemes

Table II shows the number of publications according to modulator types and modulation band. As can be seen, most of the publications corresponds to baseband implementations, even though these schemes are more likely to generate harmful flicker. Table III gathers the number of publications according to the modulation schemes and modulator type. As can be seen, the binary pulse modulation schemes are very often reported [3], [5], [6], [9], [11]–[13], [15]–[17], [19]–[23], [25], [26], [28], [30], [32], [35], [38], [43], [45]. The popularity of these modulation schemes can be explained by two main reasons:

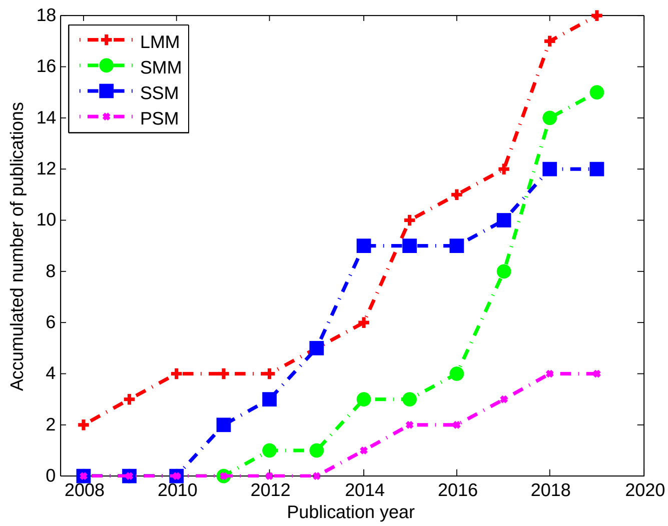
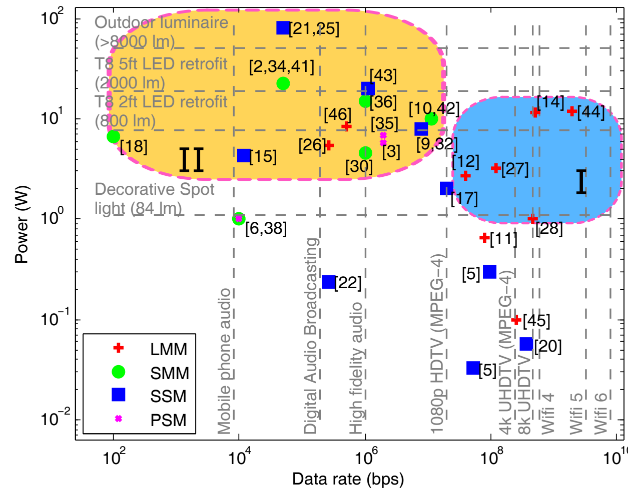


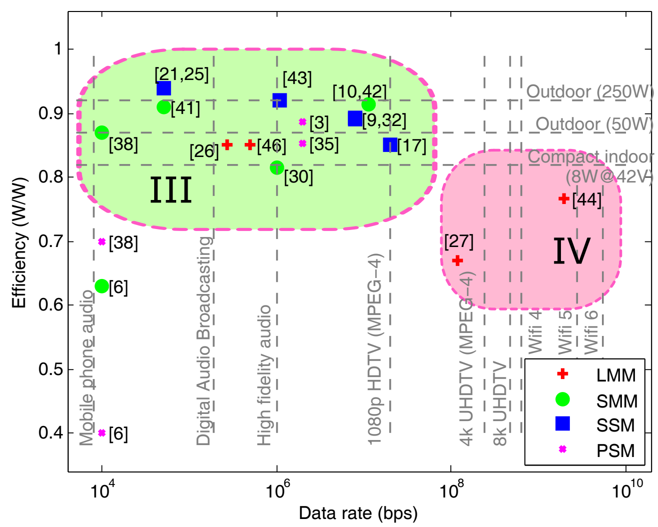
Fig. 5. Accumulated number of publications on VLC drivers.

- They can be implemented with simple solutions as SSM or PSM, but also with more complex modulators as LMM or SMM.
- Important standards such as IEEE 802.15.7 [54], JEITA CP-1221, CP-1222 and CP-1223 from Japan Electronics and Information Technology Industries Association (JEITA) [62], which are based on binary modulation schemes, are very frequently cited in the literature as a requirement of the proposed solutions.

Although multi-carrier modulations are very commonly used in wireless communications, they appear in a smaller number of publications, either under OFDM [10], [27], [29], [31], [37], [39], [39], [42], [44], [47] or under DTM [14], [40] schemes. Usually, research works less focused on VLC LED drivers address these modulation schemes, especially OFDM, as promising for VLC applications [7]. Additionally, even though LMMs are able to generate highly complex modulations, such as OFDM and DMT, most of the works in the literature do not take advantage of this capability; they usually employ these circuits to generate less spectral-efficient binary pulse modulations. In this sense, the reported LMM-based solutions could achieve a much higher data rate while keeping the same bandwidth, if more complex and more bandwidth-efficient modulation schemes were used. It is very likely that the optical communication standards IEEE 802.11bb [63] (OFDM), IEEE 802.15.13 [64] (OFDM) and IEEE 802.15.7m [65] (OFDM and



(a) Comparison of data rate and power levels.



(b) Comparison of data rate and power efficiency.

Fig. 6. VLC LED driver's performance according to modulator type.

DMT) that are expected to be released in the near future will include these bandwidth-efficient schemes.

Finally, it must be noted that in Table II and Table III only those publications that clearly reported the information about modulation schemes were considered [2], [3], [5], [6], [9]–[47].

C. Power Level

Fig. 6a depicts the output power rating (P_{LED}) and data rate of the reviewed solutions. As can be seen, the drivers that occupy specific areas of the chart can be grouped in clusters, which indicates that they have similar performance, as illustrated by areas I and II in Fig. 6a. The line indicating 1080p HDTV stream data rate (20 Mbps) is the boundary

TABLE II
NUMBER OF PUBLICATIONS ACCORDING TO MODULATION BAND AND MODULATOR TYPE.

	Circuit type				
Modulation band	LMM	SMM	SSM	PSM	**Total**
Baseband	12	3	12	4	27
Passband	8	11	0	0	19
Both	2	0	0	0	2

TABLE III
NUMBER OF PUBLICATIONS ACCORDING TO THE MODULATION SCHEMES AND MODULATOR TYPE.

		Circuit type				
Modulation scheme		LMM	SMM	SSM	PSM	**Total**
Pulse based	**Binary**					
	OOK	8	1	9	2	20
	VPPM	1	3	3	4	11
	Manchester	1	1	1	1	4
	Multiple-level					
	PAM	4	0	0	0	4
Carrier based	**Single-carrier**					
	QAM	1	3	0	0	4
	PSK	1	5	0	0	6
	FSK	0	1	0	0	1
	Multi-carrier					
	OFDM	6	4	0	0	10
	DMT	1	1	0	0	2

between both clusters. On its right side, the higher data rate solutions are located in cluster I, for which the LMM-based drivers predominate [12], [14], [27], [28], [44] and whose lower power boundary is represented by the decorative spot light ($\approx$1.0 W), the minimum power reference for practical illumination. When comparing to Wi-Fi standards, LMM achieve and exceed Wi-Fi 4 data rate; however, none among the VLC drivers achieved data rates comparable to Wi-Fi 6, which is the most advanced widely available Wi-Fi standard.

The cluster II in this figure, besides the lower data rate, is defined by power rating from 4.2 W [15] up to 80 W [21], [25]. In this cluster, SMM and SSM predominate, existing solutions suitable for most power rating applications. However, only a few SSM-based solutions [21], [25] have enough power rating for outdoor applications. Additionally, the SMM-based drivers are the most common solutions for indoor applications in the range 800-2000 lm.

D. Energy Efficiency

In this section, the energy efficiency is calculated by the ratio between the LED average power and the input power of the complete driver. Fig. 6b presents the efficiency and data rate classified accordingly to modulator types. Cluster III in this figure is located in the area with a data rate below the corresponding to 1080p HDTV streaming [3], [9], [10], [17], [21], [25], [26], [30], [32], [35], [38], [41]–[43]. The solutions that have efficiency levels compatible with commercial LED drivers, i. e. over 82%, are mostly based on SSM or SMM. All the converters in cluster III present good efficiency, yet they exhibit low data rates. In this group only [35] and [3] include all power processing stages (PFC, PC and MC).

Cluster IV groups the highest performance solutions in terms of data rate, which are 120 Mbps [27] and 2 Gbps [44]. However, these solutions are based on the less-efficient LMM. Therefore, compared to cluster III, they present lower efficiency, which is even below the reference levels for commercial lighting applications, and only [44] has all driver stages. Nevertheless, the data rates achieved by the solutions in cluster IV are able to support HDTV and UHDTV streamings. The higher data rates achieved by LMM-based solutions are possible because of wider modulation bandwidth and also owing to the use of high spectral efficient modulation schemes.

Few PSM-based solutions are proposed, which even perform with efficiency similar or lower than solutions based on SSM and SMM. As a conclusion of this comparison, efficiency compatible to commercial LED drivers was reported mostly by solutions based on SSM and SMM. A VLC LED driver capable of occupying the top-right most area in the chart of Fig. 6b would be capable of supporting applications of high data rate and simultaneously achieve good efficacy. From this analysis it is suggested that the LMM-based modulators are the only type of circuit capable of achieving these features; however, it was not yet demonstrated in the literature and to reach this target it may require a power-driven amplifier design aiming at VLC specifically.

E. Circuit topologies

This section presents a description and comparison of circuit topologies presented in the surveyed literature. Table IV shows a summary of circuit topologies classified according to modulator type, including circuit stages, power rating and efficiency. In the following, a complete description according to the proposed classification is carried out.

1) SSM and PSM: Fig. 7 illustrates the structures of these modulators together with examples of their operating waveforms. In this type of modulators, the rise and fall times, T_R and T_F respectively, are key parameters to define the maximum modulation bandwidth. These times are directly related to the performance of the switches and the LED device, which has significant capacitive impedance component at high frequency range. In the case of the SSM, shown in Fig. 7a, the switch performance, mainly because of its series equivalent resistance, affects the rise time, while the LED characteristics define the fall time. Additionally, in the modulator shown in Fig. 7b both rise and fall times are only affected by the performance of the switches, having the LED performance less influence on these times [5], [16]. Therefore, owing to this improved performance, this type of modulator can operate faster than the circuit shown in Fig. 7a.

In the case of the PSM, the fall time is affected by the switch performance and the rise time is mainly dependent on the LED characteristics. Among these modulator types, the structures depicted in Fig. 7a and Fig. 7c are more commonly found in the literature.

A slightly different approach reported in [9], [32] implements an arrangement of 12 switches and controlled current sources used as a VLC modulator, as shown in Fig. 7d. This solution uses a front-end PFC stage based on a valley-fill circuit. According to the authors, the converter achieves a high PF and a smooth control of the LED currents.

2) LMM: The reported solutions using LMM employ a wide sort of circuit topologies. It is clear to see in Table IV that most of the solutions employ equalization [11], [12], [44], [45], pre-emphasis [19], [28] or pre-distortion [45] strategies, which compensate the well-known LED or other component dynamics to achieve a wider bandwidth. This is usually performed using passive networks aided by active components [11], [12], [19], [28], [44], as illustrated in Fig. 7e as an example. They can also be realized using a delay chain [23], as presented in Fig. 7f.

Other solutions are based on using MOSFET current sources to control the LED current [27], [31]. As an example, Fig. 7g depicts the structure that performs the digital-to-analogue conversion (DAC) in the power circuit instead of in the signal processing stage. For this purpose, transistors M_i act as binary weighted current sources. Transistors M_{ci} and M_i are cascode structures that increase the modulator output impedance. This improves signal linearity by reducing current distortion regardless of LED impedance. This circuit was implemented into an ASIC and reported as suitable for high data rates (120 Mbps) achieving a reasonable power efficiency [27].

Fig. 7h shows a structure that is frequently reported as signal injector in LMM, which is the dc T-biased coupler, also known as ac-couple circuit. A modulated signal (ac input) is summed up to a dc current to build the LED stimuli current, so that the LMM does not process the dc current. Thus, better overall efficiency can be achieved because the dc part can be processed by a separate converter that does not have the requirement of wide modulation

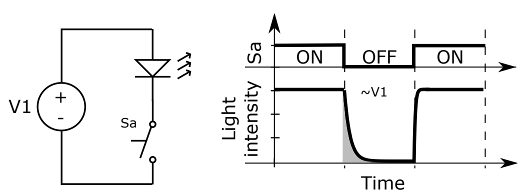
TABLE IV
CIRCUIT TOPOLOGIES SUMMARY

Ref.	Power (W)	Efficiency (%)	Circuit stages	Circuit or topology
LMM				
[11]	-	-	MC	Multi-ressonant equalization + buffer amplifier (BUF634T) + dc T-biased
[12]	1.5	-	MC	16-channel multi-ressonant equalization + buffer amplifiers (BUF634T) + dc T-biased
[13]	-	-	MC	Custom-designed two-stage class-AB amplifier + dc T-biased
[14]	11.5	-	MC	RF linear driver (ZHL-6A) + dc T-biased
[23]	-	-	MC	Current-mode logic and pre-emphasis with extra parallel buffer
[26]	5.4	85	PC+MC	Boost + series biased MOSFET modulator
[27]	3.3	67	MC	Current steering DAC, series biased MOSFETs as current sources
[28]	1.0	-	MC	Pre-emphasis circuit + emitter flower BJT stage + series biased MOSFET circuit
[29]	-	90	MC	Series biased BJT modulator
[31]	-	-	MC	Custom 4-channel current mode CMOS DAC
[39]	-	-	MC	Class A or AB + T-bias
[39]	-	-	MC	Series biased MOSFET
[44]	12.0	77	PC+MC	Low frequency transf. + rectifier + SEPIC + series biased BJT modulator with equalization
[45]	0.1	-	MC	Pre-distortion and equalization amplifiers (ZHL-6A-S+) + dc T-biased (ZFBT-4R2G+)
[46]	8.3	85	PC+MC	Ripple modulation with Class E amplifier assisted by linear class AB amplifier
SMM				
[2], [34]	22.6	-	PC+MC	Synchronous buck
[41]	22.6	91	PC+MC	
[6]	1.0	63	PC+MC	Buck
[38]	1.0	84	PC+MC	
[40]	-	-	PC+MC	
[8]	20.0	90	PC+MC	Two-phase buck
[24]	100.0	88	PC+MC	
[37]	10.0	90	PC+MC	
[10], [42]	10.1	91	PC+MC	Synchronous buck + two-phase synchronous buck
[18]	6.7	-	PC+MC	Boost
[30]	4.6	81	PC+MC	Buck (GaN FETs)
[36]	15.0	-	PC+MC	Two-phase synchronous buck
[47]	10.0	96	PC+MC	
SSM				
[5], [16]	0.3	-	MC	Series FET and parallel carrier sweep-out FET (GaAs FET)
[5]	0.033	-	MC	Series MOSFET and parallel carrier sweep-out MOSFET implemented in 0.18-$\mu m CMOS$
[9], [32]	8.0	89	PCF+PC+MC	Rectifier with valley-fill + switches in series with LED branches
[19]	-	-	MC	BJT emitter follower + pre-emphasis
[15]	4.2	-	MC	Switch (unspecified type) modulator
[20]	-	-	MC	
[17]	2	85	MC	Series MOSFET modulator
[22]	0.5	-	MC	
[21], [25]	80.0	94	PCF+PC+MC	PFC rectifier + LLC switching converter + series MOSFET modulator
[43]	20.0	92	PCF+PC+MC	Rectifier + Buck-boost + series MOSFET modulator
PSM				
[3]	5.8	89	PCF+PC+MC	Rectifier with valley-fill + buck + parallel MOSFET modulator
[6]	1.0	40	PC+MC	Buck + parallel MOSFET modulator
[38]	1.0	66	PC+MC	
[35]	6.9	85	PCF+PC+MC	Rectifier + buck-boost-buck + parallel MOSFET modulator

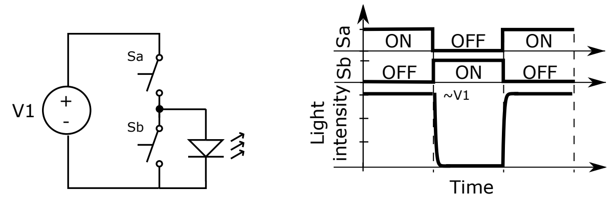
bandwidth.

Other alternative solutions to the dc T-biased coupler employ series biased BJT [29], [44] or MOSFET [26], [28], [39] to implement the modulator. Fig. 8a shows an example based on a single series transistor, while in Fig. 8b a cascode structure is employed to increase the output impedance of the current source, as in the DAC solution. However, in these solutions the transistors have to operate in linear region processing all the dc current, which decreases the modulator efficiency.

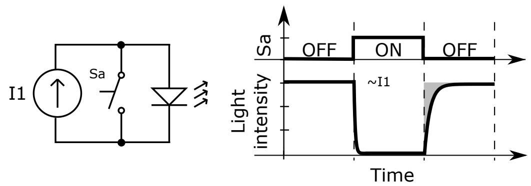
A hybrid solution presented by [46] employs as class E narrow-band SMM that is assisted by a class AB LMM. The circuit employed in this solution can be seen in Fig. 8c; it uses a T-biased coupler in which most of the current modulation is performed by a class E amplifier (85%) with some level of distortion due to the narrow band. Therefore the



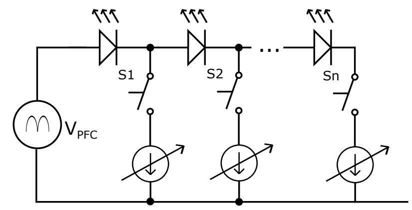
(a) SSM modulator from voltage source, one switch [15], [17], [20]–[22], [25], [43].



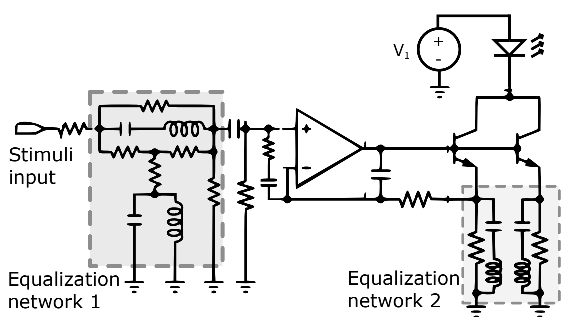
(b) SSM modulator from voltage source, two switches for charges sweep-out [5], [16].



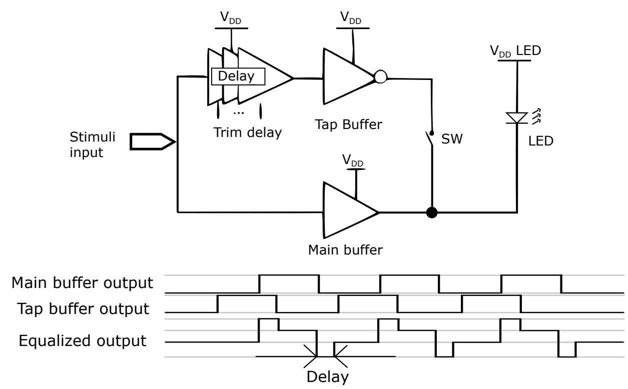
(c) PSM modulator from current source [3], [6], [35], [38].



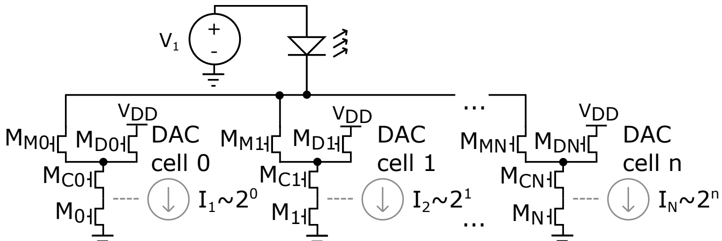
(d) SSM modulator for inductorless VLC driver [9], [32].



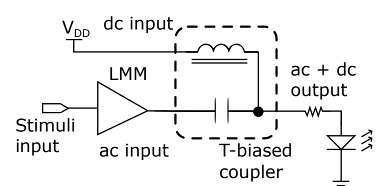
(e) LMM with analog pre-emphasis using series BJT modulator [44].



(f) LMM pre-emphasis using a delay chain [23].



(g) LMM using current steering DAC topology [27].



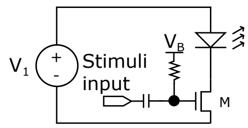
(h) LMM with T-biased coupler [11], [12], [14], [39], [45].

Fig. 7. Topologies summary

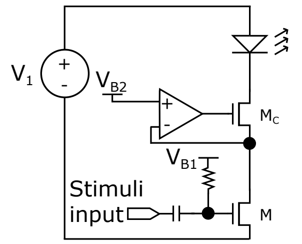
final solution efficiency achieved 85% with SMM switching at 1MHz and 250kHz of modulation bandwidth.

3) SMM: Most of the SMM-based solutions employ average current control, which is described in Section IV-B. Reference [6] proposes the use of a buck converter as modulator switching at 100 kHz tracking a much slower signal of 10 kHz, as shown in Fig. 8d. Similarly, [30] presents a buck converter, operating at 10 MHz that can track a 1 MHz VPPM communication signal that achieves an efficiency of 81 %.

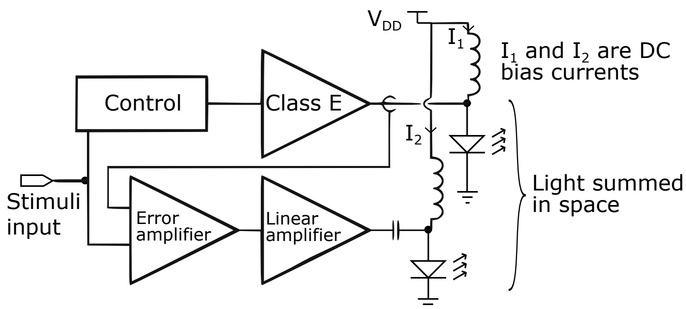
A two-phase buck converter with 4^{th} order filter is reported in [24], as illustrated in Fig. 8e. This converter operates at a switching frequency of 10 MHz tracking a communication signal with a harmonic content from dc up to 3.125 MHz. The proposed converter also achieves an efficiency up to 92 %. A similar converter is presented in [8]. Also the solution in [10] uses a structure based on a 10-MHz



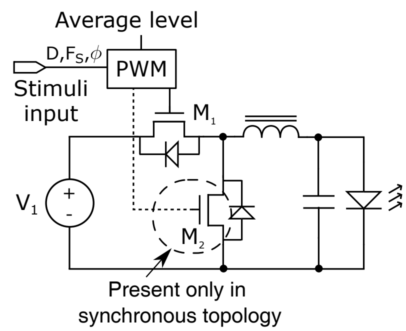
(a) LMM using series MOSFET [28].



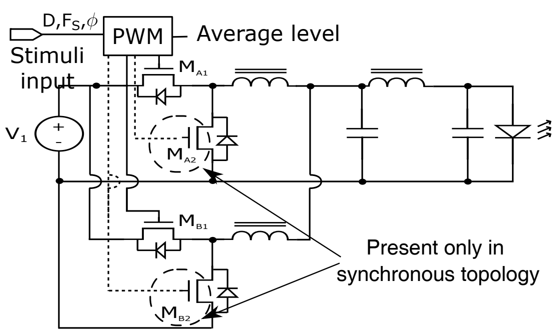
(b) LMM using series MOSFET and cascode [26].



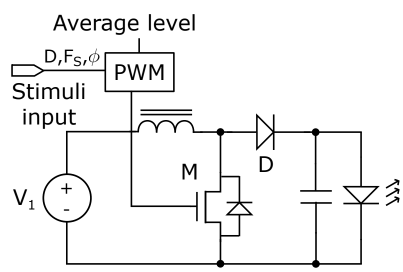
(c) SSM assisted by LMM topology [46].



(d) Buck-based SMM [6], [30] and synchronous-buck-based SMM [2], [34], [41].



(e) Two-phase-buck-based SMM [8], [24], [37] and two-phase-synchronous-buck-based SMM [10], [36], [47] with 4^{th} order filter.



(f) Boost-based SMM [18].

Fig. 8. Topologies summary (continuation)

two-phase synchronous buck modulator, as shown in Fig. 8e, and a synchronous buck converter switching at 250 kHz (not shown in the figure). The latter processes most of the power, while the former is used to achieve a wide modulation bandwidth. The prototype has 3 MHz modulation bandwidth with efficiency up to 93.6 %

Strategies based on ripple modulation have also been proposed. Reference [18] presents a boost converter, shown in Fig. 8f, in which the switching frequency is modulated for data encoding. In [36], the two-phase synchronous buck converter, shown in Fig. 8e, is used to generate a QAM modulated signal, while in [47] multi-carrier modulation is implemented for the same converter. Likewise, [2], [34], [41] explore the synchronous buck topology to perform ripple PSK modulation. Reference [41] showed that the drop of the system luminous efficacy due to VLC modulation was only 3 %.

F. Signal amplitude

In the analysis presented in this section, the higher the signal amplitude, the more the light dynamic range is used for communication. Fig. 9 presents energy efficiency according to the output current amplitude. In the analysis of the absolute values, [21], [25] reached the highest signal amplitude (3.5 A) using a SSM, and the second higher

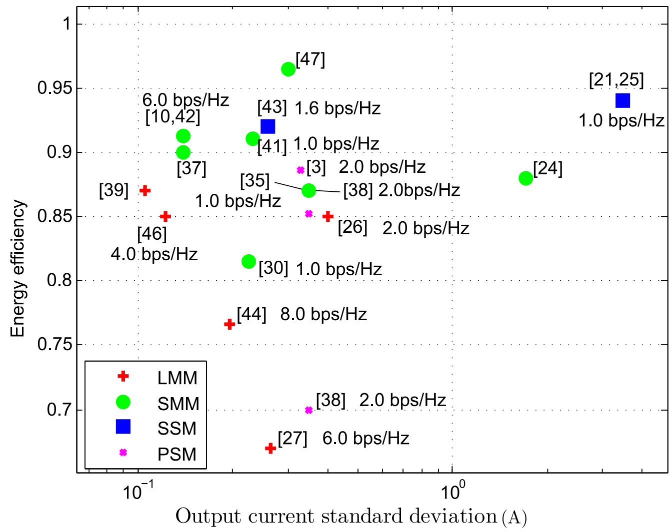


Fig. 9. Energy efficiency of solutions according to output current amplitude.

amplitude is reported in [24], which achieved 1.71A using a SMM.

This figure also shows a correlation between LMM-modulator based efficiency and the signal amplitude. In this sense, most of LMM occupy only the left-bottom part of this chart, which indicates lower signal amplitude levels and lower efficiency. Owing to the different operation principles, SMM and SSM have the higher efficiencies, however the higher signal power is poorly used in low complexity modulations by SSM, see annotated spectral efficiency values in the figure. Due to these facts, the best choice of modulator topologies to reach higher signal power with higher energy efficiency is within SMMs. This result contrasts with data rate results presented in Section V-D, in which LMM have clear superior performance. In this sense, better use and exploration of more spectral efficient modulation schemes with SMM may bring further advances in data rate with less energy efficiency penalty.

G. A prospect of new technologies

VLC has been frequently linked to the 5G and is a candidate for supporting 6G mobile network infrastructure [66], [67]. The short range communication is the trend that shrinks the coverage area of each network cell, allowing for population-dense areas to experience data communication at increasingly higher data rates. Side-by-side with the recent Wi-Fi standards such as Wi-Fi 5 (IEEE 802.11ac) and Wi-Fi 6 (IEEE 802.11ax), also the VLC offers opportunities in the last-meters communication link. It is shown in this study that the state-of-the-art LED drivers for VLC achieve data rate comparable to Wi-Fi 4 and Wi-Fi 5, as presented in Section 6a and Section 6b also supporting all the multimedia applications considered as references. The coexistence between RF-based local communications, such as Wi-Fi and LoRa networks, with VLC are a strong trend and may be a way to make VLC popular because it avoids interference in adjacent environments, thanks to the signal confinement [68]. **The confinement of VLC signal is possible with simple barriers as walls, doors or windows that are opaque to the wavelength range of visible light. Indeed, given the concern on energy savings and on privacy, usually the lighting systems service each individual environment and there is no line-of-sight between adjacent rooms. Therefore, most building~~’s~~ architecture already avoids the interference of VLC on adjacent environments.**

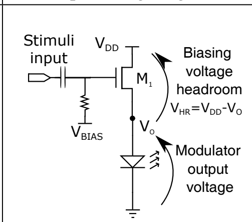
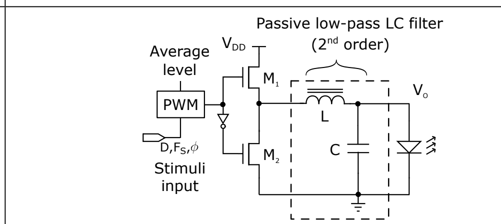
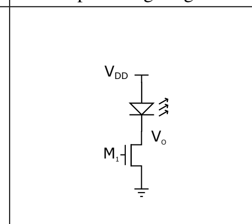
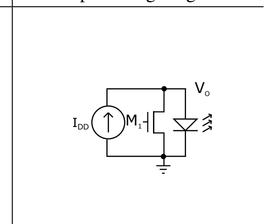
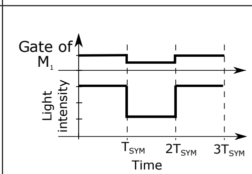
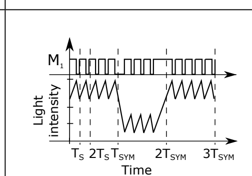
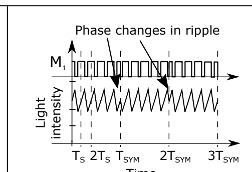
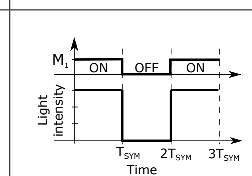
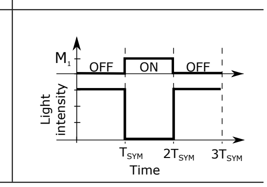
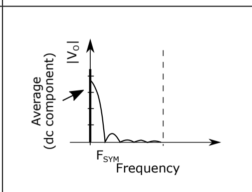
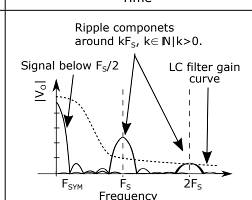
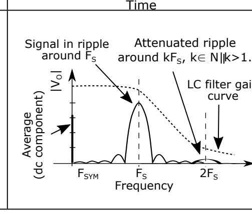
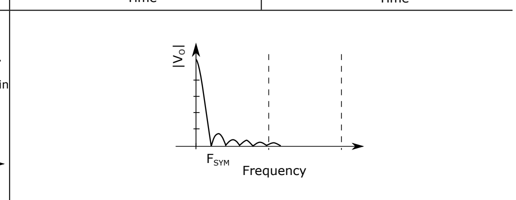
The communication link capable of taking advantage of RF and optical communications, usually called hybrid system, may also help on overcoming the well-known limitation of VLC in the uplink direction additionally to the non-line-of-sight situations. **The VLC operation in non-line-of-sight relies on reflections and it is strongly affected by multi-path effects [67].**

In the scope of electronic circuits, GaAs- and GaN-based MOSFET devices are becoming commercially available, especially GaN-based ones. The better overall electrical characteristics, such lower conduction losses and higher switching frequency when compared with silicon-based MOSFETs, allows for reducing modulator losses in wide bandwidth applications. This makes room for improvement in data rate keeping the energy efficiency in the power conversion for these type of converters. Some papers already took advantage and proved the higher modulation performance of non-Si-based FET devices in PSM that in this case achieved steeper pulses in LED current [5], [16]. Also SMM topologies can take advantage of the higher switching frequency which is possible with new semiconductor technologies [30].

A significant research effort is been applied recently on the use of micro-LEDs (μLEDs) for VLC [69], [70]. These components allow for light modulation bandwidth that may exceed 1 GHz,

TABLE V

SUMMARY OF CIRCUIT TYPES AND FEATURES.

Modulator type	LMM	SMM		SSM	PSM
		Average control	Ripple modulation		
Complexity	Intermediate, has a high number of components	Complex, high switching frequency and passive components.		Simple, single switch	
Modulation types and bandwidth	Any scheme with wide bandwidth, 100's of MHz	Any scheme with narrow bandwidth, few MHz		Only binary pulse based schemes, intermediate bandwidth, 10's of MHz	
Distortion	Due to semiconductor non-linear behavior	Non-linear converter gain and inherent current ripple	Tolerance of the filter parameters may change signal shape	High order frequency harmonics are attenuated	
Efficiency	Low, in average below 80 %	Intermediary, in average 85.5 %		High, in average 90 %	Low, in average 70 %
Power level and application	Low, in average 5.0 W, indoor low and medium power lighting	High, in average 19.4 W, indoor medium and high power lighting		Intermediary, in average 14.3 W, indoor medium and high power lighting	Low, in average 3.7 W, indoor low and medium power lighting
Example of circuit					
Example of typical waveform					
Example of typical spectrum					
Main advantage	Performs small signal amplitude with wide modulation bandwidth.	Capable of performing power control and modulation in a single stage.		Very simple implementation.	
Main limitation	Voltage headroom for semiconductor biasing causes substantial dissipated power.	Limited switching frequency, thus narrow bandwidth due to necessary filtering.	Modulator cannot be shut off because of continuous ripple transmission.	Is only capable of generating simple modulations, the data rates is affected by average light control strategy.	Same as SSM; however, has lower efficiency.

which leads to higher-data rate communication if compared to phosphor-covered LEDs. In this sense, also VLC LED drivers shall be capable of producing current stimuli taking advantage of this wider band; therefore, this trends to push modulator's bandwidth requirement even further.

H. Features summary

Table V presents a summary of the features and surveyed literature data for each modulator type. This contains the key aspects to select a VLC modulator type according to target lighting power level, efficiency or modulation scheme to be implemented. In these representations, symbol frequency (F_{SYM}), symbol period (T_{SYM}), switching frequency (F_S) and switching period (T_{SYM}) have the only purpose of correlating time and frequency domain representations.

VI. CONCLUSIONS

The current study has presented an up-to-date review on the VLC LED drivers, highlighting the most relevant facts and conclusions about the state of the art of this technology. First of all, switching mode converters are identified as a trend among the VLC LED drivers. Additionally, series switch and linear mode modulator circuits are also among the most frequent solutions in the literature.

With regard to modulation, binary modulation schemes are the majority of the reported strategies. Even though they achieve lower spectral efficiency than other strategies, their simplicity of implementation makes them the choice in most of the reported solutions. Another motivation of the extensive use of binary modulation schemes is that they have already been adopted by some VLC standards, as the IEEE 802.15.7 and JEITA CP-1221, CP-1222 and CP-1223. However, the research on VLC LED drivers might soon change its focus to more complex modulation schemes as new optical communication standards are expected to be released in a near future, such as IEEE 802.11bb (using OFDM), IEEE 802.15.13 (using OFDM) and IEEE 802.15.7m (using OFDM and DMT).

The linear mode modulator solutions presented a great variety of circuit topologies, which have on average lower power levels and lower efficiencies when compared to other modulator types. On the other hand, the buck and buck-derived modulators are the most frequent topologies among switching mode modulators, which perform with high efficiencies but still with limited data rates. Also, reasonable good efficiency was reported with series switch modulator circuits, which comes together with limitations on the modulation schemes that can be implemented. Moreover, they require an intermediate stage to regulate the LED voltage, which makes the system more complex.

Finally, signal amplitude is connected to the modulator circuit type and to the energy efficiency considering current modulator circuit topologies. The linear-mode-modulator based solutions achieved lower signal amplitude, even so, they achieved higher data rates, due to wider modulation bandwidth and adopting higher spectral efficient modulation schemes, at the cost of lower energy efficiency. On the other hand, switching-mode-modulator based solutions have the potential to achieve higher data rate with little energy efficiency penalty in VLC. This can be accomplished by using modulation schemes with higher spectral efficiency and taking advantage of the higher signal amplitude already demonstrated.

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