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Optical digital to analog conversion performance analysis for indoor set-up conditions

Aleš Dobesch [a,*], Luis Nero Alves [b,c], Otakar Wilfert [a], Carlos Gaspar Ribeiro [c,d]

[a] Department of Radio Electronics, Brno University of Technology, Brno, Czech Republic
[b] Department of Electronics Telecommunications and Informatics, University of Aveiro, Portugal
[c] Instituto de Telecomunicações, Aveiro, Portugal
[d] Escola Superior de Tecnologia e Gestao, Instituto Politecnico de Leiria, Portugal

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ABSTRACT

In visible light communication (VLC) the optical digital to analog conversion (ODAC) approach was proposed as a suitable driving technique able to overcome light-emitting diode's (LED) non-linear characteristic. This concept is analogous to an electrical digital-to-analog converter (EDAC). In other words, digital bits are binary weighted to represent an analog signal. The method supports elementary on–off based modulations able to exploit the essence of LED's non-linear characteristic allowing simultaneous lighting and communication. In the ODAC concept the reconstruction error does not simply rely upon the converter bit depth as in case of EDAC. It rather depends on communication system set-up and geometrical relation between emitter and receiver as well. The paper describes simulation results presenting the ODAC's error performance taking into account: the optical channel, the LED's half power angle (HPA) and the receiver field of view (FOV). The set-up under consideration examines indoor conditions for a square room with 4 m length and 3 m height, operating with one dominant wavelength (blue) and having walls with a reflection coefficient of 0.8. The achieved results reveal that reconstruction error increases for higher data rates as a result of interference due to multipath propagation.

1. Introduction

Visible light communication (VLC) systems currently belong to a major research topic in the field of modern communication. Solid state lighting (SSL) considered as a future technology for general lighting opens up an opportunity to combine illumination and communication means, supported on the same devices. From the system design perspective, this approach offers several advantages over standard radio frequency (RF) communication systems [1]. Benefits include the possibility to explore synergies with lighting systems, higher communication security, high data rates under unlicensed electromagnetic spectrum, space confinement, exempt from electromagnetic interference amongst others. There are, however, problems arising from the dual usage of the LED device for lighting and communication. Commercially available devices employed for lighting have limited bandwidths, normally around 20 MHz [2]. Additionally, LEDs suffer from their intrinsic non-linear characteristic [3]. In order to enhance the data rate of such devices the combination of pre- and post-equalization together with advanced modulation schemes such as orthogonal frequency domain multiplexing (OFDM), discrete multi-tone modulation (DMT) or multiple-input multiple-output (MIMO) is necessary [4–6]. Further, LEDs are normally designed to be operated under constant current. Meeting driving requirements guarantees the stated device lifetime since constant current conditions are linked to the operating temperature which directly influences LED lifetime.

An appropriate solution able to cope with the previously listed constraints can be a transmitter employing an optical digital to analog converter (ODAC) [7,8]. Conceptually, in ODAC, the multiple digital signals are fed to different LED groups inside an array as illustrates Fig. 1(b) (for illustration a 4-bit ODAC is considered). Thus, for a communication transmitter the electrical DAC stage can be removed and the digital outputs can be directly applied to the LED array compared to the conventional driving approach illustrated in Fig. 1(a). Two ODAC architectures are possible, either using a fixed number of LEDs per bit (illustrated in Fig. 2(a)), or using LED groups with a different number of LEDs (depicted in Fig. 2(b)). In the first case, DAC operation will be achieved by combining the light output of different LED groups driven with different current levels, following the usual distribution of binary weights. In the second architecture, the LEDs are driven with the same

* Corresponding author.
E-mail addresses: dobesch.ales@phd.feec.vutbr.cz (A. Dobesch), nero@ua.pt (L.N. Alves), wilfert@feec.vutbr.cz (O. Wilfert), carlos.ribeiro@ipleiria.pt (C.G. Ribeiro).

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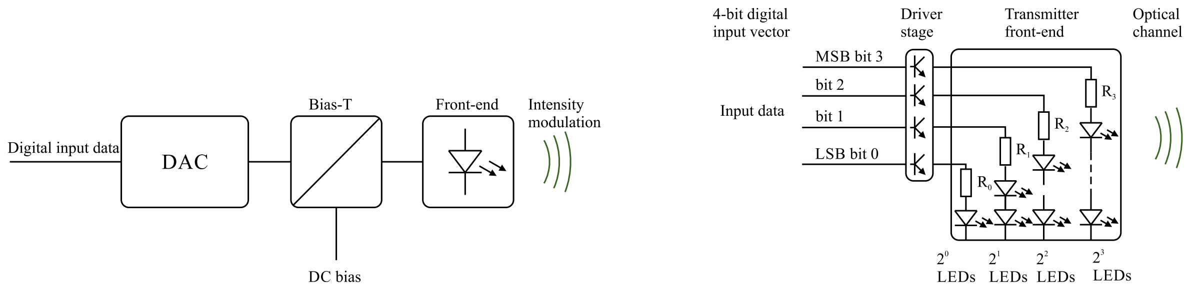
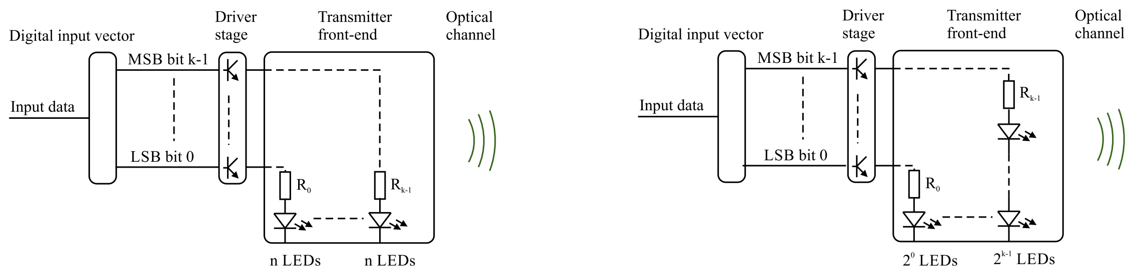


(a) Conventional front-end. (b) ODAC-based front-end.

Fig. 1. Transmitter front-end.



(a) Fixed number of LEDs per group. (b) Binary weighted number of LEDs per group.

Fig. 2. ODAC concept architectures.

current and the binary weights are given by the sum of LEDs in each group.

Obviously, the latter approach is more suitable, because it imposes the same operating conditions for all devices in the array. The digital signals interfere in the channel and are received as a recovered analog signal on the receiver side. For lighting purposes, this technique may also support dimming. Using the ODAC concept, the non-linearity of the LEDs is effectively removed. Performance is for this case dependent on the bit depth of the converter and channel induced effects. This technique also offers another advantage for communication. A recent trend in LEDs is their aggregation in arrays, known as Chip-On-Board (COB) LEDs which is in line with the proposed ODAC architecture. COB LEDs were advanced as a way of increasing LED efficacy. This approach can also be explored as a means to achieve higher bandwidth. In fact, device area and bandwidth are inversely dependent parameters, higher area devices have, in this sense smaller bandwidth [9]. Explicit proof can be found in recent GaN based micro light emitting diode (mLED) technology, proposed in [10]. These mLEDs offer a modulation bandwidth up to 400 MHz. Authors in [11] demonstrated that the spectral efficiency of their real time system employing ODAC reaches up to 6bits/s/Hz for conventional white PLCC6 LEDs. The classic bandwidth definition (−3 dB) can be pushed ten times, leading to usable bandwidths of tens of MHz, resulting in throughput of hundreds of Mbps.

The paper explores ODAC performance degeneration effects caused by the geometrical set-up and channel impulse response (CIR). In previous contributions relating to this topic, authors investigated the effects on signal reconstruction error due to geometrical considerations of the set-up, assuming low data transmission scenarios [12,13]. In [14], authors simulate outdoor VLC model of the intelligent transport system crossroad using a similar performance evaluation metric. This paper extends previous conclusions to the case of high data rate signal transmission, where the channel impulse response becomes of paramount importance. The assumed set-up scenario considers four luminaries in an empty room of 4 m × 4 m × 3 m (length, width, and height). The modeling approach takes into consideration the effects of the emitter half power angle (HPA), the receiver field of view (FOV) and channel impulse response, assuming a multipath propagation model able to consider up to two reflections.

Section 2 presents the ODAC principle and the system model description. Section 3 describes assumed channel model and the simulation set-up. Section 4 reveals the obtained results. Lastly, Section 5 gives the final conclusions.

2. System model description

Fig. 3 shows the conceptual diagram of ODAC. On the transmitter side, an arbitrary waveform generator produces a digital signal $\upsilon_{\mathrm{i}}(t)$, represented by a set of k digital bitstreams $B_{\mathrm{k}}(t)$, which are used to modulate k independent groups of LEDs in a LED array. Quantization at the transmitter side is assumed to follow the standard approach: for k LED groups the, the signal dynamic range is divided into $2^{\mathrm{k}}-1$ equal amplitude intervals. Assuming that the digital signals $B_{\mathrm{k}}(t)$, all have the same amplitude and that the LED are driven uniformly for all the k groups, the digital weights are set by the number of LEDs in each group, that is, following a binary weight distribution. The transmitted bit streams are then combined on the channel and reach the input of the receiver (in this case, represented by a simple transimpedance amplifier). The recovered signal $\bar{\upsilon}_i(t)$ is a reconstructed replica of $\upsilon_i(t)$ with approximation error dependent on the bit depth of the array (the number of LED groups, k), and channel degradation effects. In a perfect channel, exempt from reflections, delays and constrained FOV, the approximation error would be lower bounded by LSB/2, where LSB represents the strength of the least significant bit.

Assuming that the channel impulse response of each LED in the array is expressed by $h_{\mathrm{m,n}}(t)$, the reconstructed signal can be determined by adding the convolutions of the signals $B_{\mathrm{k}}(t)$ with the LED's individual impulse responses, as stated in:

$$\bar{\upsilon}_i(t) = R_{\mathrm{PD}} \sum_{\mathrm{m=1}}^{\mathrm{k}} \sum_{\mathrm{n=1}}^{2^{\mathrm{m}}-1} B_{\mathrm{m}}(t) * h_{\mathrm{m,n}}(t)\, P_0, \tag{1}$$

where P_0 is the normalized optical power corresponding to each LED in the array and R_{PD} represents the responsivity of the photodiode. As a result, Eq. (1) states that the approximated signal error depends on the CIR, the geometrical features of the set-up, including the receiver FOV, the LED half power angle, the distance between transmitter and receiver, and the presence of reflecting elements.