Experimental Evaluation of a Euclidean Distances based 3-Color Shift Keying Scheme for Visible Light Communications

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***Abstract*—The new generation of wireless communications is characterized by high demands on carrier frequency, bandwidth, and of course the immunity from electromagnetic interference, areas which put the Radio Frequency (RF) spectrum under pressure. Satisfying these requirements with the present technology and infrastructure is a new technological challenge with visible light communication (VLC) being considered as a very promising area for filling some of the technological gaps and complementing the RF technology. This paper explores the use of a method based on the Euclidean Distance approach for digitizing the incoming signal of a 3-Color Shift Keying (3-CSK) optical communication scheme. According to this, the transmitter (Tx) exploits an RGB LED while the receiver (Rx) uses an RGB photodiode, aiming to compose this way a three-channel optical communication system. The efficiency of the proposed method is examined by measuring the bit error rate (BER) versus the signal-to-noise ratio (SNR) on a basic 3-CSK transceiver.**

***Index Terms*—Visible Light Communications, Color Shift Keying, Euclidean Distance, RGB LED, RGB photodiode.**

I. Introduction

THE emerging wireless communication technologies are dealing with the constantly increasing data traffic and as a result the management of the available bandwidth is crucial. Moreover, the IoT applications have also put under pressure the telecommunication networks [1]. On the other hand, the available RF telecommunication networks demand increase of the bandwidth, better utilization of the available bandwidth and better coverage [2] [3].

The above requirements pinpoint the increased interest for telecommunication networks based on Optical Wireless Communication (OWC) solutions. The OWC cover the visible light, infrared, and ultraviolent areas of the electromagnetic spectrum. In comparison with the RF domain, the OWC provide unlicensed bandwidth of thousands of THz. Furthermore, the immunity to the electromagnetic interference is another important advantage of the OWC since not only adds robustness to the network but also can be used along with the RF technology [1]. Particularly, visible light communication (VLC) has been one of the most popular areas of OWC for several scenarios such as indoor applications, underwater localization and vehicle-to-vehicle (V2V) communication [4].

For VLC, Light Emitting Diodes (LEDs), and lasers are just a few examples of the many ways visible light may be produced. Designing a VLC system requires to consider the dimming level which can be chosen by the user during the day, the color shift changes, and the flickering [5]. In this context, the desirable white color temperature can be achieved by using red-green-blue (RGB) LEDs. For multi-colored VLC systems, the RGB LEDs are the main components for implementing the color shift keying (CSK) modulation scheme.

For the CSK, the color (wavelength) bands of the RGB LEDs are selected based on the Commission International de l'Eclairage (CIE) 1931 chromaticity diagram [6]. Optimization techniques for the selection of the color bands have been proposed while also taking into account the target illumination color and total optical power output [7]. Various studies have been carried out which proposed 4, 8, and 16-point CSK [8] [9], however these studies do not focus on the Rx-end which is based on the selected RGB photodiode.

The contribution of this paper is to propose an easily applicable and direct heuristic for applying a 3-CSK scheme which focuses on the Rx-end that is based on an RGB photodiode. In more details, this work explores the capabilities and the prospects of a Euclidian Distance based scheme for digitizing the response at each one of the three channels of the RGB photodiode. The efficiency of this scheme is examined through measurements of the bit error rate (BER) versus the signal-to-noise ratio (SNR) on a basic three channel (RGB) optical transceiver.

The rest of the manuscript is organized as follows: Section II presents the response of the photodiode to the various states of the RGB LED. The proposed 3-CSK based on the Euclidean distance is presented in Section III. In Section IV the RGB LED Tx and the photodiode Rx implementations, as well as the experimental setup are presented. The impact of the illuminance to the SNR along with the experimental BER analysis are presented in Section V and the paper is concluded in Section VI.

II. Photodiode Profile

The photodiode characterization is a very important step for applying the proposed CSK scheme. In the conventional 3-CSK scheme the total intensity of the three LED colors red, green, and blue, is controlled in order to constantly maintain the same lighting performance. Therefore, the three colors intensity measured on the Tx can be expressed as P_R, P_G, and P_B, for the red, green, and blue LED respectively.

The receiver is equipped with a three-band (RGB) photodiode (PD) which converts the optical signal into electrical.

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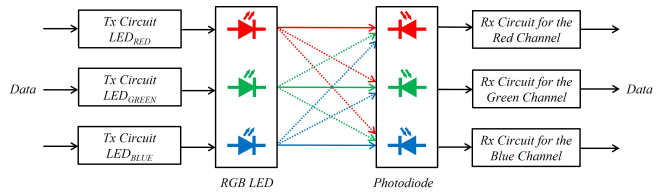


Fig. 1: The cross-channel interference among the three channel signals that are received by the photodiode. Note that a single RGB LED and a single RGB photodiode are used in this link.

Furthermore, the band areas are based on the relative spectral responsivity of the PD with respect to the wavelength. Due to the fact that the band areas overlap with each other, cross-channel interference to the received signals at the photodiode is observed. Fig. 1 depicts the cross-channel interference during the signal transmission in a 3-CSK scheme based optical link.

The intensity of the received signals at the PD can be expressed as:

$$\begin{bmatrix} P'_R \\ P'_G \\ P'_B \end{bmatrix} = \mathbf{H} \cdot \begin{bmatrix} P_R \\ P_G \\ P_B \end{bmatrix} \tag{1}$$

where $P^{'}_R$, $P^{'}_G$, and $P^{'}_B$ are the intensities of the received signals on the PD from the red, green, and blue channel respectively. $\mathbf{H}$ is the channel matrix given by:

$$\mathbf{H} = \begin{bmatrix} h_{rr} & h_{rg} & h_{rb} \\ h_{gr} & h_{gg} & h_{gb} \\ h_{br} & h_{bg} & h_{bb} \end{bmatrix}, \tag{2}$$

where the diagonal entries h_{rr}, h_{gg}, and h_{bb} are the channel gain between each LED color with the corresponding PD channel and the rest entries represent the crosstalk between channels.

The photodiode response to cross-channel interference creates the concept of the *Photodiode Profile*. The RGB LED operates based on the lighting standards for indoor applications in the color temperature of 4000K [6]. In addition, the RGB LED does not operate at maximum intensity level and the optical power at the PD is regulated by its distance from it. When using a three color (RGB) LED, eight possible combinations (states) will come up. Each state indicates which of the red (R), green (G), and blue (B) LEDs are switched on. Furthermore, the performance of the photodiode for these combinations will set the base for the data retrieval based on a Euclidean Distance scheme. Fig. 2 shows the performance of each photodiode channel for the eight possible combinations.

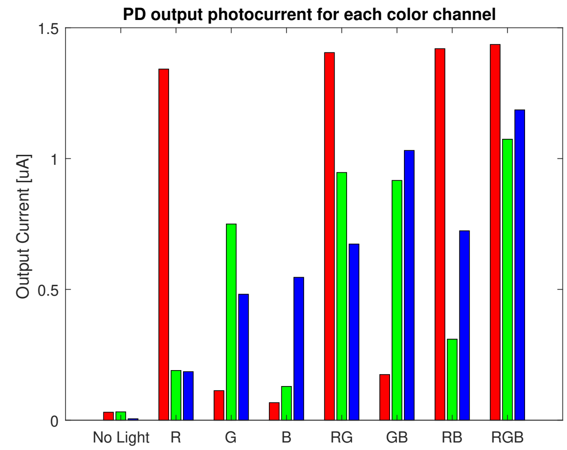


Fig. 2: The output photocurrent for each color channel at each one of the eight possible states and for an illuminance of 1943lux provided by a 4000K RGB LED. The first state is when no light was applied.

III. 3-CSK Rx Signal Retrieval Scheme based on Euclidean Distance

The chosen modulation format for the VLC link was the On-Off Keying (OOK) with Manchester encoding in order to control the illumination and prevent the flickering of the LED [6]. The optical signals at the Tx-end for the red, green and blue channels are generated by the same clock. The Rx-end detects the optical signals by measuring the photocurrent at the red, green and blue PD channels. For every half period one sample for the red, green, and blue PD channels is retrieved, making the sampling rate to be twice as the signal frequency. This sampling rate was chosen due to Manchester encoding properties to express the bit 0 by a low-to-high transition and the bit 1 by a high-to-low transition, and as a result the midpoint of the period signifies whether the bit is 0 or 1. In addition, a point in the Cartesian plane results with coordinates the above-mentioned retrieved samples for every half period. This point can be expressed as:

$$c^j_{r,g,b}(SampleR_j, SampleG_j, SampleB_j)$$

which represents the j^{th} bit that is about to be retrieved. In addition, the i^{th} photodiode state can be expressed as a point in the Cartesian plane and can be presented as $s^i_{r,g,b}$.

The signal digitization is done by calculating the Euclidean distance between each half period color sample with the eight photodiode states. The Euclidean distance between the j^{th} received color sample c with the i^{th} photodiode state is given by:

$$d^i_{rgb} = \sqrt{\left\|s^i_r - c^j_r\right\|^2 + \left\|s^i_g - c^j_g\right\|^2 + \left\|s^i_b - c^j_b\right\|^2}. \tag{3}$$

In order to choose the closest possible state, all the distances between each one of the eight states and the received sample must be calculated. The chosen state would be this with the minimum distance from the sample:

$$min\left(d^0_{rgb}, d^1_{rgb}, \cdots, d^7_{rgb}\right). \tag{4}$$

In case the minimum distance between the received color sample and the photodiode states is the same for more than one states, then for the needs of our experiments the state is chosen randomly among them. The reason for converting the optical signal into bits is because the proposed 3-CSK is applied on Physical Layer. Fig. 3 shows the Euclidean Distance among the received signal sample and the eight photodiode states.

IV. Experimental Setup

In this section the experimental setup is presented and analyzed. The experimental setup is shown in Fig. 4. It consists of the arbitrary waveform generator (AWG), the RGB LED transmitter (Tx) and the RGB photodiode receiver (Rx).

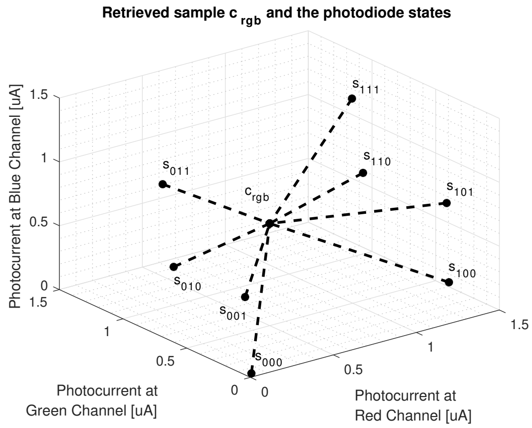


Fig. 3: Euclidean distance between the received color c_{rgb} and the eight different possible states.

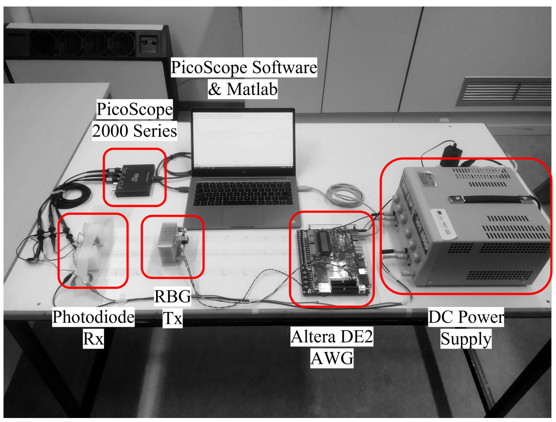


Fig. 4: The experimental setup used in the measurements.

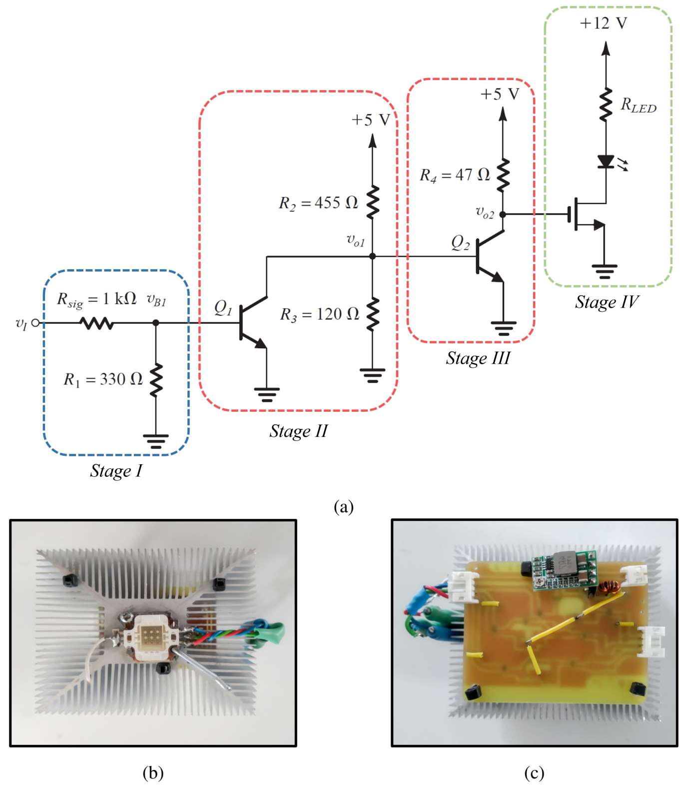


Fig. 5: (a) The LED driver for each color channel, (b) frontside and (c) backside of the implemented RGB LED transmitter.

A) The AWG generates three pseudorandom bitstreams (PRBS). The Altera DE2 FPGA board is exploited as an AWG, where the pseudorandom bitstreams are generated by implementing linear-feedback shift registers (LFSRs). Each PRBS is fed to one of the RGB LED transmitter channels and finally the RGB LED transmits the whole signal. For each color of the RGB LED a different PRBS is applied in order to emulate real time conditions and to cover all possible photodiode states. The receiver side is composed of the photodiode which receives the optical signal at each color channel and converts it to an electrical one. Each signal is observed through an oscilloscope (PicoScope 2405A) and the received data are retrieved.

B) The RGB LED transmitter is based on three LED drivers, one for each color. Fig. 5a presents the topology of a LED driver. Each driver is composed of two BJTs (Q2N2222) and an NMOS (AO3406) transistors. Particularly, the three drivers are almost identical, except the value of the resistor in series with the LED. The proper selection of these resistances will determine the color temperature of the optical signal. Actually, $R_{LED,RED}$ was 42.3Ω, $R_{LED,GREEN}$ was 13Ω and the $R_{LED,BLUE}$ was 62.6Ω. Fig. 5b and Fig. 5c present the front and back side of the Tx respectively. The RGB LED used in the Tx was a commercial 10W RGB SMD LED.

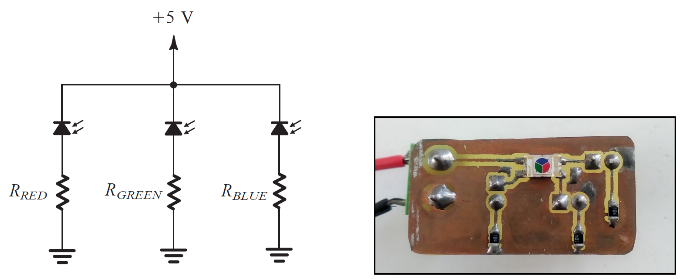
In Fig. 5a, Stage I is a simple voltage divider, which receives at its input the corresponding PRBS signal and provides a current signal to the Stage II. Stages II and III operate as voltage amplifiers. The voltage signal at the output of Stage III is applied at the gate of the NMOS transistor. Stage IV implements a series configuration LED driver, where the NMOS transistor acts as a switch to turn on and off the corresponding LED.

The LED operates with a power supply of 12V and a maximum forward current of 250mA. The selected NMOS is characterized by a low on-resistance, less than 70mΩ for V_{GS} = 4.5V, which contributes to low power dissipation. Furthermore, the switching performance requirements are covered by the selected topology due to its high driving strength. Finally, the LED current is limited by the R_{LED}.

C) The receiver consists of the RGB photodiode APS5130PD7C-P22 from Kingbright with a common cathode for each color, as shown in Fig. 6a. For the three photodiode channels the resistances R_{RED}, R_{GREEN} and R_{BLUE} are 100KΩ. In the topology of Fig. 6a, the current signal that is generated by each color photodiode is converted to a voltage signal. The receiver is a simple topology, without a signal amplification stage since our intention at this phase was to evaluate the digital signal retrieval using the Euclidian Distance method and not to develop the final complete receiver. Fig. 6b presents the PCB implementation of the Rx.

V. Experimental Results

During the experiments, the Tx transmits the corresponding PRBS signal at each color channel, while the Rx receives the



(a) (b)

Fig. 6: (a) The receiver circuit using a triple photodiode topology with a common cathode. (b) The RGB photodiode receiver implementation.

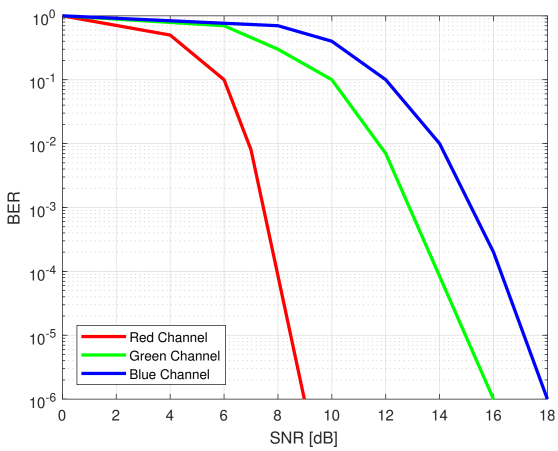


Fig. 7: Curves of BER versus SNR for the three channels of the photodiode.

optical signal at each color channel and converts it to a voltage one. The collected signal is sampled by the oscilloscope and processed at the Matlab® using the Euclidian Distance method. The SNR of the electrical signal at the Rx and the BER of the proposed scheme with respect to the illuminance are measured. The illuminance alters by changing the Tx-Rx distance.

Fig. 7 shows the experimentally measured BER at the Rx-end versus the SNR for each of the three color channels of the proposed the 3-CSK scheme. The BER is calculated by the Eq. 5.

$$BER = \frac{Erroneous\ Bits}{Total\ Number\ of\ Bits} \tag{5}$$

The red channel presents the best performance due to the sensitivity of the photodiode to the specific spectrum as it is easily observed in Fig. 2. Particularly, the red channel proved to be more robust to the cross-channel interference, as it is also expected from the Fig. 2.

The separation of the green and blue channels was a more complex task due to the significant sensitivity overlap of the photodiode green and blue channels. In addition, since the color temperature was at 4000 K (according to typical specifications), the power of the blue channel was less. As showed in Fig. 2, the interference between the green and blue channels is high, and also, they reach the saturation point almost together. The better performance of the green channel compared to the blue, is based also on the sensitivity characteristics of the photodiode to the green spectrum. The sensitivity of the photodiode to optical spectrum combined with the desirable color temperature affect the efficiency of the proposed scheme.

The experimental measurements showed that although a common RGB photodiode was used, with extended spectrum overlaps among its color channels, it is feasible to separate and retrieve the signal at each channel by exploiting the proposed Euclidian Distance method.

VI. Conclusion

Visible light communications turn to be a robust and sustainable solution for the new era of telecommunication networks, providing extended bandwidth availability at unlicensed operating frequencies. In the view of VLC systems, this work explores the use of a Euclidean Distance based method for signal retrieval in a 3-Color Shift Keying optical communication scheme. According to this, the red, green, and blue colors of an RGB LED at the transmitter operate as independent optical channels. An RGB photodiode receiver collects the optical signals, and the Euclidean Distance method is applied for the separation and retrieval of the color channels' signals. The efficiency of the proposed method is examined by measuring the bit error rate (BER) and the signal-to-noise ratio (SNR) on a basic 3-Color Shift Keying transceiver.

The proposed approach proved to be a viable solution for the separation of the signals at the three optical channels. As a future work, the development of a complete RGB photodiode receiver along with suitable amplifiers, samplers, analog-to-digital converters and the digital backend will be developed.

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