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# Experimental Characterization of the Color Quality and Error Rate for an Red, Green, and Blue-Based Light Emission Diode-Fixture Used in Visible Light Communications

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*Abstract*—An important feature of Lighting Emitting Diodes (LED) technology is the fast on-off commutation. This fact allows data transmission using modulation formats such as On-Off Keying (OOK) and Color Shift Keying (CSK). Since, CSK based on three color bands uses red, green, and blue monochromatic LED (RGB-LED) to define a pattern of chromaticities; this type of CSK provides poor color quality on the illuminated area. In this work, we present the design and implementation of a VLC system using RGB-based CSK with 16, 8, and 4 color points, mixing with a steady baseline of a phosphor white-LED, to improve the color quality of the LED-Fixture. The experimental system was assessed in terms of the Symbol Error Rate (SER) and the Color Rendering Index (CRI). Good color quality performance of the LED-Fixture was obtained with an acceptable SER. We describe the laboratory setup used to characterize and calibrate an LED-Fixture.

*Keywords*—Color rendering index, symbol error rate, color shift keying, visible light communications.

## I. INTRODUCTION

VISIBLE Light Communication (VLC) refers to wireless communications using the visible part of the electromagnetic spectrum to transmit information. Light sources based on solid-state devices such as Light Emission Diode (LED), Organic-LED (OLED), and Polymer-LED (PLED), are used in VLC. The capability of switching these solid-state devices at high frequencies allows modulating the emitted power while simultaneously illuminating an area of interest. On the other hand, the high demand for mobile communication services and Internet access has increased the use of bandwidth and led to the saturation of the radio frequency spectrum. Due to the massive use of LED devices in lighting systems, VLC is a low-cost wireless solution to address this problem [1], [2].

The IEEE 802.15.7 standard was introduced to standardize the different schemes for communication with visible light and define the modulation techniques [3]. This document standardizes three different modulation techniques: On-Off Keying (OOK), Variable Pulse Position Modulation (VPPM), and Color Shift Keying (CSK) [4]. CSK modulation sends the information using a constellation of symbols based on CIE 1931 color space. By controlling the intensity of RGB components in a LED-Fixture, the chromaticity point can be defined [5], [6], and a bit string of information transmitted. Because this modulation uses red, green, and blue monochromatic LED (RGB-LED) to define a pattern of chromaticities, which results in a low Color Rendering Index (CRI), the LED-Fixture exhibits a poor color quality. For this reason, the RGB-based CSK cannot be used in indoor lighting applications.

Some research works have been carried out related to the CSK modulation and the color performance of the LED-Fixture. In [7] billiard algorithms were used to modify the constellation design to change the average color emitted by the transmitter, and maximize the minimum distance between constellation points. The illumination and communication performance of CSK signals were analyzed in [8], where several problems of CRI are discussed. In [5], a deterministic convex optimization to design RGB-based CSK constellations concerning the cross-talk between each channel color was presented. This method allows adjusting the human color perception of the LED-Fixture. In [9], a new CSK constellation based on four colors or quadrichromatic CSK was presented. This quadrichromatic CSK increased the minimum Euclidean distance between the data symbols at the transmitter compared to the CSK constellations based on three colors presented in IEEE 802.15.7. In [10], [11], two designs of the constellation for CSK based on four colors were presented. These results have shown CRI values greater than 80 for three different average transmitted colors. Other works have been presented recently in [12]–[14], but without color quality assessments. To the best of our knowledge, no work has addressed the issue of improving the color quality of an LED-Fixture using RBG-based CSK. The latter considerably restricts the use of this modulation in indoor lighting systems.

This paper presents the experimental performance evaluation of RGB-based CSK modulation mixed with a steady baseline of phosphor white-LED to improve the color quality of an LED-Fixture. The implementation of a VLC system and a laboratory methodology for automated calibration of color points of the LED-Fixture are presented in Section II. Section III assesses the illumination and

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communication performance using the CRI and the SER, respectively. Section IV presents the conclusions.

## II. Methodology

Due to the poor color quality of the RGB components used in the CSK modulation, its application in indoor lighting should be complemented with a phosphor white-LED. The wide spectrum of phosphor white-LEDs improve the CRI on the illuminated space. To keep a constant optical power radiated with a good CRI, the LED-Fixture mixes RGB components and a phosphor white-LED. When the LED-Fixture increases the white-LED emitted power, the radiated power for each CSK symbol is decreased, and this reduction will lead to an increase in the error probability of the communication system. The purpose of this work was to characterize the impact on illumination and communication performance of a VLC system, when a steady baseline of phosphor white-LED was added to the transmission of 4, 8, and 16 color shift keying. The balance between CRI and error rate based on this dimming technique was studied over a real VLC system.

### A. Implementation of the VLC System

A line-of-sight VLC system composed of a LED-Fixture and a VLC receiver was implemented. The LED-Fixture transmitter was based on a 32-bits microcontroller and a Red, Green, Blue and phosphor-based White LED (RGBW-LED) module. The receiver was based on RGB-sensor, a 16-bits microcontroller, and a PC decoding algorithm. On the LED-Fixture side, the microcontroller adjusted the output voltage of the Digital Analog Converter (DAC) via Serial Peripheral Interface (SPI) protocol. This output voltage fixed a current in every channel of RGBW-LED using a voltage controller LED-driver. On the receiver side, an RGB color sensor converted the optical signal emitted by the LED-Fixture into three electrical signals. On a microcontroller, these signals were digitalized using a 10-bits Analog Digital Converter (ADC) and sent to PC through Universal Asynchronous Receiver-Transmitter (UART) protocol. Finally, the decoding algorithm computed a channel gain matrix, the normalized power received and the corresponding CIExy color coordinates mapping.

### B. Calibration of the CSK Constellation

A calibration procedure was carried out to ensure that the LED-Fixture emits the chromaticity points according to the IEEE 802.805.7 constellations. This calibration was in three stages:

1) Characterization of RGB-LEDs: This characterization consisted of figuring out a linear behavior with respect to one photometric quantity and the CIExy color coordinates of the RGB-LED. Luminance was the photometric variable used to describe the illumination performance, because it is the best variable to represent the optical power that the human eye perceives. The decimal value used for programming the DAC was the direct-controlled variable to modify the photometric quantity. Thus, a fitting function between the luminance and DAC values was formulated.
2) Application of IEEE Rules Design: Using the CIExy color coordinates of the RGB-LED measured, the geometric rules to design the CSK constellations presented in [3] were applied. Then, the CIExy coordinates and the RGB-LED luminance for each symbol were computed. A linear regression based on the fitting function formulated previously was carried out, and the DAC values were computed.
3) Constellation Measurements and Validation: The DAC values found were programmed in the microcontroller. The luminance and CIExy coordinates for each CSK symbol emitted by the LED-Fixture were measured. The error between the measured and the theoretical constellation was calculated and the illumination performance of the modulations was validated.

### C. An Automated Laboratory Method

The illumination performance and measurements for calibration were carried out using a spectral luminancemeter system, which was consisted of a telescope with fiber-optic connection to a spectrometer. A spectrometer software based on MATLAB captured, processed, showed, and saved data sent by the spectrometer. The luminance was measured on a Lambertian surface illuminated for LED-Fixture. To decrease the measurement time was designed a system that allowed to control the LED-Fixture and take the spectral data automatically. First, a web server and WiFi-network were implemented in the microcontroller of the LED-Fixture. Second, in the spectrometer software was created an algorithm for connecting to the WiFi-network implemented in the LED-Fixture microcontroller. Third, the spectrometer software controlled the LED-Fixture through HTTP protocol with the web server, and it measured luminance and CIExy coordinates automatically. Fig. 1 illustrates the functional diagram of the automated method.

### D. Channel Model

Due to the operating principle of the CSK based on 3 channel communication, a 3x3 channel gain matrix $H$ models the contribution of the emitted power for the RGB-LED in every RGB photodetector. In the implemented system, the $H$ related the normalized power in the transmitter with the ADC values in the receiver microcontroller. Assuming a linear relation between the normalized optical power of transmitted symbols, and the received ADC values, and a channel with Additive White Gaussian Noise (AWGN), the expression for this channel model is:

$$r_i = H \cdot s_i + n_i \tag{1}$$

where $s_i$ is the normalized power of the transmitted symbol, $r_i$ is the ADC values of the received symbol, and $n_i$ is the

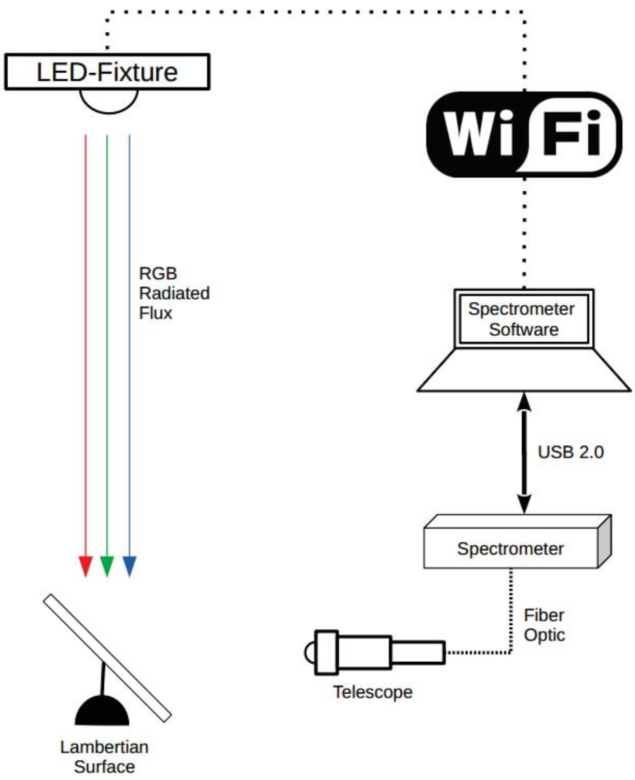


Fig. 1 Diagram of the automated laboratory method

AWGN noise vector. $H$ is the channel gain matrix defined as

$$H = \begin{bmatrix} h_{ii} & h_{ji} & h_{ki} \\ h_{ij} & h_{jj} & h_{kj} \\ h_{ik} & h_{jk} & h_{kk} \end{bmatrix} \quad (2)$$

where $h_{ii}$ represents the contribution of red LED to red photodetector, $h_{ij}$ the contribution of red LED to green photodetector, $h_{ik}$ the contribution of red LED to blue photodetector and so on.

### *E. Transmission and Color Quality Performance Trials*

The transmission and illumination performance were studied in terms of the SER, and the CRI, respectively. The SER was computed using the transmission of the 30000 symbols for 4-CSK, 8-CSK, and 16-CSK. In the receiver, the decoding algorithm estimated the channel gain matrix from three symbols of the constellation. Then, the algorithm computed the normalized optical power multiplying the inverse channel gain matrix by the received ADC values for each symbol. The bits of information were decoded by calculating the minimum Euclidean distance in the normalized power space between the received symbols and reference constellation. To characterize the impact of the AWGN in the SER of the system, noise was added to the received ADC values in a Signal-to-Noise ration (SNR) range of 10 dB to 50 dB. The CRI was measured using the laboratory setup shown in Fig. 1 while a LED-Fixture was switching at 10kHz and transmitting symbols in 4-CSK, 8-CSK, and 16-CSK formats.

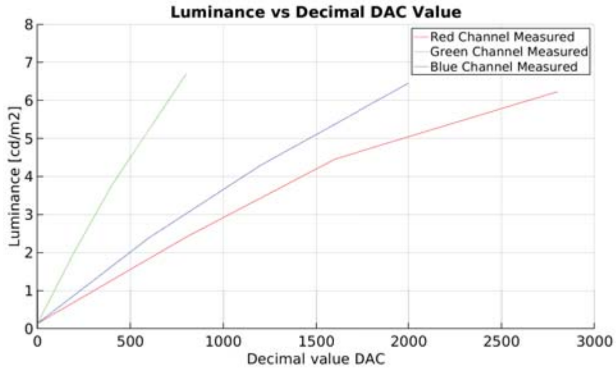


Fig. 2 Luminance characterization of RGB channels

TABLE I
LUMINANCE RELATION AND COLOR COORDINATES FOR EACH CHANNEL

| Channel | Relation $\left[\frac{cd}{m^2 \cdot DAC}\right]$ | x | y |
|---|---|---|---|
| R | 0.0022 | 0.6881 | 0.31117 |
| G | 0.0084 | 0.2072 | 0.7217 |
| B | 0.0032 | 0.1211 | 0.1172 |

## III. RESULTS

### *A. Characterization of the RGB-LED*

The optical power radiated by the red, green and blue LED with respect to the DAC value is presented in Fig. 2. These results allowed us to fit the linear function in the three channels. The red channel presents a lower contribution to the luminance, therefore, the DAC values used of red channel are higher than the green and blue channels for emitting the same luminance. The red channel also presented non-linear behavior for DAC values higher than 2600, so this channel limited a maximum luminance value to 6 $cd/m^2$. At this luminance level were measured the CIExy coordinates of the three channels, and are shown in Table I.

### *B. Validation of the IEEE Constellations*

The color and luminance measurements corresponding of the 16-CSK and 8-CSK are presented in Tables II and III. These measurements were realized at switching frequencies lower than 1Hz, due to the integration time necessary to acquire the spectral data. It means that the LED-Fixture did not work under conditions of transmission. CIExy and luminance values for each symbol were reported as the average of five measurements. The error between the theoretical and the implemented constellation was computed with Euclidean distance in the CIExy space. The corresponding results for 4-CSK are not presented due to the 4-CSK constellations using 4 points of the 16-CSK. These results reflect a good illumination performance of the 16-CSK and 8-CSK constellations according with two aspects. First, the luminance is roughly the same for all symbols, which means no-flicker function. Second, the color coordinates are very close to the theoretical constellation presented in the CSK standard [3].

TABLE II
LUMINANCE AND COLOR COORDINATES FOR 16-CSK MODULATIONS

| Symbol | 16-CSK | | | |
|---|---|---|---|---|
| | x | y | Error | L[cd/m2] |
| S0 | 0.2072 | 0.7217 | 0 | 6.05 |
| S1 | 0.2536 | 0.6039 | 0.0057 | 6.05 |
| S2 | 0.2218 | 0.4117 | 0.0043 | 6.11 |
| S3 | 0.1790 | 0.5184 | 0.0019 | 6.11 |
| S4 | 0.5315 | 0.4482 | 0.0037 | 6.12 |
| S5 | 0.3704 | 0.5847 | 0.0029 | 6.20 |
| S6 | 0.3420 | 0.3860 | 0.004 | 6.25 |
| S7 | 0.4134 | 0.4724 | 0.002 | 6.14 |
| S8 | 0.6881 | 0.3117 | 0 | 5.96 |
| S9 | 0.1211 | 0.1172 | 0 | 6.03 |
| S10 | 0.1517 | 0.3188 | 0.0019 | 6.14 |
| S11 | 0.1907 | 0.2047 | 0.0032 | 6.06 |
| S12 | 0.5036 | 0.2482 | 0.0047 | 6.20 |
| S13 | 0.5758 | 0.3356 | 0.0041 | 5.91 |
| S14 | 0.3842 | 0.2692 | 0.0023 | 6.11 |
| S15 | 0.3123 | 0.1817 | 0.0023 | 6.15 |

TABLE III
LUMINANCE AND COLOR COORDINATES FOR 8-CSK MODULATIONS

| Symbol | 8-CSK | | | |
|---|---|---|---|---|
| | x | y | Error | L[cd/m2] |
| S0 | 0.2072 | 0.7217 | 0 | 6.05 |
| S1 | 0.2218 | 0.4117 | 0.0043 | 6.11 |
| S2 | 0.1790 | 0.5184 | 0.0019 | 6.11 |
| S3 | 0.4928 | 0.4029 | 0.001 | 6.01 |
| S4 | 0.1211 | 0.1172 | 0 | 6.03 |
| S5 | 0.2068 | 0.3058 | 0.0017 | 6.09 |
| S6 | 0.4035 | 0.214 | 0.0012 | 6.01 |
| S7 | 0.6881 | 0.3117 | 0 | 5.96 |

### *C. Color Quality Performance*

The results for color quality as well as error rate were obtained using three different configurations in the LED-Fixture. In the first configuration, the total luminance was radiated by the CSK modulation with an average luminance equal to 6 $cd/m^2$. In the second configuration, CSK modulation radiated a 50% of the total illuminance, and the phosphor white-LED radiated the remaining 50%. In the third configuration, CSK modulation and phosphor white-LED radiated 34% and 66% of the total luminance, respectively. Table IV presents the color and photometric performance concerning to the CRI, the Correlated Color Temperature (CCT), and the average luminance on the Lambertian surface. These results allowed us to check a good color performance in the third configuration. In this configuration, the LED-Fixture reached CRI greater than 80, regardless of the number of points in the CSK constellation and fulfilling the constant luminance. Also, the critical problem of the CRI in the CSK modulation is evident, because, without a baseline of phosphor white-LED, the LED-Fixture presents CRI lower than 50.

### *D. Communication Performance*

The SER of the nine configurations presented in Table IV were characterized, and Fig. 3 shows these results. According to these graphs, when the luminance radiated by the CSK modulation was decreased, the SER curve shifted to the right. A right-shift of an SER curve means degradation of the communication quality. Thus, a reduction of the CSK luminance leads to a reduction in the quality of the communication, because the minimum distance between the received symbols is decreased. For the implemented VLC system, 50% reduction of the CSK luminance represents an SER right-shit equal to 4 dB. On the other hand, in the configuration where the CSK constellation radiated one-third of the luminance, the SER curve of the system was worse than the full power CSK of the next higher-order constellations. For instance, the SER performance of the 4-CSK-Thirdpower configuration is worse than 8-CSK-Fullpower configuration, and the 8-CSK-Thirdpower configuration is worse than 16-CSK-Fullpower. The latter is an important finding, because it sets a lower limit of the dimming CSK luminance to maintain an acceptable trade-off between the data rate and the error rate of the modulation schemes.

TABLE IV
COLOR AND PHOTOMETRIC PERFORMANCE RESULTS OF THE CONFIGURATIONS

| Config. | Contribution Power | | CRI | CCT | L[cd/m2] |
|---|---|---|---|---|---|
| | CSK | white-LED | | | |
| 16-CSK-Full | 100% | 0% | 46.2 | 5344 | 6.26 |
| 16-CSK-Half | 50% | 50% | 72.8 | 4431 | 6.35 |
| 16-CSK-Third | 34% | 66% | 84.5 | 4297 | 6.34 |
| 8-CSK-Full | 100% | 0% | 46.0 | 5354 | 6.21 |
| 8-CSK-Half | 50% | 50% | 72.8 | 4436 | 6.28 |
| 8-CSK-Third | 34% | 66% | 84.4 | 4264 | 6.34 |
| 4-CSK-Full | 100% | 0% | 45.9 | 5185 | 6.24 |
| 4-CSK-Half | 50% | 50% | 73.0 | 4411 | 6.2 |
| 4-CSK-Third | 34% | 66% | 84.6 | 4302 | 6.31 |

## IV. CONCLUSIONS

In this work, we characterized the color quality and communication performance of a real communication system using the three CSK schemes presented in the IEEE 802.15.7 standard. To improve the CRI, the CSK radiated power was mixed with different phosphor white-LED levels maintaining a constant optical flux. The dimming of CSK power shows that 34% of the total power emitted by the constellation and 64% emitted by white-LED could reach a CRI greater than 80, which is desirable for indoor lighting. With the penalization in the communication performance, we conclude that an acceptable balance between CRI and SER occurs with 50% of the optical power radiated by CSK constellations and the other 50% radiated by phosphor white-LED. Our own automated laboratory methodology used to characterize and calibrate the color points constellation allowed us to achieve an accurate design with a considerable reduction in trial time.

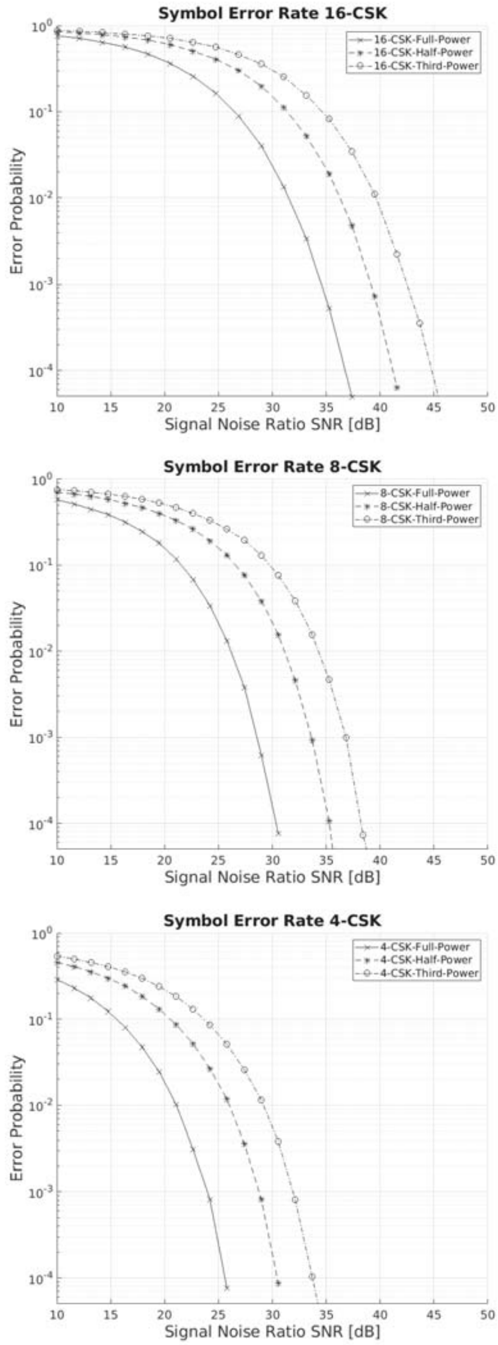


Fig. 3 SER results for 16-CSK, 8-CSK and 4-CSK modulation

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