

Article

Effect of Temperature on Channel Compensation in Optical Camera Communication

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Abstract: General-purpose Complementary Metal Oxide Semiconductor (CMOS) sensors perform the image desegregation in three channels (red, green, and blue) as a result of a band-pass wavelength filtering carried out using Foveon or Bayer filters. This characteristic can be used in Optical Camera Communication (OCC) systems for increasing the links' data rate by introducing Wavelength Division Multiplexing (WDM) or Color Shift Keying (CSK) modulation schemes. However, these techniques need a compensation stage to mitigate the cross-talk between channels introduced by the filters. This compensation is performed by a Channel State Information (CSI) estimation and a zero-forcing compensation scheme. The impact of the temperature effects of light-emitting diode (LED) emissions on the zero-forcing compensation scheme's performance has not been analyzed in depth. This work presents a comprehensive methodology and experimental characterization of this impact for Foveon and Bayer-based image sensors, assuming that the CSI is estimated under temperature conditions different from the LED's stationary temperature regime. Besides, Signal-to-Interference-plus-Noise Ratio (SINR) and Bit Error Rate (BER) performance metrics are presented in order to estimate the repercussion in an OCC link. The results reveal that the Foveon sensor obtains more unsatisfactory performance than the Bayer-based sensor. On the other hand, the blue band is the most penalized by the thermal effect.

Keywords: LED; Optical Camera Communication; temperature effects; spectrum; channel compensation



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1. Introduction

Optical Camera Communication (OCC) is an Optical Wireless Communication (OWC) technology based on the use of general-purpose cameras for gathering data from optical sources. This technology was included in the last revision of the IEEE 802.15.7 standard on Visible Light Communication (VLC) [1], where several physical layer (PHY) transmission modes were defined. The most remarkable advantage of OCC with respect to traditional VLC is the ubiquity of cameras embedded into smartphones, tablets and laptops. Therefore, the likelihood of a massive adoption of OCC by the market is higher than in the case of other VLC technologies, which would require a costly adaptation of the device's interfaces. Furthermore, although OCC is intended to provide low-speed capabilities, the inherent spatial multiplexing capacity of cameras allows an easy integration of Multiple-Input Multiple-Output (MIMO) schemes [2].

Currently, OCC is being proposed as an enabling technology in Smart Cities [3], Intelligent Transportation Systems (ITS) [4], and e-Health [5]. Moreover, OCC has led to several theoretical and experimental works related to Visible Light Positioning (VLP) [6,7], which may lead to a location-aware system feasible for marketing applications. Nevertheless, the use of OCC in the environments mentioned above is limited by the link geometry and the camera's optical system since the maximum achievable data rate in OCC is directly related to the projected size of the light source on the image sensor [8].

General-purpose Complementary Metal Oxide Semiconductor (CMOS) cameras usually present three color channels (red, green, and blue) comprising the typical RGB scheme. Each channel results from a band-pass wavelength filtering carried out typically using Foveon or Bayer-based image sensors [9]. These color-filter mosaics present a considerable overlap between their transmission spectra (Figure 1). Wavelength Division Multiplexing (WDM) or Color Shift Keying (CSK) communication schemes need to compensate the induced inter-channel interference in order to improve the Signal-to-Interference Ratio (SIR) and thus the Bit Error Rate (BER) performance [10]. This compensation is typically carried out by obtaining the Channel State Information (CSI) in the form of a deterministic channel matrix and performing a matrix multiplication by its inverse, constituting a Zero-Forcing (ZF) scheme. Many other approaches are currently being used in massive MIMO systems [11], but their higher complexity and computational cost are generally not justified in 3-channel OCC systems.

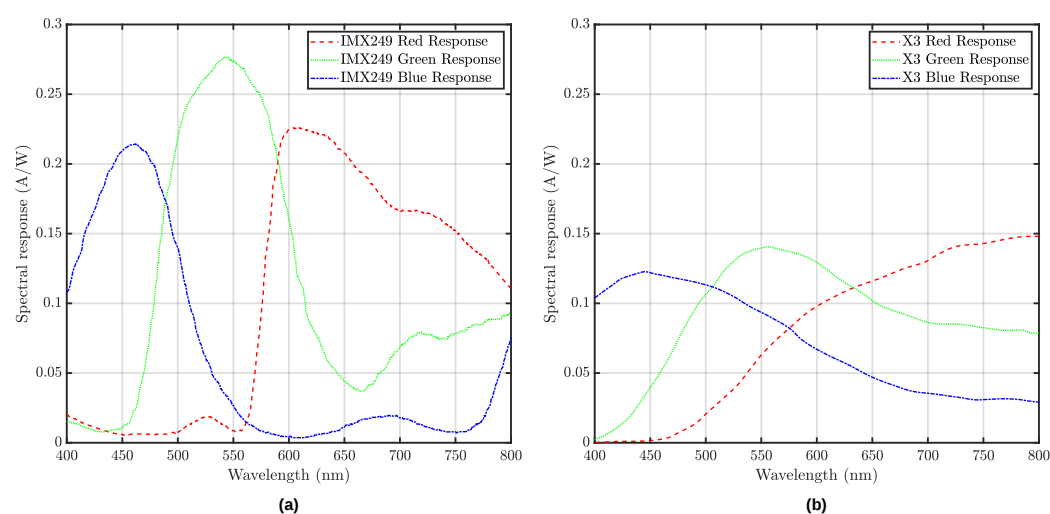


Figure 1. Image sensor filter responses. These graphs illustrate the product between filter transmissivity and silicon sensor responsivity. (a) Sony IMX249. (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

On the other hand, Light-Emitting Diode (LED) devices increase their temperature with respect to their driving current due to the Joule effect. In addition, the p-n junctions' response is very sensitive to these temperature variations, producing significant modifications on the emitted spectrum and the energy efficiency of the light source. As a general rule of thumb, the band gap energy of the substrate is reduced as temperature increases [12], and therefore its peak wavelength red-shifts. Furthermore, an increment in the vibrational energy due to temperature leads to a reduction of the quantum efficiency (electron-to-photon conversion rate) [13].

The effects of temperature on both light sources and optical camera receivers are well documented in the literature separately. Nonetheless, the impact of the aforementioned temperature effects of LED emissions on the performance of the zero-forcing compensation scheme has not been analyzed in depth. This work provides a comprehensive methodology and experimental characterization of this impact using commercially available devices. It has been assumed that the CSI is acquired subject to an initial temperature condition, different from the stationary temperature regime of the LED. Therefore, the product between the obsolete inverted CSI matrix and the actual channel matrix will not be the identity, resulting in an SIR penalty. LED lamps located outside buildings directly exposed to solar radiation, vehicle headlights, or any LED-based source subject to critical heat conditions in industrial environments can suffer from the aforementioned effects. Large time-dependent temperature gradients can occur (in both directions), and the link quality must comply with the system's requirements regardless of the environmental conditions. This work

provides experimental evidence about the necessity of consistent channel compensation mechanisms in these scenarios.

This paper is structured as follows. Section 2 performs an in-depth analysis of the related works available in the literature, Section 3 discusses the details of the OCC link, Section 4 describes the channel compensation procedure, and Section 5 introduces the methodology and the experimental setup implemented to obtain the results, which are presented in Section 6. Finally, these results are discussed in Section 7.

2. Related Work

This work underlines the importance of considering the effect of temperature on LEDs when compensating the channel in OCC. Temperature effects on those light sources have thoroughly been studied in the literature. A number of studies have found that the efficiency and the spectral features of the LEDs are very sensitive to thermal changes. Furthermore, several approaches have been proposed to perform channel compensation in VLC and OCC systems, but none have dealt with the mentioned temperature effects.

Photo-Electro-Thermal (PET) modeling of LED sources has a significant impact on luminaire design and optimization. These three domains are usually tightly coupled, and the design of illumination fixtures must take into account the interactions between them. Commercial LED lamps are customarily manufactured using arrays of LED. Due to the manufacturing process, each device presents slightly different characteristics that could affect the performance (and ultimately the reliability) of the LED system. Chen et al. proposed a 3D PET model for predicting the behavior of lamps built with non-identical LED parts [14]. The model, based on the use of a grid-like partition of the domain of interest combined with coupling equations, presented high accuracy compared to the experimental results. Almeida et al. proposed a PET model that included transient analysis for predicting the impact of driving current ripple effects on both the thermal and the photometric outputs of an LED. The authors obtained experimental evidence about the benefits of driving LED devices with rippled inputs (DC current plus a sine-like signal) for improving the lifespan of these devices without affecting the human perception [15]. This type of input enables smaller capacitance filter values, which allow the use of more reliable technologies compared to electrolytic capacitors (such as film capacitors). In addition to these models, Shen et al. included the effects of phosphor temperature in a PET model, showing that a good thermal design considering this aspect is capital to maintain performance in White LED (WLED) devices [16]. Unlike Shen et al., a dynamic PET analysis was carried out by Hui, Lee, and Tan in [17]. The authors proposed a modification of the steady-state PET equations from Chen et al. [14], including the coupling effect of phosphor-to-LED (and vice versa) in the thermo-electric domain, as well as the electro-optic efficiency reduction on phosphor due to temperature. All these models were focused on the lighting industry and aimed to develop models suitable for manufacturers and designers. Nonetheless, communication metrics have not been included in PET models yet (up to the authors' knowledge).

Regarding the emitted spectrum variation due to the p-n junction temperature, Raypah et al. carried out an investigation measuring the spectrum of a Surface Mount Device (SMD) LED at ambient and high-temperature conditions that demonstrated a red-shift in the peak wavelength and a decrease in intensity as temperature grew [18]. Some studies related to thermal effects on LED focused on the emitted color variation. Muthu et al. performed experimental measurements of color variation in RGB LEDs as a function of temperature, concluding that the blue LED has the highest color point variation [19]. Spagnolo et al. discussed LED applications in railway and traffic light signals proposing a system that compensate intensity and color stability in order to respect limits imposed by the norms [20]. Lu et al. established a relationship between color difference and temperature using a blue transparent flexible mini-LED array [21].

Furthermore, the LED luminous efficiency has been enhanced over the past few years owing to different techniques. Lee et al. investigated the thermal and optical characteristics

of a warm white LED, studying both the effects of thermal interface materials (TIM) and the impact of the driving current on the LED performance. The authors remarked the importance of a comprehensive design of the internal thermal structure and the appropriate selection of the packaging material to extend the lifetime and preserve the performance of the LED [22]. Regarding the effect of the driving current, Raypah et al. analyzed the optimal working conditions of a low-power SMD LED concerning the luminous flux and its efficacy [23]. The authors compared how those properties were affected by the injection current and the ambient temperature, concluding that the latter affected more that LED's substrate. Chen et al. carried out a study analyzing the effect of rapid thermal cycling on luminous flux and luminous efficiency of high-power LED, demonstrating that the effect could significantly impair the LED properties and interface microstructures [24].

Channel compensation is a capital processing stage in any system in which there is inter-channel interference. In VLC-based systems, MIMO and CSK (and WDM) are the two main techniques that can require compensation. MIMO VLC systems have attracted the attention of the scientific and industrial communities in recent years due to their potential use in real environments using multi-LED lamps and the current industrial trend based on the application of Orthogonal Frequency Division Multiplexing (OFDM) [25,26]. According to this trend, Hong et al. studied adaptive bit-loading and power-allocation schemes for indoor MIMO-VLC systems [27]. The authors proposed the use of 2×2 receiver arrays with angular diversity. The simulation results, which included a realistic estimation of the impulse responses, show that elevation angles close to 45° can optimize the BER performance after channel compensation. However, the transmission-side setup included four independent LED lamps separated by a large distance, and no jitter or synchronization issues were mentioned in the paper. This last aspect is essential when the spatial diversity emitter covers a significant deployment area, as highlighted by Ramirez-Aguilera et al. in [28]. A similar work based on the same angular diversity concept was presented by Wei, Zhang, and Song in [29]. In this case, the authors validated a cubic receiver under laboratory conditions, demonstrating the feasibility of the $\pi/2$ -diversity. Akande and Popoola in [30] performed a comprehensive comparison between spatial multiplexing and repetitive coding MIMO techniques for Carrierless Amplitude and Phase (CAP) modulation. The authors demonstrated that repetitive coding is a better option for highly-correlated channels due to the ill-conditioned nature of the channel matrix (similar channel gains for each channel). However, this depends on the input SNR. Luo et al. proposed the use of an RGB OCC link in [31]. The authors demonstrated spectral efficiencies up to 3 bits/s/Hz in a 60 m link in their work. Although the paper states that MIMO techniques were employed, a single-LED link was essayed. Regarding RGB channel compensation, a ZF scheme (as in [10]) was used with no output SNR penalty (typical issue of ZF) thanks to the use of imaging optics at the receiver side.

Anusree and Jeyachitra studied different compensation techniques for MIMO-VLC systems [32]. The authors analyzed the performance of ZF, ZF with successive interference cancellation (ZF-SIC), and Minimum Mean Squared Error (MMSE) equalizers. As expected, the best performance was obtained for the MMSE equalizer, which considers the channel matrix's noisy nature. Nonetheless, the covariance matrix must be known a priori or estimated before the compensation stage. In order to overcome this limitation, Gao et al. proposed using a convolutional autoencoder to denoise the channel matrix [33]. Nevertheless, this proposal was based only on simulation results and no experimental outcomes were provided.

3. Optical Camera Communication Link Model

Complementary Metal Oxide Semiconductor (CMOS) cameras usually employ Rolling Shutter (RS) scanning. This type of scanning is based on exposing the sensor to the incoming light on a row basis. The row shift time is normally grasped to perform a time-to-space conversion, capturing the light source variations along the sensor's scanning dimension. This effect is one of the most important aspects of OCC and has enabled a multitude of

communications techniques, such as Undersampled Frequency Shift On and Off Keying (UFSOOK), WDM and MIMO [31], CSK [34], and 2D-OFDM [35].

Generally, most cameras possess a Color Filter Array (CFA) that is usually located over the image sensor. This allows the camera to split signals from light sources depending on wavelengths. Figure 2 shows both Bayer and Foveon RGB filter pattern. Bayer mosaic contains 25%, 50%, and 25% of red, green, and blue regions, respectively, while Foveon mosaic presents 100% of the color. Consequently, Foveon abolishes the de-mosaicing process, and its spectral response is based on the light absorption behavior of silicon [36]. These characteristics have prompted the use of cameras to carry out WDM, CSK, and MIMO systems by using RGB LEDs as a light source. Nevertheless, as mentioned above, those filters present an overlap between their RGB channels, causing channel cross-talk. Thus, an approach to compensate this interference between channels is needed.

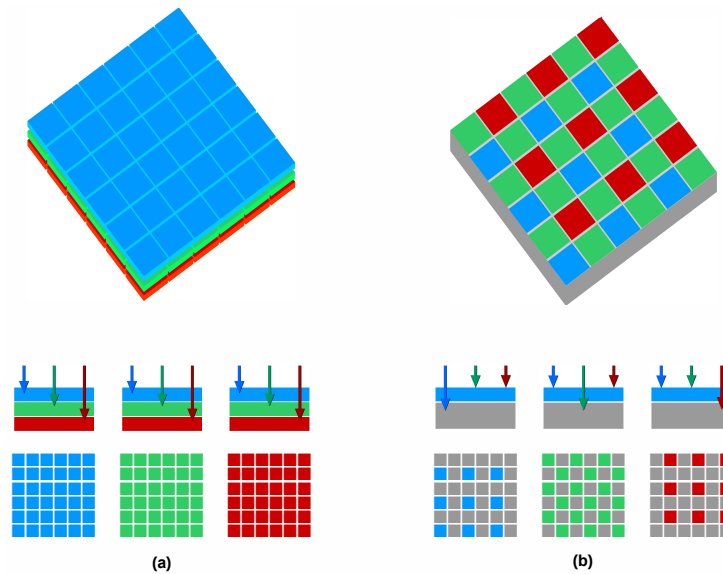


Figure 2. Filter patterns for the spectral information acquisition. (a) Foveon-based sensor. (b) Bayer filter sensor.

3.1. Link Budget

According to the typical formulation of an OWC link budget, the optical power impinging the main lens of a camera can be expressed as shown in Equation (1).

$$P_{rx} = P_{tx} R(\theta, \phi) \frac{A_{lens}}{d^2} \cos(\Psi) \quad (1)$$

where P_{rx} is the received power, P_{tx} is the optical source's radiant power, $R(\theta, \phi)$ is the source's radiation pattern at elevation θ and azimuth ϕ , A_{lens} is the main lens' cross section, d is the link range, and Ψ is the impact angle. Furthermore, thanks to the use of image-forming optics, in a perfectly focused situation the received optical power would be divided among the projected size of the light source (Equation (2) [8]).

$$A_{proj} = \frac{N_x N_y}{FOV_x FOV_y} \frac{A_{tx}}{d^2} \quad (2)$$

A_{proj} is the projected size of the light source on the sensor (expressed in pixels); N_x and N_y define the sensor's pixel resolution; FOV_x and FOV_y are the camera's horizontal and vertical fields of view, respectively; and A_{tx} is the transmitter's effective area (from the

receiver's viewpoint). Joining Equations (1) and (2) it yields the received optical power at each pixel (Equation (3)).

$$P_{px} = P_{tx} R(\theta, \phi) \frac{A_{lens}}{A_{tx}} \frac{FOV_x FOV_y}{N_x N_y} A_{px} \cos(\Psi) \quad (3)$$

P_{px} is the pixel power (in watts) and A_{px} is the pixel area. This last equation is valid for scenarios in which A_{proj} is strictly greater than one pixel. Finally, the electron yield $S_{px}^{(i,j)}$ of the i -th emitter on the j -th sub-pixel (color) after the optoelectronic conversion takes into account the filter response $F_j(\lambda)$ (from the Bayer filter or the Foveon architecture); the emission spectrum $\tilde{S}^{(i)}(\lambda, T)$, which depends on wavelength (λ) and temperature (T); and silicon quantum efficiency, as Equation (4) describes.

$$S_{px}^{(i,j)} = P_{px} \int_{\lambda} \tilde{S}^{(i)}(\lambda, T) F_j(\lambda) \Re(\lambda) \frac{E_{ph}(\lambda)}{q} d\lambda \quad (4)$$

Silicon quantum efficiency is described by the responsivity curve of the material $\Re(\lambda)$, the photon energy $E_{ph}(\lambda)$, and the electron charge q . As it can be observed, the link budget depends on two separate phenomena. The link's geometry defines the amount of energy that arrives at the main lens of the receiver, which is wavelength-independent at least in Line-Of-Sight (LOS) scenarios, which is the case under study. On the other hand, the emission spectrum, which is affected by the device's p-n junction temperature, and the wavelength-dependent behavior of the receiver define the final electron yield.

3.2. Noise Sources

The most important noise sources in OCC are shot noise, Johnson noise, and Fixed-Pattern Noise (FPN). Shot noise has a quantum nature and is related to the fluctuations that occur during optoelectronic conversion. This kind of noise comprises photo-generated noise (N_{px}), whose variance linearly increases with the photo-generated current, readout noise (N_{ro}), and dark current noise (N_d). Readout noise occurs when the pixel value is delivered by the CMOS circuitry and does not depend on the input signal level. Although shot noise is Poisson distributed, it is usually approximated by a Gaussian assuming sufficient input power (high number of incident photons). Johnson noise (N_{th}) occurs due to the thermal agitation of the receiver's molecules and is dominant under low-light conditions. Finally, FPN is related to the nonuniformity of the sensor's pixel response, although it has a residual impact on communications systems. As it can be observed in Equation (5), all the noise contributions can be summed up into an overall noise variance σ_N^2 .

$$\sigma_N^2 = (N_d + N_{px}) \cdot T_{exp} + N_{ro}^2 + N_{th}^2 \quad (5)$$

N_{px} (photo-generated shot noise variance) is equal to $S_{px}^{(i,j)}$, according to the Poisson nature of shot noise. All the above terms are referred to Root Mean Square (RMS) electrons. Combining Equation (3) with Equation (5) and considering several interfering contributions (other channels), the Signal-to-Interference-plus-Noise Ratio (SINR) formula can be easily obtained (Equation (6)). $S_{px}^{(i,j)}$ defines the rate at which electrons are converted into the device (i -th emitter to j -th receiver). Therefore, the amount of electrons in a given time window (after a row scanning in the CMOS sensor) is obtained by integrating this rate during the camera's exposure time T_{exp} .

$$SINR_j = \frac{\left(S_{px}^{(j,j)} T_{exp}\right)^2}{\left(N_d + \sum_{j=1}^n S_{px}^{(i,j)}\right) \cdot T_{exp} + N_{ro}^2 + N_{th}^2 + \sum_{j \neq i} \left(S_{px}^{(i,j)} T_{exp}\right)^2} \quad (6)$$

3.3. Emitted Spectrum versus Temperature

The photons emitted by an LED present a wavelength that is related to the energy gap of the semiconductor substrate. In addition, the energy gap is affected by the p-n junction temperature, which is usually modeled using Equation (7). According to the authors of [37], in most semiconductor materials, the energy gap diminishes as temperature increases. Therefore, as the wavelength is inversely proportional to this gap, the LED's peak wavelength increases with temperature.

$$E_g = E_0 - \frac{\alpha T^2}{T + \beta} \quad (7)$$

where T is temperature, E_0 is energy gap at 0 K temperature condition, and α and β are semiconductor-dependent constants, which are empirically determined.

Nonetheless, the LED substrate must be taken into consideration. In [12], the authors demonstrated that depending on the Indium (In) content in InGaN alloys (green and blue LEDs), the band gap may not decrease with temperature as many materials do, but can even increase with temperature. Furthermore, junction temperature affects both spectral width and luminous efficiency. In general, as temperature increases, the conversion efficiency decreases and the spectral width increases [13].

As has been already mentioned, temperature produces spectral changes on the LED emission. In this study, these variations would affect $S_{px}^{(i,j)}$ from Equation (4) as the terms $\tilde{S}^{(i)}(\lambda, T)$ are temperature-dependent. Consequently, the SINR will also be affected.

4. Channel Compensation in Optical Camera Communication

Channel compensation is usually a two-stage procedure. During the first stage, the CSI of the OCC channel is obtained in order to form the channel matrix. In this work, the CSI is derived from the contributions of each emitted spectrum to the three wavelength-divided receivers ($S_{px}^{(i,j)}$ terms). It has been assumed that the link establishment procedure includes a training sequence in which each emitter is turned on sequentially in a Time-Division-Multiple-Access (TDMA) scheme (as in [10]). The elements of this matrix, named $\mathbf{H}$ hereinafter, respond to Equation (8).

$$h_{ij} = \begin{cases} K_{cam} (S_{px}^{(i,j)} T_{exp} + N) & \text{if } S_{px}^{(i,j)} T_{exp} + N < h_{max} \\ K_{cam}(h_{max}) & \text{otherwise} \end{cases} \quad (8)$$

where h_{ij} is the response of the camera's j -th receiver to the i -th emitter and K_{cam} is a function comprising the effects introduced by the camera's analog gain, the analog-to-digital conversion, and the nonlinear gamma correction. h_{max} is the full-well-capacity of the image sensor, measured in electrons. It must be noted that $\mathbf{H}$ is subject to noise-induced errors, as the noise term N suggests (which presents the variance of Equation (5)). In addition, it has been assumed without loss of generality that the impulse response of the optical channel can be modeled as a Dirac's delta as the frequency response of the camera system is significantly smaller (bounded by T_{exp}) than the channel bandwidth of any OWC indoor scenario. Regarding the optical system's spatial response, it has been assumed that the light source presents uniform radiance.

Furthermore, the second stage of the compensation is based on calculating the inverse of the obtained matrix and multiplying it by the received vector (Equation (9)). This vector implicitly includes the current CSI $\tilde{\mathbf{H}}$, and this multiplication aims to mitigate the inter-channel interference. In an ideally compensated scenario, the interference term of

Equation (6) (right term of the denominator) would vanish, but the shot noise contribution of each channel would remain.

$$v_{comp} = \overbrace{\mathbf{H}^{-1}}^{\mathbf{I}_H} \cdot \underbrace{\tilde{\mathbf{H}} \cdot \tilde{v}_{tx}}_{\tilde{v}_{rx}} \quad (9)$$

$\tilde{v}_{tx}$ is the transmitted symbol, $\tilde{v}_{rx}$ is the received symbol and v_{comp} is the CSI-compensated symbol. The performance of the channel compensation depends on several parameters, such as the condition number of $\mathbf{H}$ [38] and the similarity between the latter and $\tilde{\mathbf{H}}$. If both matrices are identical, the compensation results in $\mathbf{I}_H = \mathbf{I}$, where $\mathbf{I}$ is the identity matrix. Static links (or under slow movement regimes) are generally assumed to work in a stationary condition. Nonetheless, as will be demonstrated in the following sections, this assumption does not hold anymore if temperature effects are included in the model.

5. Methodology

The main objective of this paper is to evaluate the effect of compensating an RGB OCC channel by using obsolete CSI in terms of temperature. As was aforementioned, the emission spectrum of an LED is highly dependent on temperature, usually displacing the peak wavelength to lower energies, decreasing the coherence (spectrum broadening) and lowering the light source's efficiency. These effects cause significant variations between the CSI of an LED at ambient temperature with respect to the same LED at its stationary temperature. In a real OCC link in which the transmitter was subject to significant temperature variations due to the environment (e.g., extreme weather conditions or industrial environments), the channel compensation procedure would result in an SINR penalty due to the difference between the reference CSI and the instantaneous CSI.

5.1. Experimental Setup

The spectra of several LEDs (from a common cathode RGB LED) were measured at different driving currents (and hence different p-n junction temperatures) using a programmable current source and a spectrometer. The LED under test was mounted on an adapter for an integrating sphere's input, and it was directly connected to the current source. The temperature of the LED was estimated using a thermographic camera pointing to the LED's back, as it is the best position to estimate the p-n junction temperature. The LED device under test was driven at different DC currents in order to induce temperature variation due to the Joule effect. No heat sink was applied to the device to allow the thermography-based measurement and avoid heat loss in the p-n junction. The experimental setup is illustrated in Figure 3. All the devices were connected to the control PC through an Ethernet switch, except the spectrometer, which used USB. An automation script was developed in order to ease the characterization procedure.

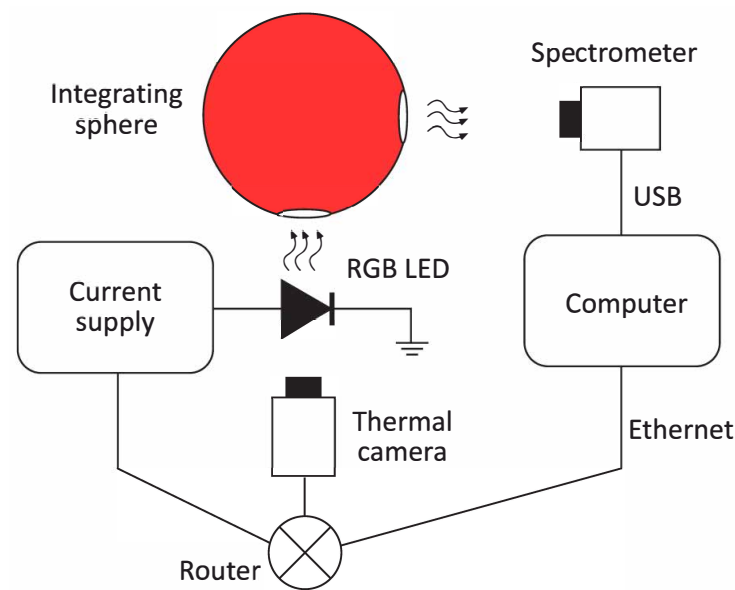


Figure 3. Diagram of the experimental setup.

5.2. Description of the Experiment

The experiment was designed as a two-stage procedure. During the first part, the spectra of the LED under test were acquired, while during the second part, these data were used to obtain different communications metrics for OCC. As was commented, a script was developed in order to automate the spectrum acquisition procedure. Figure 4 depicts the flow diagram of the whole experiment. The LED was driven from 10 mA to 150 mA in steps of 10 mA. Before starting the spectrum acquisition, a waiting time of 3 min was applied to ensure temperature stabilization in the p-n junction.

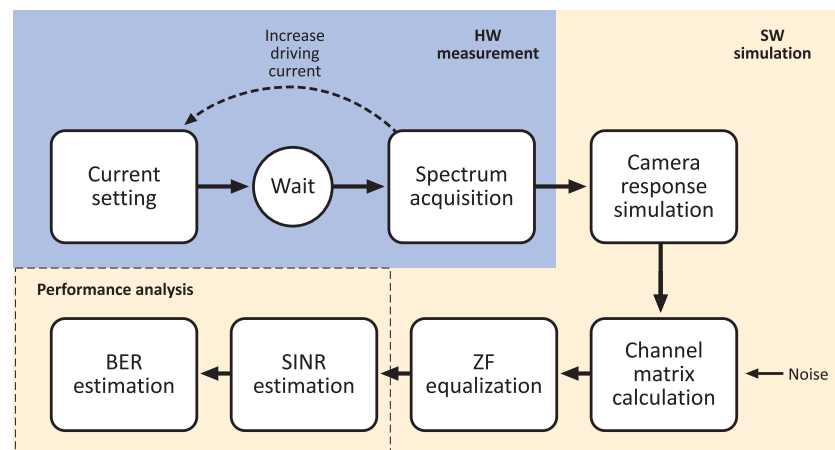


Figure 4. Flow diagram of the experimental procedure.

All the acquired spectra were energy-normalized to enable their use in the following estimation stages. This preprocessing step was needed because of the selected heating method based on the Joule effect. As temperature increased with the driving current, the total emitted power of the LED also increased. The response of a CMOS optical camera was estimated using the equations of Section 6 and the parameters of Table 1. Although the temperature effect of the CMOS image sensors is relevant and increases noise in cameras [39], it was not considered in this scheme because the cameras were assumed to be subject to normal temperature conditions. In addition, this experiment was focused on the temperature effect on the LED and not on evaluating thermal noise effects on the receiver side.

Table 1. Parameters of the experimental setup.

Parameter	Value
Current source	Yokogawa GS820
Spectrometer	Spectral Products SM442
Integrating sphere	Gigahertz ϕ 32 cm
Thermal camera	FLIR A640
CMOS sensors	Sony IMX249 and Foveon X3
RGB LED under test	Kingbright L-154A4SUREQBFZGEW
Temperature range	27 °C to 80 °C
Driving current	10 mA to 150 mA
Red peak wavelength	676 nm @ 10 mA
Green peak wavelength	563 nm @ 10 mA
Blue peak wavelength	460 nm @ 10 mA
Input SNR	30 dB, 20 dB, 10 dB
Spectrometer's integration time	25 ms

The channel matrices at different temperatures were formed by stacking the individual contributions of each LED on the three RGB bands plus the camera noise. Each row was then normalized respect to the matrix's diagonal term to avoid affecting the signal's energy during the compensation procedure. In this work, both Foveon and Bayer-based sensors were considered to compare the resulting performances. The effect of the input SNR level due to the noise signal introduced by the camera (Equation (5)) was also taken into account. This SNR level was estimated comparing the diagonal terms of the channel matrix respect to the corresponding noise power.

Finally, the impact of compensating the channel using ZF and obsolete CSI on the SINR was evaluated. The SINR resulting from the ZF compensation of two matrices at different temperatures was obtained (Equation (10)). The SINR of each wavelength band was calculated as the ratio between the target band's power respect to the addition of the interfering bands' powers (Equation (10)). This assumes that all considered LEDs emit the same power, which is not unrealistic as the light sources were driven by the same currents, presented approximately 1 mW/mA efficiency, and had the same radiation pattern. Taking into account the random nature of the input, this calculation was repeated 10,000 times to provide an average estimation.

$$SINR_i(\text{dB}) \approx 20 \log(\mathbf{I}_{H,ii}) - 10 \log\left(\sum_{j \neq i} \mathbf{I}_{H,ij}^2\right) \quad (10)$$

Using this metric, it could be possible to estimate BER of an OOK-based OOC link according to Equation (11), where $Q(\cdot)$ is the cumulative tail distribution of a standard normal (Q-function). This equation holds for both Global Shutter and Rolling Shutter schemes.

$$BER = Q\left(\sqrt{SINR}\right) \quad (11)$$

6. Results

Figure 5 depicts the measured spectra of the different RGB LEDs at various temperatures. It can be observed how the spectra change as the p-n junction temperature increases, causing peak-wavelength shifts, spectral broadening, and spectral shape distortions. It must be noted that the responses are normalized by the maximum value in order to ease the visualization of the aforementioned phenomena, so changes in LED efficiency caused by temperature are not appreciated.

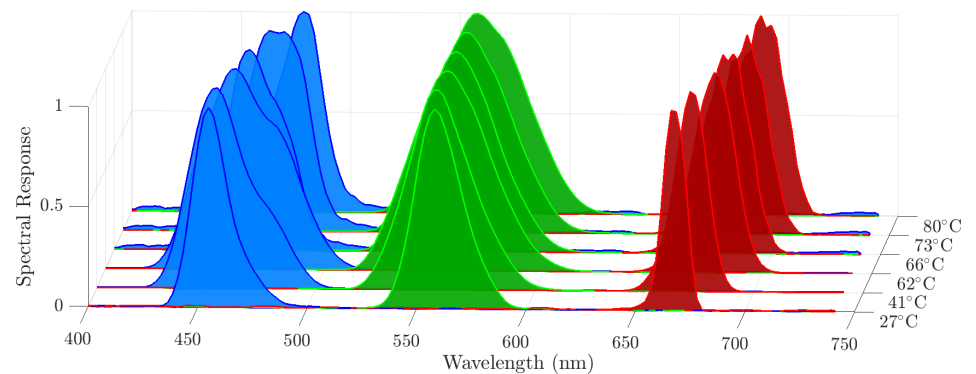


Figure 5. Emission spectra at different p-n junction temperatures.

In order to illustrate the potentially harmful effects of compensating the RGB channel with obsolete CSI, the SINR at different p-n junction temperatures was obtained using the CSI corresponding to 27 °C and 60 °C. Some exemplary thermographic images are presented in Figure 6, illustrating the p-n junction temperature estimation procedure.

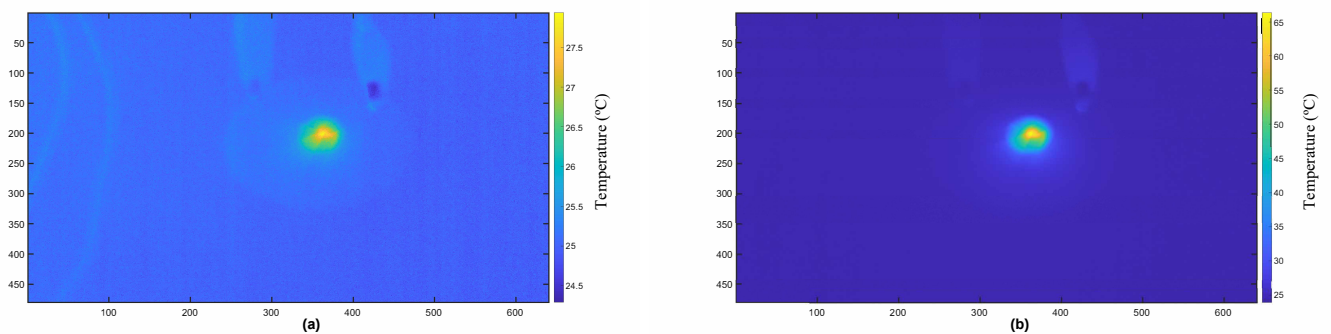


Figure 6. Examples of images of the blue light-emitting diode (LED) driven at different currents, taken by a thermographic camera. (a) LED at 10 mA and (b) LED at 100 mA. Both X and Y axes correspond to pixels.

The results section has been divided into three cases depending on the input SNR. High, medium, and low SNR values are associated with 30 dB, 20 dB, and 10 dB, respectively. This distinction has been carried out to analyze the input SNR's combined effect and the emitter's temperature variations on the system performance. Each subsection includes the effect of compensating the RGB OCC link using channel matrices at two different temperatures, as described above. Furthermore, this effect is evaluated on the two considered CMOS sensors, obtaining the SINR after the ZF compensation and, ultimately, the expected BER assuming an OOK transmission.

6.1. High SNR Case

Figures 7 and 8 show the SINR for an input SNR of 30 dB, which is labeled as high. For both IMX249 and X3 sensors, the penalty of compensating the channel with obsolete CSI affected the blue band reducing its SINR to unpractical values (below ~10 dB) regarding the reference temperature. The red and green bands were also affected, especially in the X3 device.

From Figure 9b, it can be noted a steep step beginning approximately at 62 °C. Two reasons mainly caused this for the X3 sensor: first, the blue receiver's spectral response is noticeably wider in X3 than in IMX249 (Figure 1). Second, above 62 °C, the blue LED spectra are broadened (Figure 5). Therefore, the combination of both phenomena leads to greater interference and, consequently, to an abrupt decrease in the SINR from 62 °C. Moreover, in Figure 8a, the blue LED showed a band-pass characteristic because of the compensation at 60 °C. The SINR level is theoretically at its maximum when the CSI

employed for compensation corresponds to an LED at a temperature equal to the LED's stationary temperature regime. Thus, when the LED temperature of the CSIs deviates from the CSI reference temperature, the SINR decreases. The same effect can be seen in Figure 7, in which the maximum level is at 27 °C (the corresponding temperature of the CSI used to compensate).

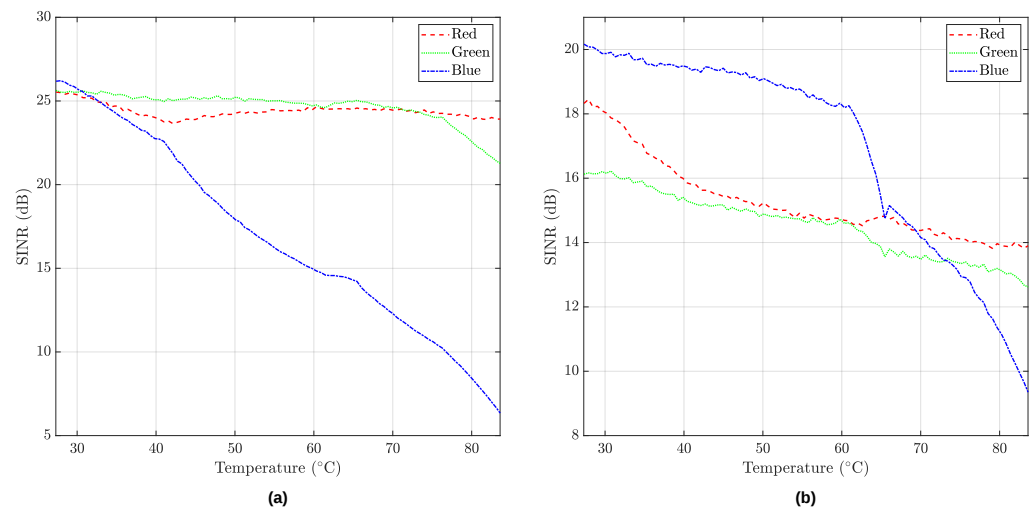


Figure 7. Signal-to-Interference-plus-Noise Ratio (SINR) at different temperatures, compensating the channel using the Channel State Information (CSI) corresponding to 27 °C and with a high SNR value (30 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

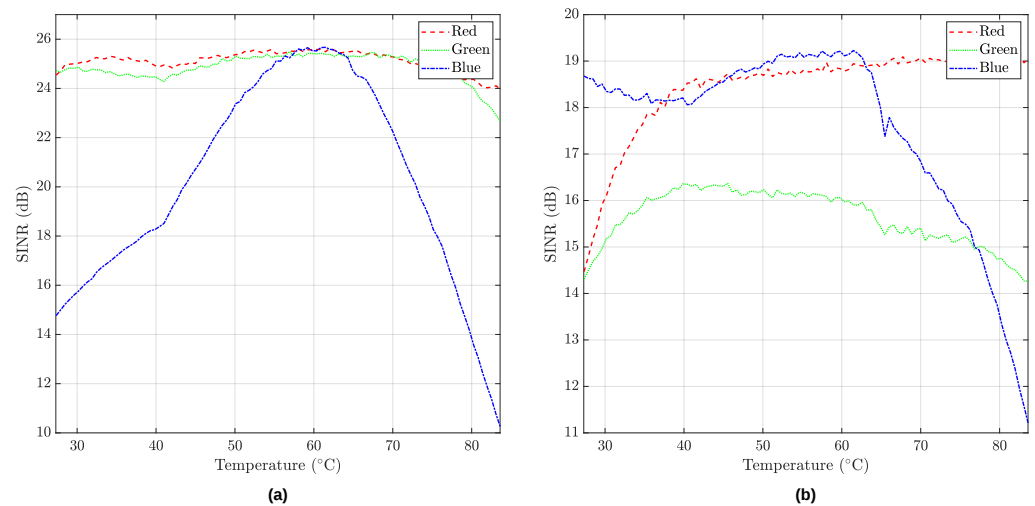


Figure 8. SINR at different temperatures, compensating the channel using the CSI corresponding to 60 °C and with a high SNR value (30 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

It can be observed from Figure 5 that as temperature increased, the blue spectrum was significantly red-shifted, intensifying its intersection with the green component of the Bayer and Foveon filters. Although the red and the green LED emission presented a similar behavior with respect to temperature increments, its contributions to the other components of the filters remained at low levels in the case of the IMX249. These effects were translated into a rapid decrease in the SINR at the blue wavelength, while both red and green components remained more stable. For the X3, due to the overlapping of its filters, red and green presented a higher decrease in SINR.

Figures 9 and 10 depict the BER performance. For a high input SNR, the BER was below the Forward Error Correction (FEC) limit [40] for most temperature differences. Although the BER increased with the temperature difference, there were values above this limit only while using the CSI corresponding to 27 °C to compensate CSIs corresponding to temperatures higher than roughly 80 °C. In Figures 9a and 10a, the BER performance of the red and green bands were well under 10^{-10} . As expected, the BER was worse in the blue band than in the red and green due to the spectra red-shifting and the RGB filters overlapping, as seen in the SINR cases. These results suggest that in those links that require high SNR levels to reach higher data rates, the temperature effect would be more significant and must be taken into consideration.

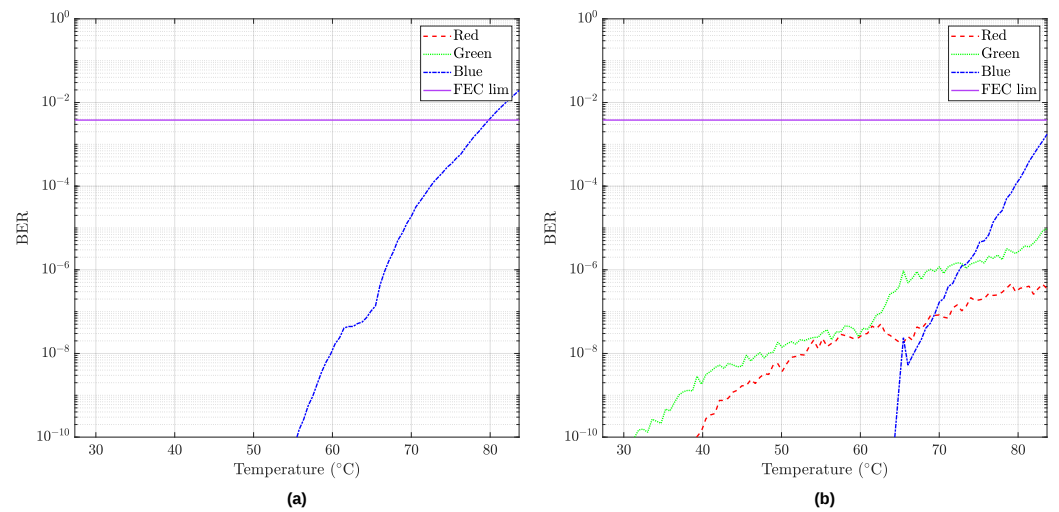


Figure 9. Bit error rate (BER) at different temperatures, compensating the channel using the CSI corresponding to 27 °C and with a high SNR value (30 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

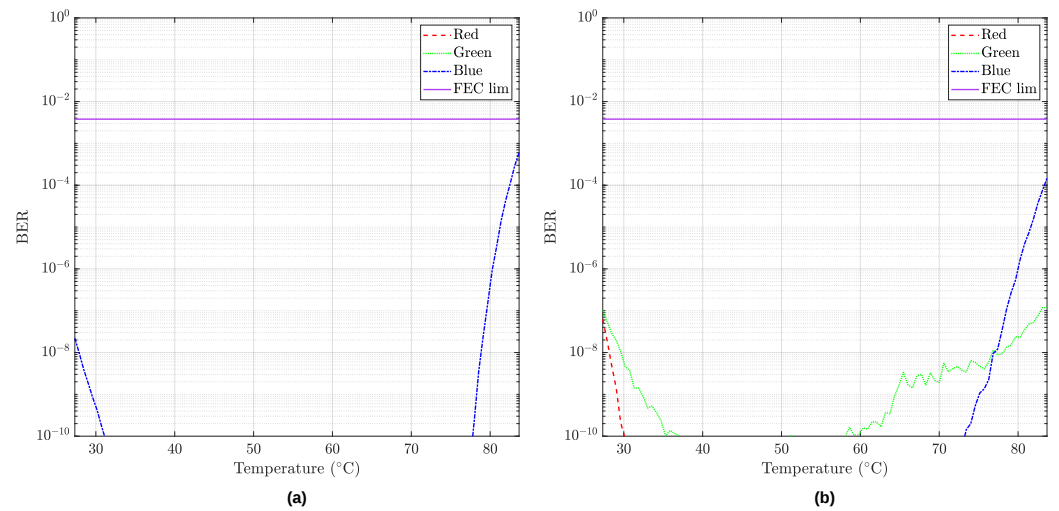


Figure 10. BER at different temperatures, compensating the channel using the CSI corresponding to 60 °C and with a high SNR value (30 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

6.2. Medium SNR Case

Figures 11 and 12 show the SINR for a SNR of 20 dB. In this case, the penalty was still evident in the blue band. However, in the X3 sensor, the higher noise level started hiding the temperature effect on its performance. In the X3, the red and green channels still

decreased in SINR when compensated with an obsolete CSI in temperature, although it was less noticeable in the IMX249.

Figures 13 and 14 depict the BER performance. In this case, most values were below the FEC limit in the IMX249, while in the X3, most values were above the limit. As in the last case, BER values were only above the limit using the CSI corresponding to 27 °C compensating CSIs corresponding to temperatures higher than roughly 80 °C in the Sony device. On the other hand, the BER was above the FEC limit using the CSI corresponding to 27 °C to compensate CSIs corresponding to temperatures higher than roughly 32 °C in the Foveon device. For those cases where the CSI was at a temperature near the operating LED, temperature was used as a reference for compensating, all the values were below the FEC limit using the Bayer-based sensor, while the vast majority of them were above $3.8 \cdot 10^{-3}$ using the Foveon sensor. Likewise, the blue band was again the most affected by temperature.

These results showed that Bayer-based sensors have an advantage over Foveon sensors, in which RGB spectral responses are considerably overlapped.

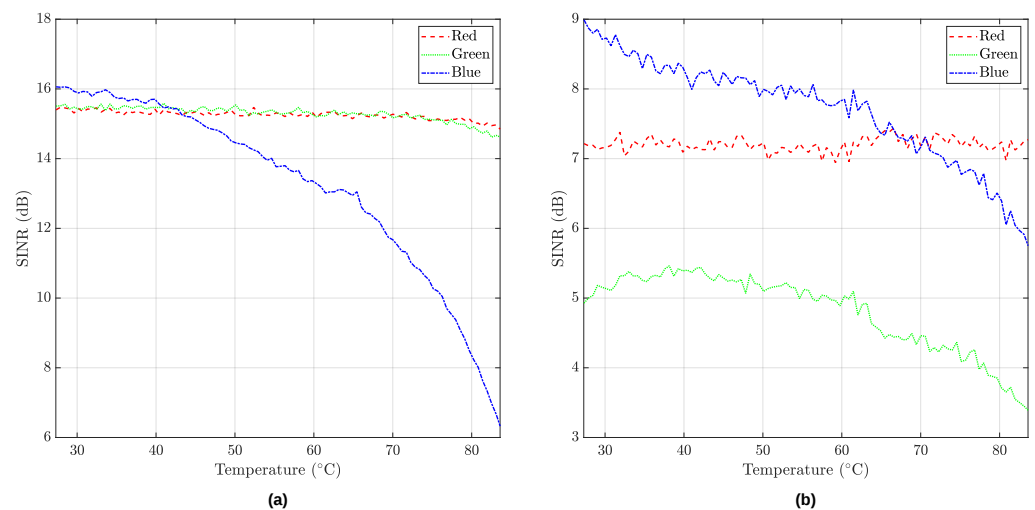


Figure 11. SINR at different temperatures, compensating the channel using the CSI corresponding to 27 °C and with a medium SNR value (20 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

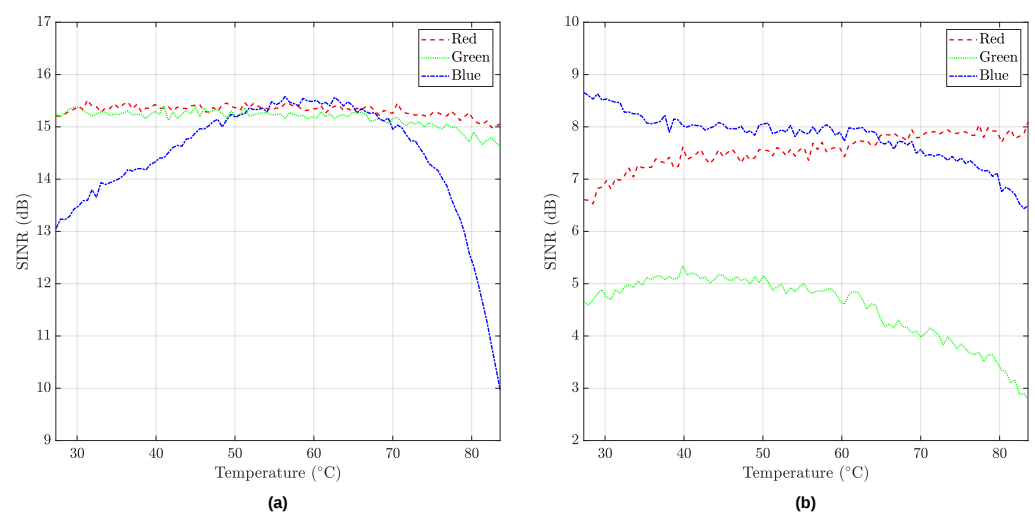


Figure 12. SINR at different temperatures, compensating the channel using the CSI corresponding to 60 °C and with a medium SNR value (20 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

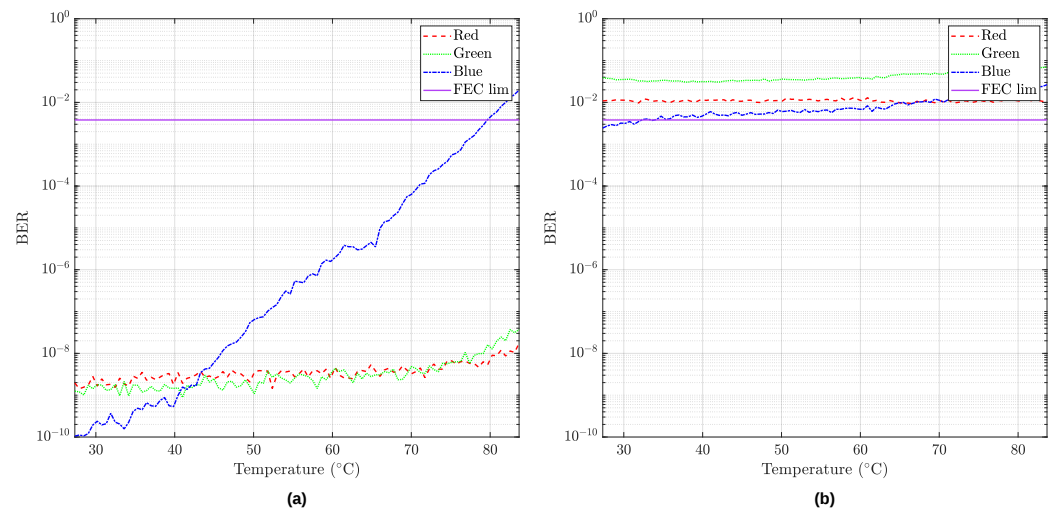


Figure 13. BER at different temperatures, compensating the channel using the CSI corresponding to 27 °C and with a medium SNR value (20 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

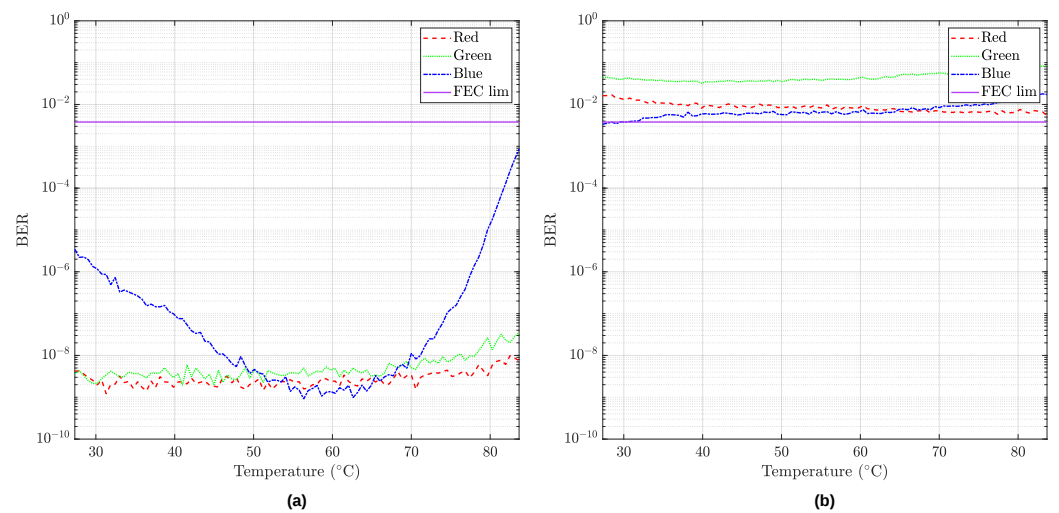


Figure 14. BER at different temperatures, compensating the channel using the CSI corresponding to 60 °C and with a medium SNR value (20 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

6.3. Low SNR Case

Figures 15 and 16 show the SINR for a SNR of 10 dB. As the noise level was high, the observed decrease in SINR in the other cases caused by compensating the channel with an obsolete CSI was not appreciated in the X3 sensor. In the IMX249, the temperature effect was still appreciable, but much less than in the previous cases. Therefore, considering the temperature effect in compensation is significant only at medium–high SNR levels.

Figures 17 and 18 depict the BER performance. Because of a low input SNR, the BER increased as the temperature increased. This effect was slightly appreciable in both devices. However, there were no BER values below the FEC limit in any case. This poor outcome occurred as a result of the ZF method, which highly penalized the BER performance in those cases when the noise level was considerably high.

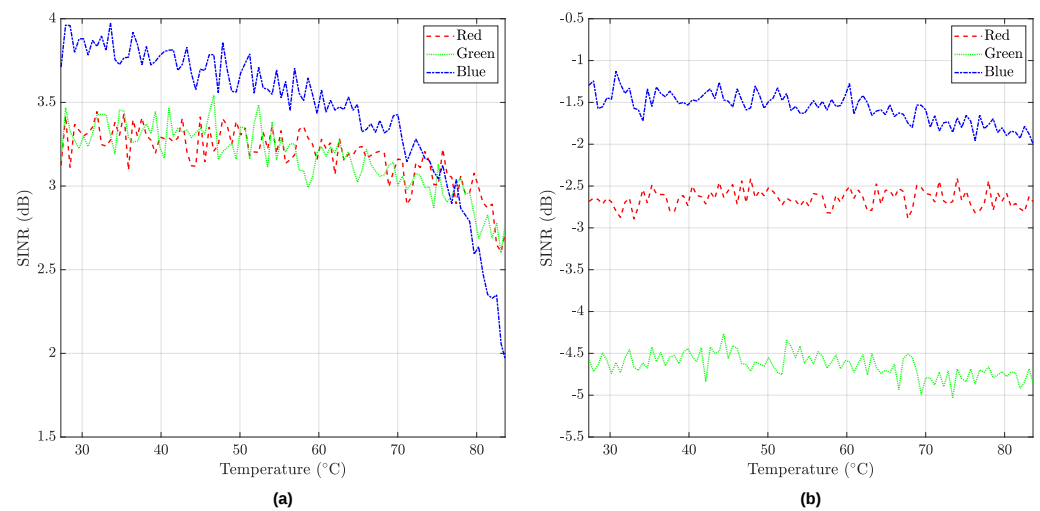


Figure 15. SINR at different temperatures, compensating the channel using the CSI corresponding to 27 °C and with a low SNR value (10 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

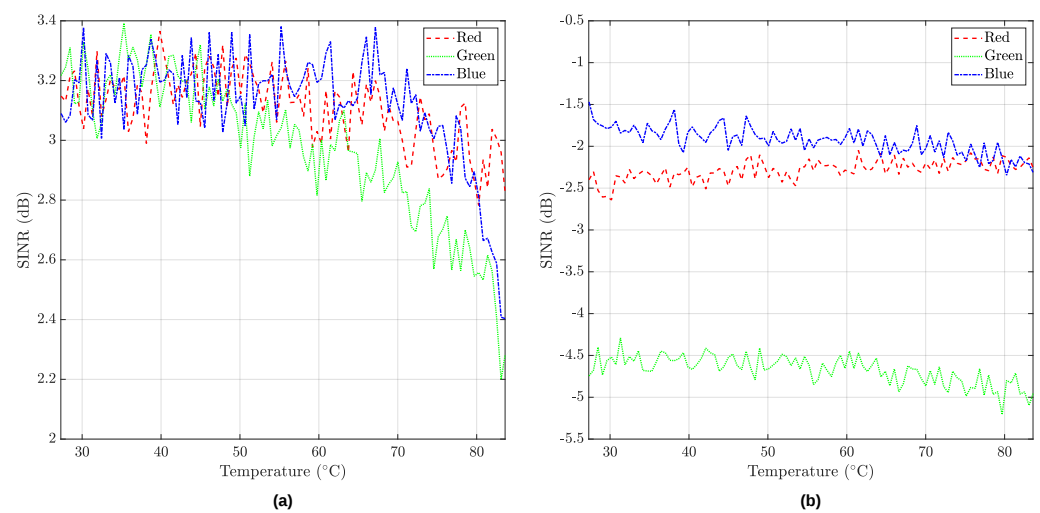


Figure 16. SINR at different temperatures, compensating the channel using the CSI corresponding to 60 °C and with a low SNR value (10 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

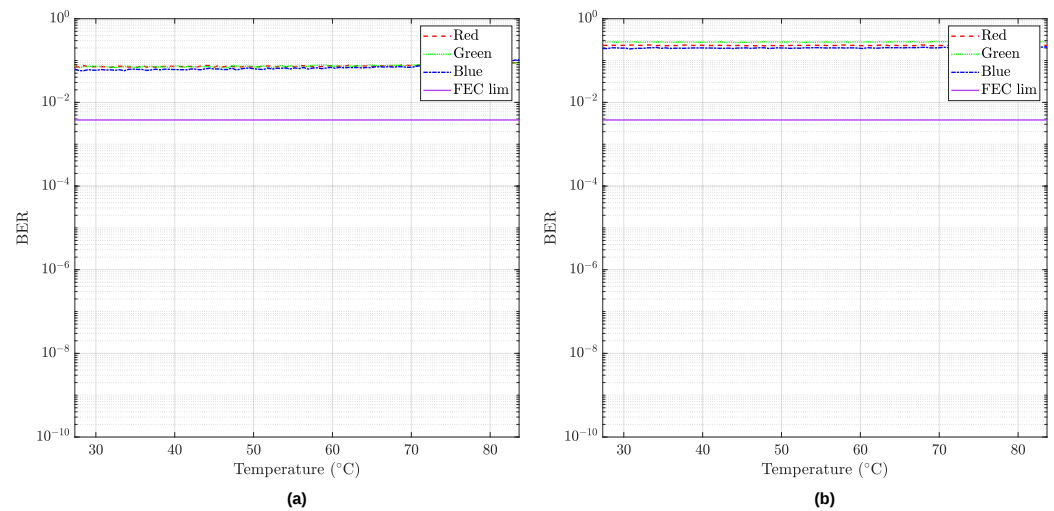


Figure 17. BER at different temperatures, compensating the channel using the CSI corresponding to 27 °C and with a low SNR value (10 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

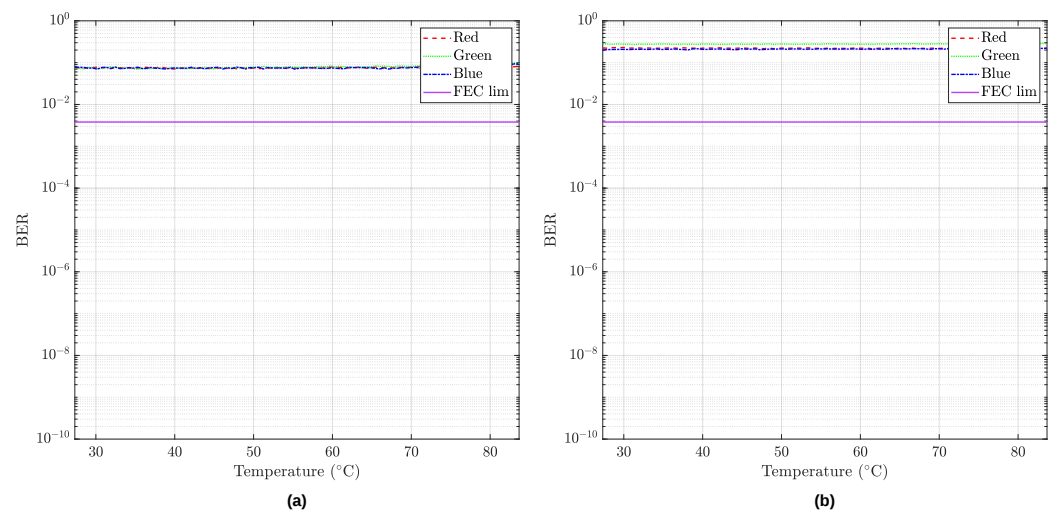


Figure 18. BER at different temperatures, compensating the channel using the CSI corresponding to 60 °C and with a low SNR value (10 dB). (a) Sony IMX249 and (b) Foveon X3. Dashed line, dotted line, and dash-dot line correspond to red, green, and blue, respectively.

7. Conclusions

The effects of temperature on light sources are well studied, showing a direct relationship between peak wavelength and spectral width concerning the p-n junction temperature. Nonetheless, these spectral variations are not usually considered when designing multi-wavelength links based on WDM or CSK, for instance. At least under reduced mobility conditions, these kinds of systems rely on the assumption that CSI does not change as the link geometry does not vary. Nevertheless, as has been demonstrated in this paper, CSI changes due to temperature effects.

The experimental part of this work was based on obtaining the emission spectra of an RGB LED at different temperatures. An experimental setup comprising a thermal camera for measuring the p-n junction temperature, an integrating sphere, and a spectrometer was implemented. The LED's stabilized p-n junction temperature was obtained after a settling period because the devices were under normal ambient conditions, and only the driving current affected the LED to produce significant changes in its temperature. However, in some scenarios where the light source would be exposed to high temperatures,

the operating LED temperature can change rapidly, causing undesired and unforeseen outcomes. No heat sink was employed in this experiment as the main objective was to analyze the temperature effect on the LEDs, and the use of such a device would have reduced the consequence caused by high temperature. The LEDs performance adding a heat sink to the test condition would improve since the LED spectral features would have been less affected.

In this work, the harmful effect of compensating an OCC RGB channel using obsolete CSI in terms of temperature has been explored. After a comprehensive characterization of the light sources at different measured p-n junction temperatures, the associated CSI were obtained by simulating the response of Commercial-Off-The-Shelf (COTS) CMOS cameras. The resulting SINR after the zero-forcing compensation was calculated. It was observed that as the temperature difference between the reference and current CSIs increased, the resulting SINR penalty was higher (lower SINR values). Specifically, the blue channel was profoundly affected, reaching impractical SINR values below 10 dB. Red and green channels presented small sensitivity to temperature-induced spectral variations in the IMX249, while in the X3 the decrease in SINR was higher. The reason for this is that the blue spectrum was significantly red-shifted, intensifying its intersection with the green component of the Bayer and Foveon filters. The decrease in the blue signal is also caused by the lower response of the blue component in both filters due to the use of a silicon-based CMOS device. Although the red and green spectra were also distorted by temperature, the SINR was not impaired in those bands in the IMX249. However, the decrease mentioned above in SINR on red and green channels might be interpreted as a result of the overlapping between the RGB filters in the X3 sensor. On the other hand, it was clearly observed that the temperature effect was masked as the input SNR level decreased. Besides, the noise affected more the X3 sensor than IMX249 due to the greater overlapping of the first one's spectral responses (Figure 1). The cross-talk between components makes the Foveon X3's associated channel matrix less robust to noisy inputs than the Bayer-based image sensors, which are better conditioned.

Regarding the BER performance, first, it was observed that for high input SNR values, the BER was below $3.8 \cdot 10^{-3}$ (FEC limit) for the majority of temperature differences between the reference CSI employed for compensating and the current CSIs. As the BER increased with temperature difference, approaches that are more sensitive to SINR variations than OOK transmissions would be strongly affected by the thermal impact during the compensation procedure. Second, for a medium input SNR, the results reinforced the usefulness of a Bayer-based image sensor over a Foveon device. While the BER was below the FEC limit for almost all the temperature difference in the IMX249 sensor, most of the values were above the limit in the X3. Finally, for a low-input SNR, this poor performance was not unexpected. In fact, the ZF scheme inevitably penalizes the BER in these low SNR cases. As in the SINR analysis, the blue LED was the most thermal-affected device in the BER performance.

These results suggest that it would be recommended to not using blue LEDs when the transmitter is subject to high-temperature gradients that can cause variations in the emitted spectra. Nonetheless, those spectral changes on GaN and InGaN LED depend on the specific compositions and should be further characterized.

It must be remarked that these results are limited by the use of Bayer and Foveon filtering schemes (with severely overlapped sub-filters) and by the essayed devices. Nevertheless, the results obtained in this work demonstrate that temperature effects must be taken into account when designing multi-wavelength links.

To conclude, future research should consider the temperature effect during the channel compensation process. Besides, further work based on this topic needs to be performed to provide techniques that mitigate this effect, such as more robust compensation techniques than ZF equalization (e.g., using a minimum mean square error (MMSE) estimator) or temperature stabilization stages in the emitting system. Finally, a more comprehensive

study linking the temperature-induced spectral variations of the optical sources and the design of the filter arrays is needed to provide more insight about this topic.

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