ISSN Online: 2756-3898, ISSN Print: 2714-500X https://doi.org/10.47514/phyaccess.2025.5.2.006

The Impact of Temperature on the Performance of White LEDs for Visible Light Communication

Abdurrasheed B Magaji[1], Florence N Ikechiamaka[2], and Akinbolati Akinsanmi[2]

[1] Department of Physics, Umaru Musa Yar'adua University, Katsina, Katsina State, Nigeria
[2] Department of Physics, Federal University Dutsin-Ma, Katsina State, Nigeria

Corresponding E-mail: abdulrasheed.magaji@umyu.edu.ng

Received 20-09-2024
Accepted for publication 10-10-2025
Published 16-10-2025

Abstract

Visible Light Communication (VLC) is a promising wireless communication technology that utilizes Light Emitting Diodes (LEDs) for high-speed data transmission. However, its performance is significantly affected by temperature variations, which impact the quality factor (Q-factor), signal integrity, and modulation bandwidth. Additionally, frequency-dependent distortions and external noise sources further degrade transmission quality, increasing Bit Error Rate (BER). This study investigates the effect of temperature on the Q-factor at different driver currents (100, 200 and 300 mA) and explores post-equalization techniques to enhance LED modulation bandwidth. An R//C equalization circuit was implemented to compensate for frequency-dependent losses, while a blue optical filter minimized interference and improved the Signal-to-Noise Ratio (SNR). Experimental results indicate that at a driver current of 200 mA and a temperature of 34.8 °C, the highest Q-factor of 14.250 was achieved. Furthermore, an adaptive equalization scheme enabled a 20 Mbps data rate over a 10 cm transmission distance, demonstrating its effectiveness in mitigating signal degradation. The findings highlight the importance of post-equalization in overcoming temperature-induced performance degradation in VLC systems. The proposed approach enhances system stability and reliability, making VLC a viable option for high-speed optical wireless communication under varying thermal conditions.

Keywords: Visible Light Communication (VLC); White LED; Q-factor; Temperature Effects; Post-Equalization; OOK-NRZ Modulation.

I. INTRODUCTION

Visible Light Communication (VLC) is a wireless communication technology that leverages the visible light spectrum (400–700 nm) for data transmission. White LEDs, widely used for illumination, are suitable for VLC due to their dual capability for lighting and communication [1], [2]. However, the performance of white LEDs in VLC systems is highly influenced by environmental conditions, particularly temperature variations, which significantly affect their optical and electrical characteristics [3].

Temperature fluctuations in white LEDs can lead to a decrease in efficiency, light output, and spectral shifts, all of which degrade signal quality and reliability. VLC systems utilize white LEDs for data transmission due to their high bandwidth, low interference, and compatibility with existing lighting infrastructure. However, the spectral characteristics of white LEDs and ambient light interference pose significant challenges to VLC performance [4], [5]. Temperature variations exacerbate these challenges by causing efficiency drop and reducing light output, which adversely affect data transmission rates. Recent studies have demonstrated that effective thermal management is crucial for maintaining LED performance in VLC applications [6], [7]. Post-equalization techniques, such as adaptive equalization and R//C circuits, have been shown to enhance modulation bandwidth and reduce frequency-dependent distortions, thereby improving system performance [8], [9], [10], [11]. This study focuses on mitigating these challenges through post-equalization techniques, including adaptive equalization and blue filtering, to enhance system performance. The objectives of this study are to investigate the impact of temperature fluctuations on the Q-factor of white LED-based VLC systems at varying driver currents (100, 200 and 300 mA), to evaluate the effectiveness of post-equalization techniques, such as R//C circuits and blue filtering, in improving system performance, and to analyze the relationship between key parameters (eye height, eye width, jitter, and Q-factor) and temperature variations to identify optimal operating conditions.

II. MATERIALS AND METHODS

A. Materials

The materials used for this study include a Luxeon Star white LED (emitter), a silicon photodiode (receiver), an arbitrary waveform generator for pseudo-random bit sequence (PRBS) generation, a digital storage oscilloscope for eye diagram analysis, an R//C equalization circuit with 10–15 pF capacitors, a blue optical filter (450–480 nm cutoff), and digital thermocouple and thermal imaging devices for temperature measurement.

B. Methods

Plate 1 depicts the experimental setup for this study, which consists of a pseudo-random bit sequence generator transmitting through a white LED to a silicon photodetector. A blue optical filter was used to isolate the blue component of the LED emission, thereby improving the Signal-to-Noise Ratio (SNR). Capacitor values ranging from 15 to 10 pF were adjusted to minimize channel distortion. Equalization was applied after the bandpass filter to reduce noise using the training sequence, and the effect of temperature on Q-factor was evaluated at driver currents of 100, 200 and 300 mA. Key parameters, including eye height, eye width, jitter, and Q-factor, were analyzed to assess performance under varying thermal conditions.

1) Investigating the Impact of Temperature on Q-factor

The Q-factor was calculated from the eye diagram using (1).

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \quad (1)$$

Where μ_1 and μ_0 are the mean voltage levels for logic ‘1’ and ‘0’, while σ_1 and σ_0 represent the standard deviations of the received voltage (or current) samples when the transmitted bit corresponds to logic ‘1’ and ‘0’ respectively [12, 13].

2) Eye Height and Width

Eye height (signal amplitude margin) and eye width (timing margin) were obtained directly from the oscilloscope’s measurement functions. These metrics quantify the signal’s noise tolerance and timing jitter margin [2, 5].

3) Jitter

Jitter was extracted from the eye diagram as the standard deviation of the zero-crossing timing. Increased jitter indicates timing uncertainty and reduced synchronization accuracy [2, 5, 8].

4) Post-Equalization Techniques

The post-equalization employed parallel R//C circuits to flatten the LED’s frequency response and extend the modulation bandwidth. Blue filtering was incorporated to suppress red-yellow spectral components, improving the detector’s response [2, 3, 5, 8].

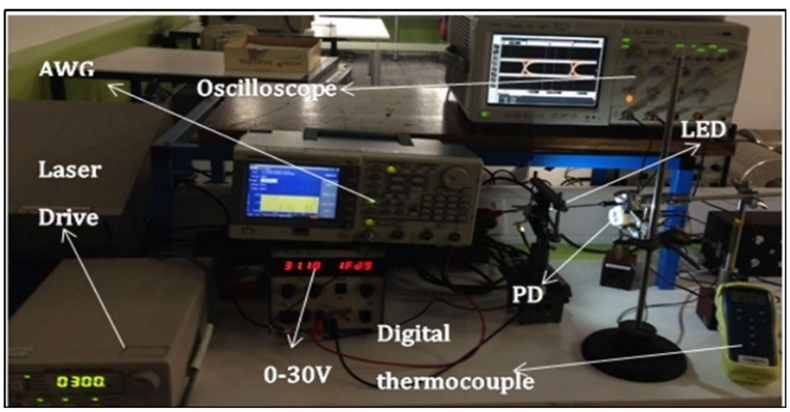

Plate 1. Experimental setup for the VLC system.

III. RESULTS AND DISCUSSION

A. Impact of Temperature on Q-factor

The results obtained show that the Q-factor decreased with increasing temperature for all driver currents as depicted in Tables I–III.

At driver current of 200 mA, the highest Q-factor of 14.250 was observed at 34.8°C, indicating optimal performance at lower temperatures. However, the Q-factor degraded significantly at higher temperatures, particularly at driver current of 300 mA, making it less suitable for high-temperature environments.

Table I. Variation of Quality Factor with Temperature at 100 mA Driver Current

Temperature (°C)	Quality Factor
34.50	13.216
52.40	12.180
117.50	11.880
120.90	11.190
122.30	10.890

Note: The highest Q-factor is 13.216 at 34.50°C.

Table II. Variation of Quality Factor with Temperature at 200 mA Driver Current

Temperature (°C)	Quality Factor
34.80	14.250
46.40	13.900
64.90	13.290
80.90	12.880
100.20	12.740
114.00	12.510
124.50	12.290
128.20	11.770
129.50	11.330
129.90	10.580

Note: The highest Q-factor is 14.250 at 34.80°C.

Table III. Variation of Quality Factor with Temperature at 300 mA Driver Current

Temperature (°C)	Quality Factor
77.20	13.299
111.60	12.308
118.80	12.256
123.30	12.189
126.70	11.940
127.60	11.680
128.20	11.210
129.10	11.153
130.70	11.062
132.30	11.006

Note: The highest Q-factor is 13.299 at 77.20°C.

Fig. 1 illustrates the variation of the quality factor (Q-factor) with temperature for three different driver currents: 300, 200, and 100 mA. At a driver current of 300 mA, the Q-factor decreases with increasing temperature, reducing from approximately 13.299 at 77.2 °C to 11.006 at 132.3 °C. Similarly, at 200 mA, the Q-factor shows a declining trend, decreasing from 14.250 at 34.8 °C to 10.580 at 129.9 °C. For the 100 mA driver current, although the data points are limited, a comparable decrease is observed, with the Q-factor dropping from 13.216 at 34.5 °C to 10.890 at 122.3 °C. These results indicate that the Q-factor consistently decreases with rising temperature across all driver currents in the VLC system employing OOK-NRZ modulation.

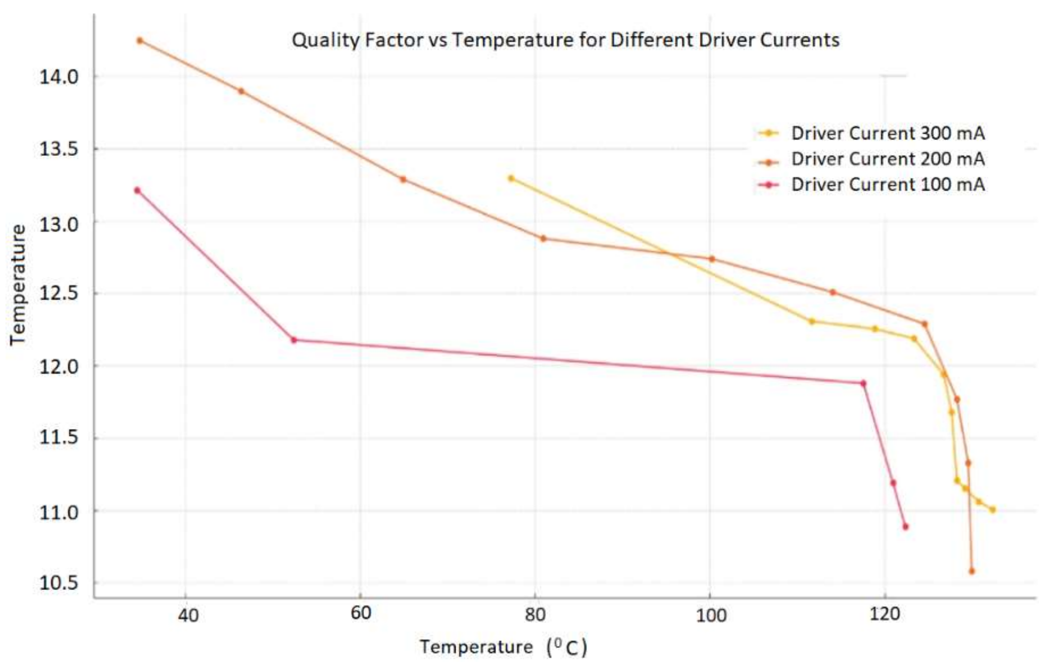

Fig. 1. Variation of Quality Factor with Temperature at Different Driver Currents.

B. Eye Height and Width

As depicted in Figs. 2 and 3, both eye height and eye width were observed to decrease with increasing temperature, indicating signal degradation. Lower driver currents (100 mA) exhibited better signal integrity at higher temperatures, suggesting greater resilience to temperature-induced degradation.

From Fig. 2, the eye height at 300 mA driver current decreases steadily from 450 mV at 77.2 °C to 280 mV at 132.3 °C. At 200 mA, it decreases from 470 mV at 34.8 °C to 320 mV at 129.9 °C, while at 100 mA, the highest values are recorded, decreasing from 480 mV at 34.5 °C to 410 mV at 122.3 °C. These observations confirm that increasing temperature consistently reduces the eye height, with lower driver currents maintaining superior signal quality.

As shown in Fig. 3, the eye width also decreases with increasing temperature from 0.80 to 0.60 ns at 300 mA, from 0.85 to 0.68 ns at 200 mA, and from 0.88 to 0.78 ns at 100 mA. The reduction in eye width corresponds to a narrower time window for error-free transmission, confirming that higher temperatures adversely affect the data transmission quality in the VLC system.

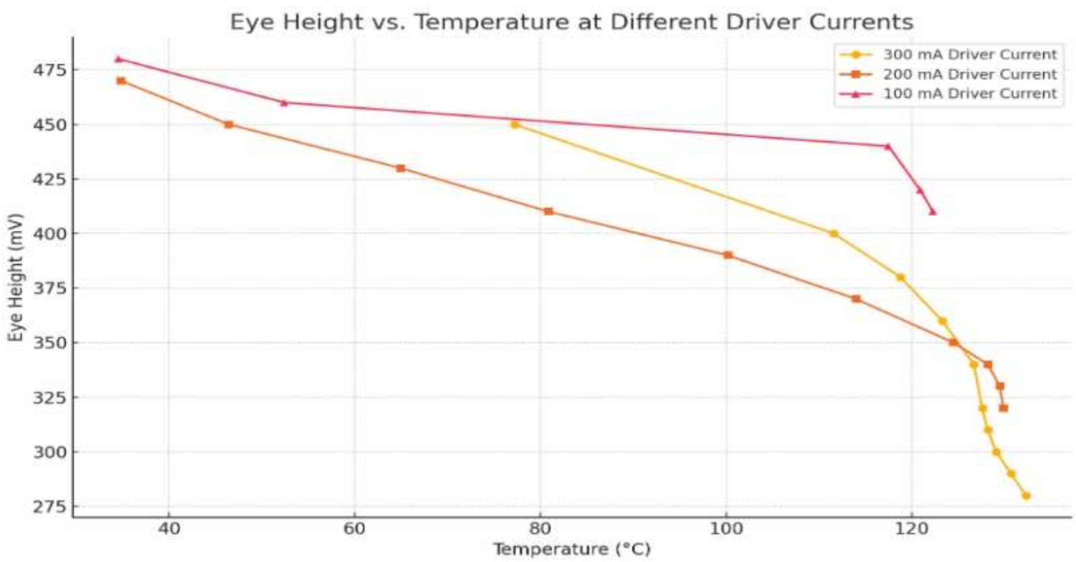

Fig. 2. Eye Height vs. Temperature at driver current (100, 200 and 300 mA).

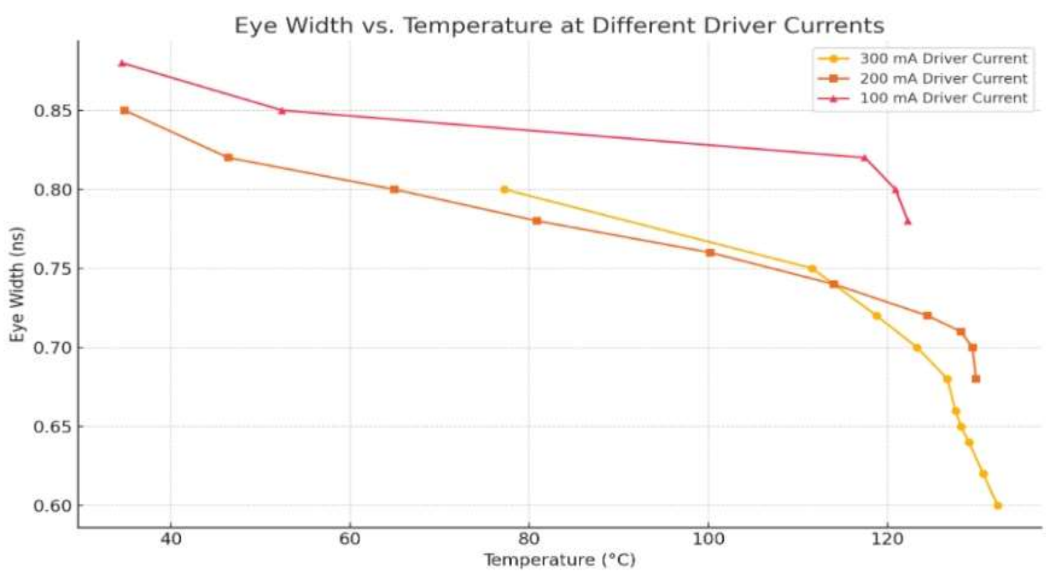

Fig. 3. Eye Width vs. Temperature at driver current (100, 200 and 300 mA).

C. Jitter

As illustrated in Fig. 4, the jitter increased with increasing temperature across all driver currents, indicating greater timing uncertainty in the received signal. At a driver current of 300 mA, jitter increased from 0.02 ns at 77.2 °C to 0.12 ns at 132.3 °C, while at a driver current of 200 mA it increased from 0.01 ns at 34.8°C to 0.10 ns at 129.9 °C. Finally, at a driver current of 100 mA, the jitter remains minimal, increasing from 0.01 ns at 34.5 °C to 0.05 ns at 122.3 °C.

Higher jitter values correspond to greater timing uncertainty in the received signal, which can result in increased bit error rates. In contrast, lower driver currents consistently exhibit reduced jitter at comparable temperatures, indicating more stable signal transmission under thermal stress.

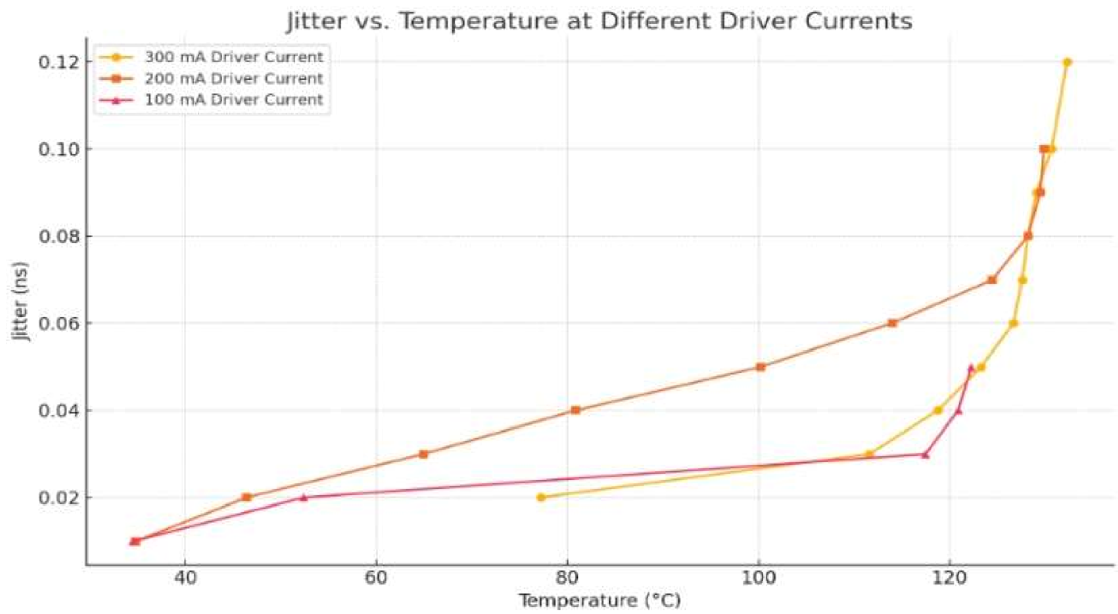

Fig. 4. Relationship between temperatures and jitter for different driver currents (100, 200, and 300 mA).

D. Post-Equalization Techniques

The use of R//C circuits and blue filtering significantly improved SNR and signal strength (Table IV). EQ2, an optimized equalization technique, enhanced the received signal strength and reduced bit error rates (BER), particularly at higher frequencies. The blue filtering impact enhanced signal strength and frequency response, maintaining higher signal levels up to 10 MHz.

Table IV. The values of received signals for EQ1 and EQ2, the SNR in dB for EQ2, and the BER for EQ2.

Frequency (MHz)	Received Signal (mV) EQ1	Received Signal (mV) EQ2	SNR (dB) EQ2	BER (EQ2)
0.5	8.2	14.3	11.56	4.98e-02
1.0	7.9	14.7	11.67	4.83e-02
1.5	7.6	15.7	11.96	4.36e-02
2.0	7.6	15.9	12.01	4.29e-02
2.5	7.4	16.5	12.18	4.00e-02
10.0	9.5	34.0	15.31	7.22e-03
15.0	7.6	12.3	10.90	6.00e-02
20.0	6.9	5.6	7.49	1.58e-01

The optimized graph shown in Fig. 5, which is a plot of the received signal (in mV) versus frequency (in MHz) for EQ1 and EQ2, demonstrates better visualization and annotations highlighting the maximum received signal points for both equalizations.

At EQ1 the signal was relatively stable, with the maximum received signal of approximately 10.0 mV at 11 MHz, while the signal increased significantly with frequency at EQ2 up to a maximum of about 34.0 mV at 10 MHz. After peaking, the signal decreases but remains higher than EQ1.

The optimized equalization (EQ2) leads to better performance in terms of signal strength, which is crucial for maintaining data integrity and communication quality in VLC systems.

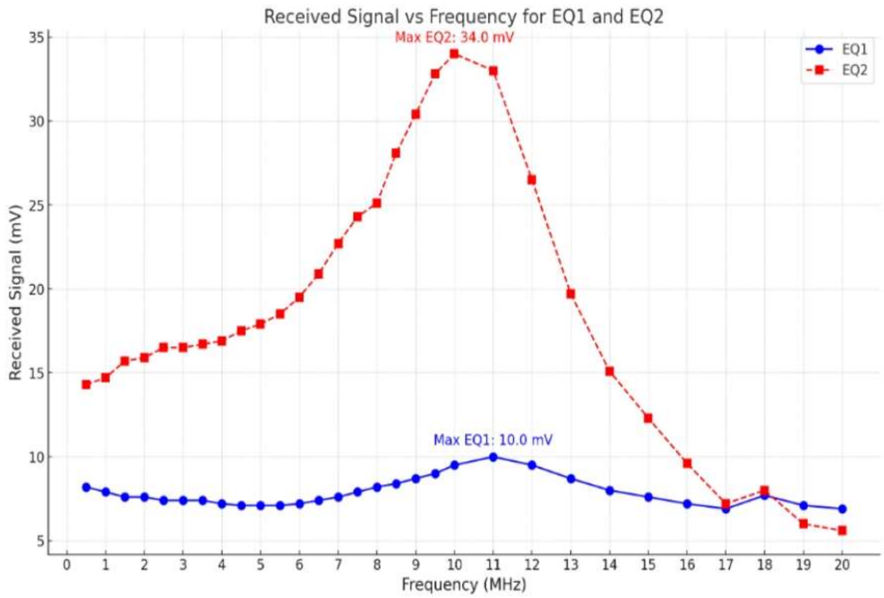

Fig. 5. The optimized graph showing the received signal (in mV) versus frequency (in MHz) for EQ1 and EQ2 with better visualization and annotations highlighting the maximum received signal points for both equalizations.

IV. CONCLUSION

This study demonstrates that temperature variations significantly impact the performance of white LED-based VLC systems. A decrease in Q-factor, eye height, and eye width, along with an increase in jitter, was observed with increasing temperature. Post-equalization techniques, such as adaptive equalization and blue filtering, were shown to effectively mitigate these challenges, improving system performance. A driver current of 200 mA was identified as optimal for balancing performance stability and thermal resistance. Future research should explore advanced modulation techniques, dynamic adaptation strategies, and integration with other wireless communication systems.

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