# On the Performance Degradation of Optical Wireless OFDM Communication Systems Due to Changes in the LED Junction Temperature*

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**Abstract**–Thermal management is a significant issue in the design of high power light emitting diodes (LEDs). In this letter, the effect of practical changes in the LED junction temperature on the performance of indoor optical wireless (OW) communication system based orthogonal frequency division multiplexing (OFDM) modulation is studied and analyzed. Junction temperature changes occur due to variations in the drive current, ambient temperature and by self-heating due to electrical power dissipation. The changes in junction temperature affect the LED forward voltage, the output luminous flux and the LED dominant wavelength. The effects of these changes on the performance of DC-biased (DCO) and asymmetrically clipped (ACO) OW OFDM systems are studied. While it is shown that the changes in the dominant wavelength are insignificant, it will be shown that significant performance degradation may occur due to small variations of LED forward voltage and luminous flux.

**Keywords:** Optical wireless communication, LED, OFDM, nonlinearity, VLC, intensity modulation, junction temperature.

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# 1 Introduction

Wireless transmission via optical carriers opens doors of opportunity in areas as yet largely unexplored. Communication technologies resulting from integrating optical carriers with wireless technology will be a significant enabler for future-generation heterogeneous communication networks supporting a wide range of wireless services/applications. Such technologies will offer significant technical and operational advantages with optical wireless communication (OW) being in some applications, a powerful alternative to and, in others, complementary to existing radio frequency (RF) wireless systems [1, 2]. Variations of OW can be employed in a diverse range of communication applications ranging from very short-range (on the order of millimetres) optical interconnects within integrated circuits through outdoor inter-building links (on the order of kilometres) to satellite links (larger than 10,000 kilometres).

The growing availability of cost-effective energy-efficient White LEDs has enabled researchers to utilize LED-based light sources for low-cost OW communication through intensity modulation (IM) with direct detection (DD) [3]. White LEDs continue to rapidly improve in terms of light output, energy efficiency, and color-rendering index (CRI). Manufacturers of White LEDs are announcing new products with high efficacy numbers, which rival traditional fluorescent light sources in terms of energy-efficiency [4, 5, 6]. As well, the arrival of OFDM modulation for OW communication enabled high data rate efficient OW communication systems [2, 7, and references therein]. However, the deployment of OFDM within optical systems still has some design challenges. LED nonlinearity factors, for instance, are shown to have a major impact on system performance. Several research attempts tried to characterize and analyze the effects of LED nonlinearity on the performance of OW OFDM systems and significant performance degradations are reported [2, and references therein]. However, analyses are conducted assuming the LED operating at the room temperature and LED parameters such as junction temperature, dominant wavelength, output intensity and others remain constant. Yet, small variations of these parameters can result in significant performance penalties. For instance and due to the LED exponential characteristics, small changes in rthe forward voltage can result in large changes in the forward current through LED [8].

In LED devices, heat is produced within the device itself due to inefficient generation of light. The wall-plug efficiency of an LED package is typically in the range of 5-40%. Meaning that 60-95% of the power is lost as heat [9]. LEDs generally have a positive temperature coefficient with respect to current, which means that the LED forward voltage $V_F$ decreases as the LED gets warmer, causing the LED to draw more current as temperature increases. Junction temperature also affects the LED luminous flux, dominant wavelength, and lifetime [10, 11, 12]. If LEDs are subjected to excessive heat, their lifetime is drastically reduced and a fundamental advantage of OW systems over their RF counterpart is undermined. A change of LED dominant wavelength, on the other hand, will cause a deviation from the peak responsivity of the photodiode (PD) and a degradation in the received signal power is anticipated. Likewise, a change in the forward voltage reduces the LED linear dynamic range and forces the OFDM time signal to be clipped at different threshold values. Therefore, significant clipping distortions can occur. Accordingly, it is the aim of this paper to study the effect of varying junction temperature on the performance of OW OFDM systems.

The organization of the remainder of this letter is as follows. In Section 2, ACO and DCO OW OFDM systems are briefly reviewed. The considered LED model and the effect of junction temperature on the LED forward voltage, luminous flux and dominant wavelength are presented and analyzed in Section 3. In Section 4, the obtained results are discussed. Finally, conclusions are drawn in Section 5.

# 2 ACO and DCO OW OFDM Systems

A general system model for OW OFDM system is shown in Fig. 1. The existing OW OFDM systems can be classified into two groups based on the subcarriers assignment and the bipolar-unipolar conversion techniques considered [13]. In the first group, the subcarriers are assigned to produce a half-wave symmetry time signal. Therefore, bipolar-unipolar conversion is attained by clipping the resultant time signal at the zero level [7, 14]. Two techniques are reported in literature where a half-wave symmetry OFDM time signal can be achieved; namely, ACO proposed in [7] and PAM-DMT (pulse amplitude modulation-discrete multi-tone) proposed in [14]. The second group assigns data to all available subcarriers. Thus, increasing the data rate as compared to the first group but the output signal is no longer symmetrical [15, 16]. Hence, bipolar-unipolar conversion can be achieved by adding a certain DC bias. This technique is called DCO technique [13].

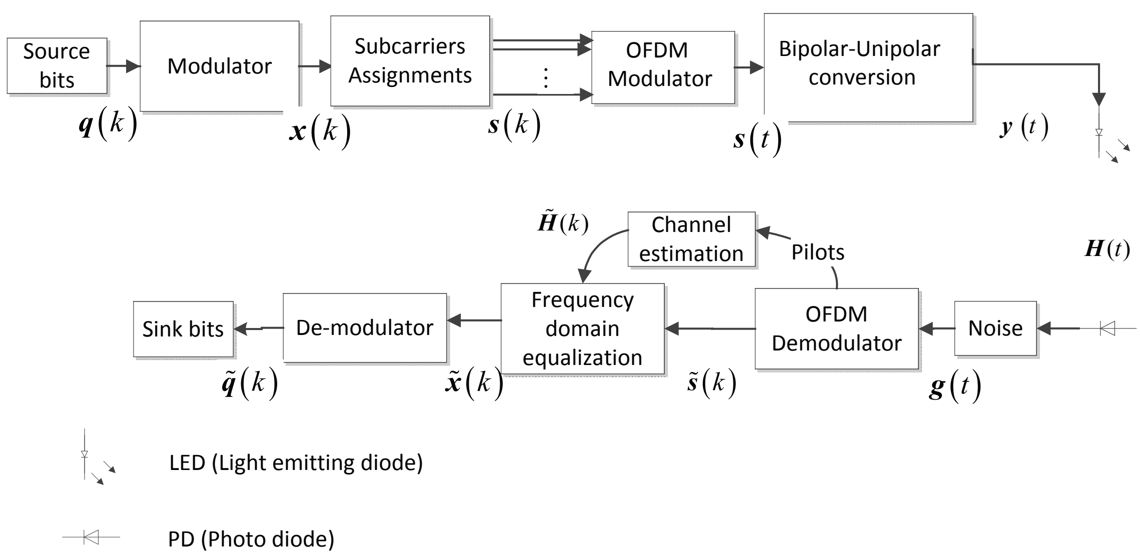



Figure 1: A general model for an OW OFDM communication system

For a DCO OW system, the source bit stream $\{q_k\}_{k=0}^{m\left(\frac{N}{2}-1\right)}$ is parsed into a block of complex data symbols denoted by $\{x_k\}_{k=0}^{\frac{N}{2}-1}$. The complex symbols are drawn from QAM (quadrature amplitude modulation)/PSK (phase shift keying) constellations, where $m = \log_2(M)$ for any $M$-QAM/PSK [2, 7]. In OW OFDM, the symbols are assigned to subcarriers to produce a real signal at the output of the inverse fast Fourier transform (IFFT) as follows

$$\{\mathbf{s}_k\}_{k=0}^{N-1} = \left[\begin{array}{cccc} 0 & \{\mathbf{x}_k\}_{k=1}^{N/2-1} & 0 & \{\mathbf{x}_k^*\}_{k=N/2-1}^{1} \end{array}\right]. \quad (1)$$

A real bipolar OFDM signal can be generated by constraining the input to the IFFT operation to have Hermitian symmetry. The DC $s(0)$ and the $s(N/2)$ subcarriers are set to zero to ensure that $\mathbf{s}(t)$ is symmetrical. The time domain optical OFDM signal $\mathbf{s}_k$ is used to modulate the optical carrier intensity. The time domain signal is bipolar; thereby, bipolar-unipolar conversion process is needed since the optical intensity cannot be negative. In DCO, the LED is biased before applying the modulating signal. After biasing, signal levels bellow the LED turn-on voltage (TOV) and higher than the maximum permissible forward voltage which corresponds to the maximum permissible AC current are clipped. For determining the lower and the higher clipping values, the LED characteristic curve is obtained from the data sheet. Clipping is necessary to avoid nonlinearity distortions, thermal runaway condition and destruction of the LED.

In ACO, however, only the odd subcarriers in the symbol $\{\mathbf{x}_k\}_{k=1}^{N/2-1}$ are modulated. Therefore, the information bit stream $\{q_k\}_{k=0}^{m\left(\frac{N}{4}-1\right)}$ is parsed into a block of complex data symbols denoted by $\{x_k\}_{k=0}^{\frac{N}{4}-1}$ and the bit assignment is

$$\{\mathbf{s}_k\}_{k=0}^{N-1} = \left[\ 0\, s_0 \cdots\ 0\ \ s_{N/4-1}\ \ 0\, s^*_{N/4-1}\ \ 0 \cdots\ \ s^*_0 \right]^T. \tag{2}$$

The resulting output real time signal from the IFFT process is half-wave symmetry, i.e., the same information in the first $N/2$ samples is repeated in the second half of the OFDM symbol. Thereby, creating a unipolar signal is attained through clipping all negative time samples. The intermodulation caused by clipping occurs only in the even subcarriers and does not affect the data-carrying odd subcarriers. A proof can be found in [17, Appendix A]. However, it reduces the amplitude by a factor of two [17, 7].

The unipolar signal is then used to modulate the intensity of an LED. At the receiver, the PD detects the transmitted intensity and the received signal is given by

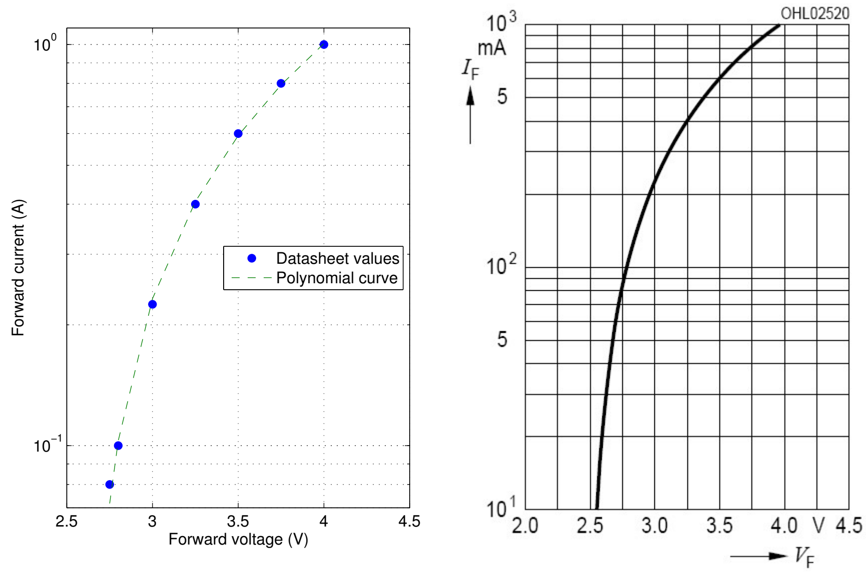
$$y(t) = h(t) \otimes s(t) + w(t), \tag{3}$$

where $\otimes$ denotes convolution, $h(t)$ is the multipath impulse response of the optical channel which is modeled as discussed in details in [18, eqn.(13)] and $w(t)$ is an AWGN (additive white Gaussian noise) that represents the sum of the receiver thermal noise and shot noise due to ambient light with overall noise power denoted by $\sigma_w^2$. The received OFDM signal is then processed to retrieve the transmitted information bits as discussed in details in [13].

# 3 LED Model

## 3.1 V-I LED response and Pre-distortion

For illustration purposes, a white LED (Golden DRAGON, ZW W5SG) from OSRAM is considered in this letter [19]. At room temperature ($T = 25\ °$), the maximum allowed forward current is 500 mA. At 350 mA, the recommended biasing point, the LED has a maximum luminous flux of 71 lm, a typical luminous intensity of 17 cd, and a 120°viewing angle at 50 % of the luminous intensity. The LED TOV is considered at $V^- = 100$ mA which corresponds to a 2.75 V drop across the LED. This is the minimum allowed forward current according to the data sheet. The maximum allowed AC/pulsed current is considered to be 1 A which corresponds to 4 V drop across the LED, *i.e.* the maximum forward voltage, $V^+$, of the measured data sheet transfer curve.




(a) (b)

Figure 2: (a) Discrete datasheet values and the LED polynomial curve. (b) The datasheet curve.

A polynomial of the second degree shows a good fit to the LED transfer characteristic as shown in Fig. 2. The curve shows the nonlinear behavior of the LED using the developed polynomial for forward voltage amplitudes in the range from 2.75 V up to 4 V.

In order to compensate for LED nonlinearity, a predistorter is considered. The predistorter uses the LED inverse characteristics as nonlinear compensator to condition the OFDM signal prior to the LED modulation [20]. For the considered LED, predistortion linearizes the LED response over the range from 0.25 V up to 1.25 V[1]. The solid curve in Fig. 3 illustrates the linearized V-I relation. Therefore, forward voltages below 0.25 V and above 1.25 V are clipped.

## 3.2 Effect of Junction temperature on LED parameters

The above discussion of LED parameters are considered at the room temperature ($T = 25°$). However, the junction temperature of the LED affects the device's luminous flux, the dominant wavelength and its forward voltage. Junction temperature can be affected by the ambient temperature and by self-heating due to electrical power dissipation.

Considering a specific LED, the output luminous flux as a function of temperature is given by [11, 8]

$$\Phi\left(T_2\right) = \Phi\left(T_1\right) e^{-k\Delta T_j}, \tag{4}$$

where $\Phi\left(T_2\right)$ is the output flux at temperature $T_2$, $\Phi\left(T_1\right)$ is the output flux at temperature $T_1$, $k$ is the LED temperature coefficient and $\Delta T_j = T_2 - T_1$ is the change in junction temperature. A study conducted in [21] revealed that luminous efficacy decreases up to 50% as the junction temperature increases. For the considered LED in this paper, the temperature coefficients as a function of the

[1]The value of the TOV is subtracted from the values of the forward voltages, i.e., a 0 V corresponds to the 2.75 V.

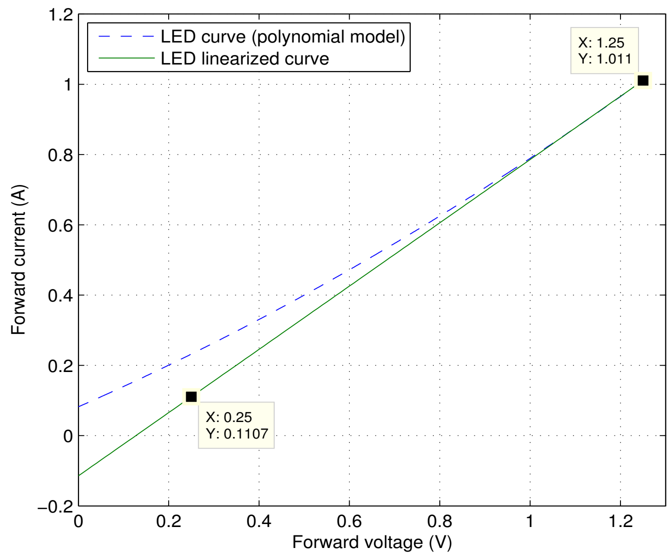


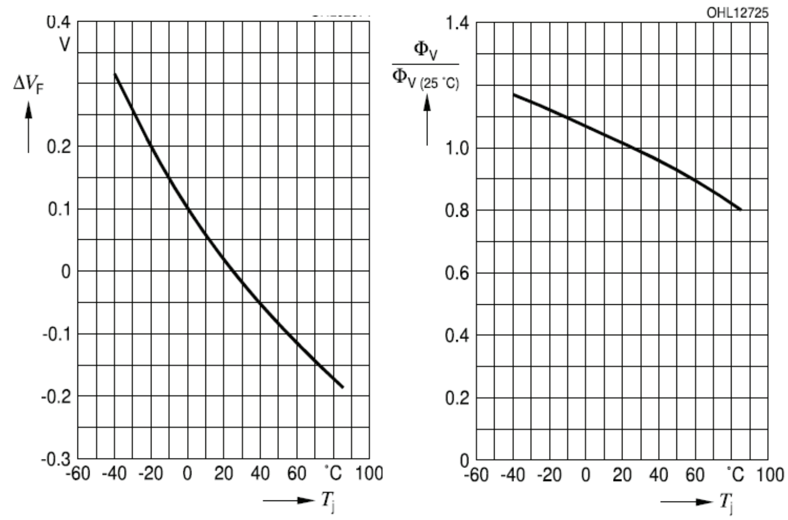

Figure 3: The V-I dashed curve using the developed LED polynomial function after subtracting the TOV from the values of the forward voltages across the LED. The linearized V-I solid curve with the predistorter [20].

forward voltage is -4 mV/Kelvin and the changes in the forward voltage and the outpout flux as a function of the junction temperature are depicted in Fig. 4.

The junction temperature of LEDs also affects their dominant wavelength. The change in the dominant wavelength as a function of junction temperature can be given by [11, 8]

$$\lambda\left(T_2\right) = \lambda\left(T_1\right) + \Delta T_j \cdot \left(\frac{nm}{^oC}\right) \tag{5}$$

As a rule of thumb, the dominant wavelength will increase one nanometer for every $10°C$ rise in junction temperature. This effect is similar to Doppler shift in RF domain. However, it can be shown that this change in dominant wavelength has negligible effects on the performance of OW systems. For instance, considering the peak wavelength of the considered LED in this letter at 540nm as shown in Fig. 5; an increase in the LED junction temperature by $100°C$ shifts the dominant wavelength from its nominal value (spectral emission shift) by 10nm. However, the corresponding reduction in the output flux for such shift is negligible according to the LED data sheet depicted in Fig. 5. In addition, the PD detects only the intensity of the optical wave. Therefore, the photocurrent will deviate from the expected level based on the spectral sensitivity (A/W) of the PD. This corresponds to electrical SNR variation at the receiver side. For instance, a THORLAB PD FDS 100 responsivity curve is depicted in Fig. 6. Responsivity change of 0.2 A/W requires that the dominant value of the wavelength changes by about 100 nm which corresponds to $1000°C$ increase in the junction temperature. Therefore, SNR variation due to dominant wavelength shift caused by variations of junction temperature is very small and can be safely ignored.




(a) (b)

Figure 4: (a) Relative forward voltage as a function of junction temperature, $\Delta V_F = V_F - V_{F(25^oC)}$. (b) Relative luminous flux, $\frac{\Phi_V}{\Phi_{V(25^oC)}}$. The value of the forward current is assumed to be $I_F = 350$ mA [19].

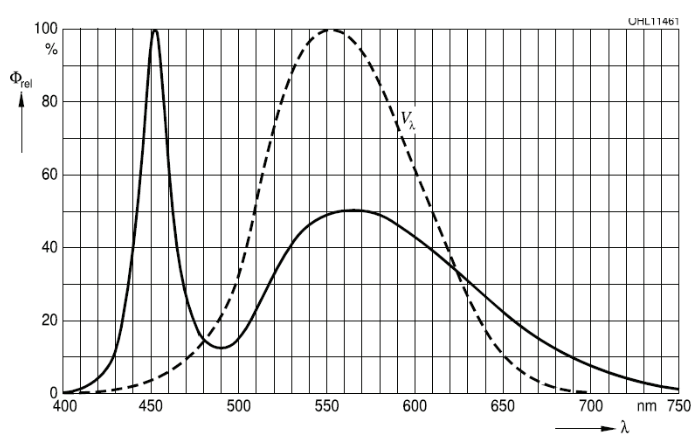



Figure 5: (LED relative luminous flux as a function of the wavelength, $\frac{\Phi_V}{\Phi_{V(25^oC)}}$. The value of the forward current is assumed to be $I_F = 350$ mA [19].

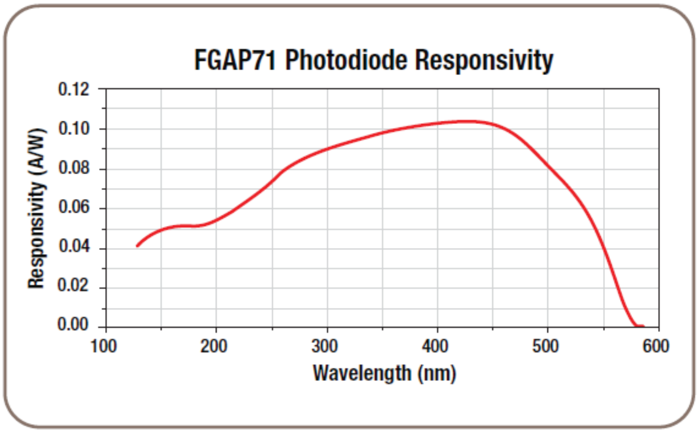



Figure 6: A THORLAB FDS 100 PD responsivity curve [22].

# 4 Performance Analysis and results

## 4.1 Performance analysis

Performance analysis of ACO and DCO OW systems in the presence of LED clipping distortions are presented in [13, Section III-B]. Following similar analysis, the effective SNR, $\rho$, as a function of the nonlinearity induced noise power, $\sigma^2_{\text{clip}}$, is given by:

$$\rho = \frac{\text{OFDM signal power}}{\text{Effective noise power}} = \frac{\sigma^2}{\sigma_w^2 + \sigma^2_{\text{clip}}}, \tag{6}$$

where, $\sigma^2_{\text{clip}}$ is given by

$$\sigma^2_{\text{clip}} = \sigma^2_{\text{uc}} + \sigma^2_{\text{lc}}, \tag{7}$$

with $\sigma^2_{\text{uc}}$ being the noise component due to the clipping/attenuation of the upper peaks of the OFDM signal, and $\sigma^2_{\text{lc}}$ being the noise component due to the clipping/attenuation of the lower peaks of the OFDM signal.

For DCO system in the presence of junction temperature, signal levels above $V^+ + \Delta V$ and below $V^-$ are clipped. This means that the junction temperature must be estimated prior to transmission and the OFDM signal will be clipped at the corresponding maximum expected forward voltage to avoid LED damage. Therefore, the overall clipping noise power can be determined by,

$$\sigma^2_{\text{clip}} \simeq \int\limits_{V^+ + \Delta V}^{\infty} \left(z - V^+\right)^2 p\left(z\right) dz + \int\limits_{-\infty}^{V^-} \left(z - V^-\right)^2 p\left(z\right) dz. \tag{8}$$

While for ACO system, only signal levels above $V^+ + \Delta V$ are clipped. The overall noise power is then obtained by adding the clipping noise power and the thermal noise power as given in (6).

Based on the calculated effective SNR in (6), the bit error ratio (BER) for any $M$-QAM constellation can be calculated as given in [13, eqn.(19)],

## 4.2 Results

The performance of ACO and DCO systems in the presence of LED clipping distortion and as a function of junction temperature are analyzed analytically and through Monte Carlo simulations. The LED model discussed in the previous section is considered. In the results, the x-axis represents the average electrical OFDM signal power before modulating the LED. The OFDM signal power is varied from 0 dBm to 30 dBm and an AWGN power of -10 dBm is assumed. As a result, the simulated electrical SNR range is from 10 dB to 40 dB which is within the reported measured SNR values for indoor OWC systems [23, 24]. Also, a channel bandwidth of $B = 20$ MHz, a number of subcarriers of $N = 1024$, and a number of guard interval subcarriers of $N_g = 4$ are considered. The simulated channel parameters are the same as configuration A parameters shown in [18, Table 1].

Analytical and simulation BER curves for DCO 16QAM system and ACO 64QAM system under different junction temperatures are depicted in Figs. 8 and 7, respectively. At low OFDM signal powers, no clipping distortion exist and the performance is irrelevant to the junction temperature. However, as the signal power increases, clipping distortion appears and higher junction temperature, which correspond to lower forward voltage, degrades the performance significantly. For instance, for DCO system and $45°C$, the forward voltage decreases by 0.1V and the BER performance degrades by about 3 dB as compared to the results at the room temperature. However, a 0.1V change in the forward voltage degrades ACO performance by about 1 dB.

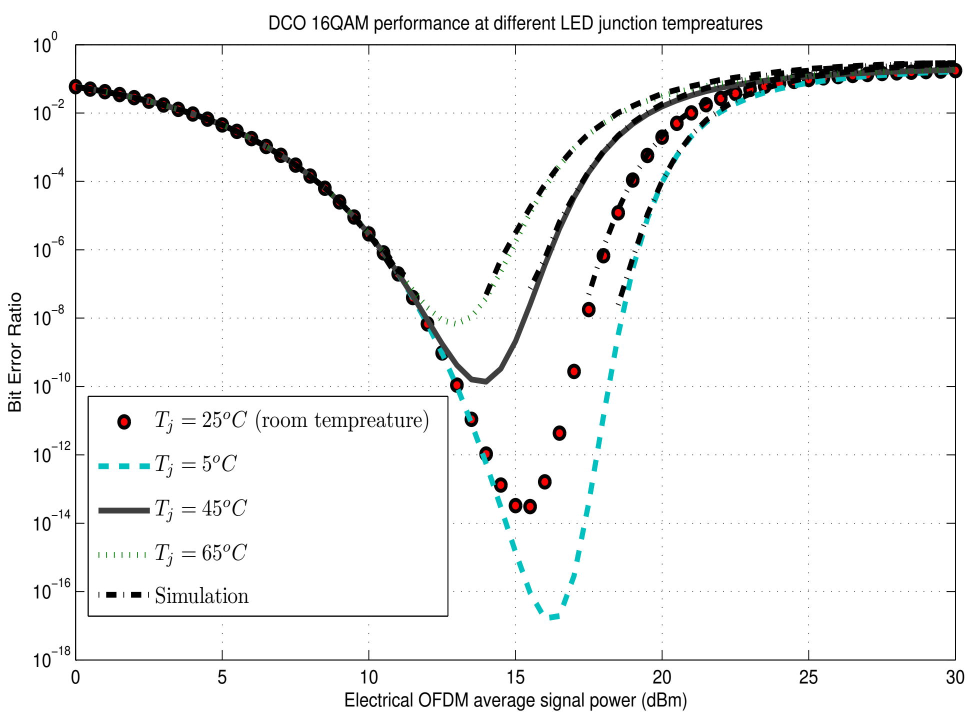



Figure 7: Monte Carlo simulation and analytical results for an 16QAM DCO system under different values of junction temperatures.

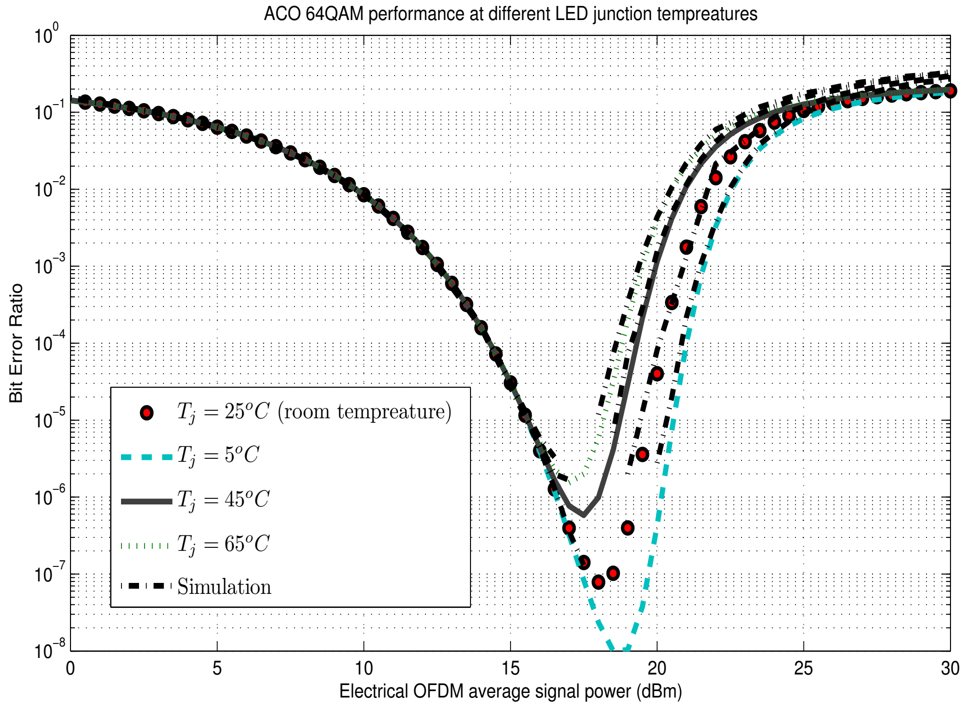



Figure 8: Monte Carlo simulation and analytical results for an 64QAM ACO system under different values of junction temperatures.

# 5 Conclusions

LEDs are major component in the design of future OW systems. The anticipated high throughput and long lifetime OW systems can be well affected by several LED parameters such as junction temperature. A small change in LED forward voltage leads to significant degradation in OW system performance. While, the change in the dominant wavelength can be safely ignored for ACO and DCO systems. ACO systems utilize larger LED dynamic range and are less affected by the small changes in the forward voltage compared to DCO systems. Future research will focus on measuring LED junction temperature and investigating its effects on the performance. The effects of changing junction temperature on thermal noise, TOV voltage, forward voltage and LED lifetime shall be investigated.

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