Optimizing LED Performance for LiFi

Optimizing LED Performance for LiFi: Bandwidth versus Efficiency

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Optical transmission is attractive for future wireless communication because signals can be confined in a specific coverage area. In designing a system based on LEDs, the trade-off between transmission bandwidth and optical power is important. As a common practice with micro-LEDs, one may drive the LED at a high current density, beyond the optimum efficiency point, to boost the bandwidth. Bit rates of multiple gigabit/s have been demonstrated, but coverage is small. However, using high current densities is discouraged by self-heating, as only a part of the electrical power is converted to optical power. A rising temperature reduces efficiency, causing a degradation of the SNR. We combine multiple models, not only the ABC photon generation and the LED dynamic responses subject to a rapidly varying current but also, the junction voltage method to estimate its temperature. We quantify the achieved throughput in a DCO-OFDM link at different temperatures. This leads to the insight that there is an optimal size of the active region and an optimal current density that maximizes the throughput of the wireless link at different temperatures. The work presented here builds upon work that we published earlier, and we place this in the perspective of a combined system model.

Introduction

The standardization of the new wireless generation (6G) is expected to start in the next years. 6G will provide higher data rates, lower latency, and more massive access compared to the last generation. Higher data rates require bigger amounts of free spectrum. Nevertheless, the RF spectrum is already very congested, thus a migration to higher frequencies, such as THz, is necessary. In this frequency range, we have ultra-violet, visible light, and infrared bands. Optical wireless communication (OWC) has the possibility to be a key technology in 6G. Therefore, it is necessary to understand and overcome some particular channel limitations in order to optimize throughput [1]. OWC uses LEDs as a light source due to their low cost. However, these devices suffer from a low 3dB bandwidth. Additionally, unlike RF, the signal power is concentrated in the line-of-sight (LoS) link, then it is highly affected by blockage. Different methods solved these limitations by using new circuit drivers, different modulation techniques, distributed MIMO, sectorization, and optimization methods among others.

Independently on the circuit driver, modulation scheme, or equalization technique, the LED 3dB bandwidth is a major limitation to achieve higher throughput. Commonly, conventional LEDs have a f_{3dB} between $10 \sim 20$ MHz, making its time response slow when shorter bit times are required. In [2]- [3], the 3dB bandwidth is increased by reducing the size of the active area. A smaller active area increases the injection current density, accelerating the process of carrier generation or recombination inside the active region. The rise and fall time will be reduced, making this kind of LED, micro-LED, more suitable for high-speed data transmission. Nevertheless, as we will see from models developed in our earlier papers and as we confirm via new experiments, there is a trade-off between efficiency and frequency response. Micro-LEDs have a poor efficiency response compared to conventional LEDs. We explore to what extent that hampers throughput if coverage is also a requirement.

LED Communication Model

We consider a reference LED with specific recombination parameters ABC(D) and an active region size A_w. The current density plays an important role in the trade-off between the efficiency and the bandwidth of the LED. The f_{3dB} increases with higher current density, thus the response of the LED becomes faster and the OWC system can transmit in shorter bit times. Nevertheless, the efficiency will be reduced causing an SNR degradation in the wireless link. In our model, we fix the total current power of the OWC system, but we change the current density by scaling the active region of the LED to ζA_w, where ζ is a scaling factor. While we optimize the throughput, ζ is a degree of freedom. If $\zeta < 1$, the current density is higher than in the reference. For example, if $\zeta > 1$, the new LED has a ζ times larger active region thus a ζ times lower current density compared to the reference LED. The scaled carrier rate equation is

$$\frac{dN_{QW}(t)}{dt} = \frac{I(t)}{\zeta q} - \Big(AN_{QW}(t) + BN_{QW}^2(t) + CN_{QW}^3(t)\Big), \tag{1}$$

where N_{QW} is the total number of carriers per normalized unit of area. The LED current $I(t)$ contains a DC component and a modulated signal: $I(t) = I_{DC} + i(t)$. The DC term may already be present for illumination. Similarly, $N_{QW}(t)$ contains a bias component N_{QW} and a modulation signal $n_{QW}(t)$. According to [4], the rate equation for the small signal is

$$\frac{dn_{QW}(t)}{dt} = \frac{i(t)}{\zeta q} - \Big(n_{QW}(t) + \tilde{B}n_{QW}^2(t) + \tilde{C}n_{QW}^3(t)\Big), \tag{2}$$

where the first term in the Taylor expansion ($\tilde{A} = A + 2BN_{QW} + 3CN_{QW}^2$) is $2\pi f_{3dB}$. The second and third-order terms in equation (2) generate distortion according to [5]. We neglect third-order distortion and assume that the second-order term is invertible [6], thus we focus on the $\tilde{A}$ term. At low modulation frequencies ($f < f_{3dB}$), the optical output generated by the small signal is

$$\phi(t) = \text{LEE}\frac{f_R}{f_{3dB}}\frac{\eta}{q}i(t), \tag{3}$$

where LEE is the light extraction efficiency, η is the photon energy and we denote $2\pi f_R = 2BN_{QW}$. In previous works [4] and [7], we referred f_R/f_{3dB} as the (differential) dIQE, which applies for small signals. Fig. 1 plots the efficiency droop when a higher current density drives the LED. Additionally, the f_{3dB} increases at higher current densities. We show that the dIQE plays a bigger role in the optimization of a DCO-OFDM link than the IQE.

Throughput of DCO-OFDM Link

DCO-OFDM can exploit the low-pass nature of the LED channel. It can maximize throughput by optimally assigning power and bit load per sub-carrier [8]- [9]. A detector with responsivity R_{PD} transforms the received optical power $h\phi(t)$ into an electrical signal, the signal power is

$$\sigma^2 = h^2\eta_{PD}^2\,\text{LEE}^2\,\text{dIQE}^2\sigma_{in}^2, \tag{4}$$

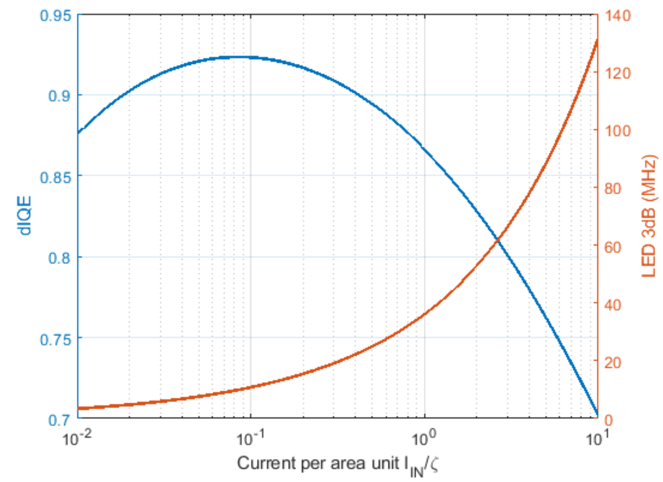

Fig. 1: Differential (small signal) efficiency dIQE and the f_{3dB} versus the current per unit area. Higher current density accelerates (higher f_{3dB}) the LED response, but reduces the efficiency.

where h is the path-loss between the transmitter and receiver, $\eta_{PD} = \eta R_{PD}/q$ and σ_{in}^2 is the variance of $i(t)$. Based on the optimization algorithm from [8], the maximum total throughput of the DCO-OFDM over a first–order low–pass LED channel is [4]

$$R = \frac{2}{\ln 2} f_{3dB} \left(\sqrt[3]{\frac{3Q_R \, \mathrm{dIQE}^2 \, \mathrm{LEE}^2}{2\Gamma f_{3dB}}} \right) - \frac{2}{\ln 2} f_{3dB} \arctan \left(\sqrt[3]{\frac{3Q_R \, \mathrm{dIQE}^2 \, \mathrm{LEE}^2}{2\Gamma f_{3dB}}} \right), \quad (5)$$

where Γ describes the penalty to use QAM to reach a certain uncoded BER [9]. We defined Q_R as the Communication-Power-over-Noise-Power-Density

$$Q_R = h^2 \eta_{PD}^2 \frac{\sigma_{in}^2}{N_0}, \quad (6)$$

N_0 is the noise density. Additionally, σ_{in}^2 must stay bellow the DC bias current by a factor of z^2 to avoid clipping, so $\sigma_{in}^2 = I_{DC}^2/z^2$ [10]. We have not yet modeled the effects that temperature has on the efficiency and bandwidth of the LED. In the next section, we discuss this topic and the degradation of a DCO-OFDM throughput caused by an increment in temperature.

Temperature Effects over the OWC Link

In the recombination process from (1), only a portion of the total number of carriers generates photons, the rest will generate heat. This heat causes a temperature increment in the junction affecting the physical characteristics of the LED such as the photon energy, and the radiative and non-radiative recombination parameters. The LED is a self-heating device when it is driven by a DC bias current, like in the case of a DCO-OFDM OWC link. Therefore, we cannot obviate its effects on the total throughput. In [11], we estimated the recombination parameters ABC at different temperatures. Fig. 2 plots the effects of the temperature over the total data rate of the OWC link. We notice not only a degradation of the total throughput but also a displacement of the optimum value ζ that maximizes the data rate. The optimum ζ value increases from 0.02 to 0.04, when the junction temperature raises from 20 °C to 60 °C.

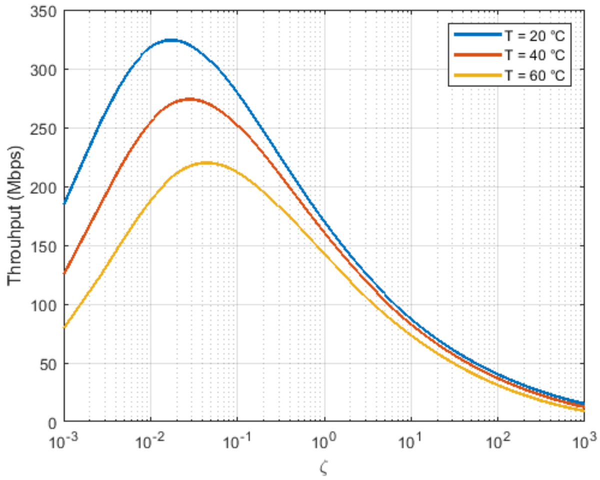

Fig. 2: Modelled effect of the junction temperature on the throughput of a DCO-OFDM link, using measured LED response. ζ is a scaling factor for the active region size.

Conclusions

Simulation of DCO-OFDM shows that the total throughput does not monotonously increase with the 3dB bandwidth. On the contrary, there is an optimum current density that maximizes the total throughput. The total throughput depends also on the efficiency of the LED. Unlike the 3dB bandwidth, there is an efficiency droop at higher current densities. This proves our statement that there is a trade-off between these two parameters. Additionally, an increment in the temperature will not only reduce the data rates of the system but modify the optimum current density.

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