CandLES - Communication and Lighting Emulation Software

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Abstract – **We present Communication and Lighting Emulation Software (CandLES), a model of wireless Visual Light Communications (VLC) that aids the design of dual-use communication and fully functional indoor lighting systems. Given a system design and an environment specification, CandLES characterizes the overall communications performance with respect to key metrics, which include achievable datarate, error rate and coverage, as well as lighting performance with respect to illumination coverage. The system and environment specifications that can be set are detailed and flexible, making CandLES a powerful tool for improving the design of such a system as well as testing its robustness to different environments.**

Index Terms – Visual Light Communication, modulation, Light Emitting Diode (LED), channel, bandwidth, bit error rate (BER), illuminance

1 Introduction

Due to the rapid ongoing advancement of solid state lighting, and the capability of white illumination LEDs to be controlled and rapidly switched, there is much interest in creating dual use systems that provide both lighting and wireless data. Researchers in this field frequently rely on modeling as an aid in determining potential performance prior to, or instead of, prototyping and demonstration of these systems. For example, [3] and [5] each rely on models that approximate aspects of their proposed VLC system designs, by means of which they calculate SNR values that can be achieved. In conjunction with a variety of supporting evidence, the SNR figures obtained in this way are used to show that the proposed systems can potentially achieve high datarates while providing illumination throughout a room.

In this paper, we present Communication and Lighting Emulation Software (CandLES), a detailed model of the entire wireless VLC/lighting system and its operating environment. CandLES models system components including the modulation, transmitters, optics, channel, noise, interference, receivers and decoding, and incorporates them into an overall system model. The software evaluates communications performance with respect to key metrics including achievable datarate, error rate and coverage, as well as lighting performance with respect to illumination coverage.

This combination of modeling all the individual components, and their joint operation as an integrated system, makes CandLES a powerful design tool. It allows us to identify which components serve as bottlenecks on performance (modulation, transmitter, receiver, optics). It enables us to rapidly evaluate improvements to the design of any component based on their effects on the system as a whole. It allows us to test robustness of a system design to changes in the environment (room size, objects, orientation, shadowing, wall colors, noise), or in operating requirements (required lighting level, field of view). It can also aid in the design of systems level solutions, such as optimal placement of lamps/transmitters, or modes of cooperation/competition between transmitters.

In the next section, we give an overview of the communications system, including its parts and interconnections. In Section 3, we discuss in more detail how CandLES models encoding and decoding of data with optical signals. In Section 4, we describe the modeling of the physical link including signal transmission, VLC channel calculation, receiver characteristics and noise.

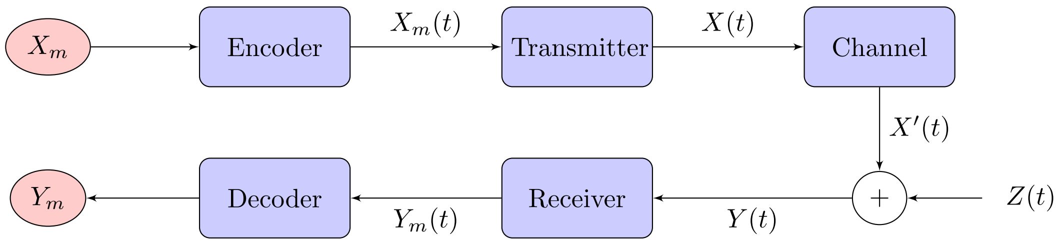


Figure 1: System Chain

Section 5 then discusses illumination characterization. For insight into the power of CandLES as a design tool, Section 6 gives results of basic case studies done using the software. Section 7 discusses other potential uses as well as future additions to the software. Concluding remarks can be found in Section 8.

2 System Overview

CandLES models the entire VLC signal chain in Figure 1. The desired message, X_m representing a bit or bit sequence, is sent through this signal chain to another location where it is recovered as Y_m. The goal is to have $Y_m = X_m$ with high probability, i.e. to minimize the bit error rate (BER).

At the transmitter, the discrete message, X_m, is first encoded into a continuous time electrical signal, $X_m(t)$, then converted into a corresponding optical intensity signal, $X(t)$. In the free space channel, this signal observes a gain and multipath distortion, and is combined with an optical noise, $Z(t)$, to produce $Y(t)$ at the receiver. Depending on the receiver structure, the signal is optically conditioned and converted to produce an electrical signal, $Y_m(t)$, which can be electronically conditioned before it is decoded into the message, Y_m.

3 Encoding / Decoding

Design of the encoding technique is of great importance because it affects the performance of all parts of the VLC system. In selecting an encoding scheme, the first question that an optical communications designer must answer is where their particular system stands on the signal power vs. signal bandwidth trade-off. The answer changes based on many factors, such as transmitter and receiver devices used, field of view, significance of multipath effects and noise power. To help answer this question, in addition to the benchmark scheme of simple on-off keying (OOK), CandLES compares performances of representative power efficient (L-pulse position modulation (LPPM)), and bandwidth efficient (L-pulse amplitude modulation (LPAM)) schemes.[1]

In free space optical channels for which typically the total noise (optical shot noise and thermal noise) is Gaussian, BER can be approximated using the Gaussian tail probability Q function as

$$BER \leq Q\left(\frac{d_{min}}{2\sqrt{N_0}}\right) \tag{1}$$

where d_{min} is the minimum Euclidean distance between two symbols, calculated as:

$$d_{min}^2 = \int_0^T (x_2(t) - x_1(t))^2 dt$$

CandLES adopts a common analysis approach in using d_{min} as the basis for comparison between each scheme and a common reference of OOK. For example, given a bit rate, R_b, and a set of constraints (average signal power, P_{ave}, or instantaneous peak power, P_{peak}), each modulation scheme can at best achieve some d_{min}, which corresponds to a BER performance via equation 1. CandLES currently models OOK, LPAM, LPPM, and L-phase shift keying (LPSK), however other modulation techniques may be added by denoting their relationship to OOK bandwidth, R_b and d_{min}. For a relevant example in infra-red wireless optical communications see [6].

4 Physical Link

Optical communications use intensity modulation with direct detection (IM/DD) where the information is encoded by varying the instantaneous optical intensity of the source. In free space, the channel exhibits multipath distortion. More precisely:

$$X'(t) = \int_{-\infty}^{\infty} X(\tau)h(t-\tau)d\tau$$

where $X(t)$ represents the instantaneous optical power of the transmitter, $X'(t)$ represents the instantaneous signal power at the receiver and $h(t)$ is the channel impulse response. Note that $X(t) \geq 0$. Most systems will have an additional optical shot noise from outside light sources. This is observed at the receiver as

$$Y(t) = X'(t) + Z(t)$$

where $Z(t)$ is the noise and $Y(t)$ represents the combined instantaneous optical power at the receiver.

[1] L stands for the order of modulation, e.g. 8PPM has 8 symbols each representing a sequence of three bits.

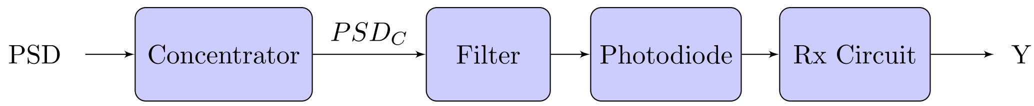


Figure 2: Receiver Path

4.1 Transmitter

CandLES assumes LED's as transmitters. Each LED is specified as having a bandwidth limitation and output light characterization in terms of total power, P_t (W), power spectral density, PSD (W/nm), and spatial radiation intensity pattern (W/rad). For purposes of illumination, the software also converts between radiometric and photometric units, taking into account the photopic luminous efficiency function of the typical human eye.

Assuming no distortion in the transmission, the optical signal is proportional to the intended modulated signal $X(t) \propto X_m(t)$.

4.2 Channel Impulse Response

In order to calculate the channel impulse response, $h(t)$, and received power, P_r, CandLES adopts a fast algorithm developed for IR free space optical communications [2]. The model takes into account: (a) locations of transmitters, receivers and obstacles, (b) reflectivity of each wall and obstacle, (c) field of view (FOV) of transmitters and receivers, (d) receiver area and (e) the number of reflections after which the path of each light ray is truncated.

Regarding the reflectivity values for surfaces, there is flexibility in CandLES to assume a different value for each color component, in essence determining the colors of walls and objects in the room. For example, most commonly we take a uniform reflectivity for all wavelengths. This is equivalent to assuming that each surface always appears to be the same color as the light that hits it, and the optical signal at the receiver has identical spectral content as the transmitted signal, i.e. $PSD_{X'} \propto PSD_X$.

4.3 SNR and Bandwidth at the Receiver

CandLES models the receiver components illustrated in figure 2. At the receiver locations, in addition to the optical signal and noise strengths (W/m^2), the light-spectral contents, $PSD_{X'}(\lambda)$ and $PSD_Z(\lambda)$, are known. These are used to determine the strengths of the electrical signal current, Y_{sig}, and shot noise, Y_{noise}, after passing through optical lenses, filters and photodiode conversion, for which the responsivity as a function of the wavelength is specified (A/W/nm).

For wide FOV receivers, CandLES incorporates a hemispherical concentrator into its receiver model, as discussed by [4]. Based on the concentrator FOV and index of refraction, n, CandLES calculates an approximate gain for the signal. This gain is uniform for all wavelengths of light, so, for example, the PSD of the received signal is scaled as

$$PSD_{X'C} = \frac{n^2}{\sin^2(FOV)} \cdot PSD_{X'} \tag{2}$$

The signal is also passed through an optical filter and photodiode. Let the spectral response of the filter be $R_{OF}(\lambda)$ and the responsivity of the photodiode be $R_{Pd}(\lambda)$. The signal electrical current is proportional to the power of the optical signal, and calculated as:

$$Y_{sig} = \sum_{\lambda} A \cdot PSD_{X'C}(\lambda) \cdot R_{OF}(\lambda) \cdot R_{Pd}(\lambda) \cdot \Delta\lambda \tag{3}$$

where A denotes the photodiode area.

The noise has two components: optical shot noise and electrical noise. In free space optics with a wide field of view receiver, the shot noise is approximately Gaussian. It may have various sources, natural and artificial, with each source possibly emitting different spectral content. Let $PSD_{ZC}(\lambda)$ denote the total spectrum for such optical noise after passing through the concentrator.

$$Y_{noise} = \sum_{\lambda} A \cdot PSD_{ZC}(\lambda) \cdot R_{OF}(\lambda) \cdot R_{Pd}(\lambda) \cdot \Delta\lambda \tag{4}$$

Accounting only for this optical noise, and assuming OOK modulation, the SNR is:

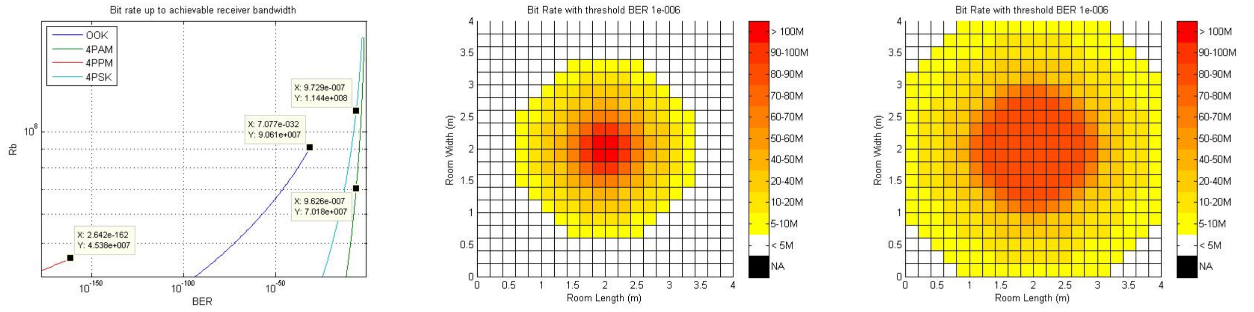
$$SNR = \frac{(Y_{sig})^2}{(q \cdot Y_{noise}) \cdot R_b} \tag{5}$$

where q denotes the electron charge.

The receiver bandwidth and the amount of electrical noise are determined by the model of receiver electronics. CandLES assumes a transimpedance configuration for the receiver, which is based on the discussion in [1]. Through an iterative procedure described there, CandLES calculates the best drain, source and feedback resistors in order to satisfy bandwidth and noise requirements. The crucial choice of photodiode area, A, is left up to the user. Namely, while equations 3, 4 and 5 show that SNR increases with A, unfortunately, so does photodiode junction capacitance, which limits the bandwidth. The SNR is adjusted to take into account the level of electrical noise, which is modeled as consisting of amplifier (FET) noise and thermal noise from the components in the receiver circuitry.

5 Illumination

The illumination functionality of CandLES "piggybacks" on the central communication capability. CandLES measures illuminance (lx), or luminous flux per



(a) (b) (c)

Figure 3: Communication performance results in an empty 4m X 4m room with 1m separation between transmitter and receiver. (a) Comparison of performances of common modulation techniques, (b) spatial performance with 4PSK, (c) spatial performance with OOK.

unit area, on all surfaces of interest, by modeling those surfaces as being covered by virtual receivers. As discussed above, both the power, P_r, and spectral content, $PSD(\lambda)$, of the light incident on each receiver are available from the channel model. From that information, and using a standard approximation for the photopic luminosity function (eye response), $V(\lambda)$, CandLES calculates the luminous flux, Φ, at each surface segment:

$$\Phi = 683 \int_{380nm}^{720nm} P_r \cdot PSD(\lambda)V(\lambda)d\lambda \qquad (6)$$

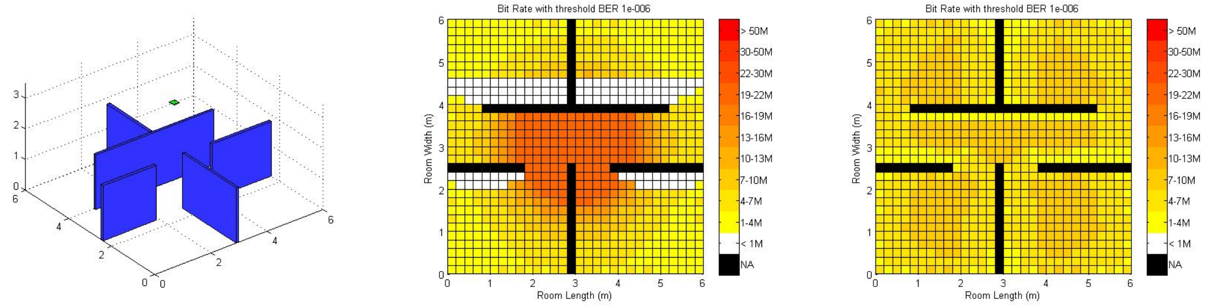
Following that, the illuminance is calculated by accounting for the area of each segment.

$$E = \frac{\Phi}{A}$$

6 Results

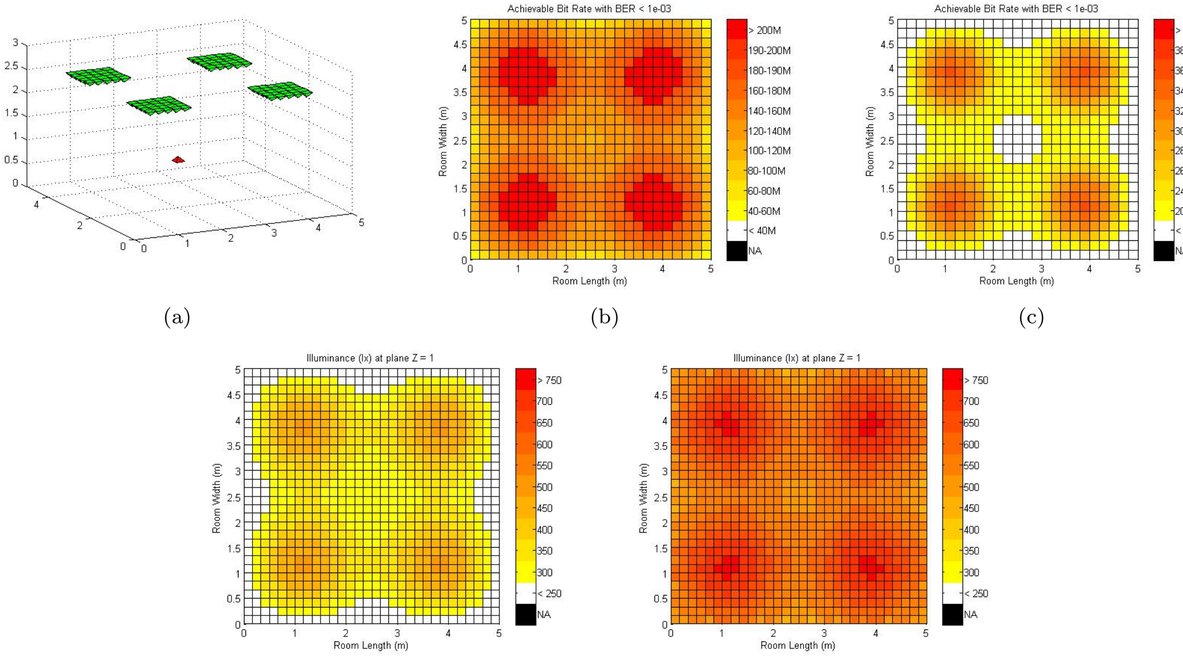
Figure 3 displays communications results for an empty 4m x 4m room. The transmitter is a single “bulb” located at the center of the ceiling and comprised of LEDs outputting a total of 1050 lumens of white light. The receiver is located 1m below the source and employs a $0.81\ mm^2$ photodiode, a wide FOV (90°) hemispherical condensing lens and a blue bandpass filter. The level of ambient noise at the receiver is 5.8 $\mu W/cm^2/nm$, which can be considered a worst case for indoor environments, i.e. daylight near a window, but not in direct sunlight [1]. Figure 3a shows the performance of the candidate modulations: OOK, 4PAM, 4PPM and 4PSK. Note that each modulation seems to have a hard limit on the datarate. This limit is based on the nominal bandwidth of the slowest system component. Figure 3b and 3c give spatial analysis of signal coverage for the same room using 4PSK and OOK, respectively. Note that for these results the receiver is pointed straight up at the ceiling, i.e. it is relying on its wide FOV rather than on tracking the transmitter.

In this scenario, we see a maximum peak rate of 114Mb/s for PSK with a BER less than 10^{-6}. OOK is bandwidth limited to approximately 90Mb/s with a BER on the order of 10^{-32}. In this situation, 4PSK acheives higher data rates while OOK is bandwidth limited, however OOK has a better overall performance when bandwidth is not the limiting factor. Observing a base rate of 5Mb/s, spatial analysis shows that OOK covers 90% of the room in comparison to 39% for PSK.



(a) (b) (c)

Figure 4: Simulated 4PPM results in a 6m X 6m X 3.5m office for a receiver at a height of 1m with (b) a single 5W transmitter at the center of the ceiling, and (c) four 1.25W transmitters spaced evenly on the ceiling.



(a) (b) (c)

(d) (e)

Figure 5: CandLES results of a scenario similar to [3]. (a) A 5m X 5m X 3m room with four transmitter arrays, (b) 256-PAM spatial results without receiver noise (MAX = 222Mb/s, MIN = 59Mb/s), (c) 256 PAM spatial results with receiver noise (MAX = 37Mb/s, MIN = 9Mb/s), (d) lighting results from LOS illumination and (d) lighting results from 4-bounce multipath illumination with 80% wall reflectivities.

For a more realistic office environment, figure 4 shows PPM results for a 6mX6m room with four sectioned cubicles. This scenario displays CandLES ability to account for multiple light paths. Namely, CandLES shows some (though limited) communication capacity in areas where there is no line of sight (LOS) signal path. Still, the coverage is very patchy, with many slow or dead spots, and very high datarates concentrated in a limited area. A useful fix for this office is illustrated in Figure 4c. There we replace the single fixture at the center of the room with four distributed synchronized transmitters that together output the same total amount of light. This achieves an improvement in the signal coverage within the cubicles.

Figure 5 displays results for a scenario similar to one described in [3]. We replace the 900 LED's (63mW each) with 100 transmitter's (570mW each) for the same total light output and similar distribution. We model similar transmitter characteristics, receiver characteristics and noise. Figure 5b displays CandLES data rate results for the room where, similar to [3], only ambient noise is taken into account. Figure 5c displays results when noise from CandLES default transimpedance receiver is included. It can be easily observed that inclusion the receiver noise and bandwidth limitations drastically reduces the overall system performance.

Figures 5d and Figure 5e display CandLES illumination results for the same system. Recall that [3] considers only the direct LOS light rays in their approximating model. The results presented here show that including reflections makes a significant difference in the level of illumination.

7 Other Features and Future Additions

CandLES provides a graphical user interface (GUI) which offers a rich capability to modify the modeled system design settings and environment parameters. The GUI also automatically outputs the most pertinent results in graphical form. Alternatively, CandLES can be accessed by directly editing the configuration file, which contains the complete specification of the system design and environment. For example, this mode may be used for changing more detailed aspects of the system specification (e.g. the input signal PSD, or the responsivity curve of a receiver photodiode), or for accessing less commonly needed outputs (e.g. the receiver frequency response).

The capability of CandLES in providing the multipath impulse response at each receiver will lead to future analysis and mitigation of intersymbol interference (ISI). In wide FOV systems, ISI becomes a very important consideration when transmitting at high symbol rates, i.e. where impulse response duration is relatively long compared to the symbol period. Accounting for ISI, and for anti-ISI techniques such as sequence detection and decision feedback equalization, will likely improve the precision of CandLES in predicting the performance for such systems.

The channel model used by CandLES is able to combine signals from multiple transmitters as measured at multiple receivers. This functionality is currently used for volumetric analysis of communications performance, and modeling of synchronized or array-based LED transmitters as shown in Figures 4 and 5. It can enable many additional future uses and additions. For example, situating multiple autonomous transmitters into the environment will allow CandLES to quantify the interference among them. Including multiple receivers into the signal field of a single transmitter, will lead to evaluation of link-sharing. Potentially, those features can be expanded toward models for multiple access and mobility, and testing of schemes for reducing contention and increasing global utility through cooperation.

More sophisticated modeling of the electrical circuits is needed for bandwidth and noise performance evaluation of alternative designs of the receiver amplifier and transmitter driver. At the receiver, current capability is limited to bandwidth and noise analysis of a default circuit layout, and the tuning of a few parameters to improve its performance. In order to evaluate other state-of-the-art receivers, their analysis must be done outside of CandLES, and their specifications then passed to CandLES as inputs. At the transmitter, there is no default driver, and the bandwidth performance is entirely based on outside analysis or experience. Future integration of SPICE into CandLES will enable detailed real-time evaluation of transient, frequency domain, and noise performance of alternative circuit designs for both transmitters and receivers.

8 Conclusion

We presented CandLES, a software modeling tool that aids in design of free-space VLC systems, which may double as lighting systems. Prior to prototyping, CandLES predicts the communication and illumination performance of a system design within a specified environment. To accomplish this, CandLES integrates models for modulation, LED, optics, channel, noise, receivers and electronics into a single software package. The output measures of system performance include data-rate coverage, error performance, signal strength, as well as illumination brightness and quality.

The presented studies illustrate the variety of uses for this software in designing VLC and lighting systems. Comparisons to results from previously published work were presented for verification.

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