Modeling and Designing of a New Indoor Free Space Visible Light Communication System[*]

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Abstract–Recent developments in solid-state light-emitting diode (LED) materials and devices is driving a resurgence into the use of free-space optics (FSO) for wireless broadband communication. This technology uses the visible spectrum provided by "white" LEDs that are becoming ubiquitous in lighting and has some desirable properties competitive with existing radio frequency (RF) communications. By leveraging the low-cost nature of LEDs and lighting units there are many opportunities to exploit this medium for widespread optical communication deployment. The optical medium, however, has particular characteristics, including directionality and susceptibility to noise sources in the visible spectrum that must be managed.

In this paper we present a new indoor FSO system, also known as a visible light communication (VLC) system that addresses achieving satisfactory data rates through diffuse link while supporting mobility under line of sight (LOS) constraints. The system model is presented with theoretical performance analysis indicating a promising rate for indoor scenarios. The new VLC prototype that can deliver in excess of 1 Mbps while providing both illumination and communication at several meters is also introduced with technical details.

Keywords: Visible light communications, optical wireless communications, free-space optical, mobility, line of sight.

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1 Introduction

RF communication is an incumbent and evolving technology that will have high utility for the indefinite future. However, there are both opportunities with the use of free space optical spectrum and some limitations on the use of RF. RF suffers from several constraints that prevent it from being used in certain scenarios. For next generation of wireless communication technologies, with the development of new laser diodes (LD) and LED materials, researchers [6] believe that FSO presents a viable and promising supplemental technology to the RF system by enabling the use for short range indoor applications in addition to previous outdoor long range cases. Nowadays, due to the development of new energy-efficient LED materials and devices, replacing old incandescent and fluorescent lights with "white" LED lights will undoubtedly happen in the future [1]. These small and power-efficient devices give rise to more interesting wireless communication applications for both indoor and outdoor scenarios as a medium for modulated FSO communications. Researchers are attracted by the opportunities here because of the low-cost and volume production of LED devices for lighting [2–6].

Pang et al. constructed a system with visible LEDs for traffic light-based communications in 1999 [7]. The group set up the system with 441 red ultra-bright LEDs in the lab over 20 meters. The system can achieve a rate at 128 kbps.

The prototype developed by Douseki et al. [8] is a indoor application for communication within a range of 40 cm deployed as a desktop lamp without batteries. Power is derived from a solar cell which also acts as a photon detector for receiving data. This prototype can support transmission up to 100 kbps under illumination at the distance 40 cm.

The prototype described by Wada et al. [9] is an extension of a pixelated system [10] in a long-range outdoor application. It uses a LED array for traffic light as a transmitter and a high speed camera as a receiver. The authors claim it can achieve a speed of 2.78 kbps within 4 m under laboratory conditions.

At the University of Oxford, Minh et al. have developed a prototype [11] that can achieve 100 Mbps. However, currently it only works for a very short distance (10 cm).

Little et al. at Boston University demonstrated a short range (3 m) duplex point-to-point white-LED system with the rate of 56 kbps [12] developed with readily-available electronics and LEDs, demonstrating the viability, simplicity, and low cost of VLC solutions rather than their upper bound in terms of achievable data rates.

Recently, the same team created a prototype that delivers in excess of 1 Mbps while providing both illumination and communication at several meters and has been demonstrated as an array of seven luminaries in the form of overhead spot lighting.

The paper is organized as follows. In Section 2, fundamental knowledge of the LED characteristics and the setup of the indoor scenario are introduced. In Section 3, the communication channel and path loss model for indoor VLC are discussed. The details of our new prototype are provided in Section 4. Section 5 concludes the paper.

2 Preliminary Framework

2.1 Room geometry

The prototype we built is for indoor applications. Therefore, we consider a typical $12x12x3m^3$ office room. In this model, the receiver is assumed to be placed at 1 m desktop level. There are four transmitters locating at the ceiling level with the horizon coordinates, (3,3), (3,9), (9,3) and (9,9). Each transmitter is equipped with eight LEDs to have enough brightness for both high speed communication and illumination functionalities. The model can be illustrated in Fig. 1.

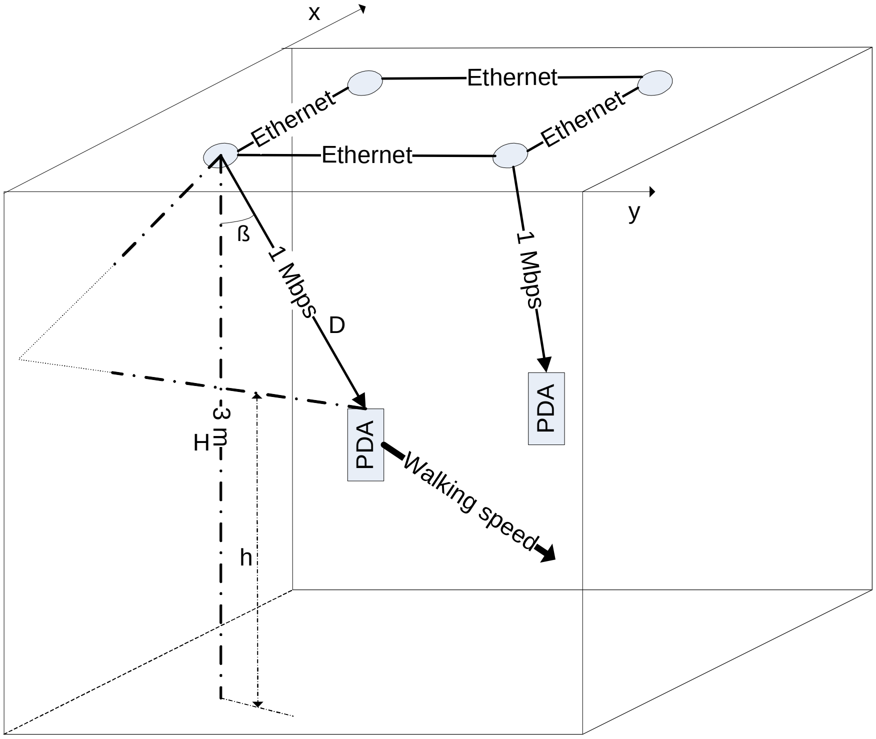

Figure 1: Proposed FSO system model for indoor applications

2.2 Optical power analysis of LED transmitter

Even though white light can be a proper mixing of red, green and blue light, at present most devices for illumination use a blue LED which illuminates a layer of yellow phosphor, with these two colors mixing to create a white emission. The optical power P_t of such LED is normally obtained from radiation spectrum $S_t(\lambda)$ by

$$P_t = \int_{\lambda_L}^{\lambda_H} S_t(\lambda) d\lambda.$$

However, typically most of manufacturers only give the normalized radiation spectrum $S_t'(\lambda)$ as in [13]. If we denote a scaling factor $c_t = S_t(\lambda)/S_t'(\lambda)$, it can be found from [15]

$$c_t = \frac{F_t}{683 \int_{380nm}^{780nm} S_t'(\lambda) V(\lambda) d\lambda},$$

where F_t is total luminous flux and $V(\lambda)$, the eye sensitivity function, can be approximated by the following Gaussian curve fitting [16]

$$V(\lambda) \cong 1.019 e^{-285.4(\lambda - 0.559)^2}.$$

In this way, we are able to have the actual optical transmit power instead of the power consumed by the whole transmitter, and in our system, it is 0.18 mW.

Currently, most LEDs have low modulation bandwidth of MHz due to the long response time of the yellow phosphor. By suppressing the slow portion in the spectrum with the method of blue filtering, the modulation bandwidth can be enhanced to 20-25 MHz [17]. Therefore, only about 50% of the total optical power is broadcasted. In the next section, we will discuss the performance with and without blue filtering.

2.3 LED and photodiode parameters

Since our system needs to also support illumination, the LEDs have to be bright enough and wide radiation angle. After investigating several LED and photodiode chips, with the consideration of complexity and cost, we chose LXML-PWC1-0040 [13] and SFH 213 [14] respectively for transmitter and receiver. Table 1 shows the parameters for the analysis.

Table 1: Summary of chip parameters and room setup [13, 14]

LED Parameters	
Half radiation angle (θ_{max})	90°
Optical transmit power (P_t)	0.18 mW (without blue filtering)
	0.09 mW (with blue filtering)
Modulation bandwidth (B)	2 MHz (without blue filtering)
	20 MHz (with blue filtering)
Photodiode Parameters	
Photodiode responsivity	0.62 A/W (870 nm)
Receiver area	1 mm^2
Other Parameters	
Room size	12×12×3 m^3
Device height	1 m
Chips on transmitter	8
Locations of transmitters	(3,3),(3,9),(9,3),(9,9)

3 Channel Model with Performance Analysis

3.1 Path Loss

The channel model we adopt is from [18]. It only consider LOS links. The diffuse link model is shown as Fig. 2. For simplicity, we consider the angle between receiver center line and source-receiver line, α, as zero. That means the receiver is always pointing vertically to the ceiling. Therefore, the path loss performance can be calculated by

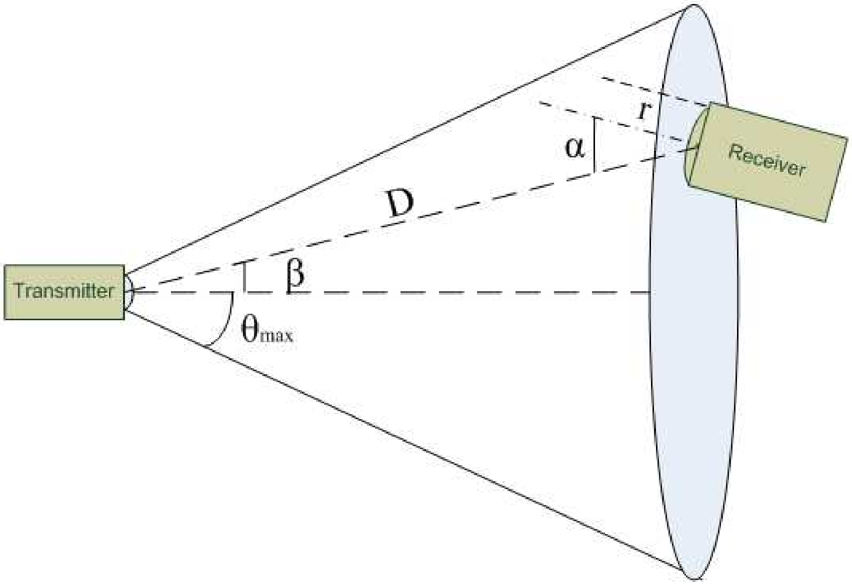

Figure 2: LOS diffuse link model for path loss [18]

$$L \approx \frac{g_t(\beta)A_r}{D^2 \int_0^{\theta_{max}} 2\pi g_t(\theta) sin\theta d\theta},$$

in which A_r donates receiver area, $g_t()$ and θ_{max} are given in [13].

The difference here is the received optical power is the summation of optical power from all LED chips in the room.

3.2 Signal-to-Noise Ratio (SNR)

In FSO, the noise could consist of several types of noise source, such as unique fluorescent light interference, thermal noise and photon-generated shot noise. Shot noise, stemming from ambient light, is a major noise source in the wireless optical communications. From [2], Conservatively, the noise power spectral density is

$$N_0 \cong N_{shot} = 2q\gamma P_n \sim 10^{-22} \mathrm{A}^2/\mathrm{Hz},$$

where q is the electronic charge, γ is the responsivity and P_n is the average power of ambient light.

Therefore, for certain bit rate of R_b we can have the receiver electrical SNR defined in [2] for any spot in the room,

$$\mathrm{SNR} = \frac{\gamma^2 P_r^2}{R_b N_0}.$$

3.3 Upper Bound of the Rate

The high intensity shot noise is the result of the summation of many independent, Poisson distributed random variables. In the limit, the cumulative distribution approaches a Gaussian distribution. Therefore, currently, for most of the researches on LOS link models, the noise is modeled as Additive White Gaussian Noise (AWGN).

Considering all possible multi-level and multi-phase encoding techniques, the Shannon theorem states that the channel capacity C, meaning the theoretical tightest upper bound on the information rate (excluding error correcting codes) that can be sent with a given SNR, is

$$C = B\log_2(1 + \mathrm{SNR}).$$

Although the actual achievable rate depends on several parameters, this rate upper bound from Shannon theorem can still give certain evaluation of performance.

3.4 Bit Error Rate (BER)

The performance of BER is related to the coding and modulation techniques. In this prototype we adopt On-Off Keying (OOK) for its simplicity and power efficiency. It is a binary level modulation scheme consisting of two symbols. Assuming that ones and zeros are equally likely, therefore, the BER can be determined from [4] as

$$P_e = Q(\frac{P}{\sqrt{R_b N_0}}) = Q(\sqrt{\mathrm{SNR}}).$$

3.5 Performance Analysis

We first calculate four parameters without any blue filtering, and have the modulation bandwidth 2 MHz. The results show in Fig. 3. The path loss and SNR are in Decibel (dB), maximum rate is in Mbps and BER is in power of 10.

If blue filtering is adopted, the optical transmit power will be reduced to approximately half, which is 0.09 mW. By only having the fast response portion and better signal shape, it is possible to enhance the modulation bandwidth to 20 MHz. The results show in Fig. 4.

From the results, even for short range LOS link, VLC still suffers from high path loss. This situation could be even worse for outdoor applications when atmospheric effects exist, such as absorption, scattering and shimmer. However, if we consider indoor scenario as free space with low Gaussian noise, the SNR and BER (without error correction coding) of OOK modulation are acceptable for low data rate (<Mbps) communications.

At the other hand, by adopting blue filtering, it is possible to enhance the chip's modulation bandwidth to as high as 10 times of the previous performance. But the improvement of the data rate also increases the shot noise variance, which eventually leads to the degradation of SNR and BER. So, simply increasing the modulation bandwidth with blue filtering cannot significantly improve the whole performance. Better modulation and coding techniques are required with it.

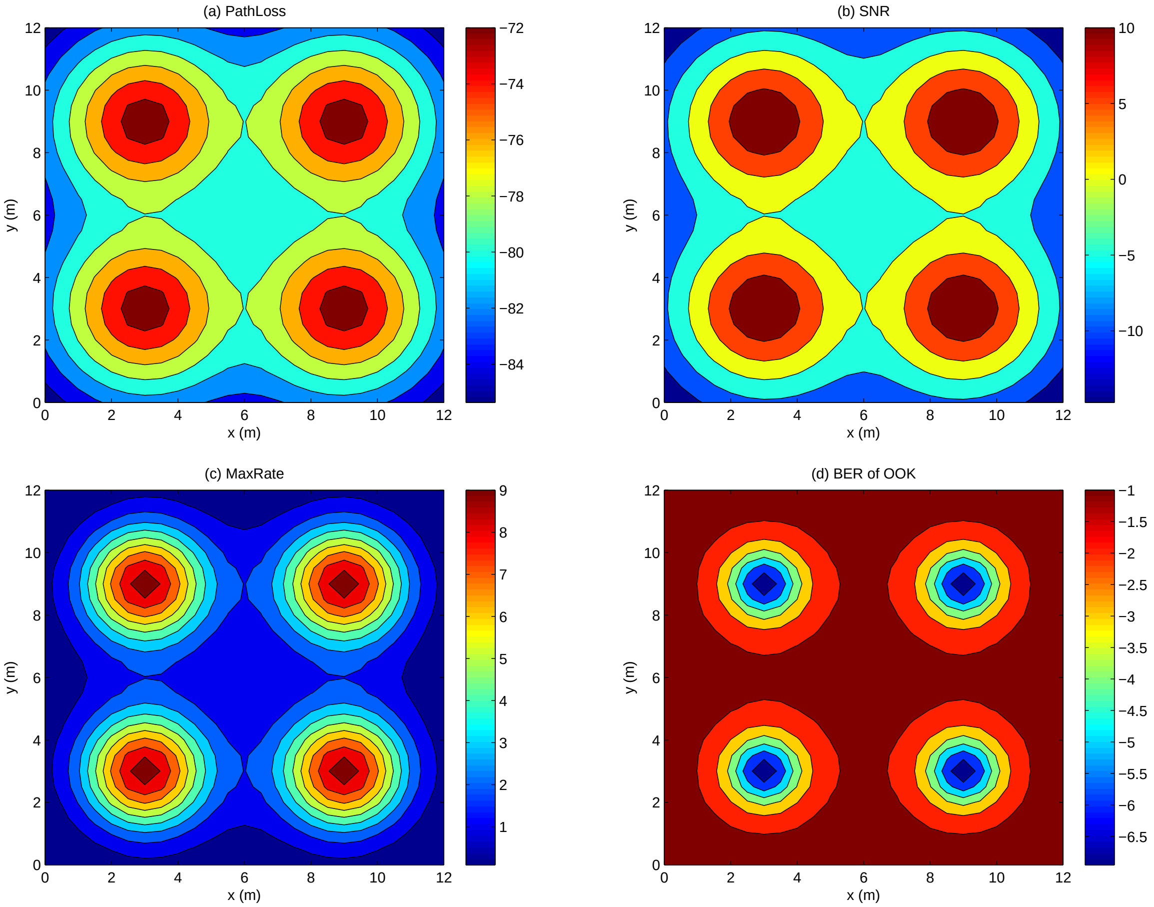

Figure 3: Path Loss (a), SNR (b), Max Rate (c) and BER of the prototype system without blue filtering

4 New VLC Prototype

Many types of optical transceivers exist; some are designed to send light through waveguides, such as fiber-optics, and others, like the transceiver demonstrated, are FSO transceivers that are able to transmit and receive data without the aid of a waveguide. Unlike most FSO transceiver though, the demonstrated transceiver generates and modulates “white” light in the visible spectrum. This feature allows the transceiver to be used in lieu of regular lighting devices, allowing this versatile and controllable lighting to replace conventional lighting.

The most important component of the transceivers is customized LED driver. The first part of it was designed to switch current toward and away from the LED; when the LED should be off, current is switched away from it to discharge any capacitance across the LED. The other part was designed to maintain the desired current through the LED when it is supposed to be on.

The typical performance of the transceiver at 2Mbps is shown in Fig. 5, with the transmitter input as the yellow signal and the receiver output as the green signal. The left half shows the operation when the transceiver is idle with the LEDs on and the right half shows data transmission.

Recently, as shown in Fig. 6, a new improved design which utilizes a current-mirror to regulate

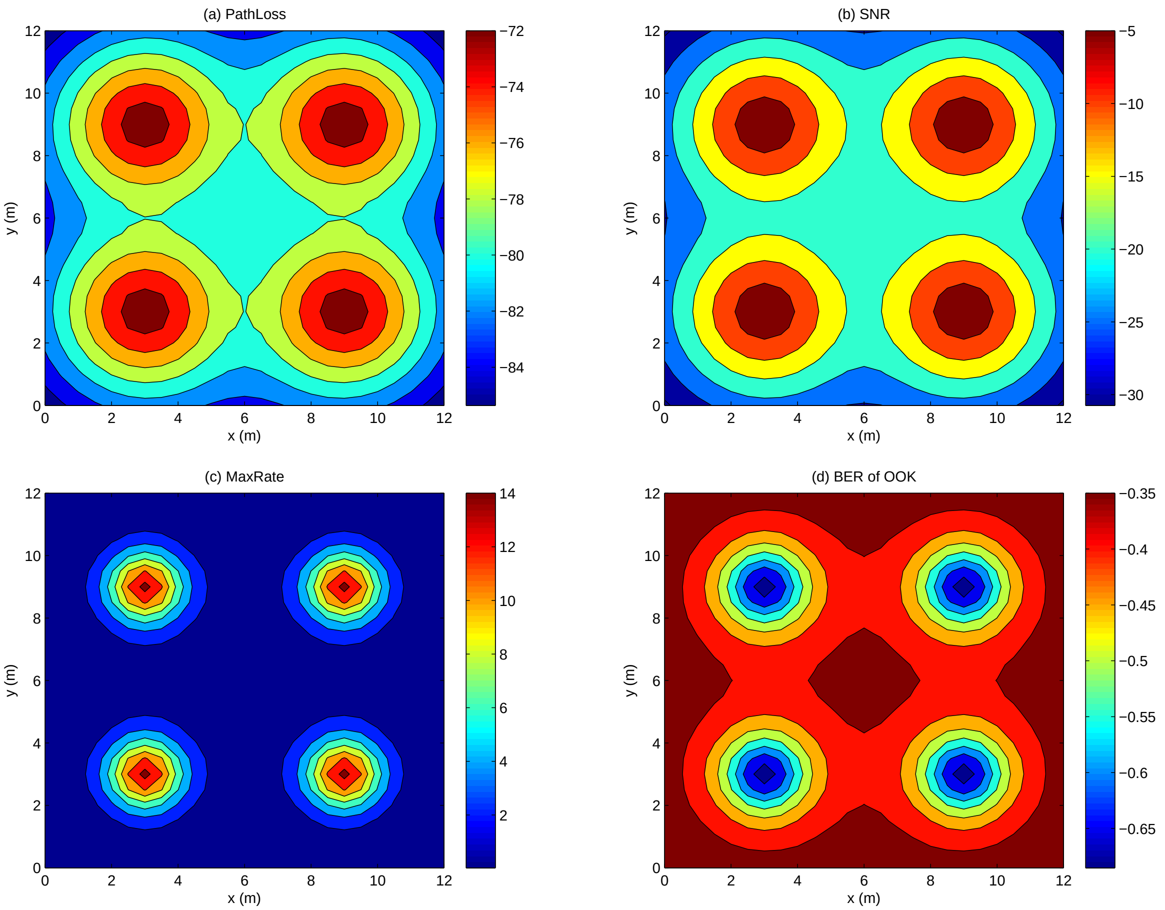

Figure 4: Path Loss (a), SNR (b), Max Rate (c) and BER of the prototype system with blue filtering

the current through the LEDs is available. Basically, we adopt a different configuration of transistors to eliminate the risk of a short between the +5V rail and ground, which is resulted from potential shoot-through across transistors.

Furthermore, this newer design offers many benefits over the existing one:

- more data sent per cycle by multi-level signaling;
- faster switch by pre-biasing the LEDs;
- reduced cost by supporting more LEDs on each driver;
- Its design is simpler, which reduces costs, improves reliability, and facilitates modeling;
- LEDs can remain on without signal.

5 Conclusion

In this paper we propose a next generation FSO system using visible light. We introduce a new prototype that can deliver in excess of 1 Mbps and has potential for transmitting in 10's of Mbps. Furthermore, we theoretically analyze the path loss, SNR, rate upper bound and BER of OOK modulation for two different scenarios, without or with blue filtering. The results show that the current system is able to support Mbps communications with acceptable SNR and BER, and with-

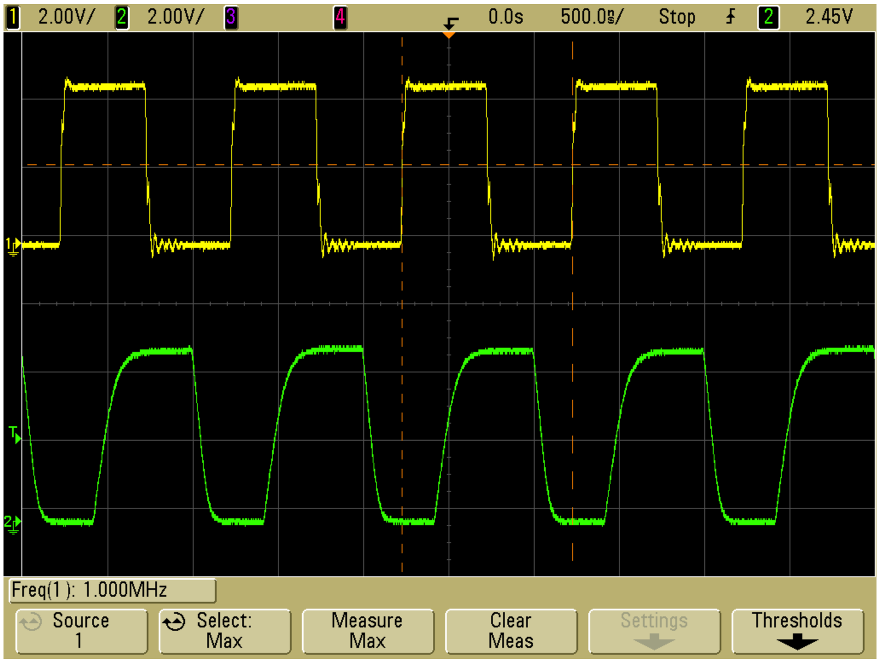

Figure 5: Waveforms of transmit and receive signals

out better modulation and coding technique, blue filtering technique alone cannot significantly improve the system.

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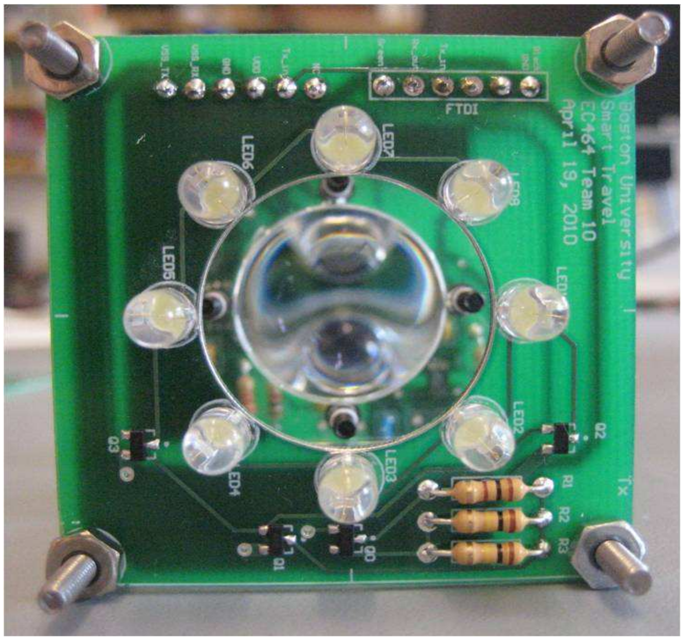

Figure 6: Improved VLC prototype for indoor applications

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