Spotlighting for Visible Light Communications and Illumination

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***Abstract*—The trend toward solid state lighting with white LEDs has motivated much research for using these devices to provide wireless broadband data communications. Much work in this area has attempted to fit VLC into currently dominant indoor lighting modes, which broadcast the light in a wide field to achieve uniform coverage throughout a room. In this paper we explore spotlighting, which is appropriate lighting for many scenarios, as an alternative for implementing high datarate VLC. We find that spotlighting VLC has several benefits over uniform lighting implementations, including enabling higher datarate densities within a room and less channel distortion. We also introduce a hybrid scheme that combines spotlighting with uniform lighting to provide wide area data coverage as well as high-datarate "white hot spots" where needed.**

I. Introduction

Light-emitting diode (LED) lighting holds the promise of numerous ecological and economical advantages over incandescent and fluorescent lighting. One potential benefit is that LEDs, being controllable and capable of rapid switching, enable visible light communications (VLC) to be implemented in addition to lighting. By taking advantage of the ability to direct and sequester light, VLC has the potential for much greater datarate densities (Mb/s/m^2) compared to the radio-based systems that presently dominate wireless data access. For example, due to opacity of walls, VLC can enable a separate, non-interfering channel for each room in an office building.

Much current research of VLC through lighting has studied broadcasting the light in a wide field of view (FOV) to achieve even signal coverage and lighting for an entire room. [1] and [2] use modeling to predict what size, number and position of LEDs is required. [3] also approaches this problem through modeling, accounting for electrical receiver noise and light paths with up to four reflections. We highlight a few conclusions from those and other papers which examine this problem: (1) Generating sufficient light for the whole room requires many and powerful LEDs. (2) For even signal and light coverage, those LEDs should be distributed throughout the ceiling. (3) [2] puts the 3 dB bandwidth for one illumination LED at ≈ 2 MHz , due to the down-shifting phosphor decay time. For the LED output itself it is ≈ 20 MHz which they isolate using a blue filter, albeit at a cost of $\approx 50\%$ less signal power. There, as in [4], high datarates are achieved through bandwidth efficient modulation. (5) In [5] it is shown that such designs, in which a single transmitter is made up of many spatially distant LEDs with wide overlapping FOVs, all LEDs may not appear to be synchronized to the receiver. They describe how cooperative transmit beamforming can be used to target a single receiver location.

In this paper we examine the spotlighting approach, where all the light from an LED source is focused and directed to provide both a high-datarate VLC signal and bright light covering a small surface. This is appropriate lighting for e.g. desks in cubicle offices and airplane passenger personal lights. We show that this approach has an important advantage in that a number of spotlights within a single room can be used to provide separate and non-interfering links to users in close proximity to each other. This spatial reuse enables very high bandwidth densities (Mb/s/m^2), compared to the wide FOV uniform intensity model. We discuss many other advantages. By focusing the light, large signal strength can be achieved with fewer or smaller LEDs, potentially simplifying the driver circuitry and reducing transmitter capacitance, which may lead to increased bandwidth. The narrow FOVs reduce multipath distortion due to reflection of the signal off walls and objects. There is no need to synchronize sources that are located far from each other. Spotlighting presents an opportunity to take advantage of the human perception of light to locate a better signal when needed.

Finally, we propose a hybrid mode, which adds spotlights to a uniform light model, to achieve both coverage throughout the room, and very high datarate spots in critical areas.

II. Basic System Model

Figure 1 illustrates an indoor VLC system. The transmitters are all located at a distance D from the plane of the receivers, e.g. ceiling to desktop, each projecting a light field of radius R on the receiver plane. The receiver FOVs are assumed to be wide throughout, to accommodate portability of user devices.

As with all optical links, intensity modulation and direct detection (IM/DD) is used, in which the transmitted waveform $X(t)$ is instantaneous optical power. The transmitted average power is

$$P_t = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)dt.$$

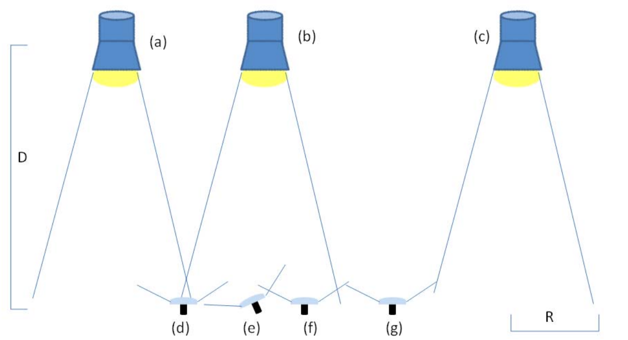

Fig. 1. (a), (b), and (c) VLC transmitters, making light fields of radius R at a distance D. (e), (f) receivers in the lighting field of (b). (d) a receiver that has two transmitters in its FOV. (g) a receiver outside of signal coverage.

The electrical current produced by the receiver photodiode is:

$$Y(t) = rA_eX(t) * h(t) + N(t) \tag{1}$$

$h(t)$ is in general a multipath channel impulse response, and $N(t)$ is shot noise due to ambient light. When the receivers have wide FOV much ambient light is collected, and it is appropriate to model this noise as white and Gaussian [6]. r is the responsivity of the photodiode (A/W) A_e is the effective receiver area (m^2), which depends on the photodiode area, angle of light incidence, and the concentrator used [7], [8].

The signal to noise ratio (SNR) for on-off-keying (OOK) is approximated as follows:

$$SNR = \frac{A_e r P_r^2}{q R_b P_N} \tag{2}$$

Where R_b is the bit rate, P_N is the ambient noise irradiance ($\mathrm{W/m}^2$) that causes the optical shot noise, q is the electron charge, $Pr = H_0 P_t$ is the received signal irradiance, and H_0 (m^{-2}) is the DC gain of the channel $h(t)$. A few notes are in order. We express SNR for OOK because this form represents a convenient basis for comparison of most other modulation schemes (See, e.g. [6]). In addition to optical shot noise, one should also account for the electrical noise from receiver components, for the specific receiver circuit that is used. The results that we present later are performed with modeling software [3], which assumes a receiver with and a receiver circuit with a design presented in [7].

The approximation (2) is equivalent to assuming that $h(t) = H_0\delta(t)$, i.e. it ignores channel distortion. Distortion of $h(t)$ occurs when portions of the transmitted signal arrive at the receiver at different times, resulting in intersymbol interference (ISI), which degrades SNR. To keep ISI low, the length of a modulated symbol should be large compared to the r.m.s. delay spread of $h(t)$ (see, e.g. [6]). For reference, we note that when modulating at a 20 MHz symbol rate, the symbol period is $T = 50$ ns.

TABLE I
MODEL PARAMETERS

Spotlights		Receivers	
Number	4	PD area	150 mm^2
P_t	2 W	FOV	90°
Light output	450 lm	conc. gain	2.25
Lamb. order	60	A_e	337.5 mm^2
BW in blue	20 MHz	BW	35 MHz
		rec. noise penalty	3 dB
Wide Lights		Optical filt.	450 ± 20 nm
Number	16	r at 450 nm	.2 A/W
P_t	2 W		
Light output	450 lm	**Environment**	
Lamb. order	1	surf. reflectivity	.6
BW in blue	20 MHz	Ambient noise	5.8 $\mu\mathrm{W/cm}^2/\mathrm{nm}$

III. SPOTLIGHTING

To show how it can benefit communication, we compare a spotlight with the scenario similar to the one described in [2], which attempts total coverage by distributing wide FOV LED chips uniformly on the ceiling, and which we name "uniform lighting". For uniform lighting, there is great overlap of the lighting fields of all LEDs, which serve as parts of a single large transmitter.

In each of the following sections we isolate the basic concepts by greatly simplifying the math. Where appropriate, we follow up with results obtained through detailed modeling with the software presented in [3]. We do not have opportunity here to explain the models in great detail, but Table I gives the most important model parameters. In addition to [3], another helpful reference for the models used is [9].

A. Transmit Power and Datarate Density

Our theoretical spotlight is a source that produces an "ideal cone" of light i.e. its entire light output is projected as a circular lighting field with a hard boundary (no light leakage). This ideal can be approximated by means of an ellipsoidal reflector. To achieve a required light irradiance P_r ($\mathrm{W/m}^2$), the needed transmitted light power P_t (W) can be determined from light field radius R at the receiver plane, regardless of distance D:

$$P_t = \pi R^2 P_r$$

If a small R is chosen, the desired irradiance is achieved with fewer LEDs. For example, to get 2 W/m^2 of light on an area of radius $R = 1/\sqrt{\pi}$ m, we need the LED source to output 2 W of light. In photometric units, for typical white LEDs, that corresponds to 450 lx from a 450 lm source. For comparison, the uniform lighting scenario from [2], which uses 961 chips with half-angle of 120°, outputs a total of 60.5 W in order to guarantee that 93% of a 5 m × 5 m room is irradiated by at least 400 lx (≈ 1.8 $\mathrm{W/m}^2$, depending on the LED spectrum).

From this approximation we see that the two cases are roughly comparable: to cover a unit area with the desired irradiance, spotlights and wide beam lights transmit a similar amount of light power. However, with ideal spotlights, all the light at any location is from the source directly overhead. A VLC transmission from that light is not competing with interference from other transmissions within the same room and in close proximity.

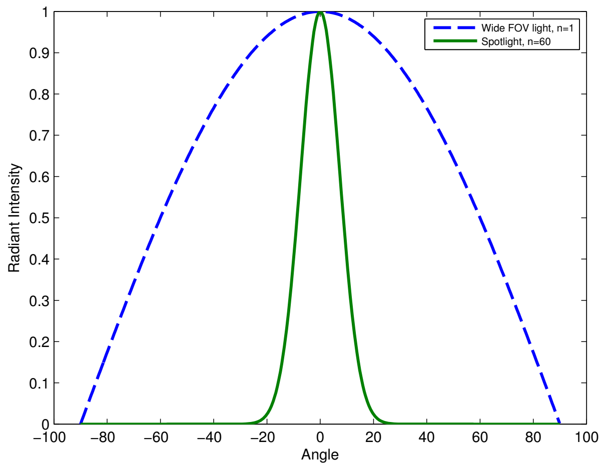

Fig. 2. The radiant intensity pattern of the spotlights (Lambertian order $n = 60$) and wide FOV sources (Lambertian order $n = 1$) used in the numerical studies.

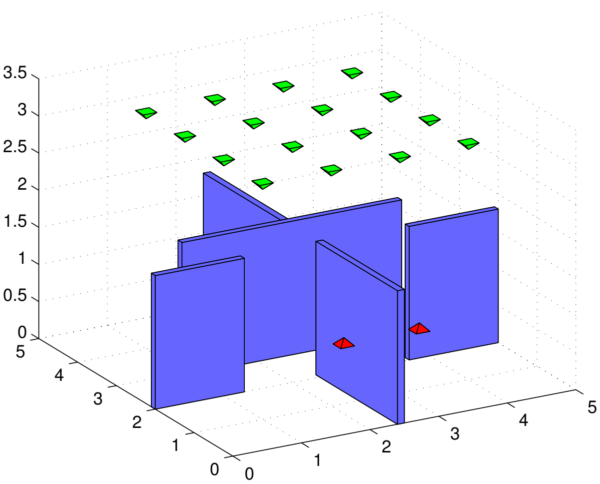

Fig. 3. Our imaginary cubicle office with 16 2 W wide FOV sources providing uniform lighting. Room dimensions 5 m × 5 m × 3.5 m. The height of the transmitters is 3.2 m, and the receiver (desktop) plane is at 1 m.

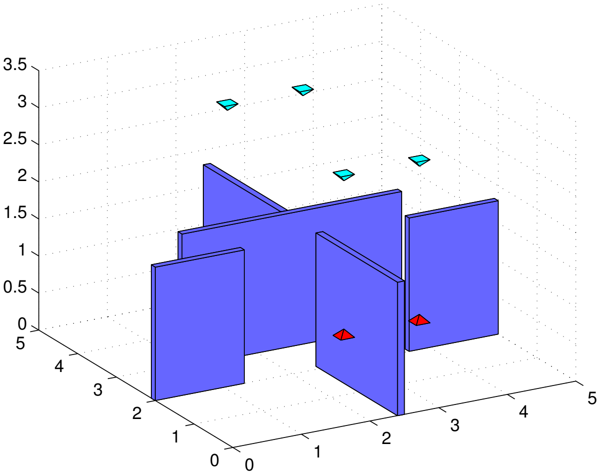

Fig. 4. The imaginary cubicle office pictured in Figure 3 but with four 2 W spotlights.

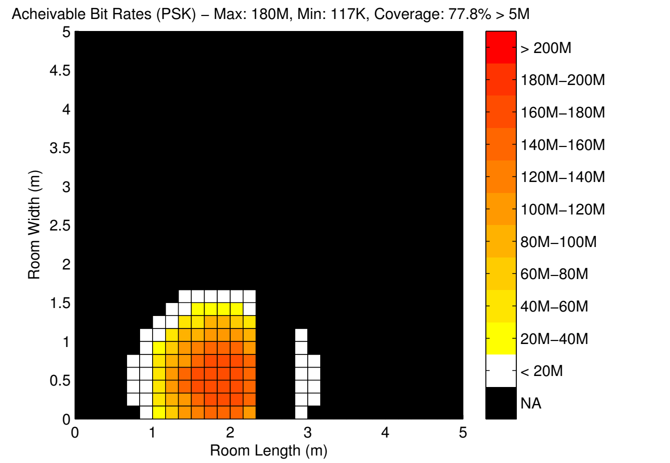

Fig. 5. The datarates provided with a ceiling spotlight on a cubicle desktop.

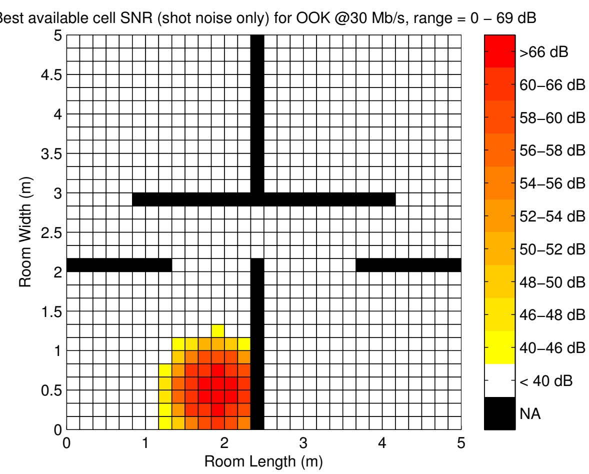

Fig. 6. SNR of a spotlight

We show this with our software modeling results. In a virtual cubicle office shown in Figure 3, we strategically replace the 16 wide FOV lights, with four spotlights, as shown in Figure 4. The radiant intensities of both types of light that we use are shown in 2. The model puts the power of light from the spotlight above the receiver at $P_r = 0.6$ mW, while the power received by the same receiver from one of the other spotlights is $P_r = 1.2$ μW – the interfering signal accounts for 0.2% of the total light. For these, and all other numerical results presented in the paper, we have accounted for all light paths of lengths up to four reflections.

One of these 2 W spotlights may provide a datarate of 180 Mb/s on the desktop in the cubicle directly below, as shown in Figure 5. The bandwidth efficient scheme of phase shift keying (LPSK) is used, with the number of symbols $2 \leq L \leq 256$. Figure 6 shows the equivalent SNR performance (2) of this spotlight. This reference SNR assumes OOK-NRZ at the nominal rate of $R_b = 30$ Mb/s, which can be achieved with a signal limited to 20 MHz of bandwidth by use of raised cosine pulses with excess bandwidth $\beta = 1/3$. An ambient noise level of 5.8μW/cm^2/nm is assumed here and throughout the paper. This can be taken as a worst case indoor noise level [7]. When the circuit noise of our simulated receiver is added, the total SNR is less by ≈ 3 dB.

B. Channel Distortion

A spotlight will typically have all its LEDs and the concentrating elements in a small space. If they are switched simultaneously, the line of sight (LOS) light from all the LEDs to all transmitter locations is synchronized. This is not the case with uniform lighting. Consider a receiver in the corner of the 5 m $\times$ 5 m room, 2 m below the ceiling; the distance to the LEDs directly above is 2 m and the distance to the LEDs in the far corner of the room is 7.5 m, a difference of 5.5 m. If all sources can be synchronized to each other, the LOS light from the far corner will arrive $5.5/c = 18$ ns after the nearest light. For large rooms this can lead to significant distortion, unless beamforming, i.e. synchronizing the LEDs with respect to a target receiver, is employed.

Multiple diverse paths of light, which occur due to reflections, are another potential source of distortion. A spotlight with a small R is less susceptible to multipath distortion, for two reasons: (1) It sees fewer potential reflecting objects in its FOV than a light broadcasting to a wide area. Intuitively, the volume of the cone of light up to the intended receiver plane is $V = \frac{\pi}{3}DR^2$. With a larger target R, more reflecting objects will be enveloped in the volume. (2) The delay for all single-reflection paths, usually the strongest of all non-LOS paths, is small when the radius R is small. It is straightforward to verify that within any cone of light projecting to a radius R, for any LOS path d_0 and path with a single reflection d_1:

$$\max d_1 - d_0 \leq 2R$$

For example, if $R = 1/\sqrt{\pi}$, then the latest a single reflection light component might arrive is 3.8 ns after the LOS component.

In our imaginary cubicle office, we have calculated realistic impulse responses. All paths with up to four reflections were considered, and the reflectivity of all surfaces was set at 0.6, i.e. they reflect 60% of incident light. Figures 7 and 8 show that the uniform transmitter will produce comparatively more channel distortion than the spotlight transmitter. The spotlight impulse response delay spread was $DS = .02$ ns. The delay spread for the uniform lighting case was much larger, but still very small, at $DS = 2.1$ ns. For both, the LOS light from the nearest transmitters clearly dominates. With signal bandwidth of 20 MHz, ISI would not affect either channel significantly.

C. A Hybrid Implementation

We have so far focused on trade-offs between a wide-FOV whole room coverage model of VLC, and a spotlight model providing a high data-rate to a small area. In this section, we show how these two modes can complement each other in a manner analogous to cells and macro-cells in cellular networks. Bright spotlights can deliver high datarates to important areas, such as working desktops. In parallel, uniform lighting can provide lower light irradiance everywhere, and therefore coverage with a lower datarate signal. The two signals may use different sub-carrier frequencies, to distinguish between them.

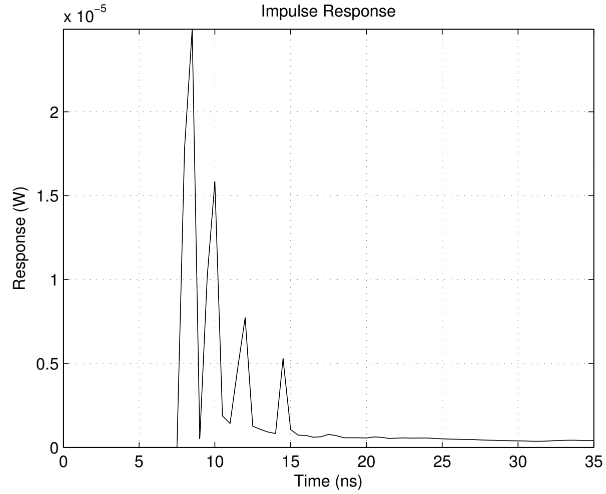

Fig. 7. Impulse response to one receiver from the uniform lights in the cubicle office pictured in Figure 3.

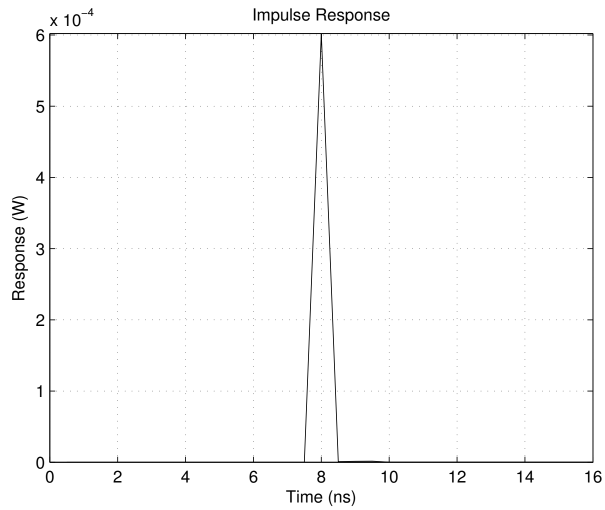

Fig. 8. Impulse response to the receiver from its own spotlight in the cubicle office pictured in Figure 4.

Figure 9 shows the datarates for all receiver locations when the uniform scheme in Figure 3 is implemented together with the spotlight scheme from Figure 4. There are five independent "cells" in the room: one under each spotlight, achieving rates 180 Mb/s, and one cell from the uniform lighting transmitter encompassing all in-between areas with rates $\approx 100 - 140$ Mb/s. The spotlights provide very little interference in the areas where uniform light provides coverage. And in their own areas, the stronger spotlights overcome the signal from the uniform lighting. In Figure 9 note the rings of somewhat lower datarates around the spotlight areas. In these border areas the

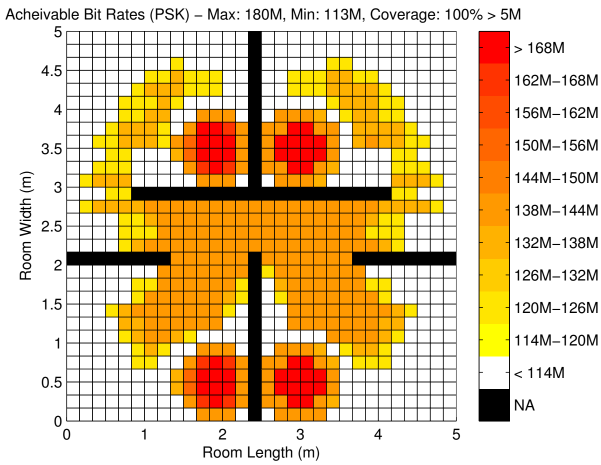

Fig. 9. Hybrid mode datarate coverage.

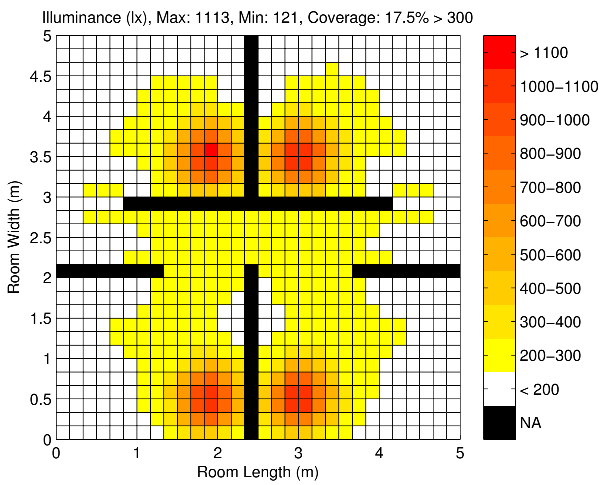

Fig. 10. Hybrid mode illumination coverage.

spotlight is not very strong, so the noise from the uniform light becomes an issue.

D. Lighting and Human Factors

Since we are dealing with visible light, lighting considerations are paramount, necessitating a discussion on how spotlighting providing VLC may also be used to support the lighting mission. Since it produces intense and focused light, spotlighting is clearly not appropriate lighting for some environments. It does have clear advantages in other settings, including for reading lights in airplane passenger cabins, and illumination of desktops in cubicle offices or libraries.

Spotlighting is often used to enhance a uniform lighting scheme in homes and workspaces. For example, desk lamps often provide bright lightning on work surfaces, while overhead lighting provides coverage to other areas where lower light intensity levels are sufficient, such as hallways and aisles. Note that this lighting type is fully compatible with the hybrid scheme for VLC proposed in the previous section. Figure 10 shows the lighting coverage of the hybrid model described above. Light intensity > 300 lx is provided on targeted surfaces, and lower amounts, $100 - 300$ lx, are provided everywhere else, e.g. in between the cubicles.

One additional advantage of spotlights for VLC, which cannot be easily quantified, is the manner in which human perception of light may be leveraged to support the data mission. When a higher speed of data is needed, users can locate a spotlight, and point their device to it. This is a feature that a radio femto-cell lacks. Essentially, human perception of light can make the overall utility of spotlighting VLC greater than what our models of signal coverage can show.

IV. CONCLUSION

We showed that spotlighting presents an opportunity to achieve very high datarate densities, as directed and focused light can be effectively segregated to provide an independent high-speed "white hot spot" on each desktop. When compared to uniform lighting modes, which incorporate many and possibly distant wide FOV sources into a single transmitter, spotlighting can simplify implementation of VLC links. It also exhibits comparatively less channel distortion, though in the particular environment that we modeled, ISI from channel distortion was not a major concern even in the uniform lighting mode. A hybrid scheme, combining spotlights with uniform lighting to simultaneously provide wide coverage and high-datarate densities, was presented. In combination with uniform lighting, spotlighting is appropriate lighting for many environments. The human perception of light can aid in improving total utilization of the high datarate spotlights.

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REFERENCES

[1] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using led lights," *IEEE Transactions on Consumer Electronics*, vol. 50, no. 1, pp. 100– 107, 2004.

[2] J. Grubor, S. Randel, K. Langer, and J. W. Walewski, "Broadband information broadcasting using led-based interior lighting," *Journal of Lightwave Technology*, vol. 26, pp. 3883–3892, 2008.

[3] M. Rahaim, T. Borogovac, and J. B. Carruthers, "Candles: Communications and lighting emulation software," in *WiNTECH '10: Proceedings of the fifth ACM international workshop on Wireless network testbeds, experimental evaluation and characterization*. ACM, 2010.

[4] J. Vucic, C. Kottke, S. Nerreter, K.-D. Langer, and J. W. Walewski, "White light wireless transmission at 200+ mb/s net data rate by use of discrete-multitone modulation," *IEEE Photonics Technology Letters*, vol. 21, no. 20, pp. 1511–1513, 2009.

[5] G. Prince and T. D. C. Little, "On the performance gains of cooperative transmit beamforming applied to intensity modulated direct detection visible light communication networks," *ICWMC '10: Proceedings of the 2010 Sixth International Conference on Wireless and Mobile Communications*, 2010.

[6] J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265–298, February 1997.

[7] J. R. Barry, *Wireless Infrared Communications*. Kluwer Academic Publishers, 1994.

[8] R. Ramirez-Iniguez, S. M. Idrus, and Z. Sun, *Optical Wireless Communications*. CRC Press, 2008.

[9] J. B. Carruthers, S. M. Carroll, and P. Kannan, "Propagation modelling for indoor optical wireless communications using fast multi-receiver channel estimation," *Optoelectronics, IEE Proceedings*, vol. 150, no. 5, pp. 473–481, 2003.