"Lights-off" Visible Light Communications*

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Abstract– In order to implement visible light communications (VLC) through indoor lighting, a set of challenges arise due to conflicting requirements from the two missions. In this paper we examine one of these challenges: how to communicate when the lights are "off." We investigate VLC with limits on transmit power, which we define to be low enough so that users will accept that the lights are in their "off" state. We argue that these limits vary based on levels of natural illumination already present in the environment. Our analysis shows that we can meet the limits while providing robust data coverage by using VLC devices of low complexity. The result is an important step toward ensuring acceptance and adoption of VLC technology.

Keywords: Visible light communications, optical wireless communications, off-state communications.

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1 Introduction

A case for replacement of incandescent and fluorescent lights with white light-emitting diodes (LEDs) can be made based on the LEDs' superior and still rapidly improving luminous efficacy (lm/W of electricity), lifespan, and ruggedness. LEDs also provide opportunity to implement Visible Light Communications through lighting systems, because they can be modulated at much higher rates than other lighting sources.

The use of light implies a key question: "How does one communicate when the lights are off?" This question is a common challenge to VLC research and applies to a number of critical use cases: enabling wireless communications to a digital display when lighting is expected to be low or nonexistent; and enabling communications in a building to support quiescent interaction among embedded devices during periods of inoccupancy.

One reason that has been cited for adoption of VLC is its ability to provide localized, non-interfering, light-based cells using unlicensed spectrum. This would support the increasing numbers of multimedia hungry mobile devices [1, 2]. Much recent research into very high data-rate VLC systems has been motivated by this consideration [3]. Then we have to realize that people frequently prefer to enjoy their multimedia in the dark.

Similarly, adding VLC and Internet access to lighting can serve as an enabler for implementing ubiquitous networking of devices into smart spaces. This vision may network light emitters and sensors with control systems to monitor spaces and adjust to conditions, including occupancy, temperature, presence of hazards, and status of devices in the room. Clearly, these essential functions must continue with the lights off.

The two major use cases that we mention have differing requirements for VLC. Smart room systems will require signal coverage and link robustness to shadowing, but may be satisfied with low data-rates. They also require low cost devices. In contrast, breaking the coming wireless gridlock requires high data-rates and data-rate densities to deliver multimedia to high end future smart phones and tablets. What they have in common is that they equally have to satisfy the lighting mission.

Instead of turning off the lights completely, we only have to convince human users that the lights are effectively (perceptibly) "off." We examine at what low levels of emission may that requirement be satisfied, and we present analysis that shows that simple strategies based on technology of low complexity can meet key communications objectives regardless of the level of natural light noise that is present in the room. Those objectives include both high data-rates and robust data coverage, though we emphasize the latter. This represents a step toward proving the viability of this technology.

Finally, we note that recent research proposes hybrid schemes in which radio-based communications are used to supplement VLC [4, 5]. Similarly, wavelength division multiplexing (WDM) systems can use low power transmission in invisible wavelengths such as IR in addition to VLC. For devices such as laptops, smart phones and tablets, which tend to bundle and accumulate communications technologies over time, both are valid strategies for

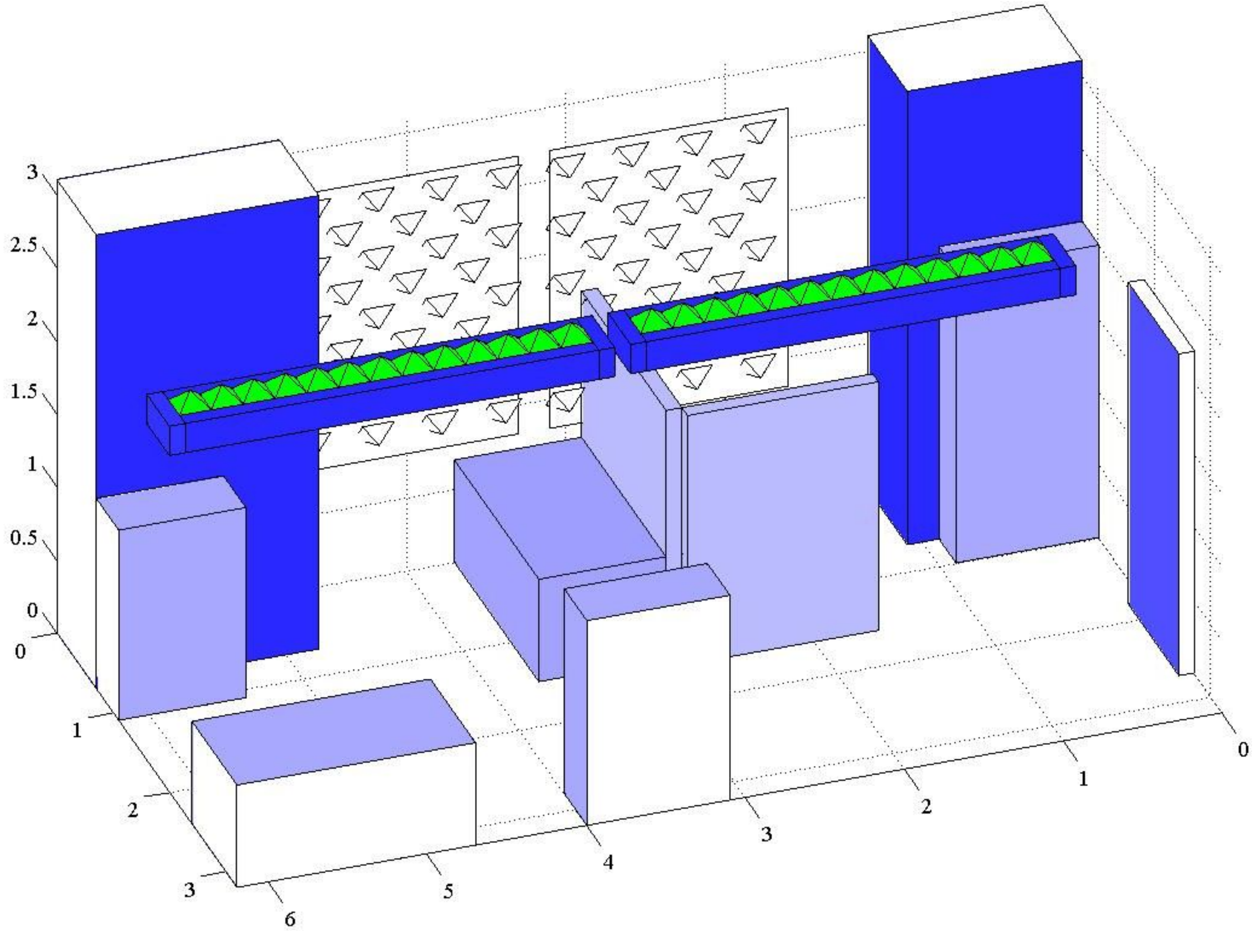

Figure 1: Model of Boston University Photonics Center Room 421. The sources of ambient noise are the windows approximated as 64 high power transmitters on the back wall. The overhead lights are strings of LEDs together playing the role of the VLC transmitter. In reality they are tube fluorescents. Measured reflectivities of all surfaces are included in the model for calculation of $h(t)$. The axes are in meters and are consistent with all locations (l, w, h) discussed in the paper.

the "lights off" state as well as for implementing a VLC uplink. This may not be acceptable when low cost and low complexity solutions are required, such as for implementing smart lighting control systems. Incidentally, the VLC uplink is a problem with similar power constraints due to factors of human comfort and subject of future work.

The remainder of this paper is organized as follows: in Section 2, we briefly review relevant optical communications concepts. In Section 3, we discuss constraints on light emission relevant to "lights off" communications. In Section 4 we present our solution strategies.

2 Background

Most optical communications, including VLC, use Intensity Modulation with Direct Detection (IM/DD) [6]. Let $x(t)$ be the instantaneous optical power (W), of a light source such as an illumination LED. The constraint $x(t) \geq 0$ holds for all t. The average transmitted power, P_t, is defined as follows:

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

If on-off keying (OOK) is used, SNR is approximately:

$$SNR = \frac{A_e r P_r^2}{q R_b P_n (1 + \gamma)} \tag{2}$$

$P_r = HP_t$ is the receive power irradiance (W/m^2) at the receiver location, where H (m^{-2}) is the DC gain of channel impulse response $h(t)$. Multipath effects are minimal given the low LED bandwidth and small room size, but our computational model does account for them. P_n is the optical irradiance (W/m^2) contributing to shot noise and γ is a parameter representing noise contributed by receiver electronics. In high shot noise regimes, the approximation $\gamma = 0$ is good, but in dark environments γ must be accounted for. A_e is the effective receiver area (m^2), which includes lensing gain and direction of light incidence, and r is photodiode responsivity (A/W). R_b is the bit rate, and we can evaluate the bit error rate at that bit rate as $BER = Q(\sqrt{SNR})$. Throughout the paper, we assume a $BER = 1e - 6$. Also, when we cite SNRs the assumed bit rate is $R_b = 20$ Mb/s and appropriate adjustments must be made for other bit rates cited.

To more easily relate to illumination, we use luminous power (lm) and illuminances (lx=lm/m^2) rather than power and irradiance. $L_n \propto P_n$ and $L_r \propto P_r$ denote ambient noise and signal illuminances, respectively. The proportionality constant depends on light spectrum. Note that a typical white illumination LED may get 225 lm/W radiated [2].

A typical white LED is also most often a blue LED with broad spectrum down-converting phosphor. The LED may achieve 20 MHz of bandwidth, but the phosphor glow limits the 3dB bandwidth to ≈ 2 MHz [7]. This is a major limitation for reaching high data rates with these devices.

VLC systems described in recent literature combine several approaches for defeating the bandwidth limitation in the "lights on" mode. The characteristic of that mode is very high transmit power, unlike the off state problem. Regardless, a few of those solution approaches are relevant here. Also, we require that the same devices that work in the "lights on" regime also work in the "lights off" regime.

Blue filtering at the receiver, which isolates the higher bandwidth blue signal at a cost of reduced signal power, is proposed by Grubor [7]. Directionality of light is also considered

Table 1: Measured baseline illumination (lux).

Time/Lights/Shades	Window Desk $(3.2, 1, 0.8)$	Corner Desk $(5.5, 3, 0.8)$	Floor $(0.5, 2, 0)$
DAY/ON/UP	1300	640	542
DAY/OFF/UP	1190	403	368
DAY/ON/DOWN	345	282	235
DAY/OFF/DOWN	114	45	35
NIGHT/ON/DOWN	237	258	204
NIGHT/OFF/DOWN	0.04	0.02	0.01

as a means for providing multiple cells within a room, thus improving data rate densities (Mb/s/m^2) [2]. Optical diversity and MIMO schemes similarly exploit the directionality of light to improve link gains, reject noise sources, and support parallel channels, but require more complex devices, including array transmitters and receivers [8, 9].

In the low transmit power regime one should consider power efficient modulations, such as pulse position modulation (L-PPM). In order to achieve the same R_b and BER performance as OOK, a link using L-PPM requires receive (and transmit) power to be adjusted as follows [10]:

$$P_{PPM} = \frac{1}{\sqrt{0.5L\log_2 L}} P_{OOK} \tag{3}$$

Due to the use of narrow pulses, PPM needs greater bandwidth than OOK by a factor $L/\log 2L$. In the VLC WPAN Standard [11] one choice of modulation that supports dimming is VPPM, which is a pulse-width adjustable version of 2-PPM.

Finally, avalanche photodiodes are desirable for use in very low shot noise environments such as a dark room [6].

3 Defining Emission Constraints

To communicate in the off mode, the lights must emit some light. We define "lights off" as a level that satisfies humans that the lighting is effectively (perceptibly) "off." To our knowledge, this is a somewhat new problem. For example, we are not aware of any existing definition of when lights are "sufficiently" off. To provide guidance we compare to related standards, measurements of a currently installed lighting system, and broadly familiar examples.

We consider two criteria: (1) illumination of surfaces within the room and (2) visibility of the sources under direct viewing. For both criteria, we tie the allowable light transmission to the amount of ambient light in the room. For example, the VLC emitter can contribute more lux in “lights off” mode in bright daylight, when the signal light is less perceptible.

For a sense of the numbers for the illumination criterion, we can look to regulations that specify minimum levels that ensure safety of movement. One example of such a regulation is reference [12] which requires at least 1 lx to be maintained in the aisles of a theatre during a showing. A handy reference for natural illuminations is reference [13]. For example, the full moon on a clear night produces about 3 lx of illumination outside. We also measured the current illumination of an office, Room 421 at Boston University’s Photonics Center (Figure 1). Table 1 shows data from three locations within the room, a working desktop next to a window, a desktop the corner of the room away from the window, and on the floor next to the door. Our modeling of this room has also produced illumination patterns that are in good agreement with the measurements. Figure 2 shows the illumination of the room from the windows during the day, and Figure 3 shows the illumination from the overhead lights during the night.

For the source visibility criterion, we first note that most modern rooms have large numbers of highly visible indicator lights, such as those on smoke detectors. It appears that meeting this criterion is less of a concern. Nonetheless, in Section 4 we give some guidance, which is based on the idea that a source is not visibly glowing if it emits a similar amount of light as the surfaces around it are emitting, by passively reflecting ambient light.

There are also less informative standards for eye safety from optical communications. These are not very applicable to our case, as the lights will emit less in the off mode than the fully on mode, but we list them as a reference. For example, 1 mW is specified for Class 2 lasers (visible wavelength) to ensure eye safety [14]. This figure is much higher than corresponding limits for UV and IR sources because long exposure by intense visible light is prevented when humans see it and turn away. To arrive at an equivalent figure for non-collimated light from a white LED, we assume a pupil of size 1 cm^2. This gives an illuminance of 225 lx. Interestingly, much higher illuminances are proscribed for overhead lighting [15] in offices.

4 VLC with Lights Off

We start with a simple calculation which gives us a sense of a wide range of indoor scenarios, from very dim to very bright ambient illuminations. Throughout this paper we target a low bit error rate of $BER = 10^{-6}$, which corresponds to $SNR = 13.54$ dB. From (2), the required receive power to achieve this for a given noise P_n is:

$$P_r = \sqrt{\frac{qP_n(1+\gamma)R_bSNR}{rA_e}} \tag{4}$$

This is the basis for Figure 4, which shows the minimum illumination the transmitter

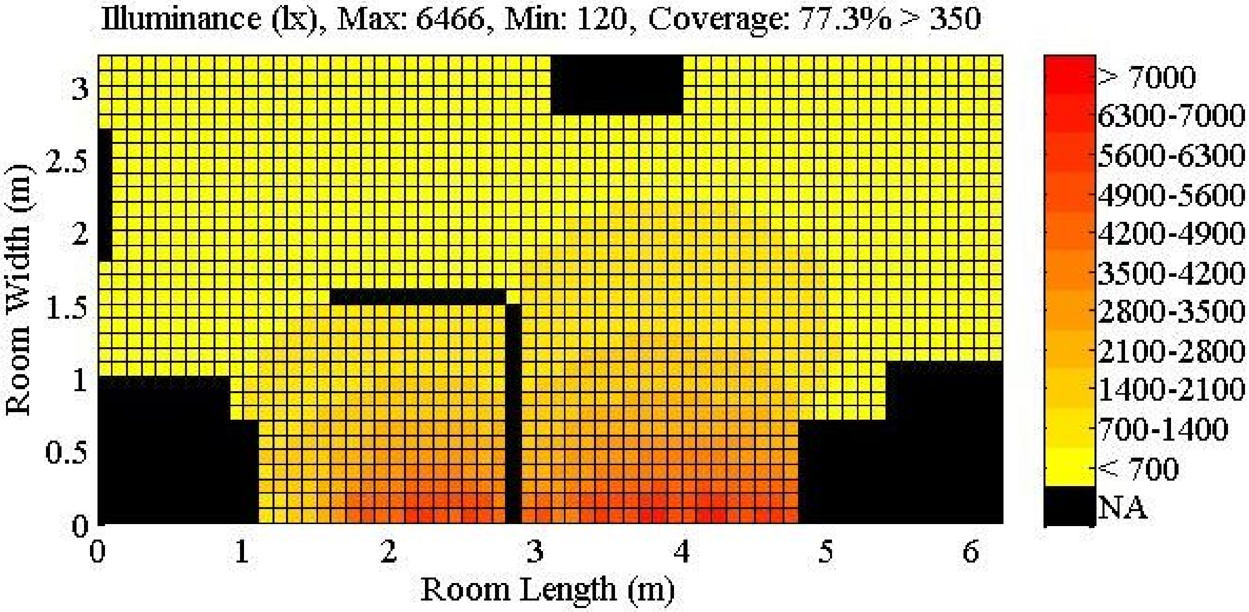

Figure 2: View from above of Room 421 illumination pattern during daytime with lights off at desktop height (h=0.8 m). Note high ambient light near windows (w=0 m).

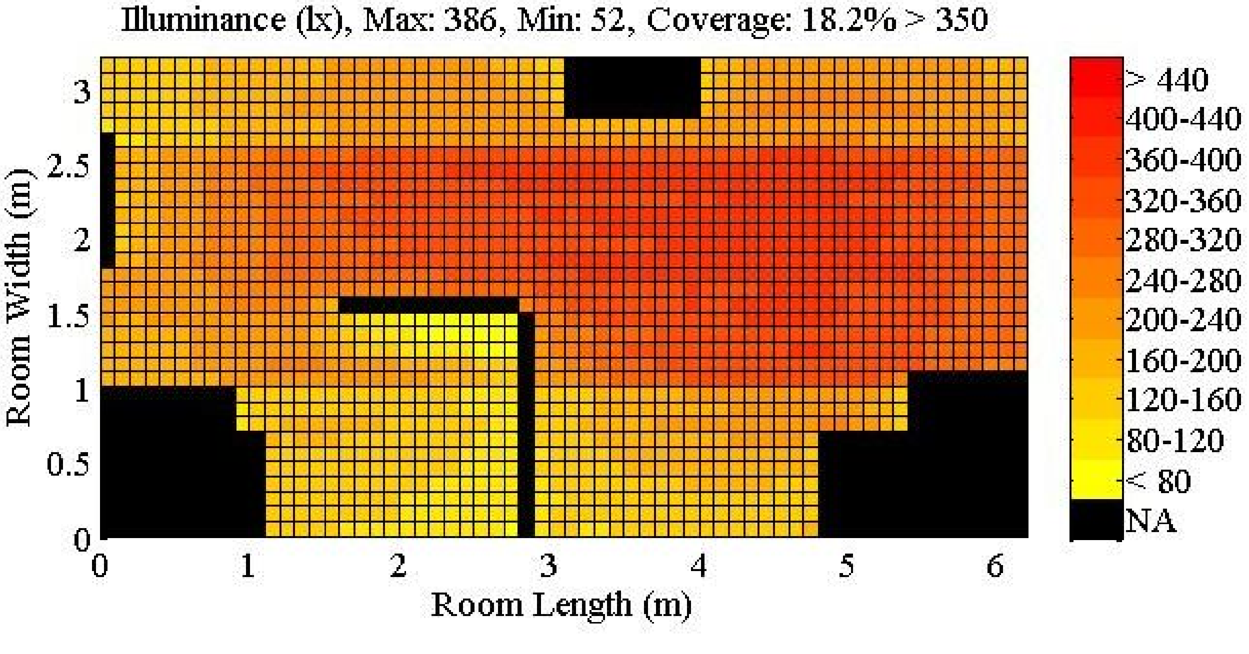

Figure 3: Room 421 desk-level illumination during the night time with lights lights fully on. Note lower illuminations (yellow) due to shadowing of LOS by cubicle wall at (l,w)=$\approx$ $(2.5, 1.5)$ m, and in other areas of the room due to other objects as well as the lamp enclosure.

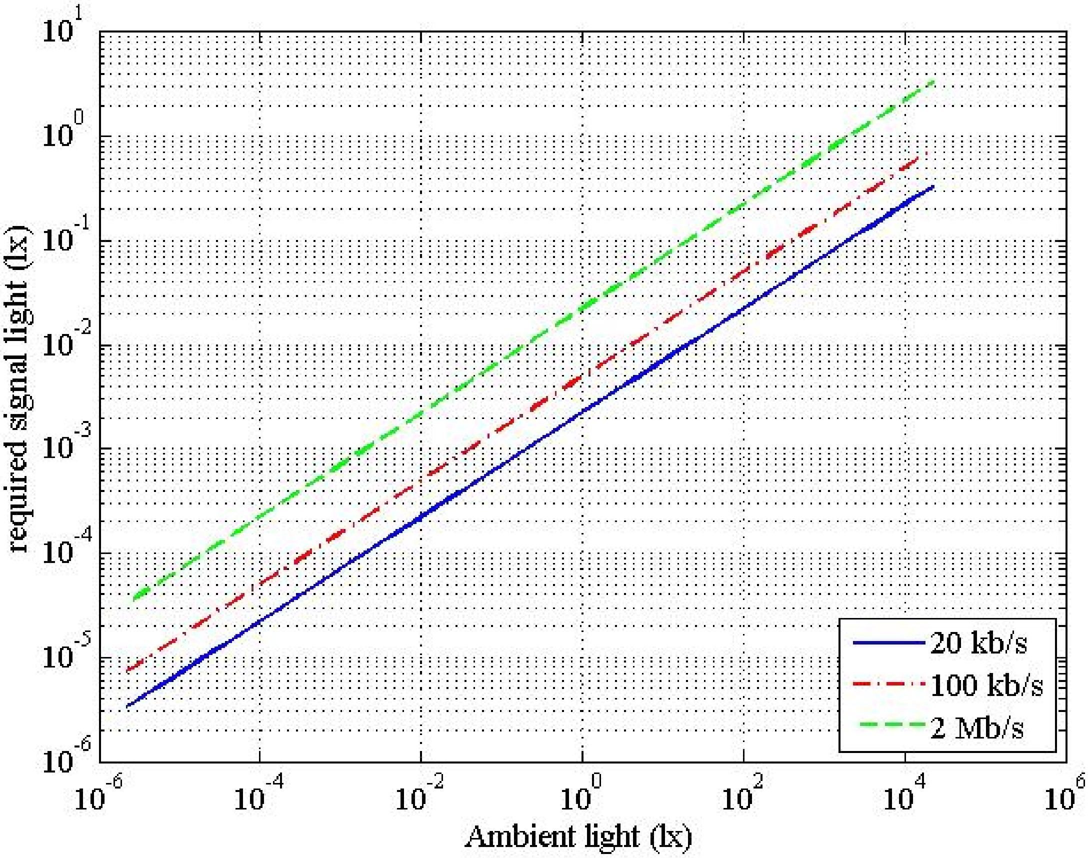

Figure 4: Off state light signal required in order to satisfy given data rates, for a wide range of ambient illuminations.

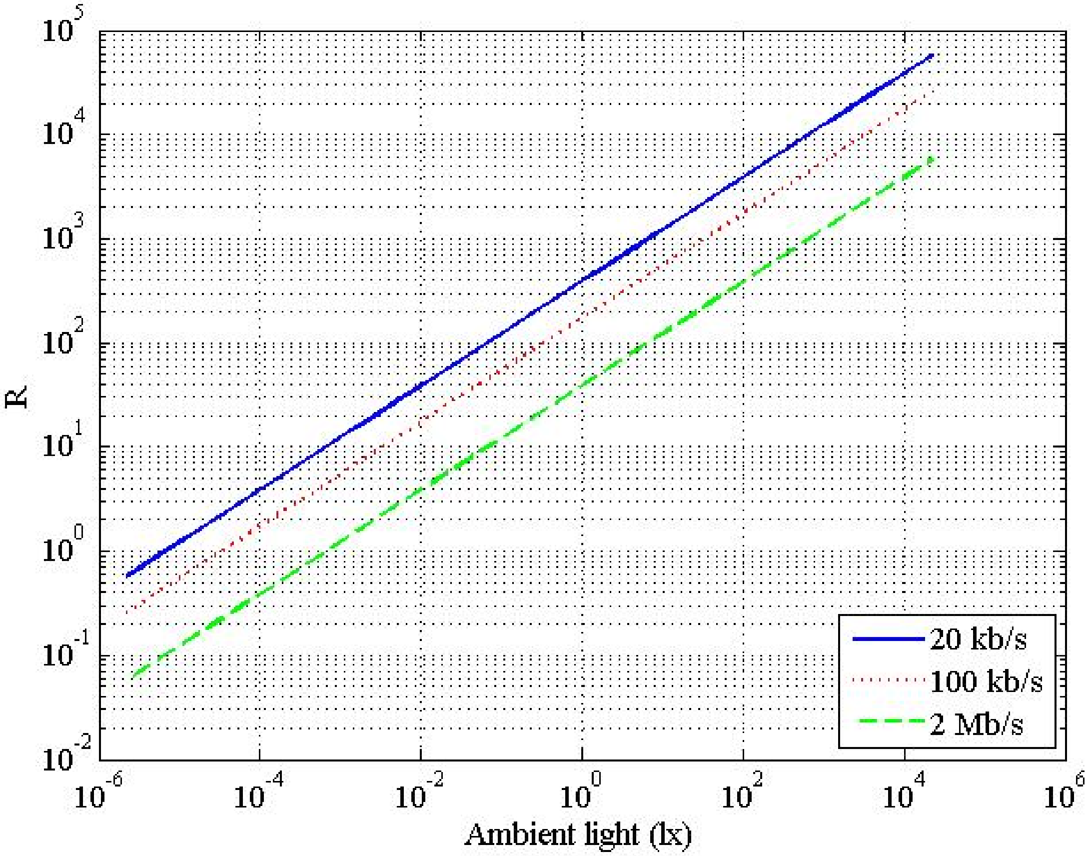

Figure 5: Ratio of data coverage area at 1 Mb/s to emitter area for which emission is not greater than ambient light reflected from a white ceiling.

must provide for a large range of background light levels to achieve bit rates $R_b = 20$ kb/s, 100 kb/s and 2 Mb/s, with parameters: $A_e = 1$ cm^2, $\gamma = 5$, $r = 0.2$ A/W. In the entire range, the signal does not add significant illumination. For example, when the natural room illumination is 10^{-4} lx, an extremely low number, one has to add 2×10^{-4} lx more in the form of signal to get 2 Mb/s. It triples the total light, but it is comparable to having three stars instead of one as the only objects in the night sky. At the other extreme, $10,000$ lx, the signal adds 2 lx. That is about what the moon might contribute during full daylight.

Ensuring no visibility of emitters is more challenging due to the high sensitivity of the human eye. We may satisfy it by using emitters with larger areas. To see this, suppose that all parts of the room are naturally illuminated at $L_n = 1$ lx. From Figure 4, to achieve 2 Mb/s with OOK, one needs about $L_p = 0.02$ lx of signal illumination on the receiver. If ceiling reflectivity is $\rho = 0.85$ it will emit $\rho L_n = 0.85$ lm/m^2. If we replace 0.25 m^2 of the ceiling by emitters, we can transmit at .85 lx, without appearing to glow. This produces 0.21 lm of signal, enough for 10.5 m^2 of coverage at 2 Mb/s.

More generally, given an ambient illuminance L_n and resulting required signal illuminance

Table 2: Model Parameters

Transmitters		**Receivers**	
Number	52	PD area	0.81 mm^2
P_t fully on	0.87 W each	FOV	90°
L_t fully on	200 lm each	conc. gain	2.25
BW in blue	20 MHz	A_e	1.8 mm^2
		Optical filt.	450 ± 20 nm
Windows		γ (Day)	0
Daylight	2.88e3 lm	γ (Night)	10
Night light	1.28 lm	r at 450 nm	0.2 A/W

L_r, we have:

$$R = \frac{A_c}{A_m} = \frac{L_r}{\rho L_n}. \tag{5}$$

Figure 5 shows this relationship for our hypothetical VLC system. At very low illumination, we reach $R = 1$ beyond which point to generate enough light the emitters have to glow brighter and be more visible than the white painted ceiling. For 2Mb/s this occurs at about $L_n = 0.001$ lx, a very low level. At high L_n, e.g. during daytime, R is large, and even small sources provide sufficient signal without visibly glowing.

The remainder of this section providess results of simulations of a more realistic VLC system operating in a detailed model of room 421, for a high ambient (daytime) and low ambient (night time) condition. For this we used a simulation model of VLC named CandLES [16]. Some of the model parameters are in Table 2. Figures 2 and 3 show the simulated illumination patterns at desktop level, which are in good agreement with our measured values in Table 1.

Table 3 captures the results for the off state communications for four conditions. Scenarios I and II correspond to daytime with lights on at 5% and 1% of their full on state, respectively. Scenarios III and IV are at night, with the lights turned down to 0.01 % and 0.001 %. In the nighttime scenarios the blinds are drawn, so the light from the outside that does penetrate into the room is very dim.

We first explain Scenario I. Figure 6 shows the shot noise SNR in the entire room. On average, the room is illuminated at 400 lx by daylight. Note that the windows are along the bottom edge and represent a very intense source of shot noise. There, sunlight illumination is over 6,000 lx. In contrast, the overhead lights are turned on at 5% of full power. At that level, they are responsible for only 2% of light in the room. Yet, the lowest SNR in the room is sufficient to achieve 1.3 Mb/s with OOK. Since at that rate we have excess bandwidth, we use L-PPM to boost that lowest datarate up to 2.7 Mb/s.

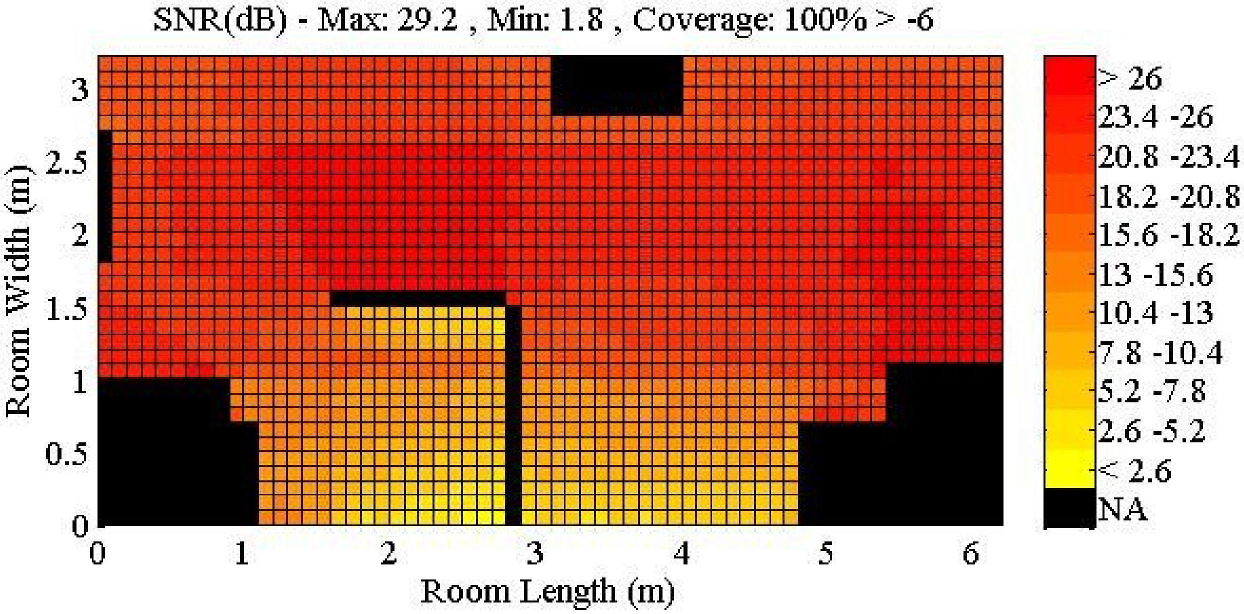

Figure 6: Off state optical SNR during the day, corresponding to Scenario I in Table 3.

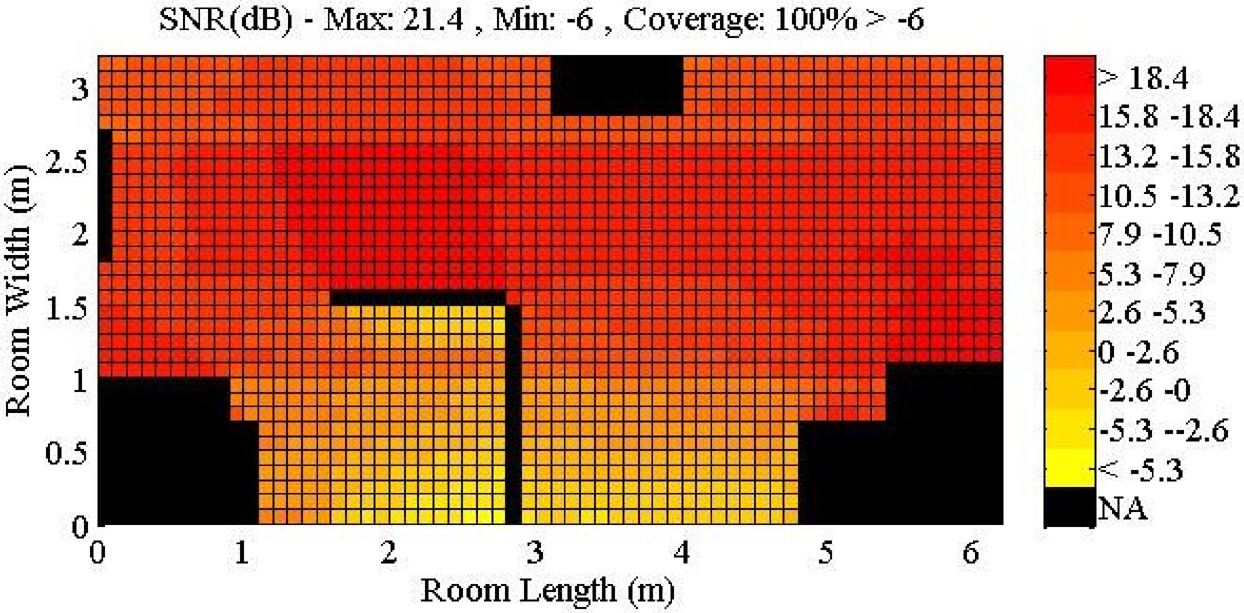

Figure 7: Off state optical SNR at night, corresponding to Table 3 Scenario IV.

Table 3: Off-state results

	Day		**Night**	
Avg. L_n (lx)	400		.02	
Scenario	I	II	III	IV
% of "ON" level	5	1	0.01	0.001
% of light in room	2	0.36	45	7.5
avg. L_r (lx)	10	2	0.02	0.002
E_s (lx)	665	133	1.33	0.13
Min SNR_{shot} (dB)	1.8	-12.2	14.0	-6.0
Max SNR_{shot} (dB)	29.2	15.2	41.4	21.4
γ	0	0	10	10
Min OOK (b/s)	1.3 M	53 k	1.8 M	20 k
Max OOK (b/s)	20 M	20 M	20 M	1.8 M
Coverage (%)	100	93	100	100
L-PPM st min SNR (b/s)	2.7 M	625 k	1.8 M	320 k

The lights installed in Room 421 are a set of fluorescent tubes. If we were to package our LEDs into the same format with the same surface area, the emittance at the 5% level would be 665 lx. That is brighter than the ≈ 340 lx level at which the walls are glowing by reflecting the light in the room. We conclude that the lights are visibly glowing when observed directly. We further lower them for Scenario II. Now the emitters are glowing at 133 lx and therefore do not appear to be glowing. Scenario II achieves poorer data rate performance but is still sufficient to provide connectivity and coverage for devices in the room. For Scenarios I and II we used $\gamma = 0$, which is a good approximation as the shot noise is very high.

The low ambient illumination scenarios are more difficult. Even though we are able to dim the lights further, the signal yields a greater percentage of the light in the room. Figure 7 is the SNR plot for Scenario IV. Here, the room is illuminated at 0.02 lx naturally. The overhead lights account for 7.5% of the light in the room. Even so, OOK produces 100% connectivity for devices at 20kb/s. There is opportunity to improve the lowest rate to 320 kb/s, by switching to L-PPM. The sources have an emittance of 0.133 lx which is much higher than the 0.04 total illumination of surfaces, so we conclude that the lights are visibly glowing. Note we have assumed $\gamma = 10$ which is appropriate for low light regimes, so the actual SNR is lower than the shot SNR given.

In the preceeding analysis, we considered shot noise from natural light but not interference from modulated sources. The assumption is that in the off state any other artificial modulated light sources in the room, such as fluorescent lamps, will be turned off first. Note also that the receiver has a very small area, which is consistent with the need for low cost and complexity required for smart room applications. Nonetheless, Scenarios I and III were able to guarantee data rates of more than 1 Mb/s, and reached 20 Mb/s in some locations.

Finally, to further improve the data rates of all of the four scenarios, receivers with larger A_e can be used as indicated by the relationship of equation 2. This is appropriate for devices that consume data rich multimedia content.

5 Conclusion

We consider a key problem related to the implementation of VLC through lighting: how to communicate with the lights off. We define this problem in terms of power constraints due to requirements on light emission in indoor spaces occupied by humans. For both daytime and night time scenarios, we show that maintaining data coverage in the lights-off mode is feasible with devices of low complexity. Furthermore, we show that very low light emission is sufficient to maintain data rates of several Mb/s. This bodes well for the future of VLC as a vehicle for implementing smart lighting systems.

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