Wireless Optical Model for Visible Light Communication

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Abstract: **In this study, we examine the performance of fixed gain amplify and forward repeaters for visible light communication (VLC) systems. We present the wireless optical channel model for VLC with the repeater and we evaluate the bit-error-rate performance for Pulse-Position Modulation (PPM) over the multipath channel with additive white Gaussian noise. The results reveal that when a repeater is placed, both the BER (bit-error-rate) and the illuminance performance can be improved at any location in a typical office space. The benefit of VLC repeaters is also discussed when the channel from the source to the destination is shadowed. It is found that when the channel is shadowed, the impact of repeaters on the communication reliability is more distinct.**

Key Words: Visible Light communications, Pulse Position Modulation, Repeater, shadowing

1. INTRODUCTION

In recent years, Visible Light Communication (VLC) has emerged as a new wireless communication technology and it is expected to find places in many wireless communication applications such as inter/intra-vehicle communication, hospitals and health care services, hazardous environments, defence and security services, aviation and underwater communications [1][2][3]. The VLC technology relies on the intensity modulation and direct detection for data transmission (IM/DD). The majority of the existing works are on utilizing LEDs at the transmitter to emit the intensity and a photo-diode (PD) at the receiver to detect the received intensity.

There are a number constraints on designing a VLC system. First of all, the main role of such systems is to illuminate the place they have been installed. Any flickering or color shift in the light is not acceptable, which can occur depending on the modulation scheme [4]. There are other constraints for designers such as full-brightness of the source, protection of the human eye and dimming-control ability. On-Off Keying (OOK) modulation scheme is commonly used in the literature for the VLC [5]. In OOK, it is possible to achieve full brightness and dimming control however color shift and flickering can appear without coding [6]. Pulse-Position Modulation (PPM) is another commonly used modulation scheme in which the same power is consumed to transmit the different symbols that provides flicker free emission. It is also possible to achieve full brightness with PPM. However, it is difficult to control the brightness of LED lighting as OOK.

In addition to its illumination role, a VLC system should convey information from source to the destination. In a typical VLC communication link, there is a number of source terminals each consisting of LED chips and there is no intermediate terminal between the source and the destination. In this work, we consider a single intermediate station in an indoor VLC channel as a repeater in order to improve the reliability and the illuminance performance of the system. There are some works in the literature that consider intermediate stations for wireless optical communication: In [7][8][9], intermediate stations are placed as relays to provide multi hop diversity to the destination for free space optical (FSO) communication. FSO links experience multipath and fading effects in long distances. Since the indoor VLC channels are not expected to fade and they are usually modeled as AWGN channels, the diversity techniques are not the subject for such channels [10]. There are also some hybrid models proposed in the literature considering intermediate terminals. In [11], a desktop lamp is demonstrated as an intermediate terminal which receives radio signal and repeats it to the desk over the visible light channel. Similarly in [12], an intermediate terminal receives information from a power-line communication (PLC) channel and then retransmits it through a visible light channel.

In radio communication, repeaters are commonly used in order to extend the coverage performance of the network. Repeater-assisted networks are different from the relay-assisted networks. In relay-assisted networks, intermediate stations relay the information to the destination in order to provide different replicas of the same information which are then combined using a combining circuit [13]. The main difference between repeating and relaying is that the relay stations do not listen and transmit at the same time but use additional scheduling

algorithms such as TDMA, FDMA and CDMA etc. On the other hand, repeaters do not need any additional scheduling algorithm and can be employed in any existing network without any prior work. One of the disadvantages of the repeaters that they introduce interference to the network caused by the delay added to the signal at the repeater circuit.

The VLC links can also be shadowed or blocked by moving objects in the environment. In [14], the chance of shadowing for VLC channels is driven according to the room geometry and human obstruction probability. Although, it is not easy to draw a general model and accurately calculate the probability of shadowing, such chance is given less than 2% in a typical office with 3m ceiling height. In [15], the effect of shadowing is investigated according to the obstacles' traffic density in the channel and installing spatially distributed multiple sources is proposed to combat shadowing. One of the main drawbacks of using multiple sources is that driving all the LED chips synchronously is a difficult task and needs a careful design of the cable lengths and the spacing between LED chips [16].

In this work, we consider a single intermediate station mounted on the desk in an indoor VLC channel as a repeater in order to improve the reliability and the illuminance performance of the system. In the considered system, all the transmission between the terminals occur in visible light medium at the same frequency band. We consider binary-PPM which is a standard modulation scheme for wireless optical Communications. Inter symbol interference (ISI) due to the propagation delay and the delay added by the repeater is also discussed as a data rate limiting factor. In this work, we limit our study to the case when there is no ISI present in the channel.

The remainder of the paper is as follows: Section 2 presents the wireless optical channel model. Section 3 discusses the transmission scheme and the receiver structure. Section 4 gives the numerical results including the optimum repeater height, BER and illuminance performance improvement with the repeater. The impact of repeaters in a shadowed communication channel is also discussed in this section. Section 5 concludes the paper with discussions.

II. WIRELESS OPTICAL CHANNEL MODEL

In order to emphasize the practical usage of repeaters for VLC, we have considered an empty room model as the physical environment. The room is 5×5×3 m, and the optical source is installed at the center of the ceiling. The main purpose of the optical source is to illuminate a desk surface. In our model, the performance of

the system is evaluated at the desktop height of 0.85 m. throughout the paper; the model without any intermediate terminal is taken as the reference model which is to be compared with the repeater-assisted model. Figure 1 illustrates the reference channel and the repeater-assisted channel models.

A. Reference Channel Model

In a typical short range VLC link, the electro-optical conversion is performed by an LED at the transmitter and a silicon photo-diode performs direct-detection of the incident optical intensity at the receiver. The received photo-current y (t) is given by [17]

$$y(t) = rI(t) * h(t) + n(t) \qquad (1)$$

Where r is the responsivity (A/W), I (t) is the transmitted intensity, n (t) is the noise, h (t) is the channel response and * denotes the convolution operation. The electro-optical conversion can be considered as linear so that I (t) = gx (t) where g is the gain of the device in unit of W/A and x (t) is the electrical current signal which is the information source. Hence, Eq. (1) can be rewritten as

$$y(t) = rgx(t) * h(t) + n(t) \qquad (2)$$

Note that, x (t) must be non-negative and the average intensity of all emissions $\lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} gx(t)dt$ are also limited due to the eye safety regulations.

The noise at the receiver consists of the ambient shot noise in the photo-diode and the thermal noise. The shot noise in the photo-diode can accurately be modeled as white Gaussian and independent of x (t). The thermal noise at the receiver is also Gaussian. Therefore, the VLC channel noise n (t) is assumed to be and additive white Gaussian (AWGN) noise [18].

VLC channel h(t) , as for other wireless optical channels, consists of a line-of-sight (LOS) and a diffuse or non-line-of-sight (NLOS) components,

$$h(t) = h_{LOS}(t) + h_{diff}(t) \qquad (3)$$

The LOS part of the channel can be modeled by delayed Dirac pulses as

$$h_{LOS}(t) = g_{LOS}\delta(t - \Delta t_{LOS}) \qquad (4)$$

Where g_{LOS} and Δt_{LOS} are the gain and the delay of the LOS components. When all the LED chips are perfectly synchronized at the source terminal, Δt_{LOS} becomes ideally zero. In [16], with the detailed cabling design, all the LOS components from each LED chip arrive receiver within

Δt_{LOS} = 5 nsec. The diffuse portion comes from the reflections of the room objects and walls. Experimental measurements [19] and ray-tracing simulations [20] have been used to estimate the diffused channel. In [21] the diffused channel is analytically modeled (integrating-sphere model) as

$$H_{diff}(f) = g_{diff} \frac{exp⁡(-j2\pi f \Delta t_{diff})}{1+jf/f_0} \quad (5)$$

Where g_{diff} and Δt_{diff} are the gain and the delay of the diffuse component and f_0 is the 3-dB cut-off frequency of a diffuse channel.

The channel response including LOS and NLOS components becomes

$$H(f) = g_{LOS} exp(-j2\pi f \Delta t_{LOS})$$
$$+ g_{diff} \frac{ex\,p(-j2\pi f \Delta t_{diff})}{1 + jf/f_0} \quad (6)$$

The VLC channel DC gain H(0) then becomes $g_{LOS} + g_{diff}$. The channel gains are given in [16] as

$$g_{LOS} = A_R(m_L + 1) \frac{cos^{mL}(\theta)cos⁡(\psi)}{2\pi d^2} \quad (7)$$

$$g_{diff} = \frac{A_R sin^2(FOV)\rho}{A_{room}(1-\rho)} \quad (8)$$

where m_L is the order of Lambertian emission, A_R is the physical area of the receiver, A_{room} is the room area, FOV is the field of view of the detector, ρ is the average reflectivity from the walls, θ and ψ are the angles of irradiance and incidence and d is the distance between the transmitter and the receiver as shown in Figure 1(a). According to the used model in Eq. (8), the gain of the diffuse portion g_{diff} is the same at every location in the room [16]. The order of Lambertian emission m_L is given in [18] as

$$m_L = -\frac{ln2}{ln(cos\phi_{1/2})} \quad (9)$$

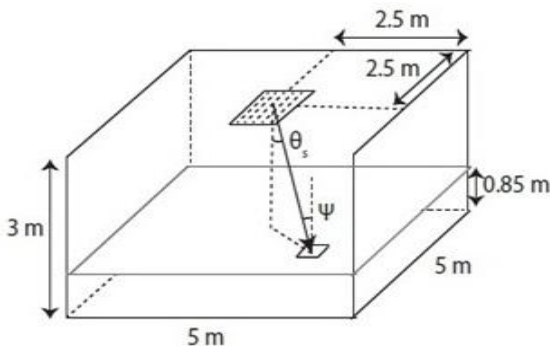Where $\phi_{1/2}$ is the LED semi-angle at half power.

Figure 1(a). Reference channel model

The average received optical power Pr is the product of the transmission power and channel DC gain [22],

$$P_r = H(0)P_t \quad (10)$$

H (0) can be increased by narrowing $\phi_{1/2}$. The LOS component considerably dominates the channel response in most cases. In [23], the multipath channel profiles for the VLC and infrared (IR) channels have been compared. It is reported that the magnitude of the reflected path for VLC channel is smaller than that for the IR channel.

Signal-to-noise ratio (SNR) is defined as the ratio of total electrical power generated by the photodiode to the noise power,

$$SNR = 2r^2 P_r^2 / N_0 B \quad (11)$$

Where N_0 is the double-sided power spectral density of the noise, Pr is the received optical power as calculated in Eq. (10) and r is the responsivity. If the data rate for 2 PPM is R_b, then the equivalent noise bandwidth B is $2R_b$. The noise term includes the shot noise and the thermal noise,

$$N_0 = N_{shot} + N_{thernal} \quad (12)$$

The thermal noise is usually constant and depends on the temperature, but shot noise is related to the amount of light incident on the photo detector. The mean-squared noise current from the photo detector is qI_{bg}. Then, the shot noise density is given in [16] as

$$N_{shot} = qI_{bg} A^2 / Hz \quad (13)$$

Where q is electron charge (1.6×10^{-19} coulomb), I_{bg} is the background light induced current. For example, the I_{bg} of 5.1 mA [24] will generate a shot noise power of 8.1×10^{-16} mW/Hz (-150.9 dBm/Hz). For many applications, thermal noise is smaller than the ambient light noise and can be neglected, $N_0 \sim N_{shot}$ [16].

Wireless optical channel can be seen as a low pass electrical channel. A white-light LED can usually provide 2 MHz modulation bandwidth [17] and the 3-dB cut-off frequency of the channel is described as H (f_{3db}) = 0.707H (0).

Using Eq. (6), with average $\Delta t_{LOS} = 2\,nsec$ and considering the channel bandwidth is dominated by the LOS component, the approximate channel bandwidth f_{3db} becomes 90 MHz In this case, the transmission bandwidth B becomes limited by 2 MHz which is the modulation bandwidth of the white light LED. When binary-PPM is

considered, the bandwidth efficiency is 1/2 and the achievable data rate R_b becomes 1 Mbps. The transmission at 1Mbps is ISI free transmission since the time dispersion in the channel is in the order of nanoseconds.

Finally, the illuminance is defined as the total luminous flux incident on an illuminated surface. The illuminance E at a point on the surface is given by [24]

$$E = \frac{I_v(0)cos^m(\theta)}{d^2}\cos(\psi) \qquad (14)$$

Where $I_v(0)$ is the center luminous intensity.

B. Repeater-Assisted Channel Model

In our repeater-assisted channel model, we place a repeater (or use an existing desk LED lamp) on the desk at the height of dr and tilt it down to the desk surface as in Figure 1(b). A possible blocking body is also indicated in the Figure 1(b).
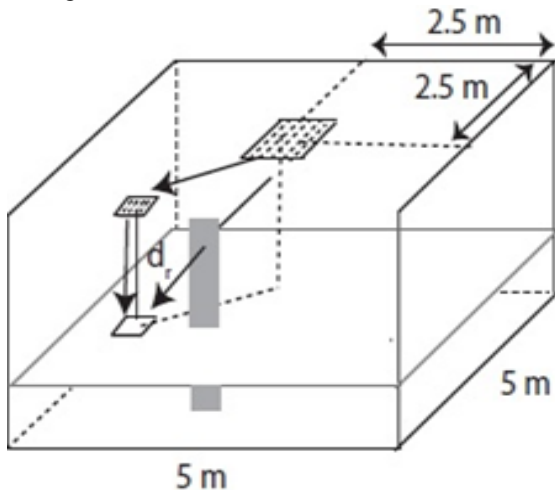

Figure 1(b). Repeater-assisted channel model with possible shadowing

The total number of LED chips used in the repeater-assisted model is kept the same as in the reference channel model. The source emits the information with no awareness of intermediate repeater in the environment. The repeater receives the emitted signal by its PD, converts it to an electrical signal, amplifies and emits the information by its LEDs.

If the optical power of the source terminal is P_s, then received photo-current $y_r(t)$ by the repeater becomes

$$y_r(t) = rP_sI(t) * h_{sr}(t) + n_r(t) \qquad (15)$$

Where $h_{sr}(t)$ the channel response between the source and the repeater is, $n_r(t)$ is the additive noise term at the repeater. The repeater amplifies the noisy signal and emits it back to the destination. The choice of the amplification

gain G in terms of the ratio of the output electrical power to the input electrical power, assuming rg = 1 for the repeater terminal, is [25]

$$G = \frac{P_r^2}{(P_sH_{sr}(0))^2 + N_0/2} \qquad (16)$$

Where P_r is the optical power of the repeater. The gain in Eq. (16) does not depend on the instantaneous channel state information (CSI) and hence it is fixed. Then, the received photo-current $y_d(t)$ by the destination becomes

$$y_d(t) = r[\sqrt{G}(P_srI(t) * h_{sr}(t) + n_r(t)) * h_{rd}(t) + P_sI(t) * h_{sd}(t)] + n_d(t) \qquad (17)$$

Where $h_{sr}(t)$ and $h_{rd}(t)$ are the channel responses for the links of the source-repeater and the repeater-source respectively, $n_d(t)$ is the noise added at the destination.

III. TRANSMISSION MODEL

We consider pulse position modulation (PPM) for the transmission which is a standard modulation technique used in optical communications. Figure 2 displays the block diagram of the M-PPM (M is the modulation order) transmission through a repeater. In M-PPM, an optical pulse is transmitted in one out of non overlapping M time-slots per symbol. The structure of the source terminal is given in Figure 2(a).
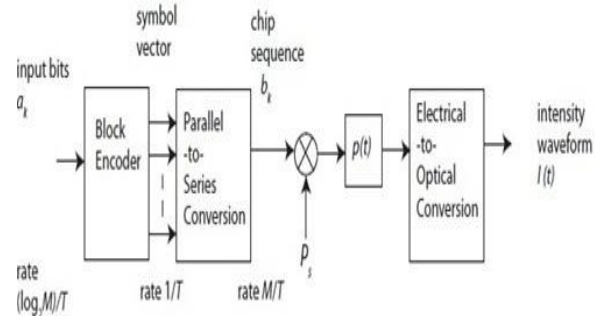

Figure 2(a). The source terminal

The bit sequence a_k at a rate of $\log_2 M/T$ is fed into the block encoder where T is the duration of PPM symbol. Block coder produces a symbol vector of length M in which one chip has $\log_2 M$ bits of information and M − 1 chip carries zero chip values. Parallel-to-series conversion then converts the vector into a chip sequence a_k at a rate of M/T. The chip sequence is scaled to the optical power P_s which is followed by the transmitter pulse shape p (t). Transmitter pulse is of a rectangle shape with unit magnitude and duration of T/M. A basis set for M-PPM, $\phi_m(t)$ for m ∈ {1,2, . . . ,M }, is

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$$\phi_m(t) = p(t - \frac{T}{M}(m-1)) \quad (18)$$

A time domain representation of the intensity waveform as sent from the source terminal is

$$I(t) = \sum_{k=-\infty}^{\infty} \phi b_k(t - kT)g \quad (19)$$

The signal reaches the repeater over the multipath channel. The noisy signal is amplified at the repeater by G to the optical power level of P_r and then emitted by its LEDs as shown in Figure 2(b).
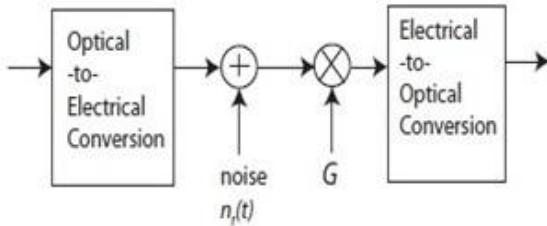

Figure 2(b). The repeater terminal

The photo-detector at the receiver, receives signals from both the source and the repeater. A matched filter

$g(t) = \sqrt{\frac{M}{T}} \, p(T-t)$ is employed at the receiver with unit energy. The sampler performs at the chip rate of T/M. The receiver makes its decision based on the largest element of the received vector u = [u1u2 . . . uM] . The decision variables to be fed into the detector at the output of the matched filter, assuming the kth chip conveys the information, are

$$u_k = rP_s[H_{sd}(0) + \sqrt{G}H_{rd}(0)H_{sr}(0)] + [\sqrt{G}H_{rd}(0)n_r + n_d] \quad (20)$$

$$u_l = \sqrt{G}H_{rd}(0)n_r + n_d \quad (21)$$

Where ℓ, k $\in$ {1,2, . . . ,M } and $\ell \neq$ k , Ps is the optical power for each symbol emitted by the source under full brightness, $H_{sd}(0)$ and $H_{rd}(0)$ are the channel DC gains for the source-repeater and repeater-destination links, n_r and n_d are the additive noises at the repeater and the destination nodes that are independent of each other with variances $N_0/2$. Then, the bit-error-rate for 2-PPM transmission with the repeater becomes [10]

$$P_e = Q\left(\frac{rP_s(H_{sd}(0) + \sqrt{G}H_{rd}(0)H_{sr}(0))}{\sqrt{N_0/2(GH_{rd}(0)^2 + 1)}}\right) \quad (22)$$

Indoor wireless optical links can be a subject of shadowing generally caused by standing people in the environment. When the source-destination link is shadowed, the communication will continue over the diffused path of that link. If the probability of blocking the LOS path of the source-destination link is P_{block}, Eq.(22) can be modified as

$$P_e = q\left(\frac{rP_s(H_{sd}(0) + \sqrt{G}H_{rd}(0)H_{sr}(0))}{\sqrt{\frac{N_0}{2(GH_{rd}(0)^2 + 1)}}}\right)(1 - P_{block})$$
$$+ Q\left(\frac{rP_s(g_{diff} + \sqrt{G}H_{rd}(0)H_{sr}(0))}{\sqrt{\frac{N_0}{2(GH_{rd}(0)^2 + 1)}}}\right)(P_{block}) \quad (23)$$

The receiver structure in Figure 2(c) is designed to perform in the absence of inter symbol interference. The received optical signal experiences time dispersion due to the reflections from walls and other surrounding materials. The measurements for VLC in [23] states that all the rays from LOS and NLOS paths arrive destination in less than 20 nsec in an indoor environment and it heavily depends on the room geometry and the wall materials. The repeater circuit also inserts a delay which causes wider time dispersion in the channel than the reference channel model. The time dispersion in the channel due to the diffused and repeated paths gives rise to inter symbol interference (ISI) which reduces either reliability or rate of the transmission. In the literature, a number of techniques have been proposed to combat the ISI for indoor wireless optical channels. In [26], a guard interval is inserted in each symbol frame with a cost of throughput. In [27], spread spectrum techniques have been considered however it decreases the bandwidth efficiency. In [28] angle diversity scheme with multi beam narrow FOV transceiver is proposed which spatially exploits the time dispersed channel components. In [29] an adaptive equalizer is employed to mitigate the effects of ISI.
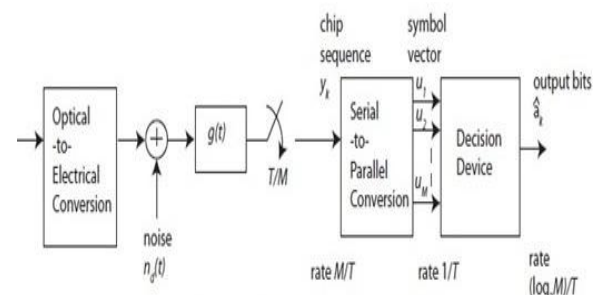

Figure 2(c). The receiver terminal

In M-PPM transmission, ISI occurs when all the paths from the source and the repeater arrive destination within a duration of longer than T/M sec. The latest path

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propagates through the diffused path of the source-repeater link then is amplified and reaches the destination through the diffused path of the repeater-destination link which makes the total propagation time of $2\tau_p + \tau_r$ sec where τ_p and τ_r are the propagation delay and the delay added by the repeater, respectively. Therefore, the maximum achievable ISI-free data rate with the repeater channel becomes $1/M$ $(2\tau p + \tau r)$ sym/sec.

In [30], a simple fast photodiode amplifier circuit is given. The propagation delay τ_r for the circuitry is given as 45 nsec which causes wider time dispersion in the channel as compared to the reference channel. In this case, the channel bandwidth depends on the power allocation between the source and repeater terminals and also their distances to the destination terminal. With the described configuration in Table 1 and d_r = 0.7 m, the 3-dB channel bandwidth distribution in the room area is given in Figure 3. Only the upper right corner of the room area is presented due to the symmetry. The minimum 3-dB channel bandwidth of the channel with the repeater is 3.42 MHz Therefore, for the repeater assisted channel, the transmission bandwidth is again limited to the modulation bandwidth of the LED chips which is 2 MHz The maximum achievable data rate for 2-PPM becomes 1 Mbps. The transmission at this rate will not experience ISI since the half of the symbol duration 0.5 usec is much larger than $2(2\tau_p + \tau r)$ which is in the order of nanoseconds.

IV. RESULTS AND DISCUSSIONS

The performance improvement with the repeater has been evaluated through analytical calculations and computer simulation. The transmission rate R_b is taken as 1 Mbps for both reference and the repeater assisted channel models. Table 1 gives the parameters considered in the evaluations. The total number of LEDs was kept the same in both reference channel and channel with the repeater for a fair comparison. The number of LED chips and the total luminous intensity for a desk lamp is consistent with the previous research in the literature. In [12], a table lamp is used as a source of VLC communication with 120 LED chips, each having luminous intensity of 1.56 cd.

Table 1. System component parameters

Semi-angle half power ($\Phi_{1/2}$)	120°
Center luminous intensity of an LED chip ($I_v(0)$)	1.56 cd
Number of LEDs in the reference model	1200
Number of LEDs in the repeater model	120/1080
FOV at a receiver (FOV)	60°
Detector physical area (A_r)	1cm²
Detector responsivity (r)	0.53 A/W
Data rate (R_b)	1 Mbps
LED chip optical power	4 mW
Signal bandwidth (B)	2 MHz
Noise density (N_0)	-150.9 dBm/Hz
Average reflectivity (ρ)	0.2

A. Effect of the Repeater Height

Figure 4 gives the relationship with the SNR improvement and the illuminance for different repeater heights d_r. The computer simulation was run for every 0.01 m² in a 5×5 m² room at the desk height of 0.85m. We define the SNR improvement in terms of SNR gain achieved by the repeater with respect to the reference channel when BER = 10^{-3} for both cases.
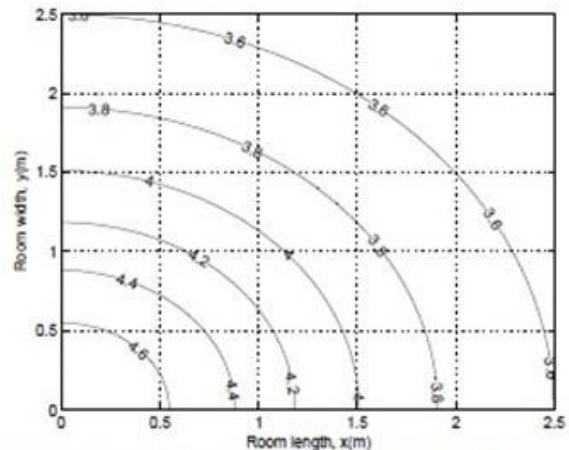

Figure 3. 3-dB channel bandwidth(MHz) distribution for the repeater assisted channel.
min=3.42MHz, mean=3.86MHz, max=4.75MHz

The channel gain $H_{sd}(0)$ is set to unity. For each location of the receiver, the DC gains of the channels $H_{sr}(0)$ and $H_{rd}(0)$ with their LOS and NLOS components are then normalized to the channel gain between the source and the destination $H_{sd}(0)$. The SNR improvement values are averaged over each repeater location.
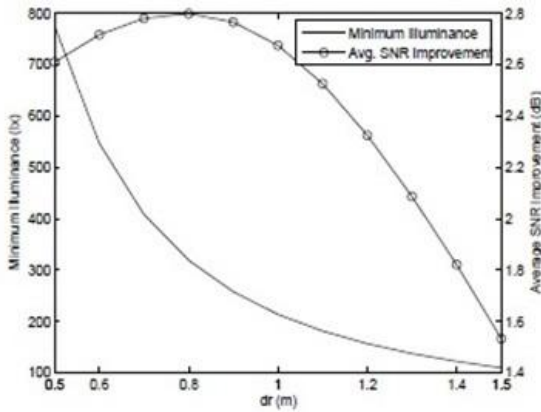
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Figure 4. SNR improvement and illuminance for different dr.

The illuminance is calculated by Eq. (14) for every 0.01 m^2 in the room and the minimum level is considered in order to achieve adequate brightness. In EN 12464-1, 400 lx is given as the minimum brightness Required for a work place. When dr is less than 70cm, the required brightness is achieved at every location in the room. When d_r is 70 cm, the average SNR improvement is 2.78 dB and the minimum illuminance at the desk surface is 408 lx. In the rest of the analysis, the repeater is placed at 70 cm height from the desk surface.
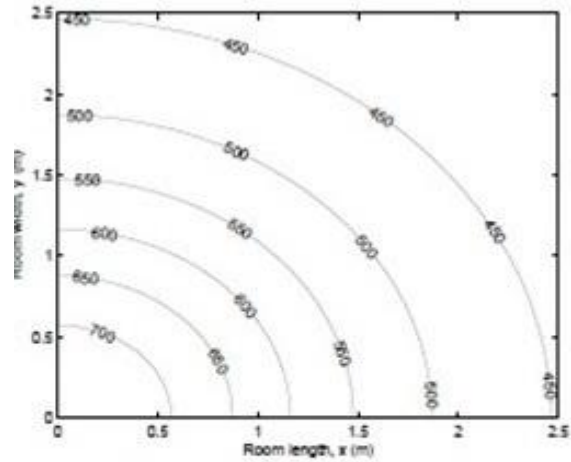
B. Illuminance Distribution

Figure 5 compares the distributions of the illuminance at the desk surface for the reference channel and repeater-assisted channel. Due to the symmetry of the room geometry, only the upper right corner of the room area is considered in the simulation. Figure 5(a) gives the distribution of the illuminance for the reference model. In the reference channel model, with 1200 LED chips (each having center luminous intensity of 1.56 cd) cannot achieve the target illuminance of 400 lx at the desk surface.
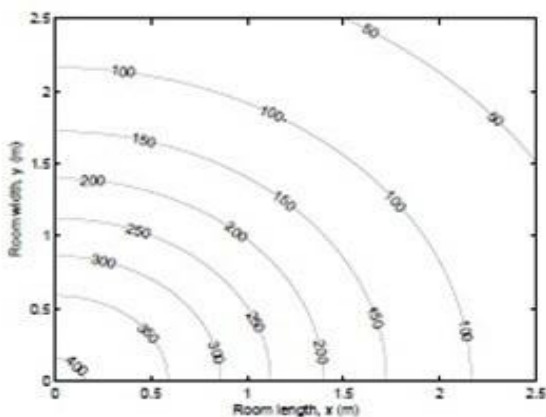
min=29 lx, mean=147 lx, max=404 lx

Figure 5(a). Horizontal brightness distribution in lx for reference channel.

When a repeater with 120 LED chips is installed at the desk and the remaining 1080 LED chips are used for the source at the ceiling, the illuminance at the desk surface is dramatically increased. The illuminance distribution with the repeater can be found in Figure 5(b).
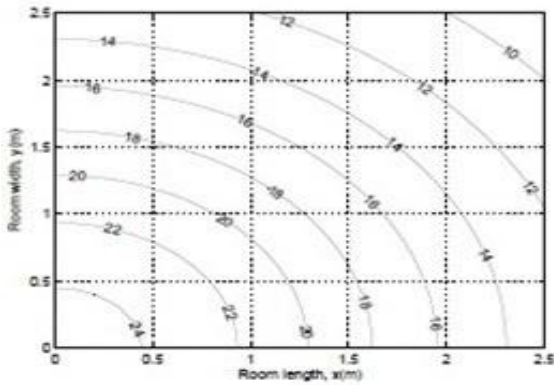

min=408 lx, mean=514 lx, max=746 lx

Figure 5(b). Horizontal brightness distribution in lx for repeater assisted channel model

In average, with the described allocation ratio of LED chips, a desk lamp increases the average illuminance 3.49 times at the desk surface with respect to the reference model.

C. SNR Improvement vs. the Receiver Location

Figures 6(a) and (b) show the actual SNR distribution inside the room on the desktop surface. SNR is derived by using Eq.(11) over 2 MHz bandwidth and the data rate R_b of 1 Mbps. In the reference channel model, the average SNR is 16.30 dB whereas the SNR is increased to 19.49 dB in the repeater assisted model. The bit-error-rate for 2-PPM is Q ($\sqrt{SNR}$) [10]. In order to achieve bit error-rate P_e of 10^{-3}, the required SNR is 9.8 dB and similarly for P_e of 10^{-6}, the required SNR is 13.5 dB. Therefore, the transmission rate of 1 Mbps is achievable in both reference channel and the channel with the repeater.

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min=8.95dB, mean= 16.30dB, max=25.66 dB

Figure 6(a). Distribution of the SNR for reference channels.

The normalized area with SNR > 13.5 dB for the reference channel is 70%, whereas the normalized area for the same SNR constraint is enhanced to 90% with the repeater assisted channel. Higher data rates are not allowed due to the modulation bandwidth of the white-LEDs.
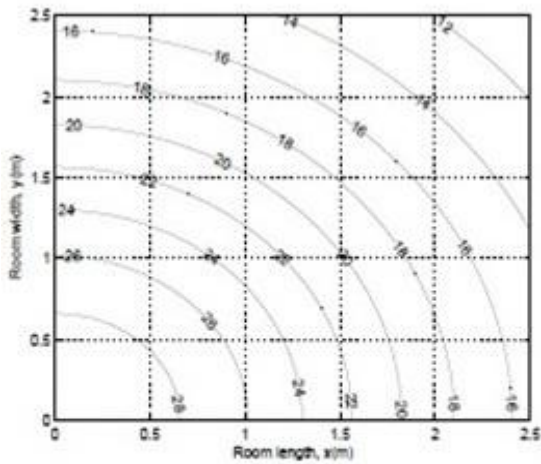
min=10.72dB, mean=19.49 dB, max=29.57dB

Figure 6(b). Distribution of the SNR for repeater assisted channel.

The SNR values presented are subject to change depending on the shot noise which is associated with the background light induced current. For instance, when the Receiver is exposed to direct sunlight, SNR may decrease.

Figure 7(a) gives the distribution of SNR improvement achieved with the repeater in the room area. Here, again the improvement in SNR is defined as the SNR gain achieved by the repeater with respect to the reference model when the BER is 10^{-3}. The improvement in SNR increases when the receiver gets closer to the center of the room. This is mainly because of the shortened distances for the source-repeater and the source-destination links which accordingly increases in the total received power. When the

receiver is at the location (1,1), the SNR improvement with respect to the reference channel is 3.8 dB. Similarly, when the receiver is at (1.5, 1.5) and (2, 2), the SNR gains become 3 dB and 2.30 dB respectively.
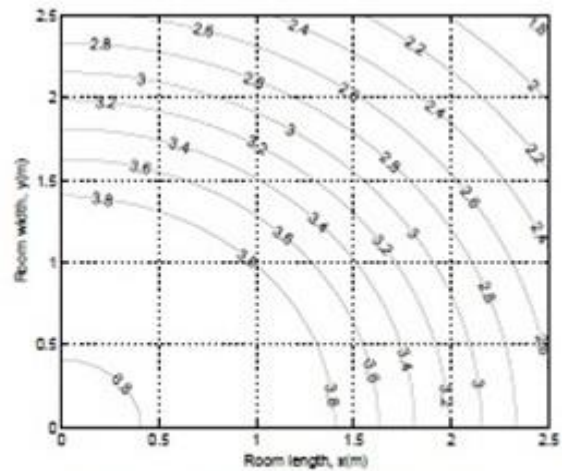

Figure 7(a). SNR distribution for BER=10^{-3}

Figure 7(b) displays the BER versus E_b/N_0 for the reference channel (solid lines) and for the channel with the repeater (dotted lines). Computer simulation results are also indicated (stars). E_b/N_0 is given with respect to the reference channel where no repeating takes place.
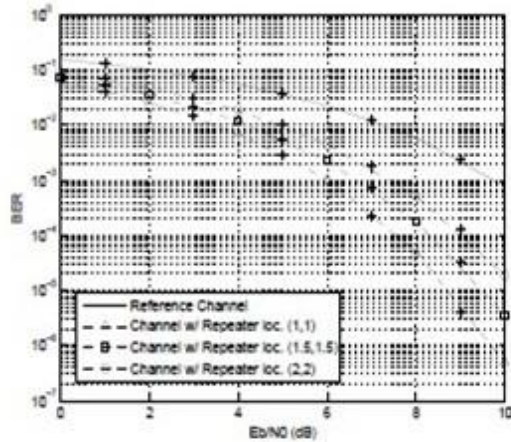

Figure 7(b). BER vs. E_b/N_o for the reference channel and the channel with a repeater.

The SNR improvement results in Figure 7(a) can also be observed in Figure 7(b).

D. Effect of Shadowing

When the room is empty and the LOS link is not shadowed, the channel with the repeater outperforms the reference model (average SNR improvement of 2.78 dB when BER = 10^{-3}).
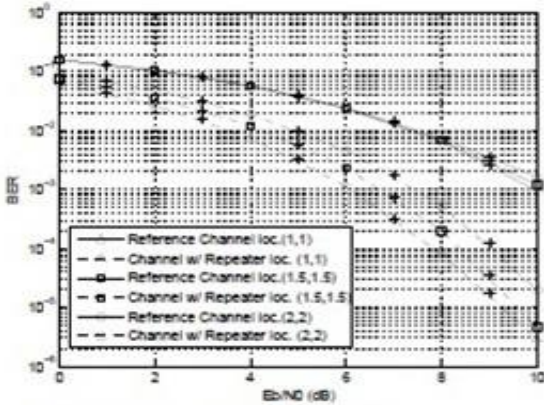
Figure 8(a). BER performance improvement for with the repeater when the channel is 1% shadowing.

When the LOS path of the source-destination link is obstructed due to the moving objects of people in the room, the data is transmitted over the diffused portion of that channel. Figure 8(a) gives the BER performance improvement with the repeater when the LOS component for the source-destination link is obstructed in 1% of time. When the receiver is at location (1,1), the SNR gain is 4.7 dB whereas in un shadowed environment the gain was 3.8dB for the same set up as shown in Figure 7(b). Similarly, the SNR gains for the locations (1.5, 1.5) and (2, 2) are 3.5 dB and 2.6 dB respectively. When the chance of shadowing is increased, the impact of the Repeater on the BER performance is more distinct.
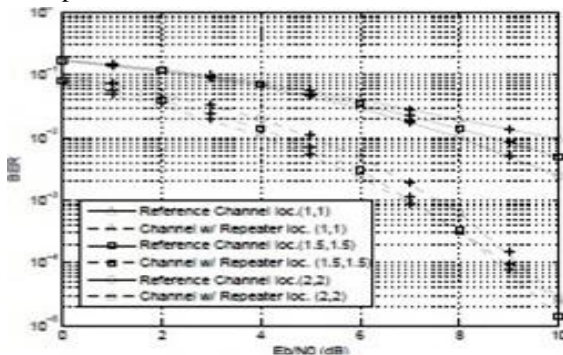

Figure 8(b). BER performance improvement for with the repeater when the channel is 10% shadowing.

Figure 8(b) displays the BER curves for the blocking probability of 10%. In this case, the SNR gains are 7.75 dB, 5.5 dB and 3.5 dB for the receiver locations of (1, 1), (1.5, 1.5) and (2, 2), respectively.

V. CONCLUSION

In conclusion, visible light communication has been recently proposed as an alternative way of data transmission. Future lighting systems will be composed of white LEDs and there might be more than one lightings in the environment. In this study, we have considered a light source (which is different than the source) mounted at a desk as a repeater terminal. We have shown that the repeater-assisted VLC networks outperform conventional VLC networks in terms of both reliability and illuminance. The considered VLC repeater can be employed in any VLC system without any prior work.

The visible light channel without any intermediate terminal can provide 90 MHz bandwidth for a typical office environment. When a repeater is included, the bandwidth efficiency of the system reduces, and the channel bandwidth becomes 3-5 MHz due to the extent of the time dispersion in the channel. In this work, the bandwidth of the transmission has been set to the modulation bandwidth of the white-LEDs, 2MHz. Both the reference channel and the channel with a repeater can support 2 MHz bandwidth. We have set the transmission data rate to 1 Mbps and considered 2-PPM modulation scheme. We have investigated power efficiency of the system with the repeater. The average SNR gain for BER of 10^{-3} with the repeater

in an unshadowed environment is found to be 2.78 dB. Whereas, when the receiver is shadowed increase in the SNR is more significant and can be up to 7.75 dB.

In this work, we have considered 2-PPM as the modulation scheme, however the results can be extended for other modulation schemes. The power allocation between different light sources is potentially the most beneficial direction for future research.

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