Performance of Visible Light Communications with Dimming Controls

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***Abstract*—Visible light communications (VLC) has recently gained popularity as an alternative to RF. However, the design and deployment of a VLC system requires an understanding of the underlying communications and how they affect the design of higher layer protocols. In this paper, we take a basic step towards getting an understanding of the impact of interference on a VLC system. Such an understanding is key to the design of MAC protocols for arbitrating access across lights in multiple rooms, while ensuring that illumination requirements are met. Specifically, we consider the interference across two rooms from VLC emitters. The emitters are assumed to use Binary Pulse Position Modulation (BPPM); the pulse width is varied to provide different dimming levels. In this setting, we use a modified ray-tracing algorithm to calculate the channel impulse response between the emitters and receivers that are located at different positions within a room. Subsequently, we analyze the performance observed at the receivers in the presence of (i) illumination and (ii) transmissions from an interfering VLC emitter. We find that in the former case, the VLC emissions from the interferer do not impact the reception at the target receiver. However, in the latter case, the performance is degraded. The extent of degradation depends on the position of the receiver. We find that increasing the dimming level increases the pulse intensity and thus, improves performance in the presence of interference. We also perform extensive simulations to provide performance results in different settings.**

I. Introduction

Visible Light Communications (VLC) is gaining popularity ever since the first VLC system (utilizing white LED light) was proposed in [1]. VLC is considered to be a promising alternative to RF in indoor settings. In a VLC system, the LED lights not only illuminate a room, but can also support optical wireless communication. Currently, IEEE has a standard [2] for VLC. White light LEDs have the advantages of reliability, security, lower power consumption, easy maintenance, and cost-effeciency. They are also harmless to the human eye. Furthermore, it could be potentially easy to deploy a VLC network, since in most cases of interest (indoors) the lighting infrastructure already exists.

In [3], the authors provide an indoor VLC system design with theoretical analysis and experimental proof of the feasibility of VLC. In [4], a typical basic configuration is provided and the performance that can be achieved with different modulation schemes is discussed. Regarding the VLC channel, a simulation based method in characterizing the infrared (IR) channel that has been proposed in [5] has been broadly adopted. Based on this work, [6] presents the VLC channel characteristics considering wavelength and spectral reflectance.

Unfortunately, the above efforts do not provide an understanding of interference between VLC emissions. To

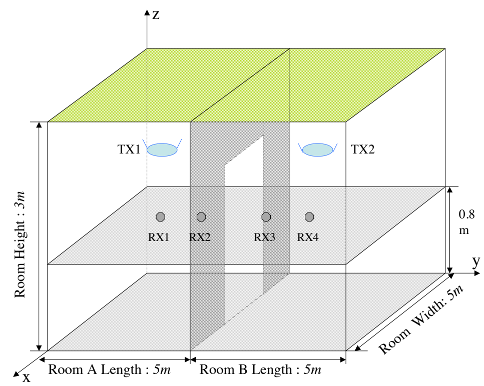


Fig. 1: The visible light system deployed across two rooms with an open door in between.

illustrate, we consider a VLC system deployed over two rooms separated by a door, with each room containing a set of emitters and receivers, as shown in Fig. 1. This type of indoor setting is typical, especially in home or office establishments. Needless to say, if the door is closed, the VLC system can provide a separate channel for each room since the visible light signal cannot go through opaque surfaces. On the other hand, if the door is open, the visible light signal in one room interferes with the signal in the next room. Understanding the impact of this interference is critical for the design of higher layer protocols for VLC, which in turn are key in making wide spread deployment of VLC a reality.

In this paper, we study the VLC communications in the presence of interference in the simple scenario shown above (Fig. 1). Although simple, the set up provides a set of key insights that can help in the design of protocols going forward. Since the primary use of the LED emitters is illumination, dimming control is one of the desired functions of the system. Thus, throughout this work, we use the Variable Pulse Position Modulation (VPPM) scheme, which combines Binary Pulse Position Modulation (BPPM) for data transmission and Pulse Width Modulation (PWM) for dimming control. Note that VPPM is easy to implement and has been discussed in [2].

Our contributions in brief: We characterize the channel based on a novel algorithm that uses a modified ray-tracing model to calculate the channel impulse response. We study the communication channel between Tx1 (see Fig. 1 and a receiver in the same room (Room 1), treating the transmission from Tx2 as interference. We utilize a simple symbol detection method and compute the Signal to Noise Ration (SNR) to characterize the quality of the connection. We use simulations to determine the SNR distribution in the room for two different cases: (a)

TABLE I: System parameters.

Room Length x(m)		5
Room Width y(m)		5
Room Height z(m)		3
Roof reflectivity		0.38
Floor reflectivity		0.6
Walls reflectivity		0.68
Door Width x(m)		3
Door Height z(m)		2
Tx1 Position		$(2.5, 2.5, 2)$
Tx2 Position		$(2.5, 7.5, 2)$
Rx1 Position		$(2.5, 2.5, 0.8)$
Rx2 Position		$(2.5, 4.0, 0.8)$
Rx3 Position		$(2.5, 6.0, 0.8)$
Rx4 Position		$(2.5, 7.5, 0.8)$
Receiver Area (cm^2)		1
Receiver FOV (deg)		85
Emitter Orientation	φ	0
	θ	90
Receiver Orientation	φ	0
	θ	90

both emitters are transmitting, and (b) Tx1 is transmitting and Tx2 is illuminating.

We also provide a BER performance analysis for the system which can account for variable data rates, dimming levels and door sizes. The results show that increasing the data rate or increasing the door size can degrade the BER performance. Increasing the dimming level of Tx1 can improve the BER performance[1] On the other hand, increasing the dimming level of the interfering emitter impacts the BER performance in a negative way, especially for the receivers close to the door.

Finally, we look at the performance when Tx1 reduces its data rate to below that of Tx2. Our results show that this strategy can improve the BER performance significantly.

II. A Visible Light Communication System Model

We consider a visible light indoor optical wireless system in two rooms with an open door between them, as shown in Fig. 1. There are two LED emitters, Tx1 and Tx2, in Room 1 and Room 2, respectively. We assume that the two emitters can transmit data and illuminate at the same time. The receivers are located on a plane that is 0.8m above the floor. We consider the receivers Rx1 and Rx2 that are located in Room 1 and are associated with emitter Tx1. Due to geometrical symmetry, we expect that the performance of the receivers Rx3 and Rx4, which are associated with emitter Tx2, to be similar to that of Rx1 and Rx2, respectively. The parameters of the system are shown in Table. I.

A. VPPM Transmitter

The transmitters Tx1 and Tx2 of Fig. 1 are at a distance of 0.5m from the ceiling and point straight up. We assume that each LED emitter uses VPPM modulation [2] and adopts the emission profile in [7]. The VPPM scheme is identical to the 2-PPM scheme when the duty cycle is 50%. The duty cycle δ, i.e. the pulse width within the slot T, corresponds to the

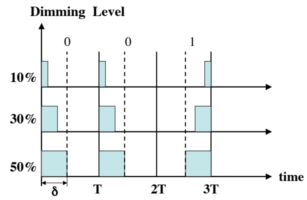


Fig. 2: An example of VPPM signals.

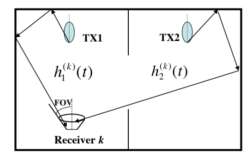


Fig. 3: Reflection of rays.

dimming level[2]. In this work, we consider the dimming level to be no more than 50% since we use BPPM (the pulse can occupy at most one half of the slot width). Fig. 2 provides a simple example of the VPPM signal. The n^{th} transmitted bit $s_n \in \{0, 1\}$ corresponds to the symbol S_n^δ, given by:

$$S_0^\delta(t) = \begin{cases} 2P_t, & \text{if } 0 \leq t < \delta T \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

$$S_1^\delta(t) = \begin{cases} 2P_t, & \text{if } (1-\delta)T \leq t < T \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where T is the duration of a VPPM symbol and P_t is the average transmitted power over the entire time slot.

B. Channel Impulse Response

The channel impulse response for the case where the emitters and the receivers reside in the same room has been presented in [8]–[10]. We extend this previous work by considering a situation where two emitters are located in two neighboring rooms with an open door in between. It is hard to calculate analytically the channel path loss in this case due to interference. Instead and motivated by [10], we propose the use of a modified ray-tracing algorithm to generate the channel impulse response $h_i^{(k)}(t)$ for the channel between emitter i and receiver k. For a receiver k in Room 1, we consider two separate channels: (i) the channel between emitter Tx1 and the receiver $h_1^{(k)}(t)$, (ii) the channel between emitter Tx2 and the receiver $h_2^{(k)}(t)$.

We calculate the impulse response $h_i^{(k)}(t)$ by means of simulation that lasts t_max sec. The simulator determines the maximum number ray_max of rays to generate. The selection of the number of rays is discussed in [11]. The distribution of the generated rays is according to the emission profile. The propagation path of each ray may contain obstacles. These obstacles include the roof, the ceiling and the walls. Note that we assume the door is open, so the door is not considered an obstacle.

When a ray reaches an obstacle, the simulator checks if the point of impact (*PI*) is on the door. If the *PI* is not on the door, it reflects the ray and the power is reduced by the reflection coefficient of the obstacle. Subsequently, a new ray is generated at *PI* with the new, reduced, power. If the *PI* is on the door, the ray propagates to the other room. The simulator computes the new point of impact PI' in the other room and generates a new ray at that point. In Fig. 3 the reflections of

[1]We find that this is because, the power intensity of a pulse increases with the width.

[2]Note that when we say the dimming level increases, we mean that the pulse width increases. This also translates to a higher average power.

while $ray\_num < ray\_max$ **do**
 step 1 : Generate a new ray starting at the emitter ; $t = 0,\ P = 1$;
 step 2 : **while** $t < t\_max$ **do**
  Propagate the ray until it reaches any obstacle plane;
  Find the point of impact *PI* where the ray intersects with the obstacle;
  if PI *is on the door* **then**
   Propagate the ray to the neighboring room;
   Find the impact point *PI'* where the ray intersects with any obstacle planes in the neighbor room;
   Calculate the contribution from PI' to the receiver;
   Generate a new ray starting at PI', with reduced power $P = \rho P$;
   Back to Step 2;
  else
   Calculate the contribution from *PI* to the receiver;
   Generate a new ray starting at *PI*;
  end
 end
 $Increase\ ray\_num\ by\ 1.$
end

Algorithm 1: Ray-tracing Algorithm for $h_i^{(k)}(t)$

the rays are shown. Only diffused reflection is considered in this algorithm. The direct power contribution of each ray is calculated each time it is reflected [10]. The calculated power is added to $h_i^{(k)}(t)$ if the ray can be intercepted by the receiver, i.e. it is within the FOV of the receiver.

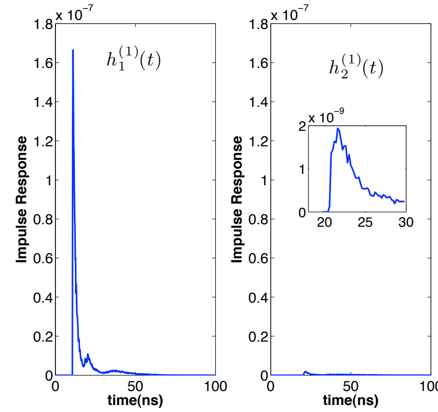
Fig. 4 presents the impulse response computed using Algorithm 1 for the channel between Tx1 and receivers Rx1 and Rx2. The number of rays is 10,000, the resolution time is 0.2ns and the simulation time is 120ns. The shapes of $h_1^{(1)}(t)$ and $h_1^{(2)}(t)$ look similar. Only the peak power of $h_1^{(1)}(t)$ is higher than $h_1^{(2)}(t)$. This is due to the positions of Rx1 and Rx2, i.e., Rx1 is closer to Tx1 and further from Tx2 while Rx2 is further to Tx1 and closer to Tx2. For the same reason, we see that the power of $h_2^{(1)}(t)$ is much smaller than the power of $h_2^{(2)}(t)$.

C. Received Signal

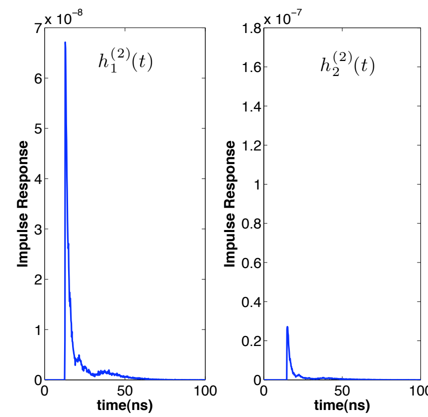
Receivers in Room 1 are associated with Tx1 and receivers in Room 2 are associated with Tx2. If not explicitly stated otherwise, we assume that the emitters Tx1 and Tx2 use the same data rate and the system is synchronized. Looking at the performance in Room 1, we consider two scenarios: (i) both Tx1 and Tx2 are transmitting data, and (ii) Tx1 is transmitting data and Tx2 is just illuminating.

Receivers Rx1 and Rx2 are connected to Tx1, therefore the signal from Tx2 acts as an interference to them. Following [5], the received signal $r_1^k(t)$ at receiver k in Room 1 is given as:

$$r^{(k)}(t) = R^{(k)} X_1(t) \otimes h_1^{(k)}(t) \ + \ I^{(k)}(t) \ + \ n(t) \tag{3}$$



(a) Impulse Response between transmitters and Rx1.



(b) Impulse Response between transmitters and Rx2.

Fig. 4: Impulse Responses.

where R^k is the responsivity of receiver k in Room 1, $X_1(t)$ is the transmitted signal of Tx1 and $n(t)$ is the noise. $I^{(k)}(t)$ is the interference from Tx2 to receiver k, given by:

$$I^k(t) = R^{(k)} X_2(t) \otimes h_2^{(k)}(t) \tag{4}$$

where $X_2(t)$ is the transmitted signal of Tx2. Note that for scenario (ii) above $X_2(t)$ is a signal with constant power. We further discuss this case in Section II-D. The variance σ_{total}^2 of the Gaussian $n(t)$ [1], [3], [5] is given by:

$$\sigma_{total}^2 = \sigma_{thermal}^2 \ + \ \sigma_{shot}^2 \tag{5}$$

The shot noise variance is given by:

$$\sigma_{shot}^2 = 2qRP_nI_2R_b \tag{6}$$

where q is the electric charge, R is the photodiode responsivity, P_n is the noise power, I_2 is the noise bandwidth factor and R_b is the data rate. The thermal noise variance is given by:

$$\sigma_{thermal}^2 = \frac{4kT_f}{R_F} I_2 R_b \ + \ \frac{16\phi^2 kT_f}{g_m}(\Gamma \ + \ \frac{1}{g_m R_D}) C_T^2 I_3 R_B^3 \\ + \ \frac{4\phi^2 K I_D^a C_T^2}{g_m^2} I_f R_b^2 \tag{7}$$

We adopt the parameters defined in [5] except for the data rate R_b. The received waveform can be calculated using (3)-(7).

D. Symbol Detection and SNR Distribution

There are various methods designed for symbol detection [12]–[14]. We need a symbol detection mechanism that is simple and effective. As discussed earlier, the system that we consider in this work has two channel impulse responses $h_1(t)$ and $h_2(t)$ for each receiver. Note that these two channel impulse responses are different and independent of each other; $X_1(t)$ and $X_2(t)$ are also different, i.e. Tx1 and Tx2 are transmitting different data. Thus, equalization [15] cannot be employed in this system. Considering BPPM where the pulse is confined to half a slot (i.e., $\delta \leq 0.5$) we can neglect ISI (Intersymbol Interference) when the slot period is sufficiently longer than the delay spread.

The non-equalized receiver performs symbol-by-symbol ML detection. We assume that the receiver is synchronized with the transmitter and the receiver has the information of dimming level and the data rate of the transmitter it is associated with, prior to the data transmission [2]. Thus the received signal $r(t)$ can be sampled into two blocks y_1, y_2 for each symbol, where y_1 and y_2 correspond to the samples in the fist half slot $slot_1$ and second half slot $slot_2$ respectively. The receiver makes symbol decisions based on the relative magnitude of y_1, y_2.

Using this symbol detection method, the SNR can be defined as:

$$\mathrm{SNR}_{s_n} = \frac{\mid P_{slot_1} - P_{slot_2} \mid}{P_{noise}}, \tag{8}$$

where $P_{noise} = \sigma_{total}$ (see (5)), s_n is the desired symbol and P_{slot_1} and P_{slot_2} are the average received power levels in the first half slot $slot_1$ and the second half slot $slot_2$, respectively. The average received power is computed based on the received signal $r^{(k)}(t)$,which can be computed by (3) We are interested in the expected value of the SNR across Room 1, which provides a measure of the communication performance in Room 1. As discussed earlier, we consider two scenarios: (i) both Tx1 and Tx2 are transmitting, and (ii) Tx1 is transmitting and Tx2 is just illuminating. Assuming the input bit stream is an independently and identically distributed (i.i.d.) Bernoulli$(1/2)$ process, the emitter in transmission mode transmits a symbol[3] 0 or 1 with probability $1/2$.

Considering the first scenario, the possible combination of symbols from Tx1 and Tx2 is one in the set $S^{(1)} = \{(0,0),(0,1),(1,0),(1,1)\}$. The expected value of the SNR for the first scenario is:

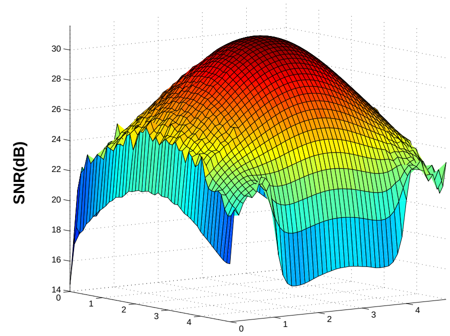
$$\mathrm{E[SNR]} = \frac{1}{4} \sum \mathrm{SNR}_{\{s_1, s_2\}} \tag{9}$$

where $\{s_1, s_2\} \in S^{(1)}$ and s_1 s_2 are the bits transmitted from Tx1 and Tx2 respectively. To compute P_{slot_1} and P_{slot_2} for a specific receiver k in Room 1, we first simulate its $h_1^{(k)}(t)$ and $h_2^{(k)}(t)$ with Algorithm 1. SNR_{s_1,s_2} is computed using (8) and s_1 is considered to be the desired symbol, we look at receivers in Room 1.

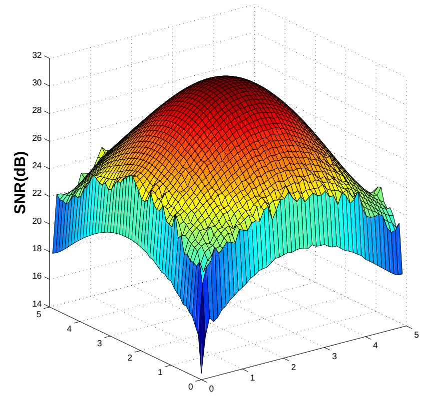
Regarding the second scenario, Tx2 is in illumination mode so that the signal $S_{illumin}$ it generates is of constant power:

$$S^{\delta}_{\text{illumin}}(t) = 2\delta P_t \tag{10}$$

[3]To evaluate the performance of the system, we consider the system is uncoded throughout this work.



(a) Both Tx1 and Tx2 are transmitting.



(b) Only Tx1 is transmitting.

Fig. 5: SNR distribution of Room 1 (datarate 1 Mb/s)

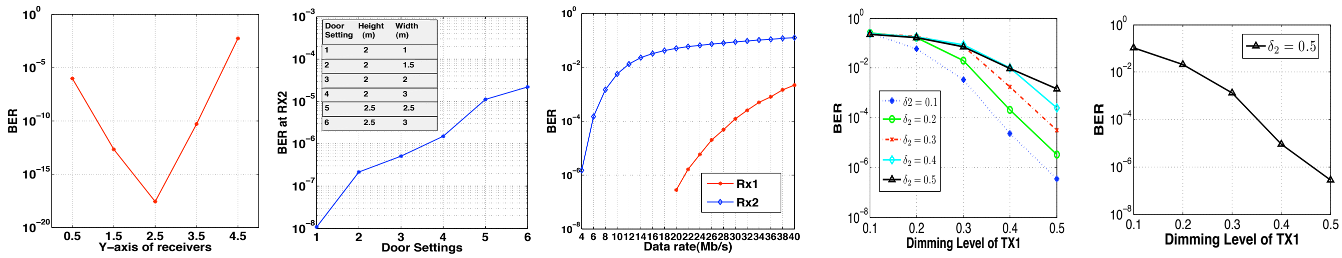
where δ is the dimming level of Tx2. Fig. 5 shows the expected value of the SNR across Room 1 for scenario (i) and (ii). The dimming level of both emitters is 0.5 and the data rate of the communicating transmitter is 1 Mbps. The receiver plane is at a distance of $0.8m$ above the floor. Comparing the results shown in Fig. 5(a) and Fig. 5(b), we observe that if Tx2 is just illuminating it does not impact the transmission performance in Room 1, while if both Tx1 and Tx2 are transmitting data, the performance in Room 1 is affected. The effect is especially harsh for the receivers in Room 1 closer to the door; for these the SNR is degraded largely.

III. BER Performance

In this section we first provide basic BER performance analysis and then look into the performance with different system parameters. Our goal is to achieve an optimal BER performance by tuning the dimming level and the data rate for the system we consider in this work.

A. Bit Error Rate Analysis

First we seek to find the BER when Tx1 and Tx2 use the same data rate. As described earlier, we consider an unequalized VPPM system. Assuming that the symbol detection method presented in Section II-D is used, the



(a) BER vs Distance. (b) BER at Rx2 vs Doorsizes. (c) BER vs Data rate for Rx1 and Rx2. (d) BER vs Dimming at Rx2. (e) BER vs Dimming at Rx1.

Fig. 6: BER for various parameters

probability of a bit error for the first scenario where both emitters transmit, can be estimated as:

$$P\{\text{bit error} \mid \{s_{1,i}, s_{2,j}\}\} \approx Q\left(\sqrt{\text{SNR}_{\{s_{1,i},s_{2,j}\}}}\right) \tag{11}$$

where $s_{1,i}$ and $s_{2,j}$ are the symbols sent by Tx1 and Tx2 respectively, and $Q(x)$ is given by :

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-u^2/2} du \tag{12}$$

For a random input data, the BER can be obtained by averaging over all possible symbols $s_{1,i}$ and over all possible interfering symbols $s_{2,j}$ from Tx2:

$$\text{BER} = \sum P\{\text{bit error} \mid \{s_{1,i}, s_{2,j}\}\} \cdot P\{\{s_{1,i}, s_{2,j}\}\} \tag{13}$$

where $\{s_{1,i}, s_{2,j}\} \in S^{(1)}$ and $P\{\{s_{1,i}, s_{2,j}\}\} = 1/4$.

B. BER Performance

We evaluate the BER performance with various combinations of the system parameters such as receiver positions, door sizes, data rates and dimming levels. If not stated otherwise, the two emitters are using the same dimming level and the same data rate.

BER vs Distance: Fig. 5(a) shows that when both emitters are transmitting, the receivers closer to the door are affected more. We calculate the BER for five receivers in Room 1, that are at different distances from the emitters. The two emitters use the same dimming level of 0.5 and a data rate of 10 Mbps. The BER results shown in Fig. 6(a) are consistent with the SNR results in Fig. 5(a).

BER vs Door Size: Our previous analysis and results have shown that the interfering signal from Tx2 impacts the performance in Room 1. It is interesting to look into how the different door sizes affects the performance. In Fig. 6(b) we show the BER at receiver RX2 for various door sizes. As expected, the larger the area of the door, the higher the BER. This is so because there is a higher likelihood that the interfering signal goes through the door when the door is larger.

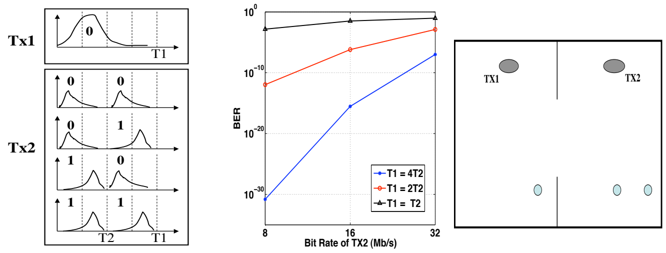
BER vs Data Rate: Up to this point, we assume that the data rates of Tx1 and Tx2 are the same. In Fig. 6(c), we show the BER for Rx2 and Rx1 with different data rates. We increase the data rate by decreasing the pulse duration to fit in more pulses within a slot. Due to the interference at Rx2, the maximum data rate in order to achieve a minimum BER requirement of 10^{-6} is 4 Mbps. For Rx1, the corresponding maximum data rate is 20 Mbps. In general, increasing the data rate results in an increase of the BER at both receivers.

BER vs Dimming: In the previous sections, we consider the case where Tx1 and Tx2 both use dimming level of 0.5. Since dimming is a special feature of VPPM modulation, we look into the impact of dimming on the performance of the system. Let δ_1 and δ_2 be the dimming levels of Tx1 and Tx2, respectively. The receivers at different locations in Room 1 are affected in different ways by the interfering signal from Tx2; thus, we look at the BER performance at Rx1 and Rx2 separately. We set the data rate of the connection to Rx1 to be 20 Mbps and of the connection to Rx2 to be 4 Mbps.

Results shown in Fig. 6(d) present the BER performance at Rx2 for different values of δ_1 and δ_2. There are five sets of data, wherein for each the dimming level δ_2 of Tx2 is fixed and the dimming level δ_1 of Tx1 is increased from 0.1 to 0.5. When δ_2 is fixed, increasing δ_1 improves the BER performance. For example, when δ_2 is 0.2, increasing δ_1 from 0.3 to 0.5 makes the BER drop from 10^{-2} to 10^{-6}. This trend is observable for each data set where δ_2 is fixed at different levels. Also, if we look at Fig. 6(d) from a different angle, i.e. considering each column as a set of data, we can conclude that if δ_1 is fixed, decreasing δ_2 can improve the BER performance. Another observation is that when δ_2 has a high value, for example if $\delta_2 = 0.5$, then tuning δ_1 does not help improving BER. This is because the higher the value of δ_2, the stronger the interfering signal, which impacts the BER performance. When $\delta_1 = \delta_2 = 0.5$ the interfering signal for Rx2 is considerable.

As for Rx1, we observe that increasing δ_1 improves the BER performance at Rx1. In Fig. 6(e) we show the results when $\delta_2 = 0.5$ and δ_1 increases from 0.1 to 0.5. We observe that increasing δ_2 does not affect the BER performance at Rx1. This is so because Rx1 is close to Tx1 and far from the door so the interfering signal from Tx2 has limited impact on Rx1.

How to improve BER when dimming is limited: The previous results imply that increasing the dimming level of the desired emitter can improve BER performance. On the other hand, it also shown that when dimming reaches its limitation the BER cannot be improved much. For example, in Fig. 6(d) we see that if $\delta_1 = \delta_2 = 0.5$, the BER at Rx2 is 10^{-3}, a value that is not acceptable for practical settings. Thus, when there are constraints on the dimming level, we can reduce the data rate of Tx1 to improve the performance in Room 1.



(a) Symbol set for Tx1 transmitting 0, $T_1 = 2T_2$ (b) BER at Rx2 for Tx1 and Tx2 using different data rates. (c) Receivers settings.

Fig. 7: Improving BER when dimming is limited.

The BER analysis in this case differs than the analysis in Section III-A. This happens because the possible combinations of symbols from Tx1 and Tx2 are not the same as those in $S^{(1)}$ when Tx1 and Tx2 use the same data rate. In the following, we assume the data flows from Tx1 and Tx2 start at the same time to ease the analysis. If the data rate R_{b_1} is half of R_{b_2}, the combination of symbols $\{s'_{1,i}, s'_{2,j}\}$ from Tx1 and Tx2 takes values in the set

$$S^{(2)} = \{\{0,00\},\{0,01\},\{0,11\},\{0,10\},\\ \{1,00\},\{1,01\},\{1,11\},\{1,10\}\} \quad (14)$$

Because $R_{b_1} = \frac{1}{2}R_{b_2}$, it means $T_1 = 2T_2$ (T_1, T_2 are the symbol duration times for Tx1 and Tx2, respectively). Fig. 7(a) illustrates the symbol set for Tx1 transmitting 0. The BER can be calculated using (13) and $P\{\{s_{1,i}, s_{2,j}\}\}$ is $1/8$ here.

Similarly, we can compute the BER for $T_1 = 4T_2$. Fig. 7(b) shows the BER at RX2 when Tx1 and Tx2 use different data rates. It is shown that increasing T_1 to be four times of T_2, i.e., reducing the data rate (R_{b_1}) of Tx1 to be $1/4$ of the data rate (R_{b_2}) of Tx2, can improve the BER performance at Rx2 significantly. Specifically, when the data rate (R_{b_2}) of Tx2 is 16 Mbps, reducing R_{b_1} from 16 Mbps to 8 Mbps, drops the BER from 10^{-3} to 10^{-6}. Moreover, if we reduce R_{b_1} to 4 Mbps, the BER is as low as 10^{-16}. Since the minimum required BER is 10^{-6}, we set the maximum data rate of Tx1 accordingly, considering performance at Rx2: for $R_{b_2} = 32$ Mbps the maximum R_{b_1} is 8 Mbps and for $R_{b_2} = 16$ Mbps the maximum R_{b_2} is 8 Mbps. However note that the transmission of Tx1 can adversely affect the receivers in Room 2. If the receiver is close to Tx2 or away from the door the impact is not as much, as shown in Fig. 7(c). The data rate of Tx1 can only be tuned to a lower value only if it does not affect the receiver in the other room.

IV. Conclusions

In this paper, we discuss the performance of a visible light system within two neighboring rooms, where two emitters, Tx1 and Tx2, are located in separate rooms and VPPM with dimming is used. We propose an algorithm to characterize the channel impulse response and the BER of the system. Our results show that if Tx2, which is the interferer, is just illuminating, it does not impact the performance of the communication between Tx1 and the receivers in the same room. However, if both Tx1 and Tx2 are transmitting, the performance is degraded, especially for the receivers closer to the door. We show that increasing the dimming level of the desired signal can improve the BER performance. Moreover, we find that when the interfering signal is strong and the dimming level reaches its limit, reducing the data rate of Tx1 improves significantly the performance of the communication between Tx1 and the receivers in the same room; however, care must be taken when applying this strategy. We believe that our findings can help in designing MAC protocols for interference management with VLC.

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