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Performance Evaluation of Multi-gigabit Indoor Visible Light Communication System

Ahmed Taha Hussein and Jaafar M.H. Elmirghani
School of Electronic and Electrical Engineering, University of Leeds, LS2 9JT, United Kingdom
{ml12ath, j.m.h.elmirghani}@leeds.ac.uk

Abstract— **This paper presents a performance evaluation of a mobile multi-gigabit visible light communication (VLC) system in two different environments. The VLC channel characteristics and links were evaluated under the diverse situations of an empty room and a room with very strong shadowing effects resulting from mini cubicle offices. RGB laser diodes (LDs) were used to mitigate the low modulation bandwidth of conventional transmitters (light emitting diodes, LEDs) in the VLC system. In addition, an angle diversity receiver (ADR) was introduced to mitigate inter-symbol-interference (ISI). Furthermore, a delay adaptation technique was used to further reduce the effect of ISI and multipath dispersion. The combination of delay adaptation and ADR (DAT ADR system) added a degree of freedom to the link design, which resulted in a VLC system that has the ability to provide high data rates (i.e. 5 Gbps) in the considered harsh indoor environment. Our proposed system used a simple on-off keying (OOK) modulation format and it was able to provide data rates of 5 Gbps and a bit-error-rate (BER) of 10^{-3} in the worst case scenario in the considered realistic indoor environment.**
Keywords— **ADR, laser diodes, multi-gigabit VLC system, delay adaptation, realistic environment.**

I. Introduction

Over the last decade, there has been increased interest in visible light communication (VLC) due to its potential to achieve high data rates and its use of inexpensive and energy efficient light emitting diodes (LEDs) and optoelectronic devices [1]. The dual functionality of a VLC system, i.e. illumination and communication, makes it a very attractive technology for many indoor and outdoor applications, such as car-to-car communication via LEDs, the use of lighting infrastructures in buildings for high speed data communication, and the use of illumination in trains and in airplane cabins for high data rate communication. Recently, a 3 Gbps VLC system based on a single μLED using orthogonal frequency division multiplexing (OFDM) has been successfully demonstrated [2]. The highest throughput achieved by LEDs to the best of our knowledge was reported in [3], where the aggregate throughput was 3.4 Gbps when using discrete multi-tone modulation (DMT), wavelength division multiplexing (WDM) and RGB LEDs. The design and implementation complexity are a major concern in these systems.

Traditional VLC systems suffer from limitations in the modulation bandwidth of the transmitters (i.e. LEDs) [4]. Therefore, alternative transmitters are needed for VLC systems to achieve high data rates (beyond 3.4 Gbps). The modulation bandwidth available in the transmitters (LEDs) is typically less than the VLC channel bandwidth, which means that the former limits the transmission rates. The main limitations in the traditional VLC system have been mitigated previously by using laser diodes (LDs) instead of LEDs, and the typical wide field of view (FOV) receiver has been replaced by an imaging receiver [4]. One of the main potential issues associated with using laser lighting is that lasers can be dangerous to human eyes. Therefore, it should be noted that while the original sources indeed have laser properties (i.e. RGB lasers), once they have been combined and had the beam scattered and diffused, the light no longer has the characteristics of laser light, but resembles white light [5]. The data rate achieved by a previously developed VLC system was 5 Gbps in the worst case scenario [4], [6]. In addition, higher data rates (10 Gbps) can be achieved when a VLC relay assisted system is combined with an imaging receiver and delay adaptation technique [7]. A fully adaptive VLC system has achieved data rates of 20 Gbps by employing beam angle and beam steering algorithms [8].

VLC systems are subjected to inter-symbol-interference (ISI) when operated at high data rates. Therefore, various techniques have been proposed to reduce the impact of ISI in VLC systems. Adaptive equalisation with a least mean square (LMS) algorithm has been used to achieve 1 Gbps [9]. An angle diversity receiver (ADR) is a simple and efficient technique that can be used to mitigate the effects of ambient light and pulse spread in optical wireless (OW) systems [10], [11]. ADR employs multiple photo detectors with relatively small FOVs, and each photo detector is aimed in a different direction with a specific azimuth and elevation angle to collect information signals [12]. A prism array based receiver has been investigated to provide angular diversity to mitigate the effects of ISI [13]. OFDM is a modulation technique that is extensively used in VLC systems as it successfully combats ISI caused by multipath propagation [14], [15].

In this paper, we introduce LDs as a source of illumination and communication for a VLC system (LD-VLC system) in conjunction with ADR. The proposed ADR has seven sub-detectors. We optimised the azimuth angle, elevation angle and FOV for each detector to obtain high system performance (i.e. low delay spread and high signal to noise ratio, SNR) under the impact of mobility and multipath propagation. A delay adaptation technique (DAT) was used to further enhance the communication link performance. We also modelled two different room scenarios: an empty room and a real environment room that has a door, windows, bookshelves, mini cubicles and other objects. The difficulty related to both room arrangements is the ability to establish a line of sight (LOS) communication link between transmitters (i.e. LDs light unit) and receiver at all possible locations. The LD-VLC system in conjuction with ADR and DAT will be referred to as DAT ADR system in the rest of the paper.

The reminder of this paper is divided into sections as follows: Section II describes the laser VLC system and rooms setup. Section III presents the LD-VLC system configurations. Simulation results and discussions of the LD-VLC system in an empty room and in a realistic room are presented in Section IV. Finally, conclusions are drawn in Section V.

II. Laser VLC System and Rooms Setup

To study the benefits of our proposed system (DAT ADR) for an indoor VLC system, a simulation based on a ray-tracing algorithm was performed in the two room configurations. The simulation model was developed using room dimensions of 4m×8m (width×length) with a ceiling height of 3 m, and the room configurations were denoted as room (A) and room (B). Figs. 1 (a) and (b) show room A, which is an empty room, and room B, which is a realistic environment as normally experienced in office arrangements where a door, windows, furniture and mini cubicles block the optical signal, respectively. Both rooms experience multipath propagation. Given typical indoor walls and floor colours and textures, typical reflection coefficients of 0.3 for the floor and 0.8 for the walls and ceiling were used for room A [16], [17]. These relatively high reflectivities (within the typical range) were selected as they result in the greatest multipath dispersion (worst case scenario), and consequently considerable pulse spread. Fig. 1 (b) shows room B which has three large windows, a door, bookshelves, furniture, chairs and cubicles that have surfaces parallel to the walls of the room. These objects can create shadowing. In room B, the door and three glass windows were assumed to not reflect any signal; therefore, their diffuse reflectivities were set to zero. Moreover, the walls and the ceiling have a diffuse reflectivity of 0.8 and the floor has a 0.3 diffuse reflectivity. Two of the walls: x=4m (excluding the door) and y=8m were covered by filling cabinets and bookshelves with diffuse reflectivities of 0.4. It was assumed that signals encountering a physical barrier were either blocked or absorbed. Additionally, desks, tables and chairs inside room B have similar reflectivities to the floor (i.e. 0.3). The complexity is distinct in room B where low reflectivity objects and physical partitions can create significant shadowing and signal blocking.

Experimental measurements of plaster walls have shown that they are roughly a Lambertian reflector [16]. Therefore, all the walls, the ceiling and the floor in rooms A and B were modelled as Lambertian reflectors with high reflectivity. To model the reflections, the rooms were divided into a number of equally sized squares with an area of dA and reflection coefficient of ρ. Each reflection element was treated as a small transmitter that transmitted an attenuated version of the received signals from its centre in a Lambertian pattern with n=1, where n is the Lambertian emission order as defined in [18].

Previous research considered only LOS and reflections up to a first order [19], [20]. However, this may not provide a full description of the characteristics of the system. Therefore, in this study reflections up to the second order were considered, since the second order reflections can have a great impact on the system performance especially at high data rates. To ensure computations can be performed within a reasonable time, surface elements of size 5 cm × 5 cm for first-order reflections and 20 cm × 20 cm for second-order reflections were used. Simulations and calculations reported in this study were carried out using MATLAB. Our simulation tool was similar to the one developed by Barry et al. [21]. In our evaluation, the channel characteristics, received optical power, delay spread, 3 dB channel bandwidth and SNR calculations were determined in similar ways to those used in [10], [18], [22].

A combination of red, green and blue lasers with a diffuser can be used to generate white light that has good colour rendering [23]. Therefore, the room's illumination was provided by eight RGB-LD light units which were used to ensure that ISO and European standards were satisfied [24]. Each LD light unit has nine (3×3) RGB-LDs. The LD lights were installed at a height of 3 m above the floor. The specifications of the RGB-LDs used in this study were adapted from the practical results reported in [25]. Fig. 2 shows the architecture of the LD light units, where the light from three lasers (i.e. RGB) is combined using beam combiners, and it then passes through multiple ground glass diffusers to reduce speckle before illuminating the room. This design is similar to the one studied in [25]. A number of different uniformly distributed LD light unit configurations (i.e. four, six and eight LD units) were tested to find the optimum number of units that ensured the ISO and EU illumination requirements were satisfied in the room. We found that eight units were the optimum for illumination, and we used this in our study; four and six light units in the room did not achieve the minimum illumination requirement (i.e. 300 lx [24]) at all locations. The height of the work desks where the transmitters and receivers associated with the user equipment are placed was 1m. This horizontal plane was referred to as the "communication floor" (CF) (see Figs. 1a and 1b). Fig. 3 shows the horizontal illumination distribution due to the eight RGB-LDs light units on the CF level. It is clear from this figure that there is sufficient illumination according to EU and ISO standards [24].

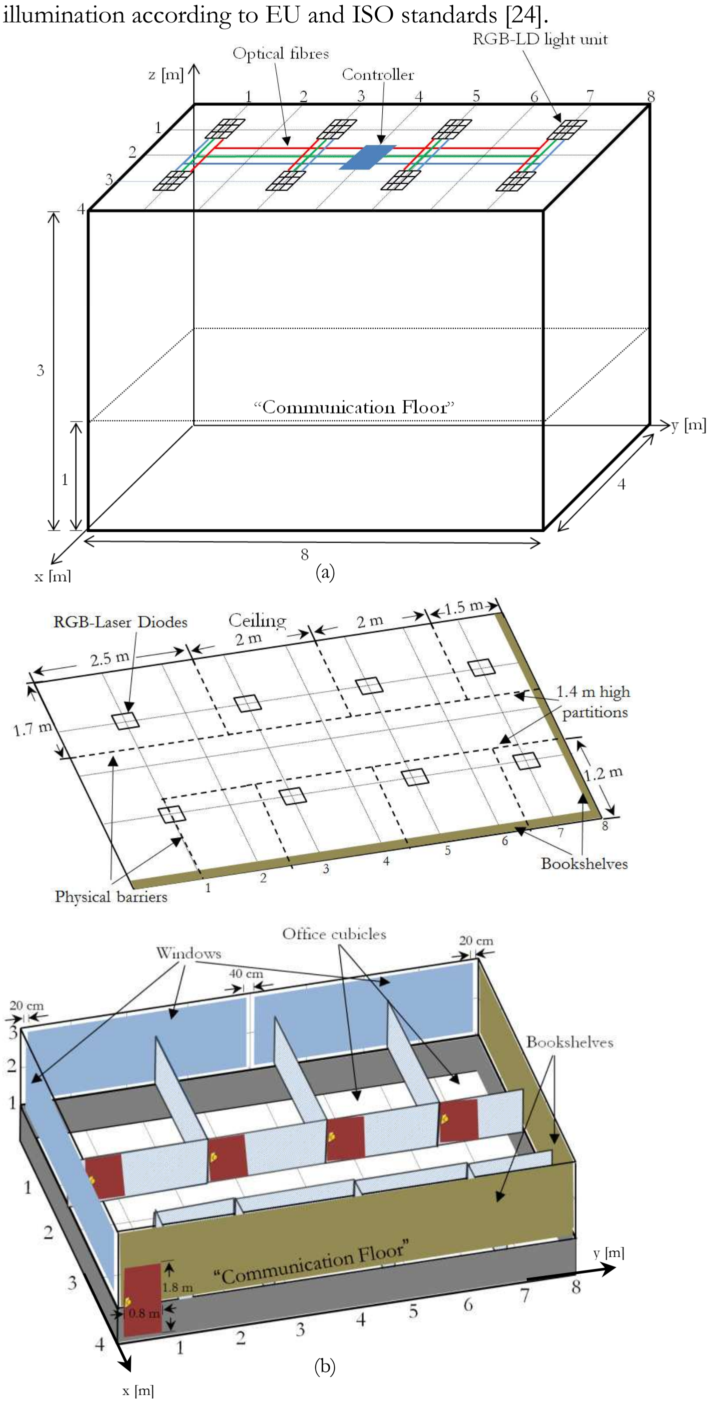

Fig. 1: VLC system rooms (a) an empty room (room A) and (b) a realistic room which has a door, three large glass windows a number of rectangular-shaped cubicles with surfaces parallel to the room walls (room B).

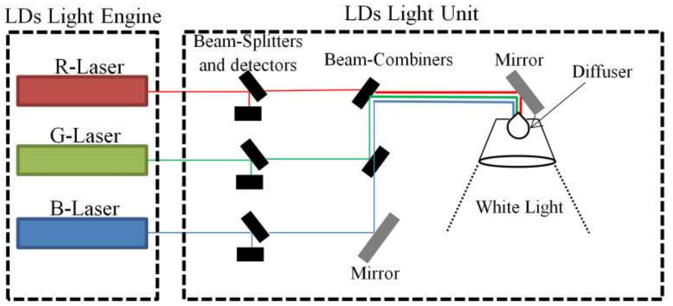

Fig. 2: RGB-LDs architecture; light from three lasers is combined using chromatic beam-combiners, then passes through multiple ground glass diffusers to reduce speckle before illuminating the room.

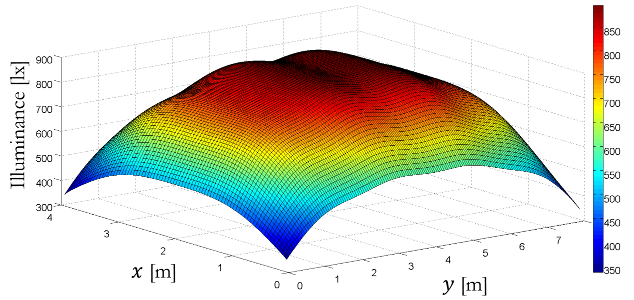

Fig. 3: Distribution of horizontal illumination on the communication floor, Minimum 336 lx and Maximum 894 lx.

III. LD-VLC System Configurations

The LD-VLC system employs eight RGB-LDs transmitters (lighting fixtures, see Fig. 1) on the ceiling connected by fibre interconnects and controlled by a central controller and an ADR with seven detectors. The ADR is a group of narrow FOV detectors pointed in different directions. A responsivity of 0.4 A/W and a photo detector area of 4 mm^2 were used for each branch. The ADR was always placed on the CF along the lines x=1m or x=2m. The direction of each branch in the ADR was defined by two angles: the azimuth angle (AZ) and the elevation angle (EL). The AZs of the seven detectors were set at 0^o, 45^o, 90^o, 135^o, 225^o, 270^o and 315^o, and the ELs for the seven branches were fixed at 90^o, 45^o, 60^o, 45^o, 45^o, 60^o and 45^o. The corresponding FOVs were fixed to 20^o, 15^o, 25^o, 15^o, 15^o, 25^o and 15^o. The AZs, ELs and FOVs were chosen through an optimisation process to achieve the best SNR and minimum delay spread. The reception angle calculations for any detector in the ADR are given in detail in [7], [10]. Fig. 4 illustrates the physical structure of the ADR. The photocurrents received in each branch can be amplified separately and can be processed using different methods, such as selection combining (SC), equal gain combining (EGC) or maximum ratio combining (MRC), to maximise the power efficiency of the system. In this study, SC and MRC were used. SC is a simple form of diversity, where the receiver simply selects the branch with the largest SNR among all the branches. In contrast, MRC utilises all branches in the ADR.

In a mobile indoor VLC system the distance between the LD light units and the receiver is a key factor; thus, sending the information signals from all LD units at the same time increases the delay spread which decreases the 3 dB channel bandwidth. To further enhance the communication links and to provide higher data rates with the ADR LD-VLC system, a beam delay adaptation technique coupled with the ADR LD-VLC system (DAT ADR) is used to mitigate the ISI and reduce the impact of multipath dispersion due to mobility at the receiver. Instead of transmitting the signals at the same time from different LD light units, the delay adaptation approach sends the signal that has the longest journey first, and then it sends the other signals with different differential delays (Δt) so that all the signals reach the receiver at the same time. To ensure that all the transmissions reach the receiver at the same time, the beam delay adaptation technique introduces a differential delay (Δt) between the transmissions. The delay adaptation technique was previously proposed in [4]. It adjusts the switching times of the signals as follows:

1- A pilot signal is sent from the first RGB-LDs.
2- The mean delay (μ) at the receiver for the first transmitter unit is estimated at the receiver side by branch 1 of the ADR.
3- Repeat step 2 for the other branches in the ADR.
4- Repeat steps 2 and 3 for the other VLC transmitter units.
5- The receiver sends a control feedback signal to inform the controller of the associated delay with each received signal from each transmitter.
6- The controller introduces a differential delay (Δt) between the signals transmitted from the transmitters.
7- The transmitter units send signals according to the delay values such that a transmitter unit that has the largest delay, i.e. longest path to the receiver, transmits first.

A pedestrian speed of 1 m/s is typical for indoor users [26], we therefore propose that the receiver re-estimates its delay values for all LD light units at the start of a 1 second frame, and if these have changed compared to the previous frame values then the receiver uses the feedback channel to update the transmitters. If the time taken to determine the value of each delay associated with each LD unit (relative to the start of the frame) is equal to 1 ms (based on typical processor speeds) then our delay adaptation method set up or training time is 72 ms (9 RGB-LDs in each unit × 8 light units × 1 ms). This training rate (once every 1 second frame) is sufficient given that the delay adaptation has to be carried out at the rate at which the environment changes (pedestrian movement). Therefore, the DAT ADR system can achieve 100% of the specified data rate when it is stationary, and 92.8% in the case of typical user movement, i.e., 5 Gbps when it is stationary and 4.6 Gbps when there are environmental changes (user or object movement in the room). It should be noted that the RGB-LDs light units (i.e. eight transmitters) should always be 'ON' to provide illumination for the room. Therefore, to prevent flickering, an on-off keying (OOK) dimming technique may be used [27].

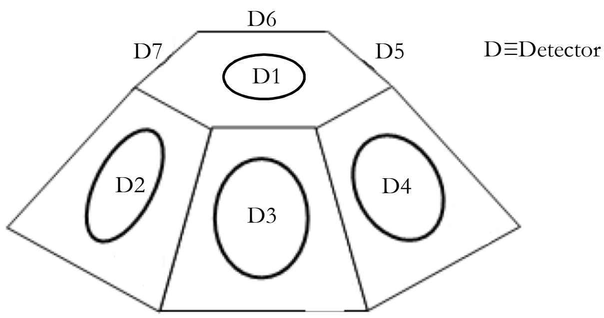

Fig. 4: Physical structure of the angle diversity receiver with seven branches.

IV. Simulation Results

In this section, we evaluate the performance of the proposed system (i.e. DAT ADR) in two different environments: in an empty room in the presence of multipath dispersion and mobility as well as in a realistic room environment with mobility. In the realistic environment, signal blockage (as a result of cubicles), a door, windows, furniture, multipath propagation and mobility are all present. To evaluate the effect of signal blockage, mobility and shadowing on the VLC communication link, we considered the room shown in Fig. 1b. The results of the DAT ADR was compared in rooms A (an empty room) and B (realistic room) in terms of impulse response, path loss, delay spread and SNR. The proposed system is examined in fourteen different locations when the ADR moves along the y-axis.

A. Impulse responses

Channel impulse responses at the room centre (i.e. x=2m and y=4m) for the DAT ADR system are shown in Fig. 5 for rooms A and B. It should be noted that both impulse responses of the proposed system are dominated by short initial impulses due to the LOS path between the transmitter and receiver. It can be clearly seen that the effect of shadowing is clear when the receiver is located at the room centre in room B (see Fig. 5). The LOS received power in room A is 4.5 μW, whereas it was 2.25 μW in room B (about 3 dB reduction in received power), and this is due to one of the LOS components being blocked by the wall of a cubicle. It should also be noted that the amount of received optical power from the reflections in room B was less than that received in room A, as shown in Fig. 5, and this is due to the existence of the door, windows, cubicles, partitions and bookshelves in room B that lead to reduced multipath propagation. These impulse responses suggest that the DAT ADR system performs better in room A (without shadowing) than in room B.

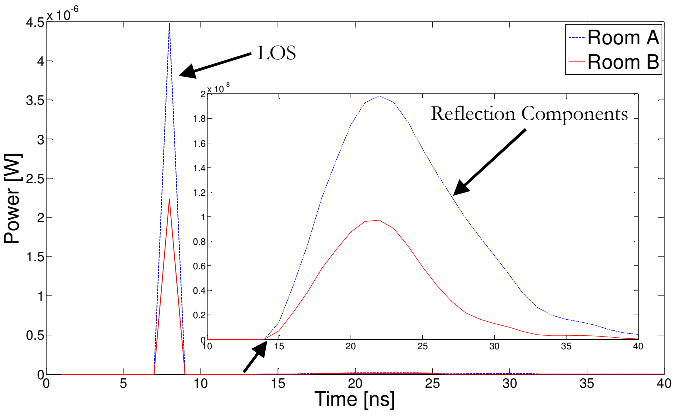

Fig. 5: Impulse responses of DAT ADR system at room centre (2m, 4m, 1m) in two different environments (rooms A and B).

B. Optical path loss

One of the main targets of any communication system is to achieve high SNR at the receiver. The SNR in OW systems is based on the square of the received optical signal power and receiver and ambient noises [18]. Therefore, the average received optical power and path loss explain part of the main VLC system performance in the two different environments. Optical path loss can be defined as [28]:

$$PL(dB) = -10log_{10}(\int h(t)dt\,) \tag{1}$$

where $h(t)$ is the system impulse response. Fig. 6 shows the optical path loss of the DAT ADR system in rooms A and B. It should be observed that the performance of the proposed system is degraded in room B at x=2m (the path loss increased by 3 dB in room B at x=2m), and this can be attributed to signal blockage as a result of cubicles, which lead to reduced received optical power. It can be noticed that the path loss is comparable in rooms A and B when the receiver moves along x=1m. This is due to the LOS links available at this line (i.e. x=1m), which protect against shadowing and mobility in this system.

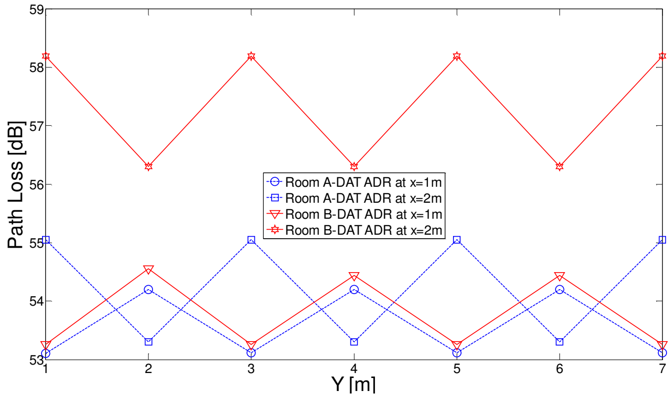

Fig. 6: Optical path loss distribution of the DAT ADR system in two different environments (rooms A and B) at x=1m and x=2m along y-axis.

C. Delay spread analysis

Indoor VLC systems are subjected to multipath dispersion due to non-directed transmission, which can cause ISI. Delay spread is a good measure of signal pulse spread due to the temporal dispersion of the incoming signal. The delay spread of an impulse response is given by [29]:

$$D = \sqrt{\frac{\sum(t_i-\mu)^2\, P_{ri}^2}{\sum P_{ri}^2}} \tag{2}$$

where t_i is the delay time associated with the received optical power P_{ri}, and μ is the mean delay given by:

$$\mu = \frac{\sum t_i P_{ri}^2}{\sum P_{ri}^2} \tag{3}$$

Fig. 7 illustrates the delay spread of the DAT ADR system in two different environments (i.e. rooms A and B). It can be noted that the proposed system has lower delay spreads in room B than in room A, and this is attributed to two reasons: firstly, the proposed system has the ability to establish a LOS link at all receiver positions. Secondly, reflections from the door and windows were set to zero, while the other two walls in room B were covered by filling cabinets and bookshelves with a smaller diffuse reflectivity of 0.4. This means that the power contribution from the reflections was minimal and this reduced the delay spread. The non-symmetry in the delay spread curve in room B is due to the presence of windows at one end of the room and the presence of bookshelves at the other end. In room B, when the receiver position is close to the windows, for example, at points (x=1m and y=1m) and (x=2m and y=1m) the delay spread becomes very low because the received power from the reflections is very low. However, when the receiver moves towards the other side of the room (i.e. receiver positions close to bookshelves), for instance, at points (x=1m and y=7m) and (x=2m and y=7m), the delay spread increased due to the power received from the signals reflected by the bookshelves.

The minimum communication channel bandwidth of the DAT ADR system in rooms A and B was 8.3 GHz (where the delay spread is 0.02 ns at points x=2m, y=1m, 3m, 5m, 7m). The significant increase in the channel bandwidth enables our proposed system to operate at higher data rates using a simple modulation technique, OOK [22]. Personick's analysis shows that the optimum receiver bandwidth is 0.7 times the bit rate

[30]. For example, a 5 Gbps data rate requires a 3.5 GHz channel bandwidth.

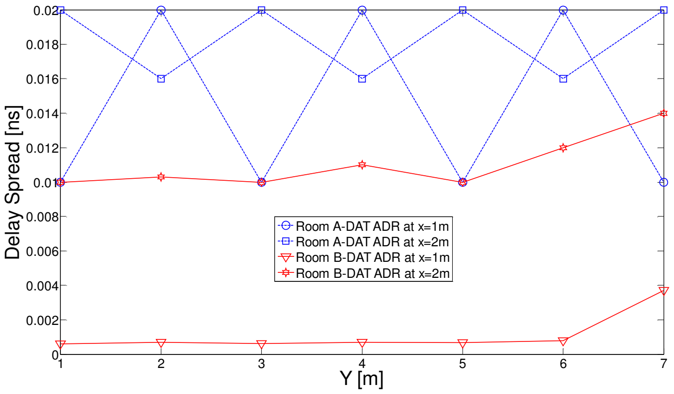

Fig. 7: Delay spread of DAT ADR system in two different environments (rooms A and B) at x=1m and at x=2m and along y-axis.

D. SNR analysis

A rectangular pulse with a duration equal to the bit period (NRZ) was employed in OOK. The SNR of the received signal can be calculated by taking into account the powers associated with logic 0 and logic 1 (P_{S0} and P_{S1}). The SNR is given by [29], [31], [32]:

$$SNR = \left(\frac{R(P_{S1}-P_{S0})}{\sigma t}\right)^2 \tag{4}$$

where R is the receiver responsivity (0.4 A/W) and σ_t is the standard deviation of the total noise, that is the sum of shot noise, thermal noise and signal dependent noise. σ_t can be calculated as:

$$\sigma t = \sqrt{\sigma_{shot}^2 + \sigma_{preamplifier}^2 + \sigma_{signal}^2} \tag{5}$$

where σ_{shot}^2 represents the background shot noise component, $\sigma_{preamplifier}^2$ represents the preamplifier noise component and σ_{signal}^2 represents the shot noise associated with the received signal. The SNR_{SC} is given by:

$$SNR_{SC} = Max_i \left(\frac{R(P_{S1}-P_{S0})}{\sigma t}\right)^2 \quad 1 \le i \le j \tag{6}$$

where j represents the number of branches (j=7 in our ADR). The MRC approach utilises all branches in the ADR. The output signals of all the detectors are combined through an adder circuit. Each input to the circuit is added with a weight proportional to its SNR to maximise the SNR. The SNR_{MRC} is given by [29], [33]:

$$SNR_{MRC} = \left(\frac{\left(\sum_{i=1}^{j} R(P_{S1i}-P_{S0i})W_i\right)^2}{\sum_{i=1}^{j} {\sigma_t}^2 {W_i}^2}\right) \tag{7}$$

where W_i is the weight of each pixel $\left(\frac{R(P_{S1}-P_{S0})}{{\sigma_t}^2}\right)$. The SNR_{MRC} can therefore be written as [29]:

$$SNR_{MRC} = \left(\frac{\left(\sum_{i=1}^{j} R(P_{S1i}-P_{S0i})\left(\frac{R(P_{S1}-P_{S0})}{{\sigma_t}^2}\right)\right)^2}{\sum_{i=1}^{j} {\sigma_t}^2 \left(\frac{R(P_{S1}-P_{S0})}{{\sigma_t}^2}\right)^2}\right)$$

$$= \sum_{i=1}^{j} \frac{\left(R^2(P_{S1i}-P_{S0i})^2\right)}{{\sigma_t}^2} = \sum_i^j SNR_i \tag{8}$$

In this paper, for the bit rate of 5 Gbps we used the p-i-n FET receiver designed in [34]. Fig. 8 shows the SNR_{SC} results against receiver location for the DAT ADR system in the two room scenarios. The DAT ADR system has a slightly lower SNR in room B at x=1m and this is due to the reduction in received power. In addition, at x=2m the SNR decreased by 3 dB in room B in all receiver locations, this is because when the receiver moves along the middle of the room some transmitters cannot be detected by the receiver due to the cubicles.

It should be noted that the results in Fig. 8 are in agreement with the general observation made in Fig. 6. For instance, the DAT ADR system in room B at x=2m had a path loss higher than that in room A, which led to a decrease in SNR. Note the variation in SNR in tandem with the path loss (see Fig. 6) due to the effects explained.

Fig. 9 illustrates the SNR_{MRC} of the DAT ADR system in the two environments. At x=1m, the simulation results of the SC and MRC techniques in rooms A and B show comparable SNR results (about 1 to 2.5 dB difference, see Figs. 8 and 9). This is due to the fact that the power received by one of the detectors is dominant, compared to other detectors, and also due to the limited number of detectors that can collect direct LOS optical signals. It is observed that at x=2m the MRC technique outperformed SC (see Figs. 8 and 9), the SNR gain was over 3 dB in all receiver locations in both environments. This is due to the two branches of ADR having received the same amount of optical signals.

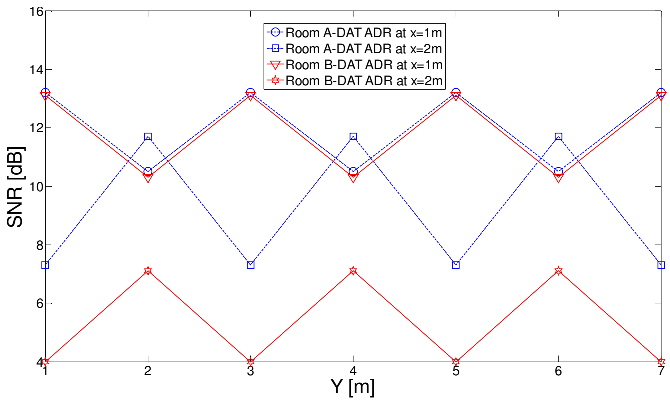

Fig. 8: SNR_{SC} of DAT ADR system in two different environments (rooms A and B) when operated at 5 Gbps at x=1m and at x=2m and along y-axis.

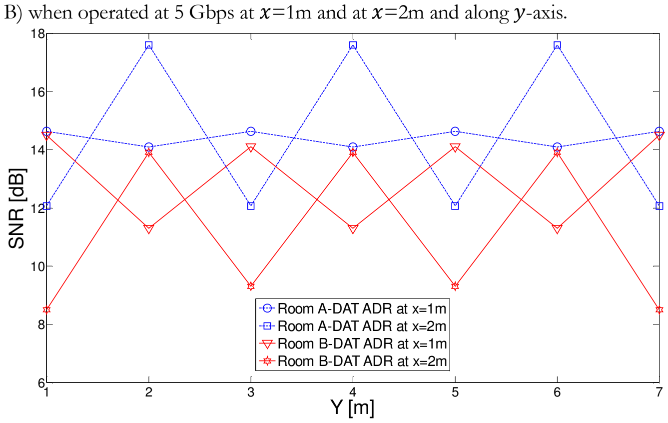

Fig. 9: SNR_{MRC} of DAT ADR system in two different environments (rooms A and B) when operated at 5 Gbps at x=1m and at x=2m and along y-axis.

The highest bit-error-rate (BER) provided by our proposed system in room A was about 10^{-5}, whereas it was approximately 10^{-3} in room B when the proposed system operated at 5 Gbps (when using MRC method). Forward error correction codes (FEC) can be used to further reduce the BER in this proposed DAT ADR system.

V. CONCLUSIONS

In this paper, we proposed, designed and evaluated a novel LD-VLC system with ADR and delay adaptation in two different environments (an empty room and a realistic room).

The DAT ADR system achieved 5 Gbps and a BER of 10^{-5} at the least successful point in the empty room with simple modulation format (OOK) and without the use of relatively complex wavelength division multiplexing approaches. However, there was degradation in the performance (BER increase) when the DAT ADR system operated in the realistic environment considered.

The DAT ADR system in a realistic room (room B) had a lower delay spread (high 3 dB channel bandwidth) but also a lower received power and overall lower SNR.

From the achieved results we can conclude that the room design can play an important role in changing the SNR distribution, delay spread and impulse response uniformity.

Future work will address methods to enhance the SNR of the LD-VLC system to achieve data rates higher than 5 Gbps.

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