White Rose Research Online
eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk
Universities of Leeds, Sheffield and York

Deposited via The University of Leeds.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/id/eprint/89028/

Version: Accepted Version

Proceedings Paper:
Hussein, AT and Elmirghani, J (2015) High-Speed Indoor Visible Light Communication System Employing Laser Diodes and Angle Diversity Receivers. In: 17th International Conference on Transparent Optical Networks (ICTON). International Conference on Transparent Optical Networks 2015, 05-09 Jul 2015, Danubius Thermal Hotel Helia, Budapest, Hungary. IEEE. ISBN: 978-1-4673-7880-2.

https://doi.org/10.1109/ICTON.2015.7193304

Reuse
Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

UNIVERSITY OF LEEDS
University of Sheffield
UNIVERSITY of York

High-Speed Indoor Visible Light Communication System Employing Laser Diodes and Angle Diversity Receivers

Ahmed Taha Hussein* and Jaafar M.H. Elmirghani, ***Senior Member IEEE***
School of Electronic and Electrical Engineering, University of Leeds, Leeds, LS2 9JT, UK
E-mail: {ml12ath, j.m.h.elmirghani}@leeds.ac.uk*

ABSTRACT
The two main challenges facing high data rate visible light communication (VLC) are the low modulation bandwidth of the current transmitters (i.e. light emitting diodes, LEDs) and the inter symbol interference (ISI) caused by multipath propagation. In this paper, we evaluate laser diodes (LDs) as a source of illumination and communication instead of LEDs for a VLC system in conjunction with an angle diversity receiver (ADR). The main advantage of using LDs is their high modulation bandwidth that enables communication at data rates of multi gigabits per second for VLC when using a suitable receiver, such as an ADR, which mitigates the ISI. Our proposed system uses simple on-off keying (OOK) modulation, and it is able to provide data rates of 5 Gbps and a bit-error-rate (BER) of 10^{-6} in the worst case scenario.
Keywords: laser diodes, angle diversity receiver, multi gigabit VLC.

1. INTRODUCTION

Visible light communication (VLC) systems have become promising candidates to complement conventional radio frequency (RF) systems due to the increasingly saturated RF band and the potential high data rates that can be achieved by VLC systems [1]. Over the last decade, significant research effort has been directed towards the development of VLC systems due to their numerous advantages over RF systems, such as the availability of simple transmitters (light emitting diodes, LEDs) and receivers (silicon photo detectors), better security at the physical layer and hundreds of THz of license-free bandwidth. However, there are several challenges facing VLC systems to achieve high data rates (multi gigabit per second). These challenges include the low modulation bandwidth of the LEDs and inter symbol interference (ISI) due to multipath propagation. Significant efforts are being directed towards finding solutions for the VLC system limitations. Among the most notable solutions are the use of pre or post equalization (or both) [2], complex multiple access and modulation techniques [3], [4], RGB LEDs [5] and parallel communication [6]. Recently, a 3 Gbps VLC system based on a single μLED using orthogonal frequency division multiplexing (OFDM) has been successfully demonstrated [7]. The highest throughput achieved by LEDs was reported in [4], which was an aggregate throughput of 3.4 Gbps using discrete multi-tone modulation (DMT), wavelength division multiplexing (WDM) and RGB LEDs. However, the complexity of the design and implementation are a major concern in these systems.

A combination of RGB lasers with a diffuser can be used to generate white light that has high quality colour rendering and efficiency [8]. Therefore, visible laser diodes (LDs) can be used as a main source of illumination instead of LEDs due to their high efficiency, especially in high power applications [9]. 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 [9]. Previous work has shown that significant enhancements in the VLC system data rates can be achieved by replacing LEDs with LDs and using an imaging receiver instead of wide field-of-view (FOV) receiver [10]. In addition, significant improvements can be achieved when VLC relay assistance is combined with the imaging receiver and delay adaptation technique [11].

Various techniques have been proposed to combat ISI in optical wireless (OW) systems. Adaptive equalization with a least mean square (LMS) algorithm has been used to achieve 1 Gbps [12]. An angle diversity receiver (ADR) is considered as a simple and efficient technique that can be used to mitigate the effects of ambient light and pulse spread in OW systems [13], [14]. 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 [15].

In this paper, we introduce LDs as the source of illumination and communication for a VLC system (LD-VLC system) in conjunction with two different receivers (wide FOV and ADR). The main goal of using LDs is to enable the VLC system to achieve multi-gigabits when employing a simple modulation technique (on-off keying, OOK), and this adds simplicity to the VLC system. In addition, an ADR is proposed for a VLC system instead of wide FOV receiver to mitigate the impact of ISI, reduce the delay spread and increase the signal to noise ratio (SNR) when the VLC system operates at high data rates under the effects of mobility and multipath dispersion. The reminder of this paper is divided into sections as follows: Section 2 introduces the design of the laser VLC system and room setup. Section 3 presents the receivers' configurations. Simulation results and discussions are presented in Section 4. Finally, conclusions are drawn in Section 5.

2. LASER VLC SYSTEM AND ROOM SETUP

To evaluate our proposed system, a simulation was conducted in an empty room with dimensions 4 m×8 m×3 m (width × length × height). Experimental measurements of plaster walls have shown that they are roughly a Lambertian reflector [16]. Therefore, all the walls (including ceiling) and the floor were modelled as Lambertian reflectors with high reflectivity (reflection coefficients of 0.3 for the floor and 0.8 for the walls and ceiling). These relatively high reflectivities (within the typically range) were selected as they result in the greatest multipath dispersion (worst case scenario), and consequently considerable pulse spread. Reflections from doors and windows are considered to be the same as reflections from walls. To model the reflections, the room was 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 transmits an attenuated version of the received signals from its centre in the same form as a Lambertian pattern with n=1, where n is the Lambertian emission order as defined in [17].

Previous research considered only line of sight (LOS) and reflections up to a first order [4], [7], [18]. However, this may not provide a full description of the characteristics of the system. Therefore, in this work, reflections up to a second order were considered, since the second reflection has a greater impact on system performance (especially at high data rates). It should be noted that reducing dA leads to improved resolution in the impulse response evaluation together with an increase in the computation time exponentially. To keep computations within practical parameters, surface elements with sizes of 5 cm × 5 cm for first-order reflections and 20 cm × 20 cm for second-order reflections were used.

The room's illumination was provided by eight RGB-LD light units that were used to ensure that ISO and European standards are satisfied [19]. Each LD light unit had nine (3×3) RGB-LD. The LD lights were installed at a height of 3 m above the floor. The specifications of the RGB-LD used in this study were adapted from practical results reported in [20]. Fig. 1a shows the architecture of the LD light units, where the light from three lasers (i.e. RGB) is combined using beam combiners, then passed through multiple ground glass diffusers to reduce speckle before illuminating the room. This design is similar to the one studied in [20]. The VLC room with the coordinates of the RGB-LD light units is shown in Fig. 1b. A number of different uniformly distributed LD light unit configurations (i.e. four, six and eight LD light units) were tested to find the optimum number of units that ensures that ISO and EU standards for illumination are 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 [19]). The height of the work desks where the transmitters and receivers associated with the user equipment were placed was 1 m. This horizontal plane was referred to as the "communication floor" (CF). The transmitted power from each RGB-LDs was 2 W. Fig. 1c shows the horizontal illumination distributions from the eight RGB-LD light units at the CF level. It is clear from this figure that there is sufficient illumination according to EU and ISO standards [19].

The simulations and calculations reported in this paper were carried out using the MATLAB program. Our simulation tool is similar to one developed by Barry et al. [21]. In our evaluation channel characteristics, optical power received, delay spread, 3 dB channel bandwidth and SNR calculations were determined in similar ways to those used in [10], [13], [17], [22].

3. RECEIVER CONFIGURATIONS

We used two types of receiver, an ADR with three branches and a single wide FOV (FOV = 90^{o}) element with photo sensitive area of 1 cm^2. The latter is the most basic receiver configuration widely investigated in previous research [16]-[18]. An ADR is a group of narrow FOV detectors pointed in different directions. The ADR consists of three branches with photodetectors that have a responsivity of 0.4 A/W each. The ADR uses a photo detector area of 4 mm^2. The ADR was always placed on the CF, and results were obtained along the lines x = 1 m or x = 2 m. The direction of each branch in an ADR is defined by two angles: the azimuth angle (AZ) and the elevation angle (EL). The AZs of the three detectors were set at 0^o, 180^o and 0^o, and the ELs for the three branches were fixed at 90^o, 60^o and 60^o. The corresponding FOVs were fixed to 30^o, 25^o and 25^o. The AZs, ELs and FOVs were chosen through an optimisation process to achieve high SNR and low delay spread. The reception angle calculations for any detector in the ADR are given in detail in [11], [13]. Fig. 1d 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. MRC can achieve better performance compared to the other methods [10], [13], [23]. Therefore, in this work the ADR LD-VLC system employed an MRC approach.

4. SIMULATION RESULTS

We evaluated the performance of the proposed LD-VLC system using a wide FOV receiver and an ADR in an empty room in the presence of multipath dispersion and mobility. The proposed systems were examined in 14 different locations when the receivers moved along the *y*-axis. The results are presented in terms of impulse response, delay spread, 3 dB channel bandwidth and SNR. Due to the symmetry of the room, the results for $x = 3$ equal the results for $x = 1$, therefore only results for $x = 1$ m and $x = 2$ m are shown along the *y*-axis.

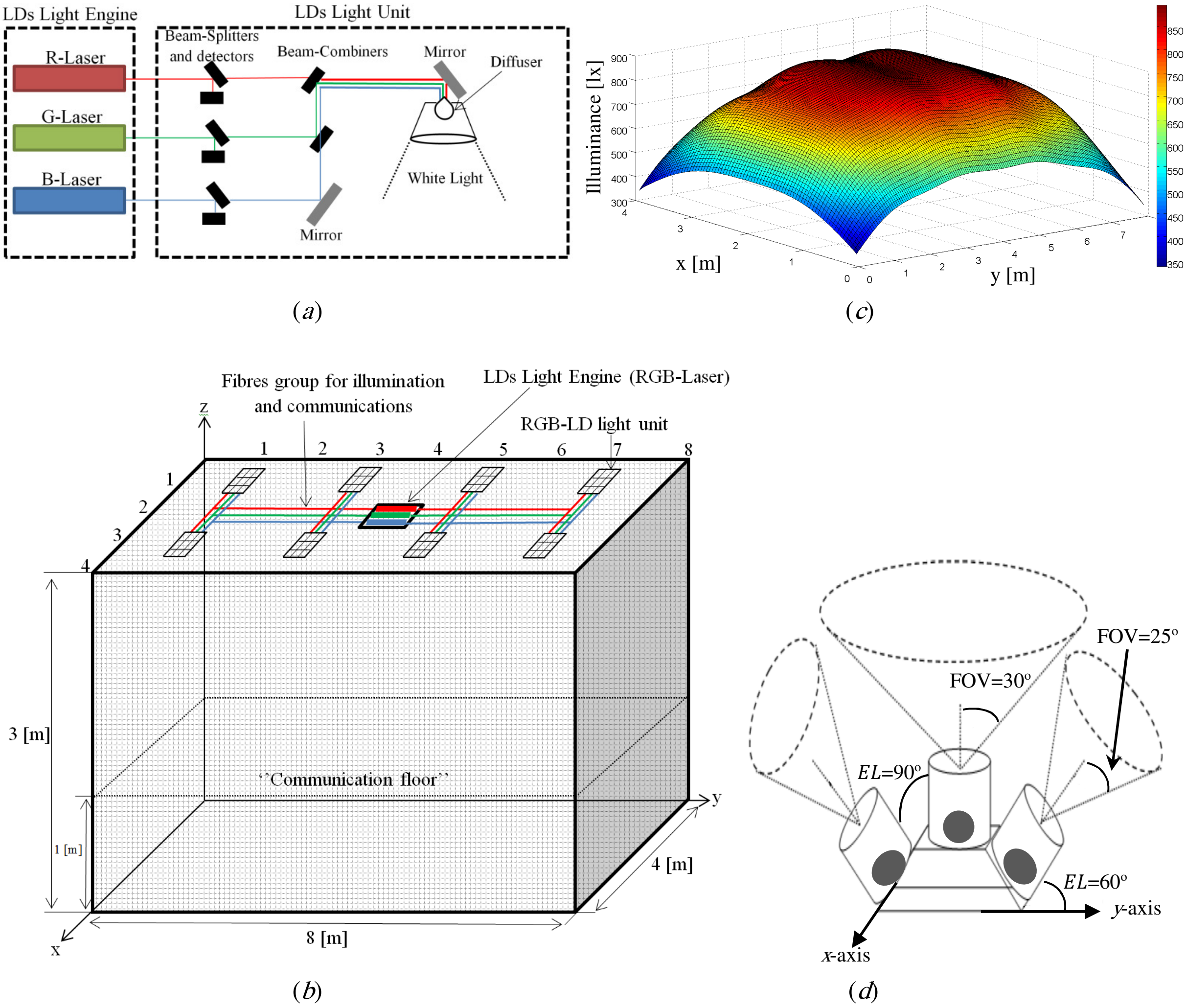


Figure 1. RGB-LD architecture, VLC system room, illuminace distribution and physical structure of ADR (a) architecture of RGB-LD white light; light from three lasers is combined using chromatic beam-combiners, then passes through multiple ground glass diffusers to reduce speckle before illuminating the room (b) VLC room (c) distribution of horizontal illumination at the communication floor, Min. 336 lx and Max. 894 lx (d) ADR with three branches.

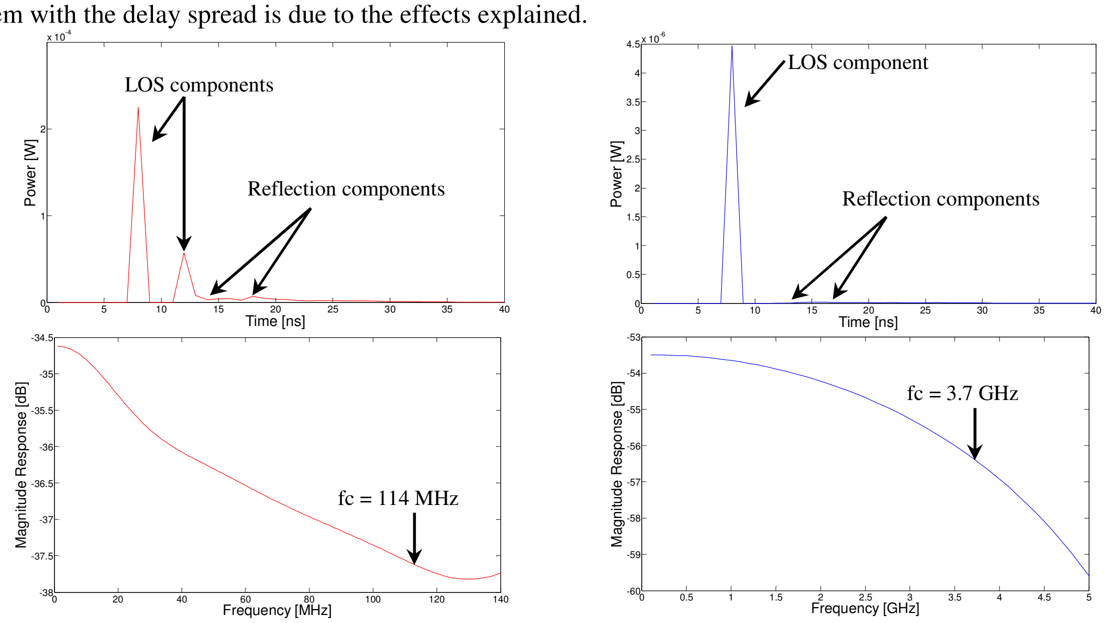
4.1 Impulse Response

The impulse responses and magnitude responses of the two receivers (wide FOV and ADR) at the room centre are depicted in Fig. 2. It can be seen that the ADR's impulse response (Fig. 2b) is better than that of the wide FOV receiver in terms of signal spread. The impulse response of the wide FOV receiver (Fig. 2a) contains many peaks that correspond to different direct LOS components coming from different RGB-LD light units. The impulse response of the wide FOV receiver also shows that the LOS as well as first and second order reflection components have a great impact on the signal, because these components cause the signal to spread over a large time-range, which is due to the wide FOV of this receiver (90°). Our simulation results show that the LD-VLC system in conjunction with an ADR increases the communication channel bandwidth from the 114 MHz offered by the wide FOV LD-VLC system to about 3.7 GHz (see Fig. 2).

4.2 Delay Spread and 3 dB Channel Bandwidth Analysis

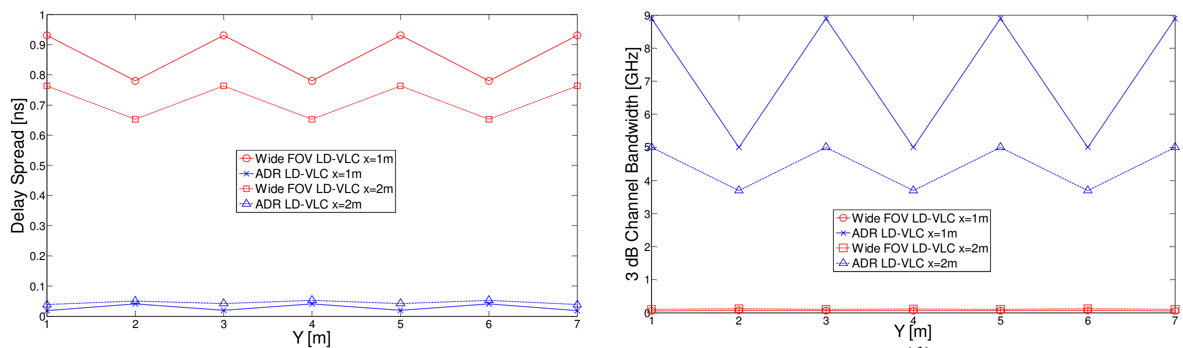
Fig. 3a presents the communication system delay spread associated with the wide FOV and ADR LD-VLC systems. The results show that the ADR LD-VLC system has a lower delay spread than the wide FOV LD-VLC system at all the receiver locations considered. In the ADR LD-VLC system, the results indicate that employing an ADR instead of a wide FOV receiver can reduce the delay spread by a factor of 12 in our system (when operating in a typical room) from 0.65 ns to 0.053 ns for the worst communication path (centre of the room, x = 2 m and y = 4 m). This improvement is due to the limited range of the rays accepted by the narrow FOV associated with each branch of the ADR. In addition, it can be noticed that when the wide FOV receiver is located under one of the LD light units (i.e. at locations x = 1 and y = 1, 3, 5, 7), the delay spread is higher than in other locations. This is attributed to the rays coming from the other LD light units (seven other LD light units) having to travel a longer distance to reach the receiver (distance between transmitters and receiver is maximum). In contrast, when the receiver is located midway between LD light units (i.e. at locations x = 2 and y = 2, 4, 6) the delay spread is the lowest. The ADR performance does not follow the wide FOV receiver, because it uses multiple detectors aimed towards different locations in the room, and each detector has a certain FOV.

Although, the transmitter modulation bandwidth problem in the VLC system can be solved by replacing LEDs with LDs, the channel bandwidth remains an issue that needs to be solved to achieve multi-gigabit per second data rates. We dealt with channel bandwidth by using an ADR instead of a wide FOV receiver. The 3 dB channel bandwidth achieved by the two receivers is shown in Fig. 3b. The results show that the ADR provides a larger bandwidth compared to the traditional wide FOV receiver. The minimum communication channel bandwidth of the wide-FOV receiver was 70 MHz at x = 1 m and y = 1 m. In contrast, the minimum channel bandwidth in the ADR LD-VLC system was 3.7 GHz at x = 2 m and y = 4 m (this value enables a data rate of up to 5.2 Gbps [24]). This increased channel bandwidth enables the VLC system to operate at higher data rates while using a simple modulation technique (OOK) [25]. At the least successful receiver location (x = 2 m and y = 4 m), a significant bandwidth enhancement can be achieved (a factor of 32 - from 114 MHz to 3.7 GHz) when our ADR VLC-LD is used instead of the wide FOV VLC-LD system. Note that the variation in channel bandwidth in tandem with the delay spread is due to the effects explained.



(a) (b)

Figure 2. Impulse and frequency responses of the two receivers, (a) wide FOV receiver (b) ADR at room centre (x=2m, y=4m, z =1m).

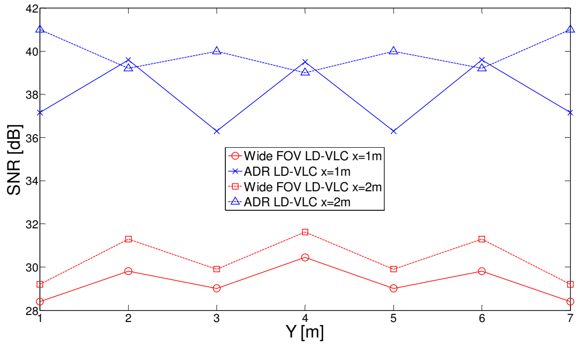


(a) (b)

Figure 3. Delay spread and 3 dB channel bandwidth, (a) delay spread in fourteen different locations when all the receivers move along the y-axis, (b) the 3 dB channel bandwidth of the two systems, when the receivers move along x=1m and x=2m.

4.3 SNR Analysis

In this study, for the bit rate of 50 Mbps we used the p-i-n BJT transimpedance preamplifier in [26]. A higher data rate of 5 Gbps was also considered, and here we used the p-i-n FET receiver design in [27]. A significant improvement in the SNR at low data rates (50 Mbps) was achieved when the ADR LD-VLC system was used instead of the wide FOV LD-VLC system. It can be clearly seen that the ADR achieves about 7 dB SNR gain over the wide FOV receiver at the centre of the room (x = 2 m and y = 4 m), which represents the worst communication paths for the ADR receiver (SNR gain is higher in other locations as shown in Fig. 4a). To evaluate the performance of the ADR system at higher bit rates, the SNR was calculated at 5 Gbps. Fig. 4b shows the SNR of the ADR when it is operated at 5 Gbps; the lowest SNR achieved by the ADR LD-VLC system was 13.5 dB in the room corner. This means that the bit error rate (BER) provided by our ADR LD-VLC system is better than 10^{-6} at 5 Gbps. The 3 dB channel bandwidth achieved by the wide FOV receiver (see Fig. 3b) does not enable it to transfer data at a rate of 5 Gbps; therefore, we only present results for the ADR at high data rates (i.e. 5 Gbps).



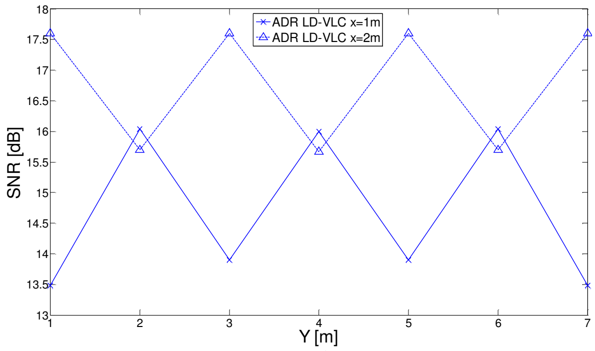


Figure 4. SNR of the wide FOV and the ADR LD-VLC systems, (a) SNR of the two systems operating at 50 Mbps (b) SNR of the ADR LD-VLC system operating at 5 Gbps and using MRC combing scheme, at x=1m and at x=2m along the y-axis.

5. CONCLUSIONS

We proposed, designed and investigated a novel LD-VLC system that uses LDs instead of LEDs as the transmitters in conjunction with two different receivers (wide FOV receiver and an ADR) to deal with the main constraints of a traditional VLC system, namely the low modulation bandwidth of the LEDs and ISI caused by multipath dispersion. Our ADR LD-VLC system has the ability to decrease the delay spread of the wide FOV LD-VLC system by 91% from 0.65 ns to 0.053 ns at the room centre (x = 2 m and y = 4 m), which leads to an increase in the channel bandwidth by a factor of 32 from 114 MHz to 3.7 GHz. Our ADR LD-VLC system provides full mobility within the test area in the presence of multipath propagation and achieves a BER better than 10^{-6} at 5 Gbps when using a simple modulation format (OOK). Future work will address methods to enhance the SNR of the ADR LD-VLC system to achieve data rates higher than 5 Gbps.

ACKNOWLEDGEMENTS

Ahmed Taha Hussein would like to acknowledge with thanks the Higher Committee for Education Development in Iraq (HCED) and the University of Mosul for financial support during his research.

REFERENCES

[1] A. T. Hussein, and J.M.H. Elmirghani, "*A Survey of Optical and Terahertz (THz) Wireless Communication Systems*," IEEE Communications Surveys & Tutorials, (to be submitted), 2015.

[2] H. L. Minh, D. C. O Brien, G. Faulkner, L. Zeng , K. Lee, D. Jung and Y. Oh, "*80 Mbit/s visible light communications using pre-equalized white LED*," in Proc. 34th European Conference on Optical Communication (ECOC), pp.1-2, 2008.

[3] A. M. Khalid, G. Cossu, R. Corsini, P. Choudhury, E. Ciaramella, "*1-Gb/s transmission over a phosphorescent white LED by using rateadaptive discrete multitone modulation*," IEEE Photonics Journal, vol.4, issue 5, pp.1465-1473, 2012.

[4] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, "*3.4 Gbit/s visible optical wireless transmission based on RGB LED*," Optics express, vol.20, no.26, pp.501-506, 2012.

[5] C. Kottke, J. Hilt, K. Habel, J. Vučić, and K. Langer, "*1.25 Gbit/s visible light WDM link based on DMT modulation of a single RGB LED luminary*," In European Conference and Exhibition on Optical Communication, vol.4, no.66, pp.1-3, 2012.

[6] Z. Xie, K. Cui, H. Zhang, and Z. Xu, "*Capacity of MIMO visible light communication channels*," In Photonics Society Summer Topical Meeting Series, pp.159-160, 2012.

[7] D. Tsonev, H. Chun, S. Rajbhandari, J. McKendry, S. Videv, E. Gu, M. Haji, S. Watson, A. Kelly, G. Faulkner, M. Dawson, H. Haas, and D. O'Brien, "*A 3-Gb/s Single-LED OFDM-Based Wireless VLC Link Using a Gallium Nitride μLED*," IEEE Photonics Technology Letters, vol. 26, no.7, pp.637–640, 2014.

[8] S. Soltic, and A. Chalmers, "*Optimization of laser-based white light illuminants*," Optics express, vol.21, no.7, pp.8964-8971, 2013.

[9] J. Wierer, J.Y. Tsao and D.S. Sizov, "*Comparison between blue lasers and light‐emitting diodes for future solid‐state lighting*," Laser & Photonics Reviews, vol.7, no.6, pp.963-993, 2013.

[10] A. T. Hussein, and J.M.H. Elmirghani, "*Mobile Multi-gigabit Visible Light Communication System in Realistic Indoor Environment*," Journal of Lightwave Technology, vol.33, issue 15, 2015.

[11] A. T. Hussein, and J.M.H. Elmirghani, "*10 Gbps Mobile Visible Light Communication System Employing Angle Diversity, Imaging Receivers and Relay Nodes*," Journal of Optical Communications and Networking, vol.7, issue 8, 2015.

[12] T. Komine, J. Lee, S. Haruyama and M. Nakagawa "*Adaptive equalization system for visible light wireless communication utilizing multiple white LED lighting equipment*," IEEE Transactions on Wireless Communications, vol.8, no.6, pp.2892-2900, 2009.

[13] A. G. Al-Ghamdi, and J.M.H. Elmirghani, "*Analysis of diffuse optical wireless channels employing spot-diffusing techniques, diversity receivers, and combining schemes*," IEEE Transactions on Communications, vol.52, no.10, pp.1622-1631, 2004.

[14] A. G. Al-Ghamdi, and J.M.H. Elmirghani, "*Characterization of mobile spot diffusing optical wireless systems with diversity receiver*," IEEE International Conference on Communications (ICC), 2004.

[15] A. G. Al-Ghamdi, and J.M.H. Elmirghani, "*Performance evaluation of a triangular pyramidal fly-eye diversity detector for optical wireless communications*," IEEE Communications Magazine, vol.41, no.3, pp.80-86, 2003.

[16] F. R. Gfeller, and U. H. Bapst, "*Wireless in-house data communication via diffuse infrared radiation*," Proc. IEEE, vol.67, no.11, pp. 1474-1486, 1979.

[17] J. M. Kahn, and J. R. Barry, "*Wireless infrared communications*," Proc. IEEE, vol.85, no.2, pp. 265-298, 1997.

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

[19] "*European standard EN 12464-1: Lighting of indoor work places*," [online] Available:*http://www.etaplighting.com/uploadedFiles/Downloadable_documentation/documentatie/EN12464_E_OK.pdf.* Last access on 01/02/2015.

[20] A. Neumann, J. J. Wierer, W. Davis, Y. Ohno, S. Brueck, and J. Y. Tsao, "*Four-color laser white illuminant demonstrating high color-rendering quality*," Optics express, vol.19, no.104, pp.982-990, 2011.

[21] J. R. Barry, J. M. Kahn, W. J. Krause, E. A. Lee, and D. G. Messerschmitt, "*Simulation of multipath impulse response for indoor wireless optical channels* ," IEEE Journal Selected Areas Communication, vol.11, no.3, pp.367-379, 1993.

[22] M. T. Alresheedi, and J.M.H. Elmirghani, "*10 Gb/s Indoor Optical Wireless Systems Employing Beam Delay, Power, and Angle Adaptation Methods With Imaging Detection*," Journal of Lightwave Technology, no.30, no.12, pp.1843-1856, 2012.

[23] A. G. Al-Ghamdi, and J.M.H. Elmirghani, "*Optimization of a triangular PFDR antenna in a fully diffuse OW system influenced by background noise and multipath propagation*," IEEE Transactions on Communications, vol.51, no.12, pp.2103-2114, 2003.

[24] Personick, S., "*Receiver design for digital fiber optic communication systems, I & II*," Bell Syst. Tech. J, vol.52, no.6, pp.843-886, 1973.

[25] F. E. Alsaadi, M.A. Alhartomi, and J.M.H. Elmirghani, "*Fast and Efficient Adaptation Algorithms for Multi-Gigabit Wireless Infrared Systems*", Journal of Lightwave Technology, vol.31, no.23, pp.3735-3751, 2013.

[26] J.M.H. Elmirghani, H. Chan, and R. Cryan, "*Sensitivity evaluation of optical wireless PPM systems utilising PIN-BJT receivers*," IEE Proceedings-Optoelectronics, vol.143, no.6, pp.355-359, 1996.

[27] B. Leskovar, "*Optical receivers for wide band data transmission systems*," IEEE Transactions on Nuclear Science, vol.36, no.1, pp.787-793, 1989.