Channel Characteristics Analysis and Experimental Demonstration of a Diffuse Cellular Indoor Visible Light Communication System

D. Wu, Z. Ghassemlooy, S. Rajbhandari and H. Le Minh,
Optical Communication Research Group, School of CEIS, Northumbria University, Newcastle Upon Tyne, UK
E-mail: dehao.wu@northumbria.ac.uk

ABSTRACT
This paper presents a spatial optical power distribution of a non-directed cellular indoor visible light communication (VLC) system using a light emitting diode (LED) and a holographic light shape diffuser (LSD). To realize a cellular system with a maximum coverage area and a minimum power consumption, both hexagonal and rectangular geometries are studied and analysed with and without the LSD. The simulation results show that more uniform optical power distribution can be achieved using the hexagonal geometry with a 30° holographic LSD diffuser compared to the rectangular cellular shape with no LSD. In addition, a practical link for a single cell is designed, which operates at a date rate of 5 Mb/s using the on-off keying non-return-to-zero (OOK-NRZ) data format. The measured results for both the received optical power and the Q-factor distributions are shown and discussed.

Keywords
Visible light communication, light emitting diodes, power distribution, cellular optical wireless communications, bit error rate

1. INTRODUCTION
LEDs are being widely used as sources in short-range indoor optical wireless communication (OWC) links for local area network (LAN). They promise numerous advantages compared with the conventional radio frequency (RF) systems, such as offering a potential huge bandwidth, a secure link as rays cannot penetrate walls or opaque objects, and freedom from spectrum regulations and licensing. Due to the fast dynamic response of most current available LEDs, they can be modulated with fast switches, enabling high transmission data rates. With the increasing popularity of high definition television and video over the internet, the indoor OWC access technology employing LEDs becomes one possible and economical solution to address the bandwidth congestion currently being experienced in most access networks [1-3]. With the availability of highly efficient white LEDs (created by combining the prime colours: red, green, and blue or by using a blue emitter in combination with a phosphor), we are witnessing a surge in research and development in indoor VLC systems. Equalization has been employed for VLC systems in [4, 5] to improve the transmission data rate. In [6, 7], the application of orthogonal frequency division multiplexing (OFDM) over a VLC channel has been investigated with significantly reduced intersymbol interference (ISI) at high transmission data rates. [8, 9] has reported a novel diffused cellular indoor VLC system with the analyses of both power and Q-factor distributions. The common link configurations for indoor OWC systems are a line-of-sight (LOS), a diffuse and a hybrid LOS-diffuse [10-12]. Normally, the diffuse system provides a larger coverage area and an excellent mobility [13, 14], but at the cost of lower data rates, higher path losses and multipath induces ISI caused by signal reflections from walls and other objects within the room. On the other hand, directed LOS links, where the beam is confined within a much narrower field of view (FOV), offers a much higher channel capacity, a higher data rate and a longer range [15, 16]. However, directed LOS links offers a reduced coverage area and in some applications it requires alignment and/or tracking systems to maintain the link availability.

To achieve higher data rates as well as a wider coverage area, a cellular system would be the preferred option [17-19]. In cellular systems, there should in principle be a minimum overlapping between coverage areas to achieve the optimum power efficiency. There are a number of cell shapes that could be adopted such as the circular, square, equilateral triangle, and the hexagonal. For a given distance between the center of a polygon and its farthest points, the hexagon has the largest area of the three [20, 21] with no un-covered regions between cells. In this paper, we analyse models for both rectangular and hexagonal shapes with and without LSD. We have adopted the hexagon shape to ensure a more uniform distribution of the optical radiation. We report a practical single cell cellular indoor VLC link employing a blue LED as the transmitter. In order to increase the cell coverage area with a uniform power distribution LSDs [22] of different angles are employed.

The rest of the paper is organized as follow. In Section II, geometries of transmitters, characteristics of LSD, the LOS channel, and receiver are described. In Section III, simulation results are shown and experimental work is outlined followed by the discussion. Finally, the conclusion is given in the last Section IV.

2. SYSTEM DESCRIPTION
2.1. System Overview
The proposed indoor cellular VLC systems are shown in Figs. 1(a) and (b). To achieve a higher transmission
bandwidth, we use the commercially popular (Luxeon Star/O) royal blue LEDs type as transmitters that are mounted at the ceiling for lighting as well as communications. In each cell, the transmitter consists of a holographic LSD to attain more a uniform optical power distribution. The full width half maximum (FWHM) divergence angles of LSD we used are 10°, 20° and 30°, respectively. At the receiving end, the optical receiver, mounted on a mobile terminal, has a dedicated FOV of 30° to ensure a seamless connectivity as well as alleviating the need for pointing and tracking schemes. Fig. 2 depicts the system block diagram of a signal cell VLC system. As shown, the data is modulated and then transmitted by LED. The light rays firstly propagate through a holographic diffuser to achieve more uniform beam profile, and then pass through the indoor OWC channel to an optical receiver. An optical filter is used in front of the receiver, which removes unexpected noise from the background light.

2.2. Transmitter
LEDs, with no light shaping lenses, can be essentially considered as the Lambertian source [10]. In many applications, however, there are requirements for specific radiation distributions to ensure a full coverage and an optimum link performance. In such cases optical beam shaping lenses are used at the transmitter. Here the light source positioned at the centre of a cell is composed of an LED and an optical lens. With the transmitter’s FWHM of 7°, the cell radius is 12.2 cm. This is equivalent to a coverage area of 474 cm². To achieve a wider coverage area with a uniform radiation distribution pattern, a holographic LSD (10°, 20°, and 30°) is employed.

2.3. Holographic LSD
Using the holographic LSD, the effective divergence angle of the transmitter can be extended as given by [22]:

\[ \theta_{\text{output}} = \sqrt{(\theta_{\text{Source}})^2 + (\theta_{\text{LSD}})^2} \]  

where \( \theta_{\text{output}} \) is the effective output angle, \( \theta_{\text{Source}} \) is the FWHM angle of source, and \( \theta_{\text{LSD}} \) is the divergence angle of LSD.

The hologram is a two-level surface relief diffractive element that affects only the phase of light passing through it. The far-field radiation pattern passing through the hologram is approximately the Fourier transform of the surface relief structure [18, 23]. In order to simplify calculation of the beam intensity through the holographic LSD, we have divided the LSD into an array of ‘pixels’ and the light intensity is considered uniform within the pixel footprint (see Fig. 3).

2.4. Optical Wireless Channel
The LOS channel DC gain for OWC system using a LED without an optical filter and an optical concentrator at the receiver is given by [24]

\[ H(0)_{ij} = \begin{cases} \frac{(m+1)A}{2m^2} & \cos^n(\phi_{ij}) \cos(\phi_{ij}), \quad 0 \leq \phi \leq \phi_c, \\ 0, & 0 \geq \phi_c \end{cases} \]  

where \( A \) is the photodetector surface area, \( \phi_{ij} \) is the irradiance angle, \( \phi_{ij} \) is incidence angle, \( \phi_c \) is the FOV (semiangle) at the receiver and \( H \) is the distance between transmitter and receiver. \( m = \frac{\ln2}{\ln(\cos\phi_{ij}/2)} \) is the order of Lambertian radiant which is related to the transmitter semiangle \( \phi_{ij} \), (at half power). The received power is given by:

\[ P_{\text{RX}} = \int P_{\text{TX}} H(0)_{ij} \]  

where \( P_{\text{TX}} \) is the transmitted optical power of LED, and \( P_{\text{RX}} \) is the received optical power at the receiving plane.
2.5. Receiver

The receiver front-end consists of a commercial PIN photodetector and a trans-impedance amplifier. The specifications for the receiver are given in Table I. The photodiode is used to convert the received optical power into the electrical current, and the output current is given as:

\[ i = P_{\text{rec}} R \]  

where \( R \) is the photodiode responsivity (A/W).

The electrical signal-to-noise-ratio (SNR) is given by:

\[ \text{SNR} = \frac{(P_{\text{rec}} R)^2}{\sigma^2_{\text{total}}} \]  

where \( \sigma^2_{\text{total}} \) is the total noise variance and it is given by [25]:

\[ \sigma^2_{\text{total}} = \sigma^2_{\text{shot}} + \sigma^2_{\text{amplifier}} \]  

where the shot-noise variance \( \sigma^2_{\text{shot}} \) is given by:

\[ \sigma^2_{\text{shot}} = 2qR(P_{\text{rec}} + P_n)B_n \]  

where \( P_n \) is the noise power of the ambient light, the noise-bandwidth \( B_n = I_2R_b \), \( R_b \) is data rate and \( I_2 \) is the noise-bandwidth factor [26].

The amplifier noise variance is given by:

\[ \sigma^2_{\text{amplifier}} = i^2_{\text{amplifier}}B_a \]  

where \( B_a \) is the amplifier bandwidth.

The total noise variance is therefore:

\[ \sigma^2_{\text{total}} = 2qR(P_{\text{rec}} + P_n)I_2R_b + i^2_{\text{amplifier}}B_a \]  

The BER for OOK modulation scheme is calculated as:

\[ \text{BER} = Q(\sqrt{\text{SNR}}) \]  

where \( Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-y^2/2} dy \).

3. RESULTS AND DISCUSSIONS

According to the description in previous section, we characterize the performance of the proposed VLC systems by simulating the received power distribution of different configurations. The system specifications and parameters are given in Table I. A different cellular geometry is considered and discussed below:

3.1. Rectangular Geometry

We have used Matlab to simulate the optical power distribution of the indoor cellular VLC system. Using (2) to (5), the normalized power distribution for a 4-cell structure (see Fig. 1(a)) is illustrated in Fig. 4. The maximum received power (-20 dBm) is normalized as 1. Fig. 4(b) is the contour plot of the power intensity at the receiving plane. It is can be seen that most of the power is concentrated near the centre of each cell decreasing sharply towards the cell edges. In a 4-cell configuration with a circular foot print, the area within dotted line circle (see Fig. 4(b)) is defined as the 3-dB power attenuation area from the centre of a cell. The rest of the area is defined as the no coverage area or the ‘dead zones’ with no optical illumination. The 3-dB coverage area \( A_{\text{cov}} \), where the power attenuation is less than 3-dB for 4-cell is around 1800 cm², is given by:

\[ A_{\text{cov}} = \sum_{i=1}^{N} A_{\text{cover}} \]  

where \( N \) is the number of cells.

The complete area of receiving plane is given by:

\[ A_{\text{total}} = A_{\text{cov}} + A_{\text{dz}} + A_{\text{ol}} \]  

where \( A_{\text{dz}} \) and \( A_{\text{ol}} \) shown in Fig. 4(b) are the ‘dead zones’ and the overlapping areas, respectively.

To achieve a uniform distribution within each cell, we have used a 30° LSD. Figs. 5(a) and (b) display predicted normalized power distributions and power density contours for a 4-cell configuration. The peak received power in the centre of cell is -29.6dBm. The 3-dB coverage area is marked in Fig. 5(b). Using (13), the total coverage area is
Fig. 4 (a). Predicted normalized power distribution at the receiving plane without LSD for 4-cell model

Fig. 4 (b). Predicted power contour plot at the receiving plane without LSD for 4-cell model

Fig. 5 (a). Predicted normalized power distribution at the receiving plane using a 30° LSD for 4-cell model

Fig. 5 (b). Predicted power contour plot at the receiving plane using a 30° LSD for 4-cell model

around 8000 cm², which is 4.4 times increase compared to a 4-cell model with no diffusers. Note the increase in the power distribution at the boundary regions, which is due to cells overlapping.

3.2. Hexagonal Geometry

Using (2) to (5), the normalized power distribution of the hexagonal geometry is depicted in Fig. 6. Fig. 6(a) illustrates power concentration near the centre of each cell decreasing sharply towards the cell edges. Fig. 6(b) is the contour plot of the power density at the receiving plane. Using the same definition of 3-dB power attenuation area in a 4-cell configuration, the simulation results show that the coverage area for a 7-cell model is around 3200 cm².

Figs. 7(a) and (b) display the predicted power distribution and the power density contours for a 7-cell hexagonal structure with a 30° LSD. The maximum received power at the cell centre is -29.6dBm. The coverage area with the 3-dB variation of intensity is around 16800 cm². Compared with a 7-cell model without diffusers, the coverage area is increased by 525%, which is 81% higher than the rectangular geometry.
3.3. Practical Measurements
To comparing with the simulating power distribution, experimental one cell VLC links has been set up and measured. Fig. 8 shows the proposed experimental cellular indoor VLC system and the profile of the divergence angle of the transmitter with the holographic LSD. The metallic frame has a dimension of 1.8×1.5×1 m³, which is divided into four or seven compartments (or cells). Each cell consists of an LED transmitter, a diffuser and an optical receiver. The separation between the source and receiver is 1 m. In this paper, we only show the practical results for a single cell at a data rate of 5 Mb/s using the OOK-NRZ modulation scheme.

Fig. 9 outlines the measured optical power distributions with and without holographic LSDs for a single cell. Comparing the power density profiles of a links with and without a 30° holographic LSD (Figs. 9(a) and (d)), it can be seen that a 3-dB transmission boundary has increased from 8 cm to 20 cm (i.e. 625% increase in the coverage area for a single cell link). The peak received power at the cell centre is -21dBm for the non-LSD scenario, and it is -30.5dBm for the case using 30° LSD.
Next we measure the eye diagrams for links with and without the holographic LSD in order to determine the Q-factor. Fig. 10 shows the spatial distribution of the Q-factor. The case without LSD is shown in Fig. 10(a). For a Q-factor > 5 corresponding to a BER < 10^{-6} (using OOK-NRZ), the effective coverage area is ~625 cm². The coverage area increases to ~1600 cm² using a 30° LSD.

As shown in Figs. 10(b) to (d) using wider angle LSDs, the Q-factor distribution becomes more uniform within a cell compared with the case with no LSD where the Q-factor is the highest at the cell centre.

4. CONCLUSION

From the simulation and experimental measurements above, some conclusions can be achieved. In this paper, we have modeled, simulated and measured the received power distributions for a practical indoor VLC link employing holographic LSDs with different degrees. The investigation has shown that by using holographic LSDs with suitable angles, a uniform power distribution can be obtained thus increasing the coverage area in indoor VLC systems. The simulation results showed that for the hexagon geometry and using a 30° holographic LSD diffuser, the received optical power distribution becomes uniform, which is 81% better than the link with a rectangular geometric and a non-LSD scenario.

ACKNOWLEDGMENT

I would like to acknowledge Dr David Johnston and Mr Andrew Burton for their help, and the support by EU Cost Actions of ICO802 and ICO110.

REFERENCES


Biographies

Dehao Wu received the Bachelor’s degree in optical and information engineering from the Nanjing University of Post & Telecommunication, P.R. China in 2007, and the M.Sc. degree in microelectrical and telecommunication engineering from Northumbria University, Newcastle, U.K., in 2009. Now he is working towards the Ph.D degree on indoor cellular optical wireless communication systems in Optical Communication Research Group at Northumbria University. His research interests include the area of optical communications, Indoor optical wireless and visible light communications.

Zabih Ghassemlooy (SM’02) received the B.Sc. (Hons.) degree in electrical and electronics engineering from the Manchester Metropolitan University, Manchester, U.K., in 1981, and the M.Sc. and Ph.D. degrees in optical communications from the University of Manchester Institute of Science and Technology (UMIST), Manchester, in 1984 and 1987, respectively with Scholarships from the Engineering and Physical Science Research Council, U.K.

From 1987–87 he worked as a Demonstrator at UMIST and from 1987 to 1988 he was a Post-doctoral Research Fellow at the City University, London. In 1988 he joined Sheffield Hallam University as a Lecturer, becoming a Reader in 1995 and a Professor in Optical Communications in 1997. He was the Group Leader for Communication Engineering and Digital Signal Processing, and also head of Optical Communications Research Group until 2004. In 2004 he moved to the University of Northumbria at Newcastle as an Associate Dean for Research in the School of Computing, Engineering and Information Sciences. He also heads the Northumbria Communications Research Laboratories within the School. In 2001 he was a recipient of the Tan Chin Tuan Fellowship in Engineering from the Nanyang Technological University in Singapore to work on the photonic technology. In 2006, he was awarded one of the best Ph.D. research supervisors at Northumbria University. He was a visiting professor at the Aicara University, Turkey and Hong-Kong Polytechnic University, and is currently a visiting Professor at the Technological University of Malaysia.

Dr. Ghassemlooy is the Editor-in-Chief of The Mediterranean Journals of Computers and Networks, and Electronics and Communications. He currently serves on the IEEE Photonics Letters, International Journal of Communication Systems, Journal of Electrical and Computer Engineering, Iranian Journal Electrical and Electronic Engineering, the EURASIP Journal of Wireless Communications and Networking, Contemporary Engineering Sciences, Research Letter in Signal Processing, Hindawi Journal of Electrical and Computer Engineering, and also has served on the Publication Committee of the IEEE TRANSACTIONS ON CONSUMER ELECTRONICS, the editorial board of the Inter and the Sensor Letters. He is the founder and the Chairman of the IEEE, IET International Symposium on Communication Systems, Network and Digital Signal Processing, a committee member of The International Institute of Informatics and Systemics, and is a member of technical committee of a number of international conferences. He is a College Member of the Engineering, and Physical Science Research Council, UK (2003-2009) and (2009-), and has served on a number of international Research and Advisory Committees. His researches interests are on photonics switching, optical wireless and wired communications, visible light communications and mobile communications. He has received a number of research grants from U.K. Research Councils, European Union, Industry and U.K. Government. He has supervised a large number of Ph.D. students (more than 33) and has published over 380 papers (129 in journals + 9 book chapters) and presented several keynote and invited talks. He is a co-editor of an IET book on Analogue Optical Fibre Communications, the proceedings of the CSNDSP ’2010, ’08, ’06, CSDSP’98, and the 1st International Workshop on Materials for Optoelectronics 1995, UK. He is the co-guest editor of a number of special issues: The Mediterranean Journal of Electronics and Communications on “Free Space Optics-RE”, July 2006, the IEE Proceeding Journal 1994, and 2000, IET Proceeding Circuit, Devices and Systems, Special issue on the best papers for CSNDSP Conference, 2008, IEE Proceeding Circuit, Devices and Systems, Special issue on the best papers for CSNDSP conference, 2006, International Journal Communication Systems 2000, Journal of Communications 2009, Ubiquitous Computing and Communication Journal —Selected papers from CSNDSP 08 conference, 2009, International Journal of Communications—Special issue on Optical Wireless Communications, 2009. From 2004-06 he was the IEEE UK/IR Communications Chapter Secretary, the Vice-Chairman (2004-2008) and the Chairman (2008-2011).

Sojan Rajbhandari (M’08) received the Bachelor’s degree in electronics and communication engineering from the Institute of Engineering, Pulchowk Campus, Tribhuvan University, Kathmandu, Nepal, in 2004, and the M.Sc. and Ph.D. degrees in electrical/electronic engineering from Northumbria University, Newcastle, U.K., in 2006 and 2010, respectively. His Ph.D. dissertation was focused on indoor optical wireless communications.

Since 2009, he has been with the Optical Communication Research Group at Northumbria University as a Postdoctoral Researcher. His research interests include the area of optical communications, free-space optics, modulation techniques, equalization, error control code artificial intelligence, and wavelet transform.

Dr. Rajbhandari has served as a Reviewer for several leading publications including the JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, and several international conferences. He is a co-editor of the proceedings of the NOC 2011.

Hoa Le Minh received the Bachelor’s from Hochiminh city University of Technology, Vietnam in 1999, the M.Sc. degree from Munich University of Technology, Germany in 2003 and Ph.D. degrees in electrical/electronic engineering from Northumbria University, Newcastle, U.K., in 2007. From 1999-2001, he was a lecturer in Faculty of Electrical and Electronics Engineering, Hochiminh city University of Technology, Hochiminh, Vietnam. From 2002-2004, he was a research assistant in Carrier Products, R&D Department, ICN - CP D NT OS 2 Optical Solutions Siemens AG, Munich, Germany. From 2004-2007, he was a part-time lecturer in School of Computing, Engineering and Information Sciences, Northumbria University, UK. From 2007-2010, he was the research fellow in Dept. Engineering Science, University of Oxford, UK. In 2009, He was the tutor in St. Edmund College, University of Oxford, UK. From 2010-now, he is the Senior Lecturer in School of Computing, Engineering and Information Sciences, Northumbria University, UK. His research interest includes Photonics networks, all-optical switching, processing, optical fibre communications, Indoor/outdoor optical wireless and visible light communications.