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Indoor Non-directed Optical Wireless Communications - Optimization of the Lambertian Order

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ABSTRACT

For an indoor non-directed line of sight optical wireless communication (NLOS-OWC) system we investigate the optimized Lambertian order (OLO) of light-emitting diodes (LEDs). We firstly derive an expression for the OLO from a conventional Lambertian LED model. Then, we analyze the indoor multi-cell NLOS-OWC channel characteristics including the optical power distribution and the multipath time dispersion for two cases of one-cell and four-cell configurations. Furthermore, we estimate the transmission bandwidth by simulating the channel frequency response. Numerical results presented show that, by using OLO a significant improvement of the transmission bandwidth can be achieved for an indoor NLOS-OWC system, in particular, for multi-cell configurations.

1. Introduction

Compared to RF communications, indoor OWC systems promise a higher transmission bandwidth due to their inherent optical frequencies. With the increasing requirement of higher speed, higher power efficiency, lower path loss and lower multi-path distortion in future optical wireless local area network (WLAN), a directed line-of-sight (LOS) indoor OWC system, which has an extremely high bandwidth has attracted more attention in recent years [1, 2]. Due to the small divergence angle of the transmitter, the path loss is much lower and the multipath induced distortion is negligible. Moreover, a directed LOS link normally employing a photo detector (PD) with a smaller surface offers a large bandwidth and improved sensitivity [3]. Such links require a very precise alignment between the transmitter and receiver particularly when the user is mobile. Additionally, in the directed LOS configurations the field of view (FOV) of the receiver is quite narrow to ensure reduced ambient light noise, but at the cost of an increased transmission path blocking. On the other hand, diffuse configurations can provide a larger coverage area and an excellent mobility, but at a cost of low data rates, high path losses and multi-path induced inter-symbol interference (ISI) [4, 5]. Compared with the LOS transmission, NLOS links offer a larger coverage area and an excellent mobility and without any need for precise alignment or a tracking mechanism. Compared with the common diffuse configurations [6], NLOS-OWC links provide a lower path loss, lower ISI, and a higher transmission bandwidth. Therefore, NLOS-OWC links employing wide-angle transmitters and receivers are more convenient to use, particularly for mobile terminals.

LEDs are being widely used as sources in short-range indoor OWC links for local area network (LAN) [7, 8]. Due to the fast dynamic response of most currently available LEDs, they can be switched on and off at a much faster rates, thus enabling high speed data transmission [9]. With the increasing popularity of high definition television and video over the Internet, the indoor OWC access technology employing LEDs becomes a possible and economical solution to address the bandwidth congestion currently being experienced in most access networks [10, 11].

Most current research on NLOS-OWC systems has been focused on a uniform received power distribution as well as on the techniques to reduce ISI. A uniform received power distribution for NLOS-OWC systems using a novel genetic algorithm was proposed in [12, 13] without increasing the multipath distortion. In [14], the authors introduced a novel LED arrangement in order to reduce SNR fluctuations. In [15, 16] the analysis of multipath time dispersion for the indoor OWC channel was carried out for NLOS-OWC system. It was shown that lower multipath distortion can be achieved by optimizing the divergence angle of LED and by employing a special configuration. However, a more uniform optical power distribution was proposed in [17, 18] achieving lower ISI by employing a holographic diffuser. In [19] a system employing spotlights for higher data rate transmission was reported, demonstrating that indoor NLOS-OWC links using LEDs with small divergence angles offer lower channel distortion than those with large divergence angles. Therefore, to achieve a higher transmission bandwidth and a more uniform optical power distribution, multi-cell NLOS-OWC systems are the preferred solution. However, in previous studies little attention has been given to OLO of LEDs and its impact on the time dispersion and the channel transmission bandwidth. As a matter of fact, the divergence angle is an essential parameter of an LED and it significantly affects the received power distribution and the channel distortion in indoor NLOS-OWC systems.

The OLO is defined as the optimum divergence angle of LED for an indoor OWC system. By using OLO, we minimize the path loss of the received optical signal. Meanwhile, compared to a system using a standard divergence angle of the LED (120° for a conventional LED without lenses), the multipath distortion can significantly be reduced. However, OLO depends on the number of cells employed in the system. In this paper, a multi-cell NLOS-OWC links with OLO is proposed. Using the conventional Lambertian model, we derive a new expression for OLO followed by investigation of the received power distribution for two cases of one-cell and four-cell configurations, considering optimized and non-optimized LED divergence angles. To estimate the multipath time dispersion of the channel, the root-mean-square (RMS) delay spread with and without the angle optimization are simulated. Lastly, the transmission bandwidth of the proposed multi-cell NLOS-OWC channel is analyzed. The rest of the paper is organized as follows. In Section 2, we present the system configuration, and describe the channel DC gain, OLO, and multipath characteristics. In Section 3, we present some numerical results to study the channel characteristics in different scenarios of LED positioning and angle distribution. Finally, the conclusions of this work are summarized in Section 4.

2. System Description

A. System configuration

The proposed one-cell and four-cell indoor NLOS-OWC systems are shown in Fig.1, where the room has a dimension of $W \times L \times H$ m^3 (width, length, height). The link depicted in Fig. 1(a) has only one cell to cover the receiver plane, which employs a group of LEDs. In this case the optical footprint has its maximum and minimum intensities at the center and the edge of the cell, respectively. To achieve a more uniform optical power distribution, a four-cell topology can be adopted as shown in Fig. 1(b). The ceiling is divided into n-cell labelled as C_i and having identical footprints with a radius r (projecting onto the floor). An LED transmitter T_x is mounted at the center of each cell, pointing downward to the floor plane. The divergence angles and the transmitted optical power of LEDs for all cells are assumed to be the same, so that each cell has a similar coverage area on the floor plane. On the floor plane, the optical receiver R_x has a dedicated FOV of φ_c and is oriented toward the ceiling to ensure seamless connectivity. As it is shown in Fig. 1, for each cell C_i, the received optical power at the receiver end consists of the power from both the LOS from $C_i$and multiple reflected paths from the neighboring cells.

B. Channel model with Lambertian source

The emission from an LED can be modeled using a generalized Lambertian radiant intensity [20]. In NLOS-OWC configurations, the transmitters located in the ceiling, point downward to the floor and the receiver is pointing to the ceiling. The DC gain of the indoor LOS OWC channel is given by [20]:

$$H(0) = \begin{cases} \frac{(m+1)A}{2\pi d^2}\cos^m(\phi)T_s(\theta)g(\theta)\cos(\theta), & 0 \le \theta \le \varphi_c \\ 0, & \theta \ge \varphi_c \end{cases}, \quad (1)$$

where A is the photo-detector surface area, ϕ is the irradiance-angle, θ is incidence angle, φ_c is the FOV (semiangle) of the receiver and d is the distance between transmitter and receiver. Also, $T_S(\theta)$ is the optical filter gain, and $g(\theta)$ is the optical concentrator gain. m is the Lambertian radiant order relating to the transmitter semiangle $\varphi_{1/2}$, (at half power), which is given by [20]:

$$m = -\frac{\ln 2}{\ln(\cos\varphi_{1/2})}, \quad (2)$$

The output power of a Lambertian radiant radiated into the solid angle $d\Omega$ based on the irradiance-angle ϕ can be presented as [21]:

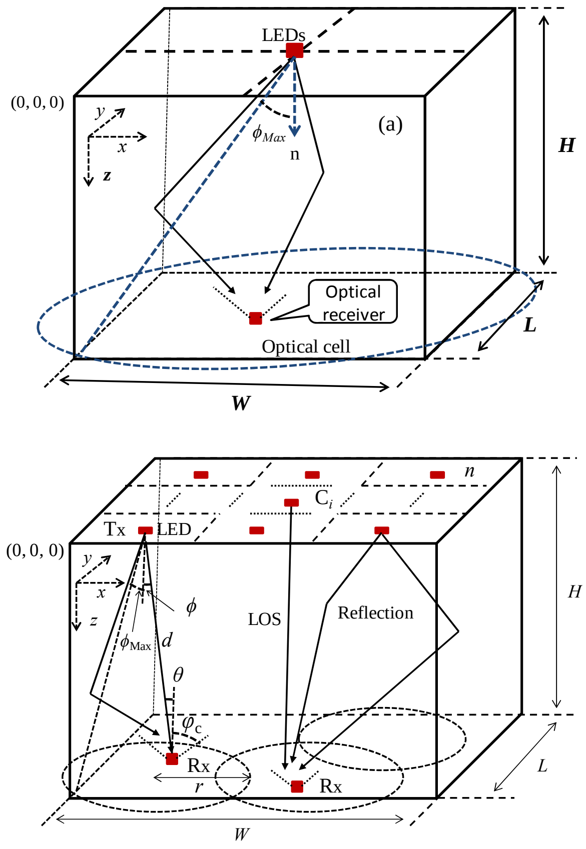

Figure 1: Indoor non-directed cellular OWC systems: (a) one cell, and (b) four cells

$$dP_i = \frac{(m+1)}{2\pi} P_i \cos^m(\phi) d\Omega \,, \tag{3}$$

where

$$P_{\text{Tx}} = \int_{\text{Hemisphere}} dP_i \,,$$

P_{TX} is the total LED transmit optical power within C_i.

In practice, the semi-angle at half power of a Lambertian beam can be adjusted using some optics. Therefore m varies with the divergence angle of the Lambertian beam, which can be adapted for an indoor COWC link. For instance, a semi-angle at the half power down to $\phi_{1/2} \cong 7^{\text{o}}$presents$m \cong 110$.

Assuming the optical receiver consists of a PD, for the multi-transmitter system, the received optical power of the LOS path is given by:

$$P_{\text{Rx LOS}} = P_{\text{Tx}} H(0) \,. \tag{4}$$

where, P_{Tx} is the overall transmitted optical power of LEDs.

C. Optimum Lambertian order

In indoor NLOS-OWC systems, the received optical power consists of the power of the LOS path and the reflected paths. Due to different multipath propagation delays, the ISI would limit the transmission bandwidth. To circumvent this problem and to achieve a higher transmission bandwidth, we should maximize the optical power from the LOS path and minimize ISI. The received optical power from the LOS can be calculated using (1) to (4). For each cell shown in Fig.1, the received optical power is maximum at $\phi = 0$ and minimum at $\phi = \phi_{\text{Max}}$. The corresponding minimum received power which varies with m is:

$$P_{\text{Min}} = P_{\text{Tx}} \frac{(m+1)A}{2\pi d_{\text{Max}}{}^2} \cos^m(\phi_{\text{Max}}) T_s(\theta) g(\theta) \cos(\theta) \,, \quad 0 \le \theta \le \varphi_c \tag{5}$$

where

ϕ_{Max} is the maximum irradiance angle and d_{Max} is the corresponding maximum distance between the transmitter and the receiver within a cell. To increase P_{Min} , it is necessary to maximize P_{Min} for a given$m$. To do this, we calculate the partial derivative of (5) with respect to m, which is given by:

$$\frac{\partial P_{\text{Min}}}{\partial m} = P_{\text{Tx}} T_s(\theta) g(\theta) \cos(\theta) \frac{A}{2\pi d_{\text{Max}}{}^2} \cos^m(\phi_{\text{Max}}) \times \{1 + (m+1)\ln(\cos(\phi_{\text{Max}}))\} \,. \tag{6}$$

Defining $K = P_{\text{Tx}} T_s(\theta) g(\theta) \cos(\theta) \frac{A}{2\pi d_{\text{Max}}{}^2}$, which is independent of m, (6) can be simplified to:

$$\frac{\partial P_{\text{Min}}}{\partial m} = K \cos^m(\phi_{\text{Max}}) \{1 + (m+1)\ln(\cos(\phi_{\text{Max}}))\} \,. \tag{7}$$

To find the OLO m_{opt} , we set $\frac{\partial P_{\text{Min}}}{\partial m} = 0$, which gives:

$$m_{\text{opt}} = \frac{-1}{\ln(\cos(\phi_{\text{Max}}))} - 1, \tag{8}$$

Given the definition of ϕ_{Max} above, we have:

$$\phi_{\text{Max}} = \cos^{-1}(\frac{H}{d_{\text{Max}}}). \tag{9}$$

From (2) and (8), we can calculate the optimum transmitter semi-angle $\varphi_{1/2\,\text{opt}}$ at half power, which is given by:

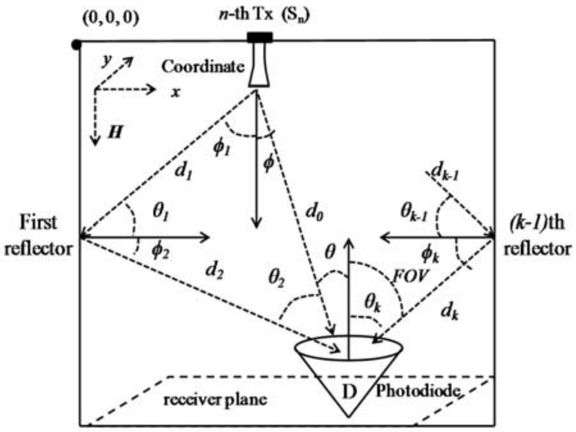

Figure 2: Geometry of source, detector and reflectors

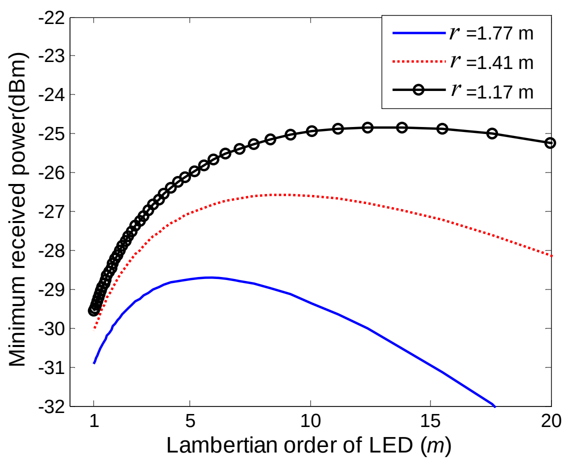

Figure 3: Minimum received optical power within a cell against the Lambertain order at a range r

$$\varphi_{\frac{1}{2}\text{opt}} = \cos^{-1}\left(\exp\left(\frac{-\ln(2)}{\frac{-1}{\ln(\cos(\phi_{\text{Max}}))} - 1}\right)\right), \quad 0 < \varphi_{1/2\,\text{opt}} < 90^o. \tag{10}$$

D. Multipath characteristics

As explained previously, in high data rate indoor NLOS-OWC systems, the path loss and the multipath-induced time dispersion limit the link performance. The maximum available data rate can be predicted if the channel impulse response $h(t)$ and the RMS delay spread are known. As shown in Fig. 2, the optical power distribution and the multipath dispersion at the receiver plane can be characterized by $h(t)$. For an NLOS-OWC channel, using (1) and (2), the impulse response for a particular source S and a detector D (x, y, z), is given by [15]:

$$h^0(t; S, D) = \frac{(m+1)A}{2\pi d^2}\cos^m(\phi)T_s(\theta)g(\theta)\cos(\theta)\text{rect}\left(\frac{\theta}{\varphi_c}\right)\delta\left(t - \frac{d_0}{c}\right), \tag{11}$$

where d is the LOS distance between S and D and c is the speed of light. The rectangular function $\text{rect}(x)$ is defined as:

$$\text{rect}(x) = \begin{cases} 1 & \text{for}|x| \le 1, \\ 0 & \text{for}|x| > 1. \end{cases} \tag{12}$$

Assuming that all reflectors (i.e. plaster and acoustic-tiled walls, unvarnished wood) are approximately Lambertian[16], the channel impulse response with multiple optical sources and multiple reflections is [22]:

$$h(t;\ S, D) = \sum_{n=1}^{N_{\text{source}}}\sum_{k=0}^{\infty} h_n^k(t;\ S, D) \tag{13}$$

The channel impulse response for a k-bounce is given by[23]:

$$h^k(t;\ S, D) = \int_{\Psi}\left[\xi_0\xi_1 \ldots \xi_k\rho^k\text{rect}\left(\frac{\theta_k}{\varphi_c}\right) \times \delta\left(t - \left(\frac{\sum_{k=0}^{\infty} d_k}{c}\right)\right)\right] dA_{\text{ref}}\ , \quad k \ge 1 \tag{14}$$

where

$$\xi_0 = \frac{(m+1)A}{2\pi d^2}\cos^m(\phi_1)\cos(\theta_1)\, dA_{ref}\cos\theta_1$$

$$\xi_1 = \frac{dA_{ref}\cos\phi_2\cos\theta_2}{\pi d_2^2}$$

$, \ldots ,$

$$\xi_k = \frac{A\cos\phi_{k+1}\cos\theta_{k+1}}{\pi d_{k+1}^2}T_s(\theta_{k+1})g(\theta_{k+1}).$$

The integration in (14) is performed with respect to the surface of all reflectors, dA_{ref} is being the small area of the reflecting element, and ϕ_k and θ_k are the angles of irradiance and incidence, respectively. Also $d_k$is the distance from k bounces to the detector (see Fig. 2).

The RMS delay spread is given by [24, 25]:

$$S = \left[\frac{\int(t-\mu)^2h^2(t)dt}{\int h^2(t)dt}\right]^{\frac{1}{2}}, \tag{15}$$

where μ is the mean delay given by:

$$\mu = \frac{\int th^2(t)dt}{\int h^2(t)dt}, \tag{16}$$

And t is the propagation delay time.

TABLE I
SPECIFICATION FOR INDOOR NLOS OWC SYSTEMS

LED wavelength (λ)	(500~1000) nm
LED launched power	200 mW
LED spacing	0.05 m
Room (length, width, height)	5 × 5 × 3 m³
Half angle FOV of receiver	60 (deg)
Active area of photodiode	1 cm²
Gain of the optical filter	1.0
Refractive index of the lens at the photodiode	1.5
Reflection coefficient (wall, ceiling, floor)	(0.8, 0.8, 0.3)
One-cell configuration	
Number of LEDs per cell	144
Four-cell configuration	
Number of LEDs per cell	36
Cell size	2.5 × 2.5 m²

3. NUMERICAL RESULTS AND DISCUSSION

Here, we present some numerical results to study the channel characteristics of multi-cell indoor NLOS-OWC systems. The specifications and parameters are given in Table I. Two different configurations are considered and simulated.

A. Optical channel path loss

With reference to the cell radii of different scenarios, shown in Table I, OLOs can be calculated using (8) and (9), which are $m_{\mathrm{opt}} = 5.7$ for $r = 1.77$ m, $m_{\mathrm{opt}} = 9$ for $r = 1.41$ m and $m_{\mathrm{opt}} = 13$ for $r = 1.17$ m, respectively. Alternatively, using (5) and (8), normalizing the total launched power to 1 W, we have plotted in Fig. 3 the minimum received power as a function of m to determine OLO. We notice that P_{Min} increases with m attaining its maximum values at m= m_{opt}, and then gradually decreases. By employing OLO, the full width at half maximum (FWHM) divergence angles of LEDs have been adjusted from 120º (the standard divergence with $m = 1$) to 56º for four-cell configuration. In addition, Fig. 3 shows that for an indoor COWC system employing OLO rather than using the standard LO $m = 1$, the minimum received optical power increases from -30.9 dBm to -28.7 dBm for $r = 1.77$ m, from -30.1 dBm to -26.6 dBm for $r = 1.41$ m and from -29.6 dBm to -24.8 dBm for $r = 1.17$ m. Moreover, we notice a sharp decrease in the optimum received power for $r = 1.77$ m when the value of m deviates from m_{opt}. This illustrates that optimizing m is critical for large area cells.

B. Optical power distribution

The spatial distributions of the received power from LOS for the one-cell and four-cell configurations are shown in Figs. 4(a) to (d) for the cases of non-optimized and optimized divergence angles. From Fig. 4(a), we notice that in the case of one-cell configuration with a typical (non-optimized) FWHM the divergence angle of 120º, the received power varies between -5.8 dBm to -13.3 dBm. Using (10), the optimized FWHM angle of the LED is ~108º and the corresponding OLO is ~1.3. The received power in the OLO case varies between -5.2 dBm to -13.3 dBm as can be seen in Fig. 4(b). Comparing Figs. 4(a) and (b), we notice that the maximum received power from LOS is only slightly increased by optimizing the divergence angle.

Similarly, Figs. 4(c) and (d) compare the received power of the four-cell configuration with and without the divergence angle optimization, respectively. From (10), the optimized FWHM angle of the LED is 56º and corresponding OLO is ~5.57. The received power varies between -8.4 dBm and -12.4 dBm for the non-optimized angle (120º FWHM) and between -5.6 dBm and -11.7 dBm for the optimized angle. In this case, angle optimization allows additional 0.7 dB and 2.8 dB for minimum and maximum received powers, respectively.

C. RMS delay spread

At the receiver the link performance could considerably be affected by the ISI. Here, we investigate the channel delay dispersion for the proposed configurations as shown in Figs. 5 (a) to (d) which depicts the RMS delay spreads of different configurations with and without angle optimization. We notice that the optimized and non-optimized scenarios have similar distributions and the RMS delay spread varies by 0.3 ns and 0.6 ns for the one-cell systems. The maximum RMS delay spread occurs at positions (0.5, 0.5, 3) m, (0.5, 4.5, 3) m, (4.5, 0.5, 3) m and (4.5, 4.5, 3) m.

For the four-cell configuration, we see from Figs. 5(c) and (d) that the maximum RMS delay spreads correspond to the positions (0, 0, 3) m, (0, 5, 3) m, (5, 0, 3) m and (5, 5, 3) m for the non-optimized case, and (2, 2, 3) m, (4, 2, 3) m, (2, 4, 3) m and (4, 4, 3) m for the optimized case. There is a significant RMS reduction after optimization: it decreases from 1.5 ns to 0.4 ns.

D. Transmission bandwidth

Since the largest multipath distortion occurs at the point with the maximum RMS delay spread in a typical room, the transmission bandwidth constraint can be estimated by simulating the frequency response at this point. Following the above analyses of maximum RMS delay spread for different configurations, the normalized channel frequency responses at the position corresponding to the largest RMS delay spread for the one-cell and four-cell configurations are plotted in Fig. 6. We notice that the -3 dB transmission bandwidth of the optimized one-cell system is ~94 MHz, which is slightly larger than the 91 MHz bandwidth of the non-optimized case. In the case of four-cell system, the -3 dB transmission bandwidth for the optimized case has a significant improvement compared to the non-optimized case. It increases from 39 MHz for the non-optimized configuration to 185 MHz with angle optimization.

4. CONCLUSION

In this paper, we have derived the OLO for a particular indoor OWC configuration and in particular analyzed the performance for one-cell and four-cell systems using the optimum and non-optimum Lambertian orders. The channel characteristics including optical received power distribution and multipath dispersion were also simulated and analyzed. The results presented outlined that the received optical power and the transmission bandwidth can be improved by adopting LO optimization. While this improvement factor depends on the room dimension and the number of cells, it is much more significant for indoor multi-cell configurations.

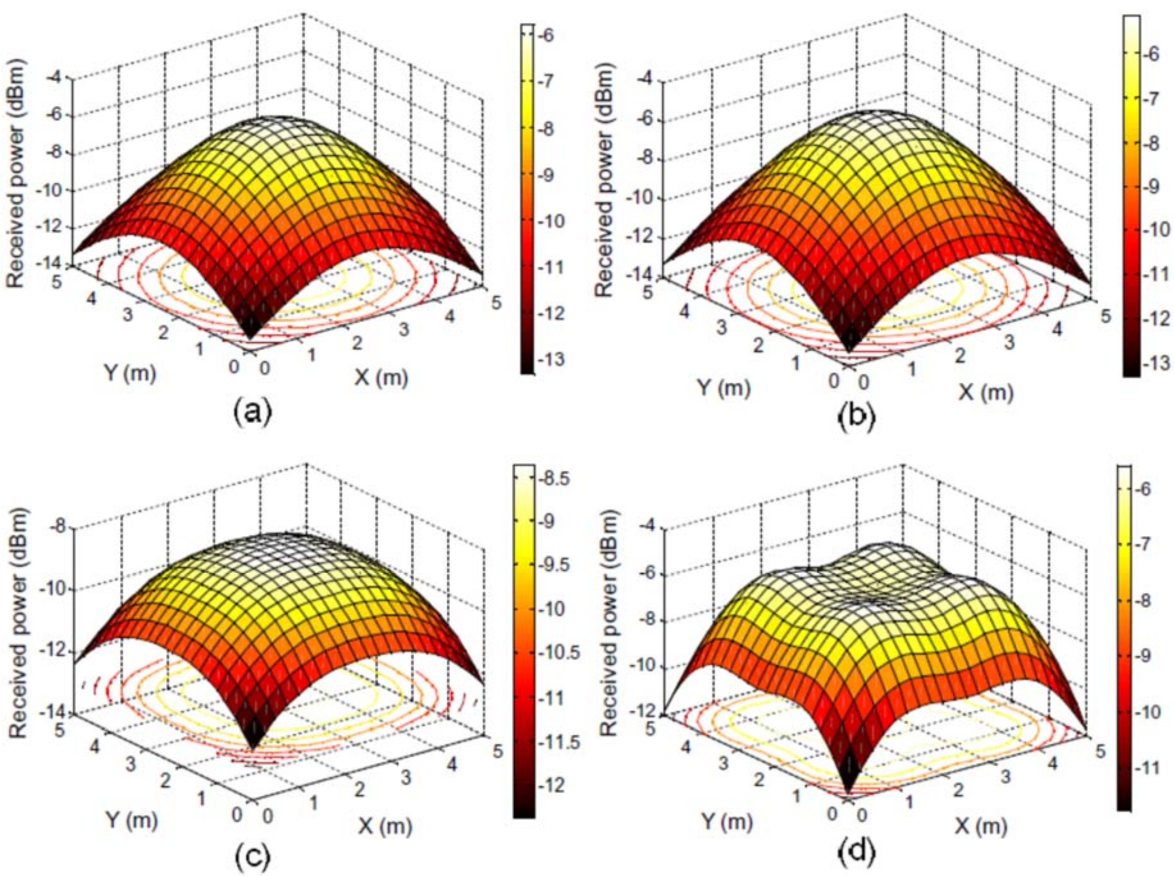

Figure 4: Spatial distribution of the received power: (a) one-cell with 120° FWHM angle, (b) one-cell with the optimum 108° FWHM angle, (c) four-cell with 120° FWHM angle, and (d) four-cell with the optimum 56° FWHM angle

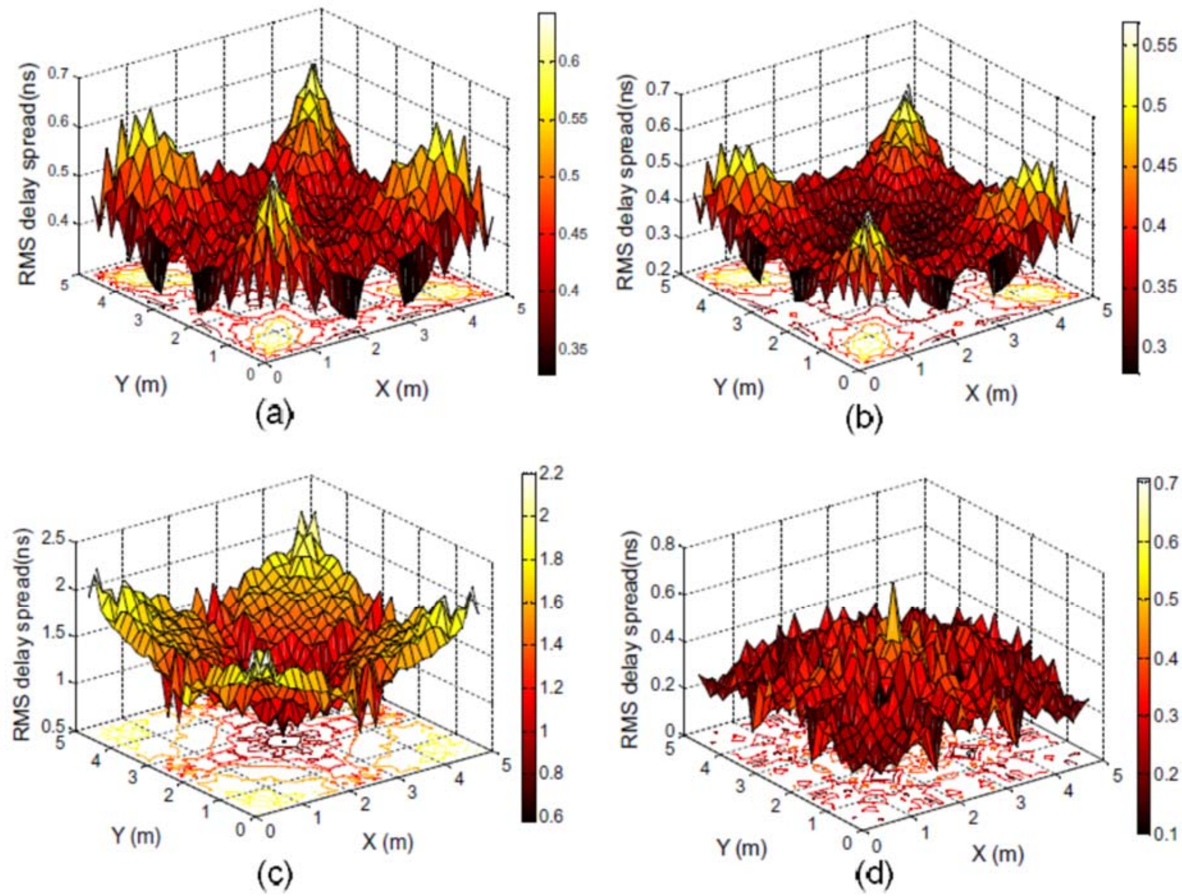

Figure 5: Spatial distribution of RMS delay spread: (a) one-cell with 120° FWHM angle, (b) one-cell with 108° FWHM angle, (c) four-cell with 120° FWHM angle, and (d) four-cell with 56° FWHM angle

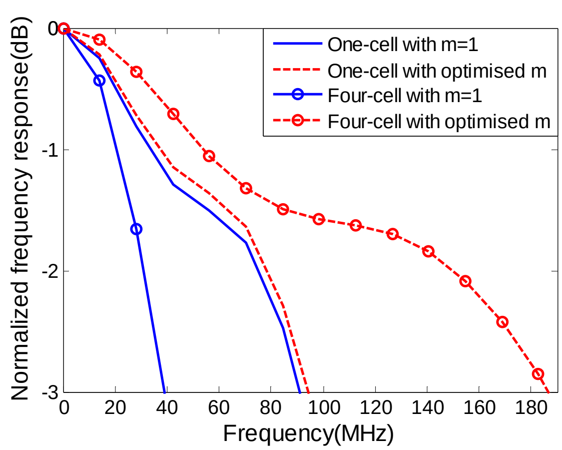

Figure 6: The channel frequency response at maximum RMS delay spread point for one-cell and four-cell configurations

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BIOGRAPHIES

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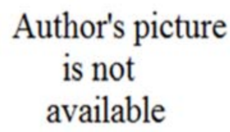
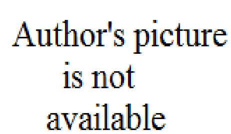
From 1986-87 worked in UMIST and from 1987 to 1988 was a Post-doctoral Research Fellow at the City University, London. In 1988, he joined Sheffield Hallam University as a Lecturer, becoming a Reader in 1995 and a Professor in Optical Communications in 1997. From 2004 until 2012 was an Associate Dean for Research in the School of Computing, and Engineering, and in 2012 he became Associate Dean for Research and Innovation in the Faculty of Engineering and Environment, at Northumbria University in Newcastle, UK. He also heads the Northumbria Communications Research Laboratories within the Faculty. 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. He is the Editor-in-Chief of the International Journal of Optics and Applications, and The Mediterranean Journal Electronics and Communications. He is the vice-chairman of the FP7 EU Cost Action IC1101 (2011-2015), and founder and chairman of IEEE, IET International Symposium on Communication Systems, Networks, and digital signal processing.He is a visiting Professor at University Tun Hussein Onn Malaysia. His research interests are in free space optics, photonics switching, optical wireless and wired communications, visible light communications and mobile communications. He has received a number of research grants from UK Research Councils, European Union, Industry and UK Government, has supervised a large number of PhD students (more than 40) and published over 455 papers (162 in journals + 4 books) and presented several keynote and invited talks at international event. He is a co-author of a CRC book on "Optical Wireless Communications – Systems and Channel Modelling with Matlab (2012); a co-editor of an IET book on "Analogue Optical Fiber Communications". From 2004-06 he was the IEEE UK/IR Communications Chapter Secretary, the Vice-Chairman (2004-2008), the Chairman (2008-2011), and Chairman of the IET Northumbria Network (Oct 2011-). Personal Web site: http://soe.northumbria.ac.uk/ocr/people/ghassemlooy/



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 received 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 in indoor cellular optical wireless communication systems in Optical Communication Research Group at Northumbria University. His research interests include the area of free-space optics, indoor optical wireless communications (OWC), modulation techniques and FPGA based protocols in OWC.

Mohammad-Ali Khalighi received his B.Sc. and M.Sc. degrees in Electrical Engineering from Sharif University of Technology, Tehran, Iran, in 1995 and 1997, respectively, and his Ph.D. in Electrical Engineering (Telecommunications) from Institut National Polytechnique de Grenoble (INPG), France, in 2002. From 2002 to 2005, he has been with GIPSA-lab, Télécom Paris-Tech (ENST), and IETR-lab, as a post-doctoral research fellow. He joined EcoleCentrale Marseille and Institut Fresnel in 2005 as an Assistant Professor. His main research areas of interest include optical wireless communication and wireless sensor networks.



Xuan Tang received the diploma (with Hons) in electrical engineering from Nan Yang Polytechnic, Singapore in 2007, and BEng (1st class Hons) degree in Electrical and Communication Engineering from Northumbria University, Newcastle upon Tyne, U.K, in 2008.In 2012 she received PhD degree in Free-space Optical Communications from Northumbria University. 2008 and 2009 she also worked as a Teaching Assistant and as a Research/Teaching Assistant in the Electrical Engineering Department at Northumbria University. She is currently a postdoctoral researcher working on optical wireless communications at Optical Wireless Information Systems Lab., School of Electronic Engineering, Tsinghua University, China. Her research interests include optical wireless communications, digital communications and digital signal processing. She has published 12 papers in journals and international conferences.