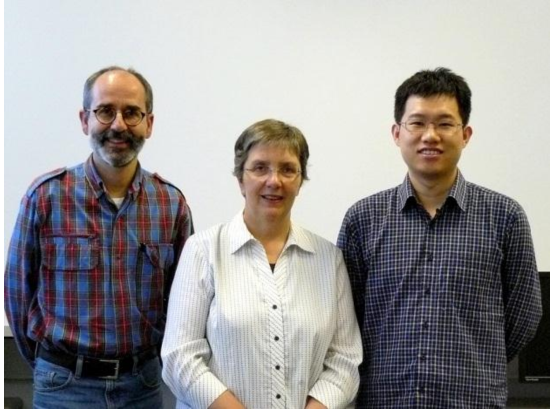
MONASH University
Engineering

Hemispherical Lens Based Imaging Receiver for MIMO Optical Wireless Communications

Dr. Thomas. Q. Wang, Dr. Y. Ahmet Sekercioglu and Prof. Jean Armstrong

Department of Electrical and Computer Systems Engineering
Monash University,
Melbourne, Australia
{Tom.Wang, Ahmet.Sekercioglu, Jean.Armstrong}@monash.edu



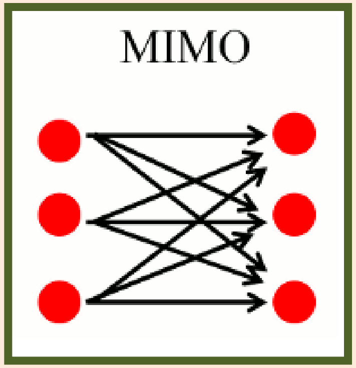
This work was supported under an Australian Research Council's (ARC) Discovery funding scheme (DP 1094218).

Outline

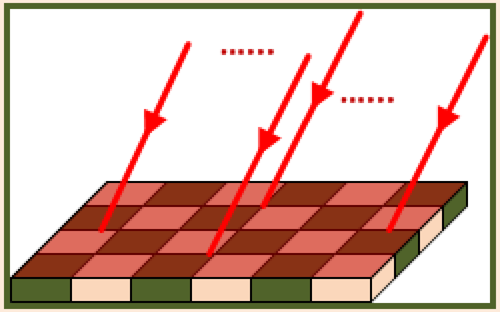
- Introduction
- System description and analysis
- Simulation results
- Summary

MIMO Optical Wireless System with Imaging Receiver

- ✓ MIMO has potential to increase the data rate and the robustness of optical wireless systems

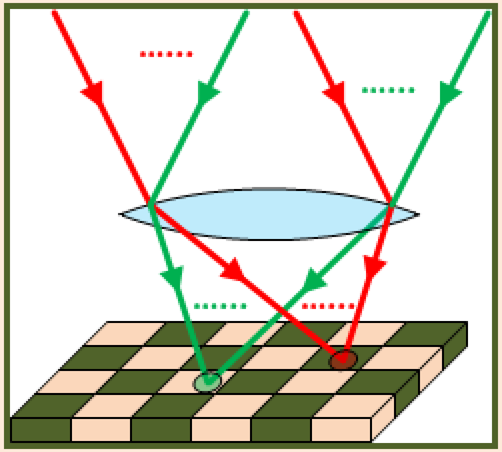


- ✓ Non imaging receiver
  - -- evenly distributed power
  - --very little diversity

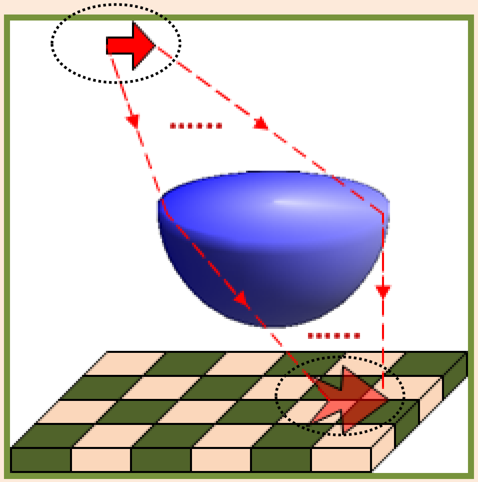


- ✓ Imaging receiver using conventional lens
  - -- significant spatial diversity
  - -- small field of view (FoV)

✓ Can we increase the FoV with a different lens?
✓ Given a different lens, can we still have spatial diversity?



Imaging Receiver Using Hemispherical Lens



- ✓ Hemispherical lens
  - -- gives wide field of view, used for cloud recording as early as 1920s
  - -- forms distorted images
  - -- not a problem for IM/DD
- ✓ Contribution of this work
  - -- Study the MIMO channel gain with hemispherical lens based receiver
  - -- Calculate total received power as a function of angle of incidence and show the wide FoV of the receiver
  - -- Demonstrate spatial diversity by observing the images of the LEDs and calculating the channel matrix.

System Description

- ✓ N_t Generalized Lambertian LEDs installed on the celling, pointing down

  -- LED is placed at $S:(l\sin\varphi\cos\theta, l\sin\varphi\sin\theta, l\cos\varphi)$

  Therefore φ is the angle of incidence

  -- emitting un-polarized light

  -- Radiation pattern: $R_o(\phi) = \frac{(m+1)}{2\pi}\cos^m\phi$

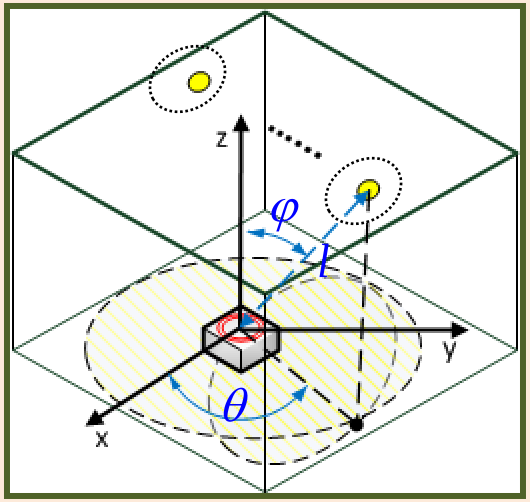
  where $m = -\ln 2 / \ln(\cos\Phi_{1/2})$

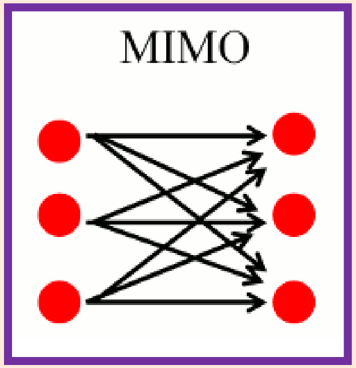
- ✓ The receiver put on the floor, pointing up

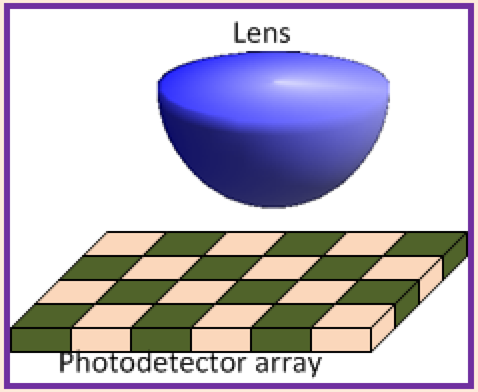
  -- Lens is of radius *R* and refraction index *n*

  -- N_r photodetectors

  -- A N_r X N_t Channel Matrix







Analysis

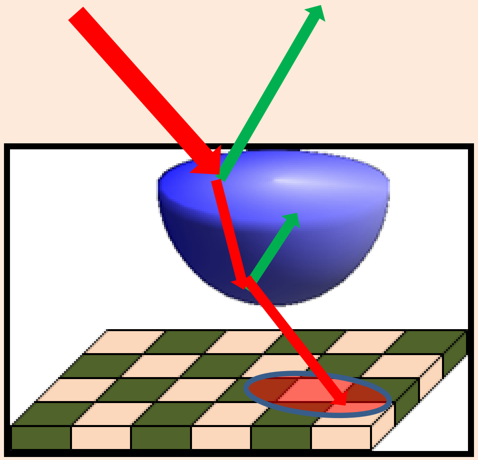
- ✓ Ray tracing

-- reflection and refraction on the surface of the lens

-- two refractions: change the direction the ray travels and are governed by Snell's Law

$$n_1 \sin\alpha_1 = n_2 \sin\alpha_2$$

n_1 n_2: refractve index of media 1 and media 2, respectively. α_1: angle of incidence α_2 : angle of refraction



receiver

-- two reflections: results in the loss of optical power governed by Fresnel equations

$$R_p(\alpha_1,\alpha_2) = \frac{n_1\cos\alpha_2 - n_2\cos\alpha_1}{n_1\cos\alpha_2 + n_2\cos\alpha_1} \quad R_s(\alpha_1,\alpha_2) = \frac{n_1\cos\alpha_1 - n_2\cos\alpha_2}{n_1\cos\alpha_1 + n_2\cos\alpha_2}$$

--For un-polarized light, the power transmission coefficient is $T = 1 - \frac{1}{2}\left(R_s^2 + R_p^2\right)$

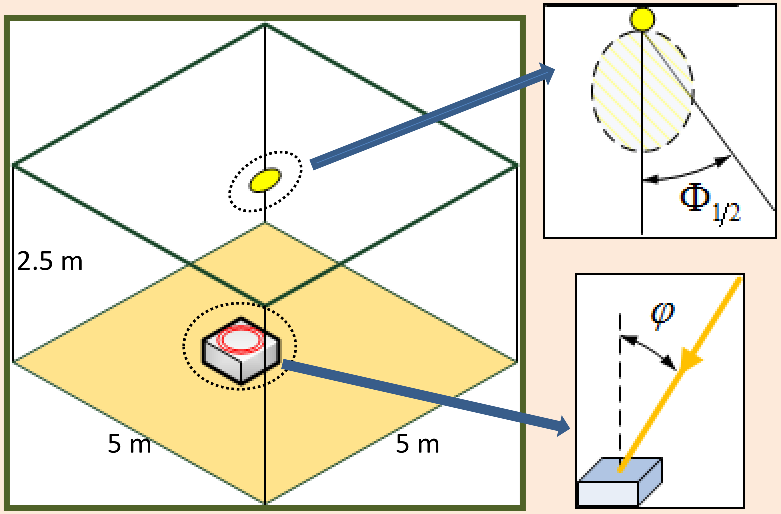
- ✓ Channel gain

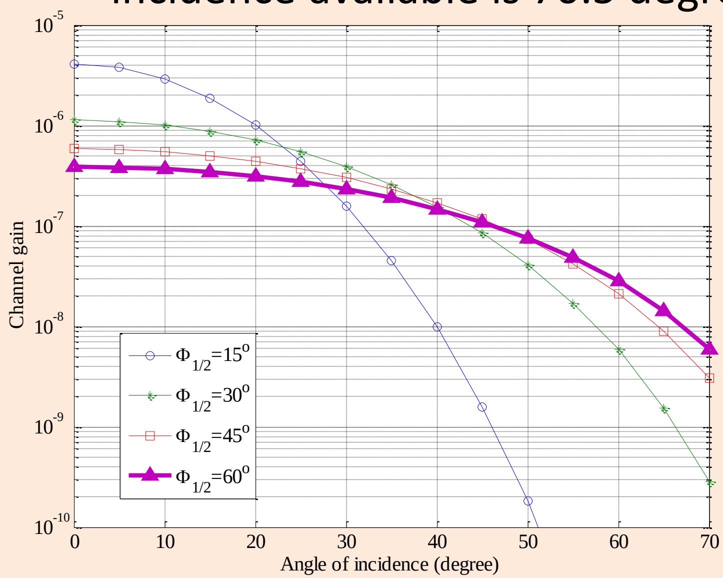
$$\frac{P_o}{P_t} = \frac{(m+1)\cos^m\phi\cos\varphi T_{\text{air-lens}}(\alpha_1)}{2\pi l^2} \iint_{\alpha_3<\arcsin(n_1/n_2)} T_{\text{lens-air}}(\alpha_3,\alpha_4)\, r\,dr\,d\beta$$

Simulation Results

Calculated total received power as a function of angle of incidence

- ✓ Settings
  - -- 5 m x 5 m x 2.5 m room
  - -- One LED on the ceiling pointing down with semi-angle $\Phi_{1/2}$
  - -- Receiver put on the floor pointing up with 5 mm lens and a photodetector.
  - -- Therefore the maximum angle of incidence available is 70.5 degrees



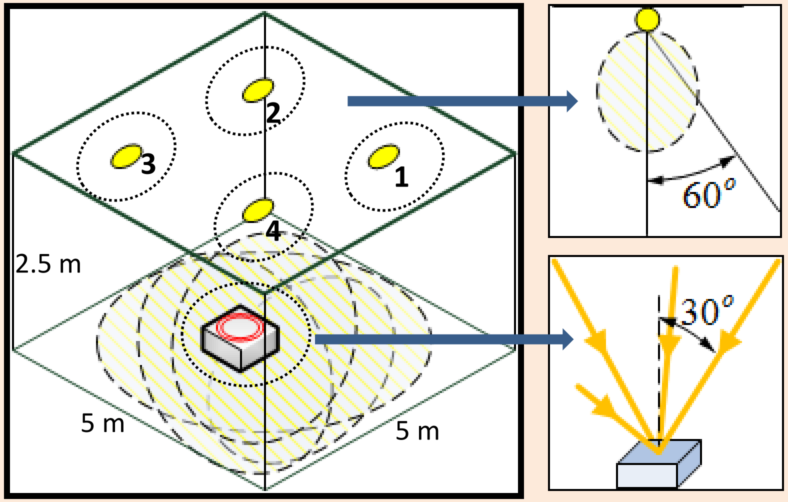


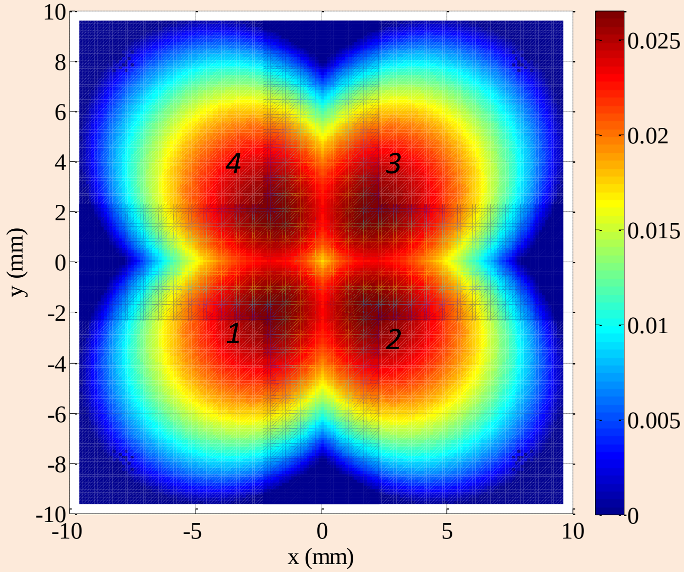
Channel gains versus the angle of incidence for Lambertian emitters with varying half power semi-angles

- ✓ Channel gain drops at different rates
- ✓ Adequate gain provided by some of LEDs at large angel of incidence
- ✓ Field of view depends on half power semi angles of transmitters:
  - -- Large half power semi-angle = Greater field of view
- ✓ Large half power semi-angle
  - -- Adequate gain out to 70 degrees angle of incidence

Power Density on Imaging Plane

- ✓ Settings
  - -- 5 m x 5 m x 2.5 m room
  - -- four Lambertian LEDs, with semi-angles 60 degrees, on the ceiling making 30 degrees of angle with the receiver
  - -- Receiver put at the center of the floor pointing up with 5 mm lens and four photodetectors. Each covers one quadrant.





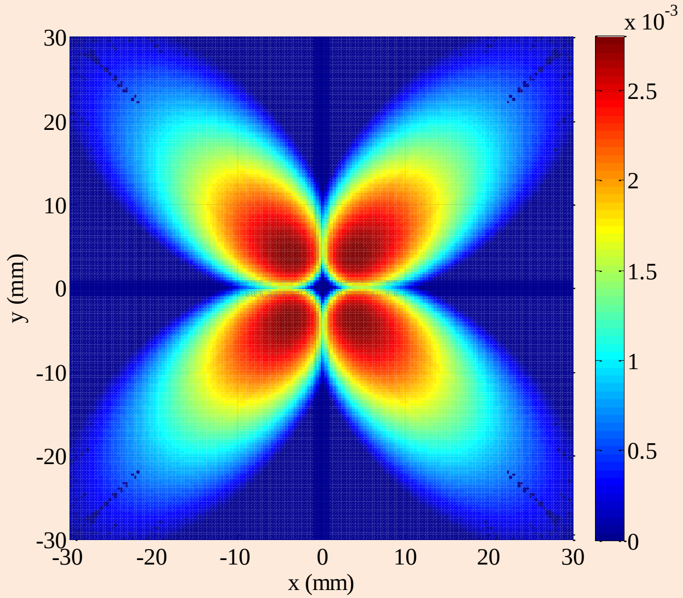
Four LEDs with 30 degrees of angle of incidence

- ✓ Images of four LEDs are clearly separated
  - -- System with four photodiode receivers would have significant diversity

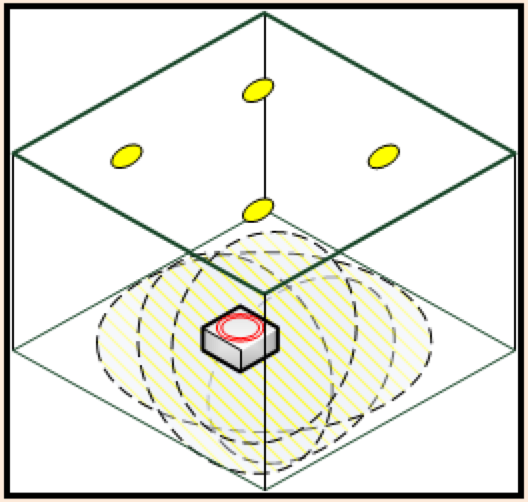
$$\mathbf{H} = \begin{bmatrix} 0.009 & 0.151 & 1.124 & 0.151 \\ 0.152 & 0.01 & 0.157 & 1.13 \\ 1.136 & 0.158 & 0.011 & 0.158 \\ 0.152 & 1.13 & 0.157 & 0.01 \end{bmatrix} \times 10^{-6}$$

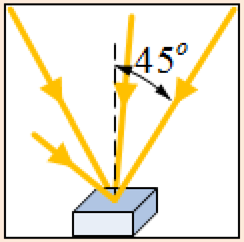
- ✓ Little correlation between rows or columns
  - -- Good diversity

Effect of more widely spaced transmitters



Four LEDs with 45 degrees of angle of incidence





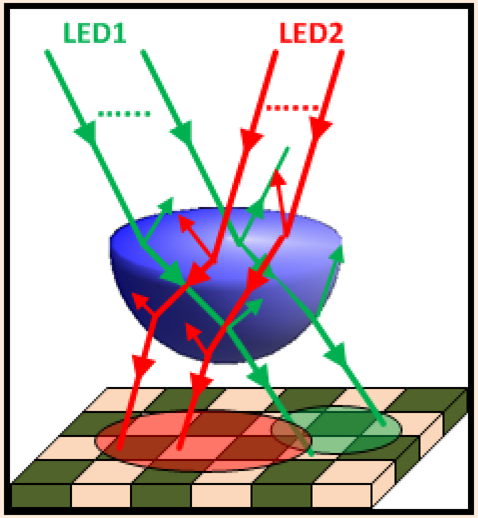
- ✓ With more widely spaced transmitters
  - -- Angle of incidence increases
  - -- Overall received power decreases
  - -- Completely separated images

$$\mathbf{H} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

- ✓ No correlation between rows and columns
  - -- Full diversity

Imaging with Hemispherical lens vs Non Imaging

Imaging

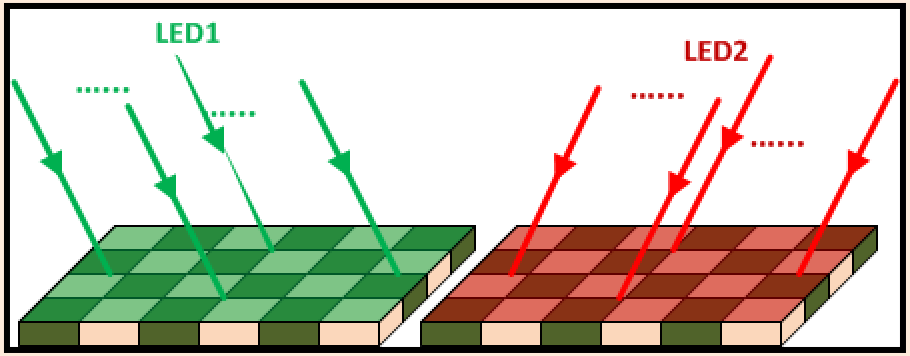


- ✓ Optical power distributes unevenly in each image
- ✓ Various LEDs form separated images

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N_t} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N_t} \\ \vdots & \vdots & \cdots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \cdots & h_{N_r,N_t} \end{bmatrix}$$

- ✓ The channel matrix is of full rank
- ✓ Therefore provides full diversity order

Non-imaging



- ✓ The optical power distributes evenly among the photodetectors

$$\mathbf{H} = \underbrace{\begin{bmatrix} h_1 & h_2 & \cdots & h_{N_t} \\ h_1 & h_2 & \cdots & h_{N_t} \\ \vdots & \vdots & \cdots & \vdots \\ h_1 & h_2 & \cdots & h_{N_t} \end{bmatrix}}_{\text{Unit-ranked}}$$

- ✓ Therefore no diversity provided

Summary

In this work, we have answered the following questions:

Can we increase the FoV with a different lens?

→ The imaging receiver has large field of view with a hemispherical lens– as large as 70 degrees for a Lambertian LED

Given a different lens, can we still have spatial diversity?

→ Spatial diversity is also provided by the lens– full ranked channel matrix

Reference

[1] J. R. Barry, J. M. Kahn, E. A. Lee and D. G. Messerschmitt, “High-speed nondirective optical communication for wireless networks,” *IEEE Network Magazine*, vol. 5, no. 6, pp. 44-54, Nov. 1991.

[2] M. Kavehrad and S. Jivkova, “Indoor broadband optical wireless communications: optical subsystems designs and their impact on channel characteristics,” *IEEE Wireless Communications,* vol.10, no.2, pp. 30-35, Apr. 2003.

[3] L. Zeng, D. C. O’Brien, H. L. Minh, G. E. Faulkner, K. Lee, D. Jung, Y. Oh and E. T. Won, “High data rate multiple input multiple output (MIMO) optical wireless communications using white led lighting,” *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 9, pp.1654-1662, Dec. 2009.

[4] K. D. Dambul, D.C. O'Brien and G.. Faulkner, “Indoor Optical Wireless MIMO System With an Imaging Receiver,” *IEEE Photonics Technology Letters*, vol. 23, no. 2, pp. 97-99, Jan. 2011.

[5] S. Hranilovic and F.R. Kschischang, “A pixelated MIMO wireless optical communication system,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 12, no. 4, pp. 859-874, July/Aug. 2006.

[6] J. M. Kahn and J. R. Barry, “Wireless Infrared Communications,” *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265-298, Feb, 1997.

[7] J.M. Kahn, R. You, P. Djahani, A. G. Weisbin, B. K. Teik and A. Tang, “Imaging diversity receivers for high-speed infrared wireless communication,” *IEEE Communications Magazine*, vol. 36, no. 12, pp. 88-94, Dec. 1998.

[8] D. C. O’Brien, “Multi-Input Multi-Output (MIMO) indoor optical wireless communications,” *Signals, Systems and Computers, 2009 Conference Record of the Forty-Third Asilomar Conference on,* pp. 1636 – 1639, Nov. 2009.

[9] S. D. Perli, N. Ahmed, and D. Katabi, “PixNet: Interference-Free Wireless Links Using LCD-Camera pairs,” *In Proceedings of MOBICOM'2010,* Chicago, pp.137-148, 2010.

Reference

Reference

[10] W. Yuan, K. Dana, M. Varga, A. Ashok, M. Gruteser and N. Mandayam, “Computer vision methods for visual MIMO optical system,” *in Computer Vision and Pattern Recognition Workshops (CVPRW), 2011 IEEE Computer Society Conference on,* pp. 37-43, 2011.

[11] M. J. Langford, A. Fox, and R.S. Smith, “Langford's basic photography the guide for serious photographers 9th Edition,” Focal Press.

[12] L. Zeng, D. C. O’Brien, H. Le-Minh, L. Kyungwoo, J. Daekwang, and O. Yunje, “Improvement of Date Rate by using Equalization in an Indoor Visible Light Communication System,” *in Proc. IEEE ICCSC*, pp. 678-682, 2008.

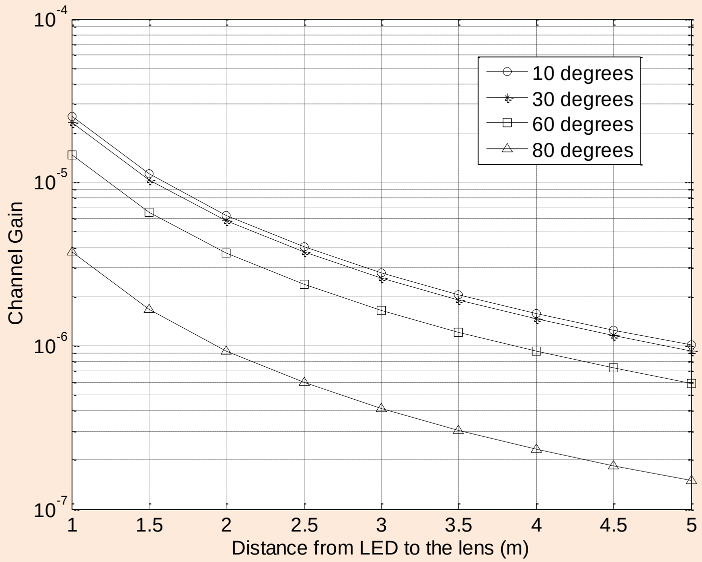
[13] F. R. Gfeller and U. H. Bapst, “Wireless in-house data communication via diffuse infrared radiation,” *Proc. IEEE*, vol. 67, pp. 1474–1486, Nov. 1979.

[14] K. D. Möller, “Optics,” University Science Books, Mill Valley, California.

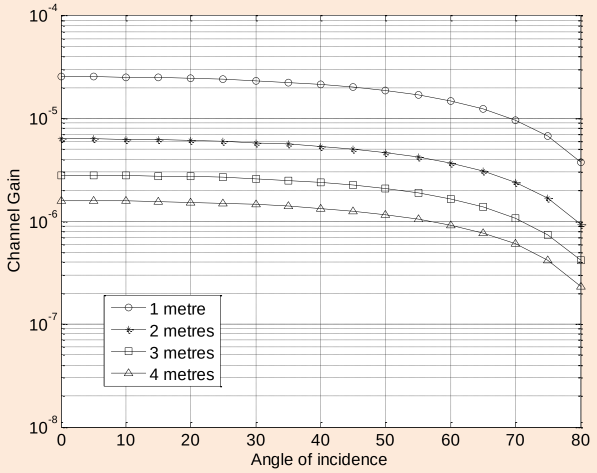
[15] J. R. Barry, J. M. Kahn, W. J. Krause, E. A. Lee, and D. G. Messerschmitt, “Simulation of multipath impulse response for wireless optical channels,” *IEEE J. Select. Areas in Commun.*, vol. 11, no. 3, pp. 367–379, Apr. 1993.

Thank you!

Additional Graphs



- ‘Total’ channel gain versus distance
  - Total received power on photodetector/power transmitted by LED
- LED semi-angle 15 degrees
- **LED pointing directly at receiver**



- ‘Total’ channel gain versus angle of incidence
  - Total received power on photodetector/power transmitted by LED
- LED semi-angle 15 degrees
- **LED pointing directly at receiver**