IEEE P802.15
Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	TG7r1 Channel Model Document for High-rate PD Communications
Date Submitted	[September, 2015]
Source	Murat Uysal (Ozyegin University), Tuncer Baykas (Istanbul Medipol University), Farshad Miramirkhani (Ozyegin University), Nikola Serafimovski (pureLiFi Ltd.), Volker Jungnickel (Fraunhofer HHI)
Re:	
Abstract	
Purpose	Providing channel models which allow a fair comparison of different physical layer (PHY) High Rate PD Communications proposals submitted to TG7r1 in response to the Call for Proposals (CFP).
Notice	This document has been prepared to assist the IEEE P802.15. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.
Release	The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15.

Table of Contents

List of Figures

List of Tables

1. Definitions

MIMO	Multiple Input/Multiple Output
LOS	Line Of Sight
LBS	Location Based Service
LED	Light Emitting Diode
SAP	Service Access Point
PD	Photodiode

2. Introduction

The Task Group 802.15.7r1 (TG7r1) is aiming at the development of a Physical (PHY) and Media Access Control (MAC) layer for short-range Optical Wireless Communications in optically transparent media using light wavelengths from 10,000 nm to 190 nm [1]. The Task Group prepared a Technical Considerations Document (TCD) as a guideline for proposal preparation. It addresses the technical aspects of interest to the TG7r1 committee in regards to a draft standard that may fulfill performance-related issues, reliability issues and availability issues [2]. According to the Technical Considerations Document, OWC can be classified into:

> **Image Sensor Communications** which enables optical wireless communications using an image sensor as a receiver.
> **High Rate PD Communications** which is high-speed, bidirectional, networked and mobile wireless communications using light with a high speed photodiode receiver.
> **Low Rate PD Communications** which is wireless light ID system using various LEDs with a low speed photodiode receiver.

In regards to the definition of low speed and high speed, the throughput threshold data rate is 1 Mbps as measured at the PHY SAP. Throughput less than 1 Mbps rate at the PHY SAP is considered low rate and higher than 1 Mbps at the PHY SAP is considered high rate.

The main goal of this document is to provide channel impulse responses in set environments that allow a fair comparison of different physical layer (PHY) High Rate PD Communications proposals submitted to TG7r1 in response to the Call for Proposals (CFP).

When the task-group was formed, there was no generic OWC channel model available that fit firmly into the environments defined in TCD [2]. Since the TG7r1 was formed, a number of channel modeling related documents have been presented and discussed at the IEEE 802.15.7r1 meetings. The most reliable channel modeling approach for OWC is considered to be done using Ray Tracing. However, for real environments with details pertaining to the propagation

environment, the Ray Tracing approach is very computationally intensive. Therefore the IEEE 802.15.7r1 committee has decided to use a subset of channel impulse responses prepared by members of the committee to compare various technical proposals. The impulse responses were chosen by the committee as the most representative subset from the most immediate use-cases of OWC. In addition, although the absolute performance of the various proposed systems may change from one environment to another, the relative performance of the proposed systems will not change.

The committee may also create a general library that will provide both analytical and numerical tools that should be used in the future to explore various system performance in different environments that include various environmental factors and analysis.

All the models presented and submitted as recommendation in this document are based on simulations conducted in several environments. To facilitate the use of the models, this document also includes a MATLAB files which include channel impulse responses (CIR). The use of the provided CIRs is mandatory for all simulations that will be part of the technical proposals to ensure consistent and fair comparison of PHY layer proposals for High Rate PD Communications Use Cases/Applications submitted to 802.15.7r1.

The remainder of the document is organized as follows: Sections 3 presents the Channel Modeling Methodology. Sections 4 to 7 include scenarios considered by TG7r1. Section 8 provide conclusions. Appendix A contains MATLAB instructions for the simulation of CIRs.

3. <u>Channel Modeling Methodology</u>

A realistic OWC channel model should account for the effect of wavelength dependency, realistic light sources as well as different types of reflections such as specular and mixed cases of diffuse and specular. In an effort to develop more realistic OWC channel models, a new modeling approach based on ray tracing is used [3][4]. Based on these works, this section provides an overview of this approach and explains how CIR is obtained for a specified environment.

The proposed approach in [3][4] is based on Zemax®; a commercially available optical and illumination design software [5]. Figure 1 illustrates the main steps of adopted channel modeling methodology. First, a three dimensional simulation environment is created where one can specify the geometry of the indoor environment, the reflection characteristics of the surface materials and the specifications of the light sources and detectors. The computer aided design (CAD) objects can be further imported in the simulation environment to model furniture and any other objects. Zemax® further allows defining the wavelength-dependent reflectance of surface coating for each material. For light sources, commercially available LEDs can be used which are readily available in Radiant Source Model (RSM) database supported by Zemax®. RSM file for a light source contains the measured radiant or luminous intensity of the source as a function of wavelength, position, and angle. As such, this file can be accurately used to characterize the

behavior of the source in both the near- and far-fields. In Zemax[®], detectors can be modeled as planar surfaces, curved surfaces and even three-dimensional volumes. In our study, a rectangular detector is used which detects coherent or incoherent illumination on a rectangular surface.

After the simulation environment in Zemax[®] is created, its non-sequential ray tracing feature is used to determine the CIR. In non-sequential ray-tracing, rays are traced along a physically realizable path until they intercept an object. The line-of-sight (LOS) response is straightforward to obtain and depends upon the LOS distance. Besides the LOS component, there is a large number of reflections among ceiling, walls, and floor as well as any other objects within the environment. The rays of light hit the other walls and are reflected towards the receiver. The receiver can only detect the rays entering its field of view. Those rays which are not directed towards the receiver, hit against the walls, ceiling and the floor and some of them are reflected towards receiver again for the other bounces. Rays may strike any group of objects in any order, or may strike the same object repeatedly; depending upon the geometry and properties of the objects.

The Zemax[®] non-sequential ray-tracing tool generates an output file, which includes all the data about rays such as the detected power and path lengths for each ray. The data from Zemax[®] output file is imported to Matlab[®] and using these information, the CIR is expressed as

$$h(t) = \sum_{i=1}^{N_r} P_i \, \delta(t - \tau_i) \tag{1}$$

where P_i is the power of the i-th ray, τ_i is the propagation time of the i-th ray, $\delta(t)$ is the Dirac delta function and N_r is the number of rays received at the detector.
Once we obtain CIRs, we can calculate fundamental channel parameters [6]. For example, truncation time (T_r) is defined as

$$\int_0^{T_{tr}} h(t)\,dt = 0.97 \int_0^{\infty} h(t)\,dt \tag{2}$$

which denotes the region of CIR with most energy concentrated. While the above formula assumes 97% of the total energy in the calculation, other percentages can be also chosen based on the application requirements. RMS delay spread is defined as the square root of the second central moment of the CIR and given by

$$\tau_{RMS} = \sqrt{\frac{\int_0^{\infty} (t - \tau_0)^2 \, h(t)\,dt}{\int_0^{\infty} h(t)\,dt}} \tag{3}$$

which is commonly used to quantify the time-dispersive properties of multipath channels. Similarly, mean delay spread is defined as

$$\tau_0 = \frac{\int_0^\infty t \times h(t)\,dt}{\int_0^\infty h(t)\,dt} \tag{4}$$

Channel DC gain is one of the most important features of a OWC channel, as it determines the achievable signal-to-noise ratio for fixed transmitter power. It is given by

$$H_0 = \int_{-\infty}^{\infty} h(t)\,dt \tag{5}$$

For a particular correlation level c (typically chosen as 0.9, 0.7 or 0.5), coherence bandwidth (B_c) is defined as the minimum frequency separation for which the norm of the frequency correlation function across this level. It is defined as

$$B_{0.9} = \min\left(\Delta f\right) \text{ such that } \left|H\left(\Delta f\right)\right| = 0.9 \tag{6}$$
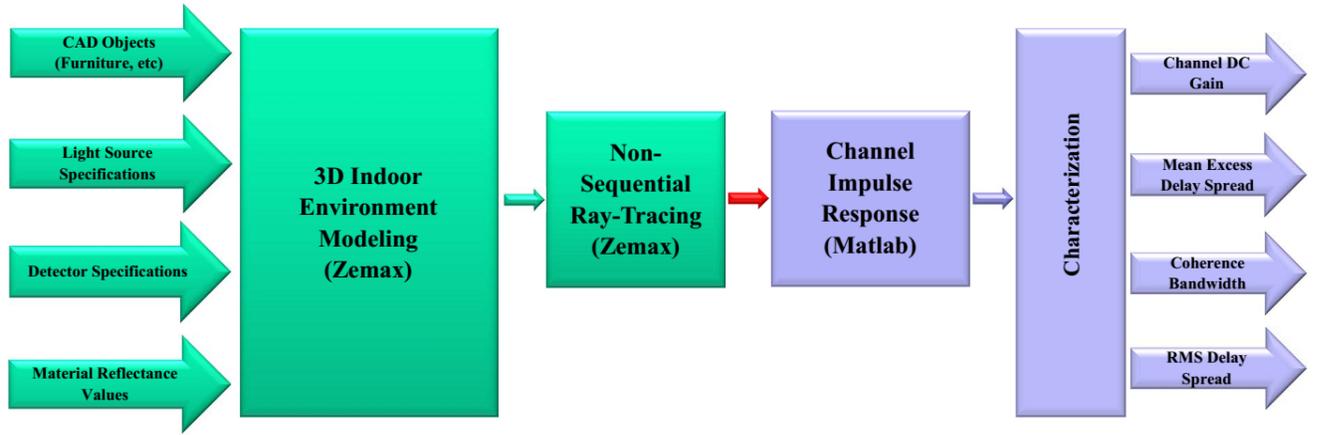
Figure 1. Channel modeling methodology

4. <u>Scenario 1 Open Office/Office with Cubicles</u>

The first scenario is created for office application/use cases. It includes typical office places including furniture (e.g., desk, chairs, cubicles etc), various equipments (e.g., computers, printers etc) and personnel. In Figure 2, the locations of the desks and cubicles are shown. The simulation parameters are provided in **Table 1**. Figure 3 illustrates arrangement of luminaries in office room, emission pattern of each luminary, simulated illumination levels in Zemax and illumination level contours in Matlab.

| (a) | (b) |
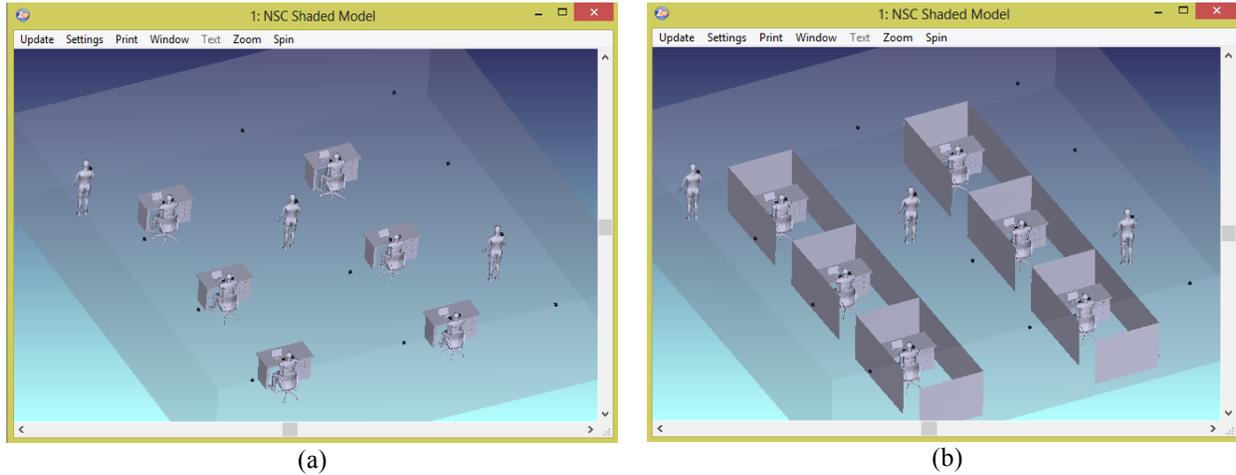
Figure 2. Typical office places including (a) open office and (b) office with cubicles with personnel

Table 1. Simulation parameters for open office/office with cubicles

Room size	14m × 14m × 3m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
Objects	6 desks and a chair, 6 laptops on each desk, 6 cubicles (optional) 9 human bodies

Objects specifications	Cubicles: Plaster
	Desk: Pinewood (Typical height of 0.85m)
	Chair: Pinewood
	Laptop: Black gloss paint
	Human body:
	  ▪ Shoes: Black gloss paint
	  ▪ Head & Hands: Absorbing
	  ▪ Clothes: Cotton

Luminary Specifications	Brand: LR24-38SKA35 Cree Inc. Half viewing angle: 40°
Number of luminaries	32
Receiver Field of View	85 degrees
Receiver area	1 cm^2

(a)

(b)

(c)

(d)

Figure 3. (a) Arrangement of luminaries in office room (b) Emission pattern of each luminary (c) Simulated illumination levels in Zemax (d) Illumination level contours in Matlab

To obtain representative CIR values 24 test points are chosen which are categorized into three groups as shown in Figure 4. The groups are:

- In the corridors at a height of 1.7m with 45º rotation (e.g., people who stand with a cell phone in hand), Locations D1-D12 blue color in Figure 4.
- On the top of chairs at a height of 0.95m with 45º rotation (e.g., people with a cell phone in hand), Locations D13-D18 red color in Figure 4.
- On the top of chairs at a height of 1.1m with 45º rotation (e.g., people who sit with a cell phone in hand to his/her ear) D19-D24 green color in Figure 4.
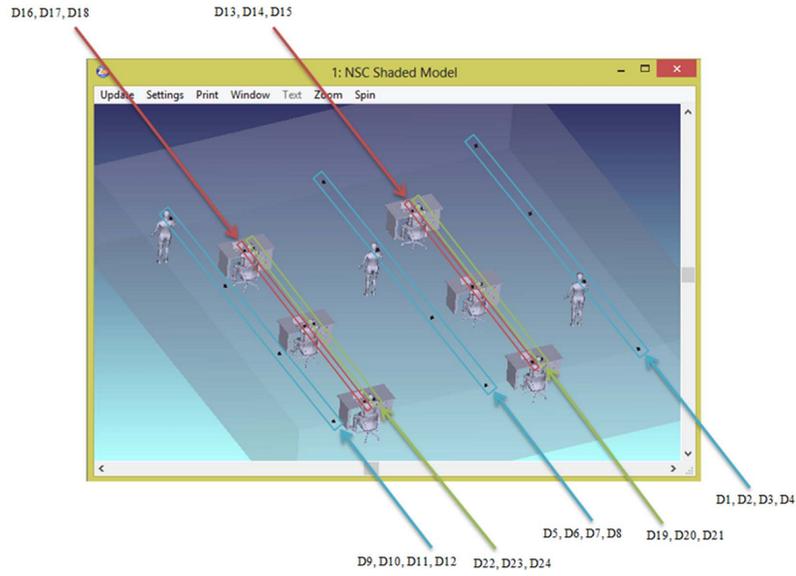
Figure 4. 3D location of test points in open office with human bodies

Resulting CIR values are provided in Figure 5 and channel characteristics are provided in **Table 2**.

D1	D2	D3	D4
D5	D6	D7	D8
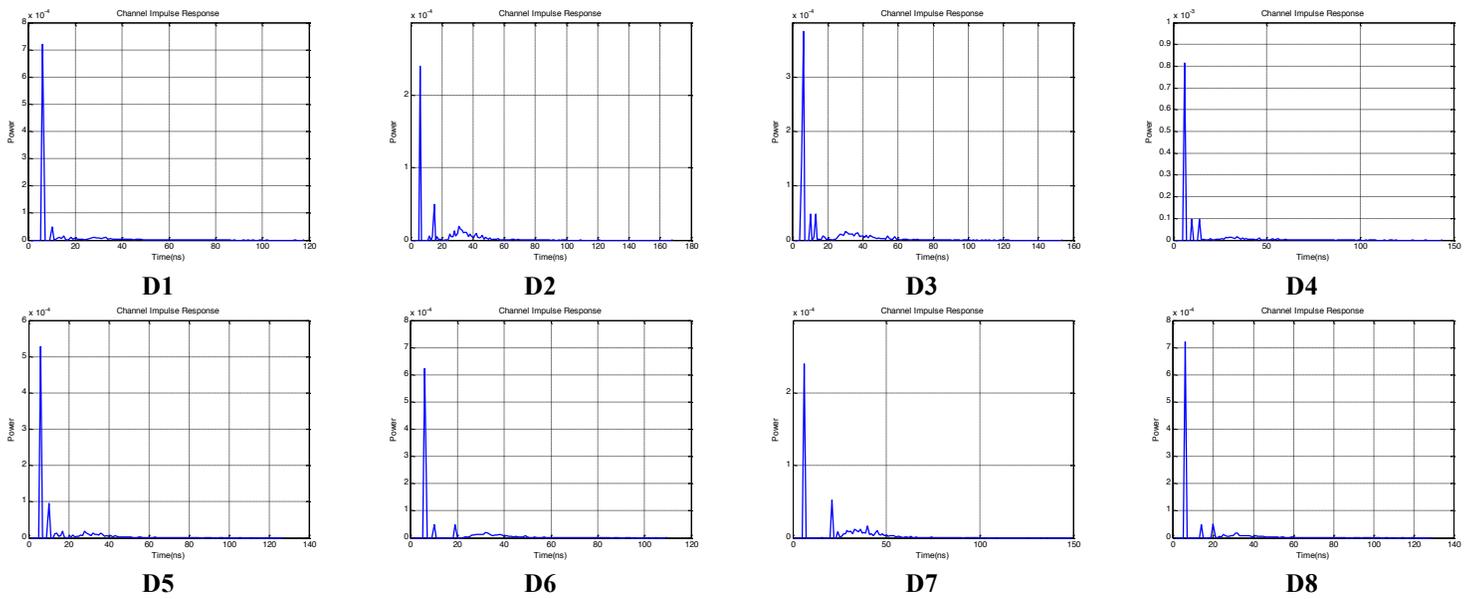
Figure 5. Channel impulse responses of test points in open office room with human bodies

Table 2. Channel parameters of open office room with human bodies

	$T_{97\%}$ (ns)	t_{RMS} (ns)	H_0
D1	48	13.30	1.00×10^{-3}
D2	56	17.04	5.26×10^{-4}
D3	57	17.15	9.22×10^{-4}
D4	55	14.98	1.26×10^{-3}

D5	51	14.73	9.06×10^{-4}
D6	51	15.38	9.96×10^{-4}
D7	61	18.80	5.19×10^{-4}
D8	56	15.95	1.06×10^{-3}
D9	51	13.99	9.29×10^{-4}
D10	48	13.84	1.20×10^{-3}
D11	63	17.24	9.21×10^{-4}
D12	61	17.85	7.08×10^{-4}
D13	50	13.15	8.74×10^{-4}
D14	53	13.97	8.45×10^{-4}
D15	58	15.79	5.16×10^{-4}
D16	48	12.39	9.03×10^{-4}
D17	58	16.23	4.96×10^{-4}
D18	53	14.63	7.41×10^{-4}
D19	49	12.99	1.05×10^{-3}
D20	52	13.65	7.09×10^{-4}
D21	55	15.41	6.57×10^{-4}
D22	57	16.15	5.15×10^{-4}
D23	57	16.11	5.84×10^{-4}
D24	60	15.95	6.75×10^{-4}
Ave	54.5	15.27	8.13×10^{-4}

The next set of CIRs are obtained in an office environment which includes cubicles as shown in Figure 1Figure 6. The simulation parameters and positions of luminaries are kept the same. The resulting CIR values are shown in Figure 7.

Figure 6. 3D location of test points in office with cubicles with human bodies
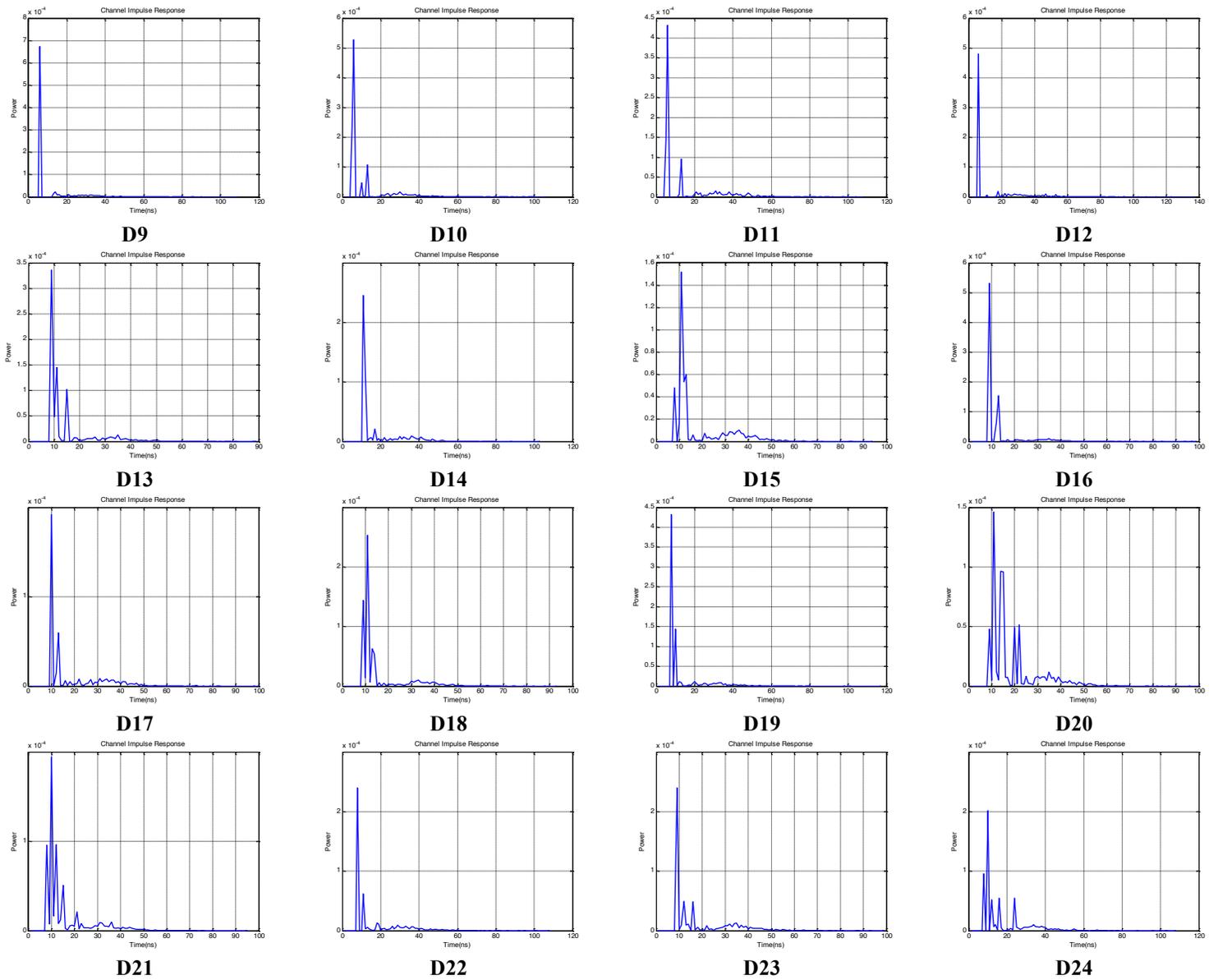
Figure 7. Channel impulse responses of test points in office with cubicles with human bodies

Table 3. Channel parameters of office room with cubicles with human bodies

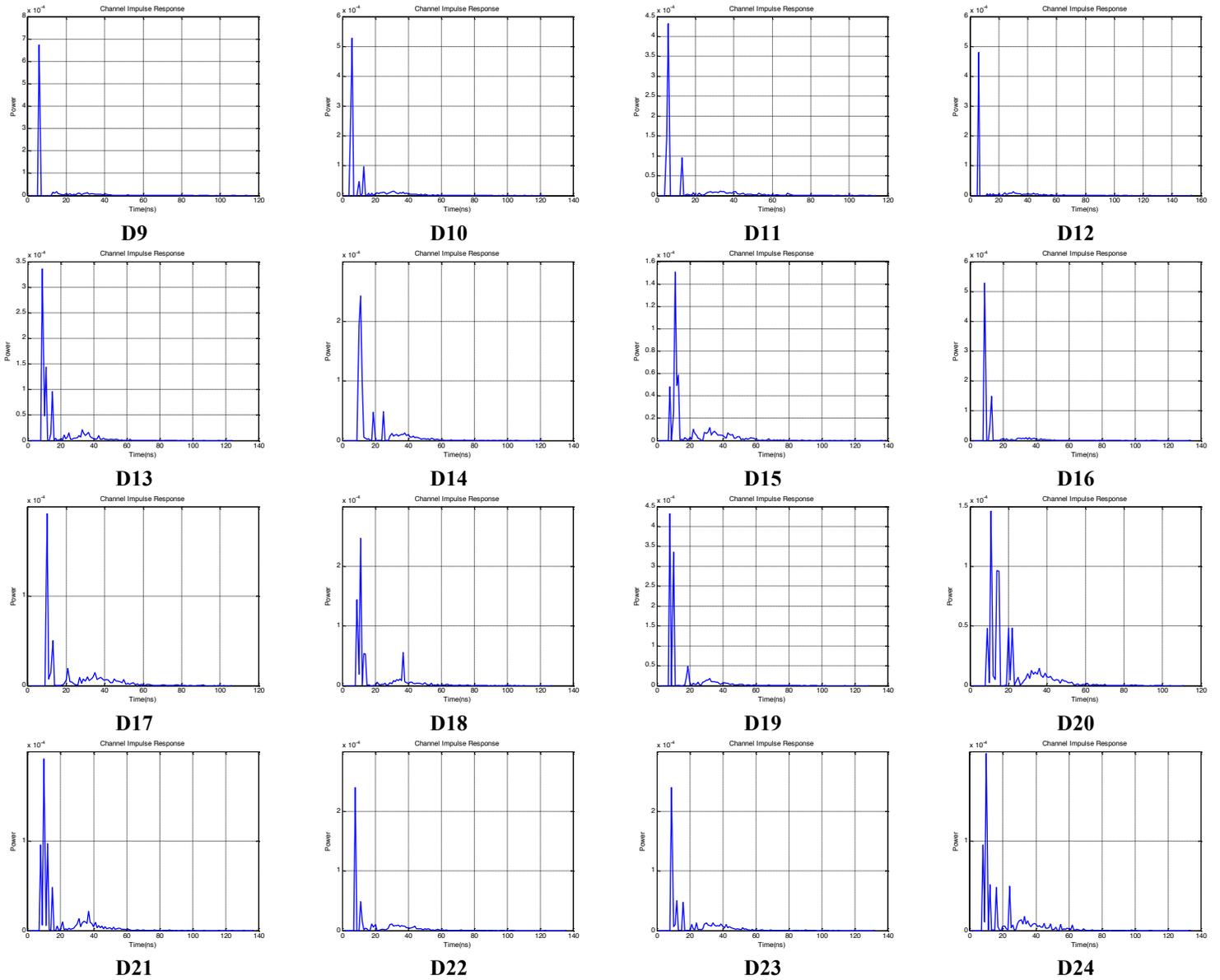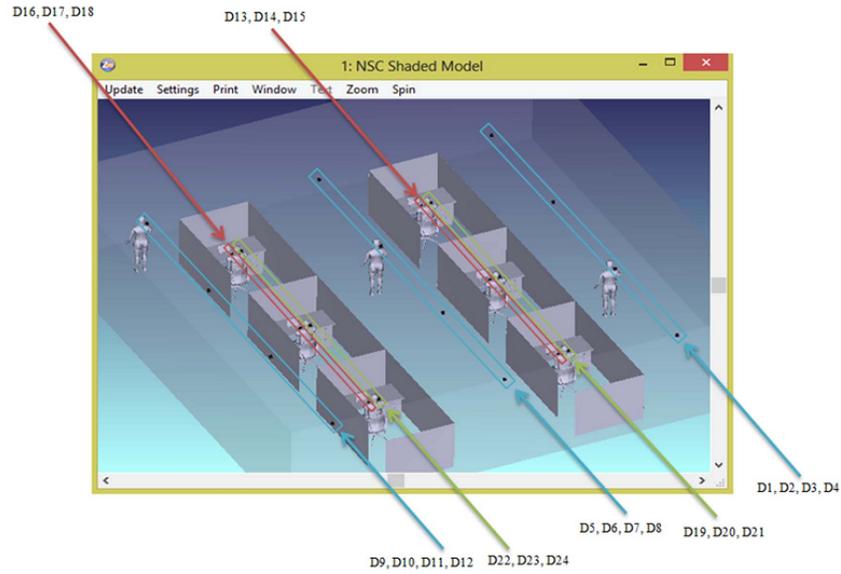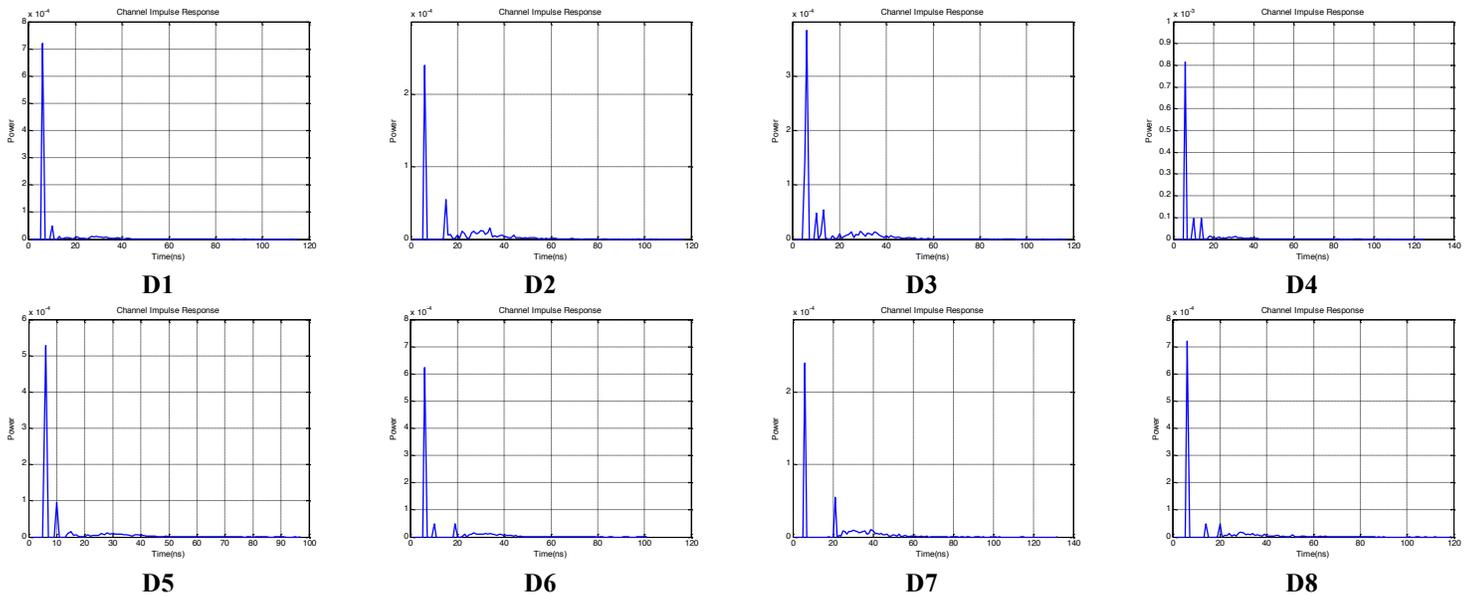|	$T_{97\%}$ (ns)	t_{RMS} (ns)	H_0
D1	41	11.26	9.55×10^{-4}
D2	53	15.38	5.03×10^{-4}
D3	50	14.41	8.85×10^{-4}
D4	44	11.98	1.22×10^{-3}
D5	46	12.91	8.32×10^{-4}
D6	47	14.04	9.54×10^{-4}
D7	57	17.08	4.77×10^{-4}
D8	54	14.75	1.06×10^{-3}
D9	42	11.39	8.87×10^{-4}
D10	46	12.47	1.14×10^{-3}
D11	50	14.60	9.19×10^{-4}
D12	54	15.90	6.92×10^{-4}
D13	41	10.02	8.00×10^{-4}
D14	46	11.88	5.33×10^{-4}
D15	47	12.39	4.91×10^{-4}
D16	39	9.44	8.89×10^{-4}
D17	47	12.60	4.12×10^{-4}
D18	43	10.71	6.78×10^{-4}
D19	43	10.88	7.51×10^{-4}
D20	46	10.71	6.67×10^{-4}
D21	44	10.74	6.45×10^{-4}
D22	51	13.62	4.73×10^{-4}
D23	49	13.24	5.54×10^{-4}
D24	47	12.15	6.24×10^{-4}
Ave	46.95	12.68	7.51×10^{-4}

With respect to previous scenario, *i.e.*, open office with human bodies, a channel DC gain decrease of approximate 7.6% on average is observable. This decrease is explained with the presence of cubicles. The rays within cubicles hit the cubicle walls and decay more rapidly than those rays in the open office. RMS delay spread decreases by an average of 16.9% because the light rays cannot pass through the cubicle walls and therefore the delay spread values are smaller.

5. <u>Scenario 2 Office with Secondary Light</u>

According to TCD "The standard must support at least one optional PHY mode that supports cooperative signal processing (for example multi-hop transmission, cooperative diversity, etc.) among multiple transmitters with negligible impact on latency" [2]. To provide a realistic simulation case for such a system an office environment with two light sources are created. The first one is the main light source at the ceiling and the other one is mounted on the desk to provide task lighting. Figure 8 illustrate the office where Figure 9 provides the information about the location of the luminaries and the illumination pattern of each luminary.
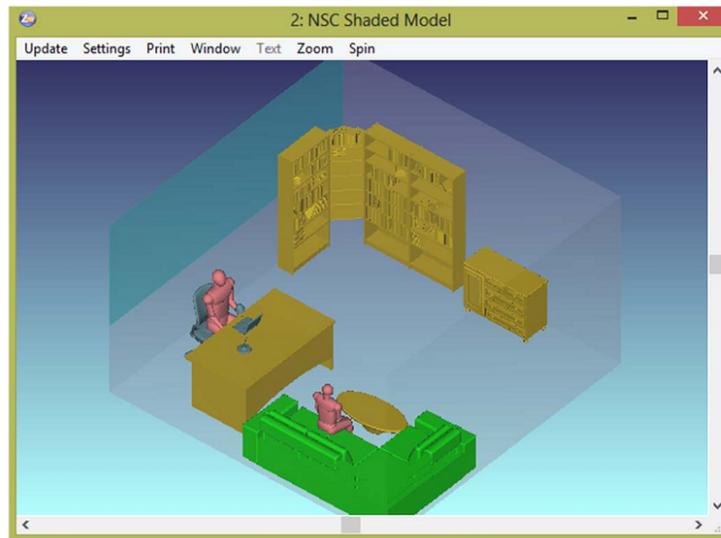

Figure 8. Office room with secondary light

(a)

(b)
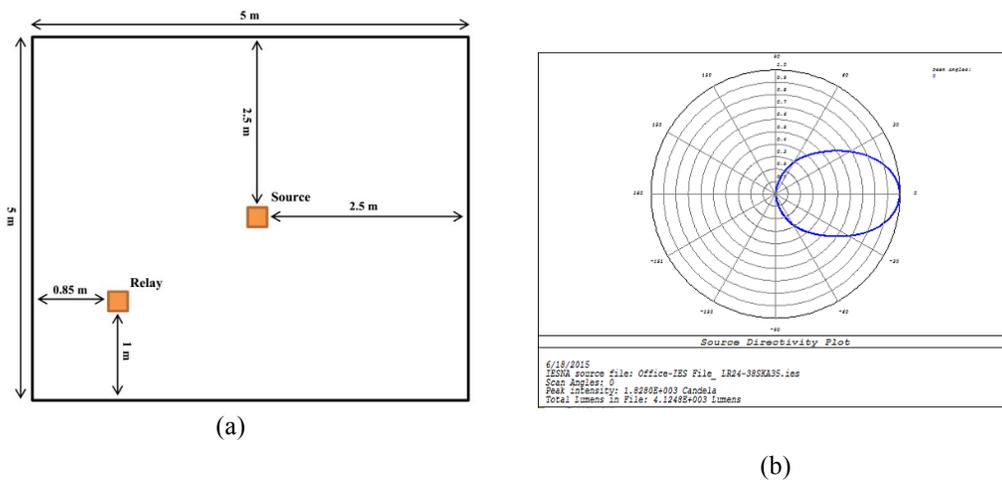
Figure 9. (a) Arrangement of luminaries in office room with secondary light (b) Emission pattern of each luminary

The simulation parameters are provided in **Table 4**. Two test points are chosen. Location D1 is on the desk next to the laptop at a height of 0.88 m (e.g., a USB-type device connected to laptop) and Location D2 is on the top of desk light at a height of 1.5m with 45º rotation toward the source on the ceiling, as shown in Figure 10.

Table 4. Simulation parameters for office with secondary light

Room size	5m × 5m × 3m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
Objects	1 desk and a chair paired with desk 1 laptop on the desk, 1 desk light on the desk, 1 library 1 couch, 1 coffee table, window, 2 human bodies

Objects specifications	Desk: Pinewood (Typical height of 0.88m)
	Chair: Black gloss paint, Laptop: Black gloss paint
	Desk light: Black gloss paint, Library: Pinewood, Window: Glass
	Couch: Cotton, Coffee table: Pinewood
	Human body:
	   ▪ Shoes: Black gloss paint
	   ▪ Head & Hands: Absorbing
	   ▪ Clothes: Cotton

Luminary Specifications	Brand: LR24-38SKA35 Cree Inc. Half viewing angle: 40º
Number of luminaries	1 on the ceiling 1 for the desk light
Receiver Field of View	85 degrees
Receiver area	1 cm^2

Figure 10. Location of test points in office room with secondary light

Resulting CIRs are shown in Figure 11, whereas the channel parameters are provided in **Table 5**.

(a)   (b)   (c)
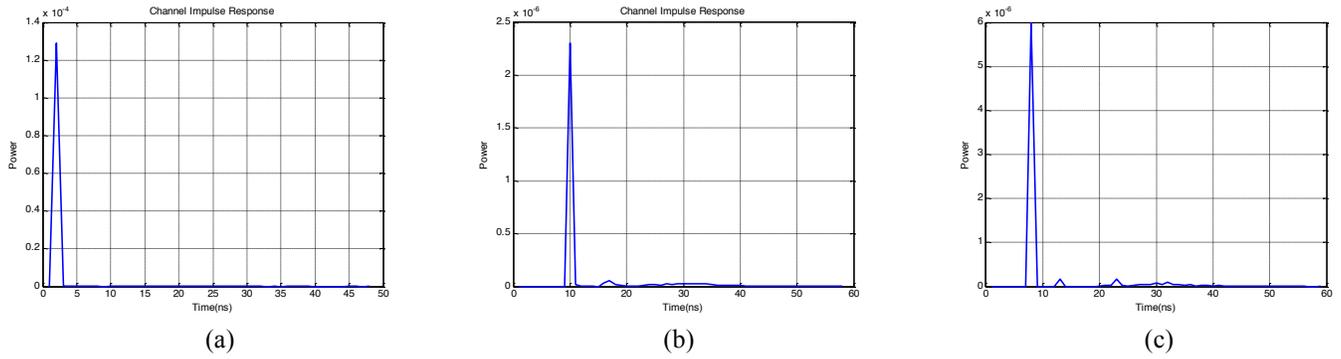
Figure 11. (a) Relay transmitter to destination (b) Source to destination (c) Source to relay receiver

Table 5. Channel parameters of office room with secondary light

	$T_{97\%}$ (ns)	t_{RMS} (ns)	H_0
Desk Light (Relay) Transmitter To Destination	2	1.37	1.30×10^{-4}
Ceiling Light (Source) To Destination	35	7.76	2.81×10^{-6}
Ceiling Light (Source) To Desk Light (Relay) Receiver	35	8.32	7.13×10^{-6}

6. <u>Scenario 3 Home</u>

In this scenario a living room is considered with table, chairs, couch, coffee table as shown in **Figure 12**. The simulation parameters are provided in **Table 6**. Arrangement of luminaries in home, emission pattern of each luminary, simulated illumination levels in Zemax and Illumination level contours in Matlab are shown in Figure 13.
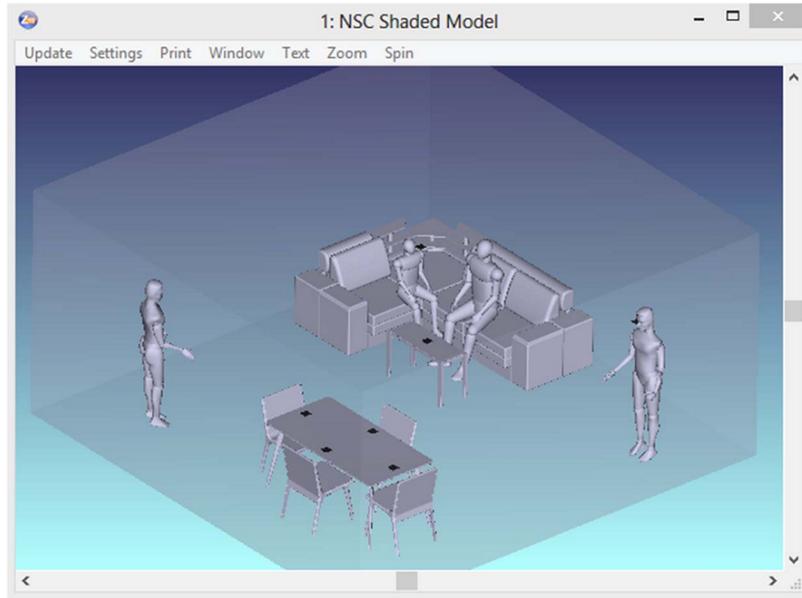
Figure 12. Home environment

Table 6. Simulation parameters for home environment

Room size	6m × 6m × 3m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
Objects	Table with 4 chairs Couch Coffee table 4 People
Object Specifications	Tables: Wooden with size of 2m × 1m × 0.9m Chairs: Wooden matched with table Couch: Cotton Coffee table: Glass Human body: ■ Shoes: Black gloss paint ■ Head & Hands: Absorbing ■ Clothes: Cotton
Luminary Specifications	Brand: CR6-800L Cree Inc. Half viewing angle: 40º
Number of luminaries	9
Receiver Field of View	85 degrees
Receiver area	1 cm^2

(a)

(b)

(c)

(d)

Figure 13. (a) Arrangement of luminaries in home (b) Emission pattern of each luminary (c) Simulated illumination levels in Zemax (d) Illumination level contours in Matlab

8 test points are chosen which are categorized into four groups:

- Location D1 On the coffee table at a height of 0.6 m with 45° rotation
- Locations D2-D3 Next to the wall at a height of 1.7m (e.g., standing people) with 45° rotation
- Locations D4-D7 On the table at a height of 0.9 m
- Location D8 On the top of couch at height of 1.1 m (e.g., sitting people) with 45° rotation

The locations are illustrated in Figure 14. Resulting channel impulse responses are shown in Figure 15 and channel parameters in **Table 7**.
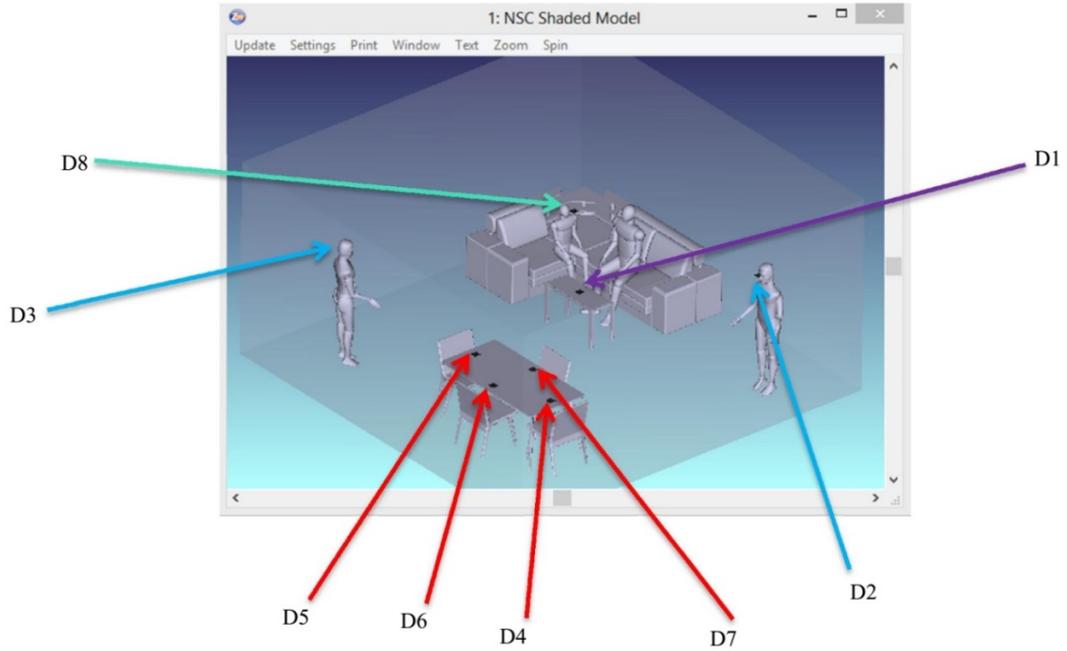
Figure 14. 3D location of test points in home environment
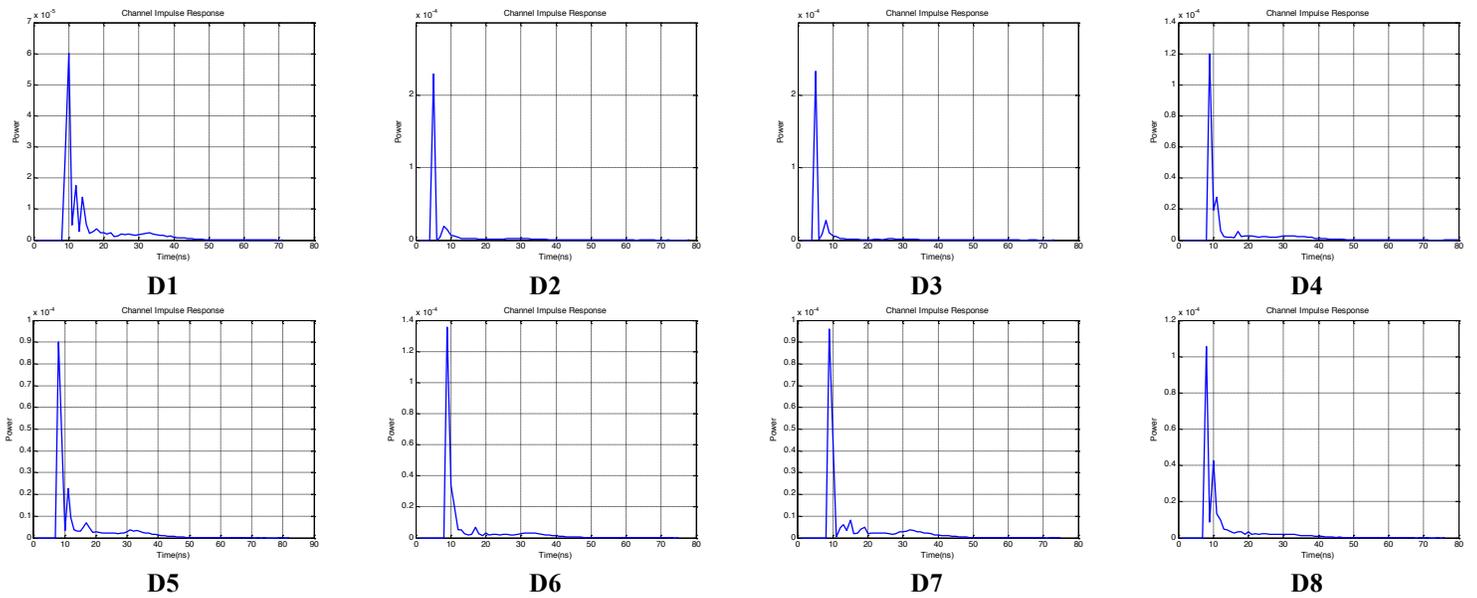
Figure 15. Channel impulse responses of test points in home

Table 7. Channel parameters of home environment

	$T_{97\%}$ (ns)	t_{RMS} (ns)	H_0
D1	40	9.64	1.82×10^{-4}
D2	33	8.30	3.31×10^{-4}
D3	31	7.19	3.26×10^{-4}
D4	40	9.90	2.44×10^{-4}
D5	40	10.16	2.58×10^{-4}
D6	39	9.62	2.74×10^{-4}
D7	41	10.30	2.31×10^{-4}
D8	37	8.83	2.47×10^{-4}
Ave	37.62	9.24	2.61×10^{-4}

7. <u>Scenario 4 Manufacturing Cell</u>

The last scenario considered by this document is for a manufacturing cell with two robots in a factory environment as shown in Figure 16. Locations of the transmitters and receivers are provided in Figure 17 and Figure 18 respectively.
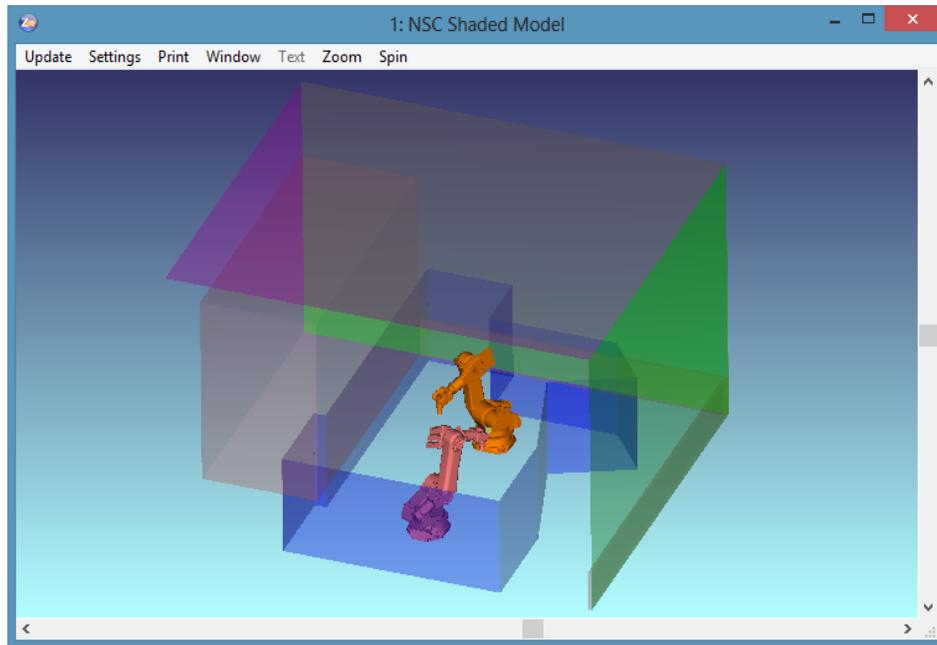
Figure 16. Manufacturing cell with two robots

(a)

(b)
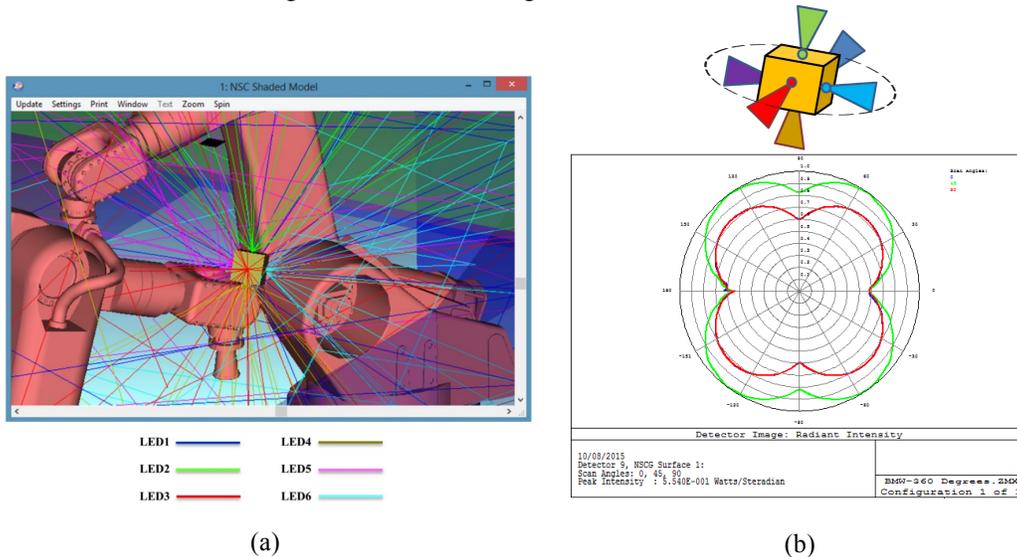
Figure 17. (a) 3D location of six LEDs arranged on the six sides of a cube (b) Emission pattern of six LEDs which cover 360º
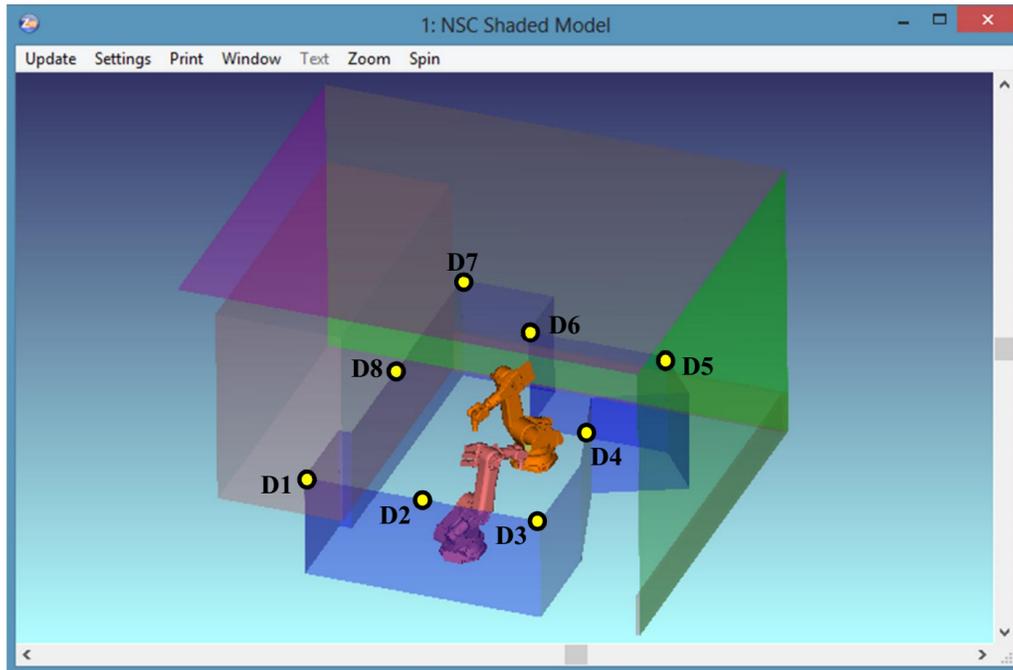
Figure 18. Location of test points which arranged on the top of the Plexiglas boundary

Table 8. Simulation parameters for manifacturing cell environment

Room size	8.03m × 9.45m × 6.8m (See p.18 for exact layout)
Materials	Red Walls: Concrete Green Walls: Aluminum metal Blue Walls: Plexiglas (PMMA) Ceiling: Aluminum metal Floor: Concrete
Objects	Two robots
Object Specifications	Robot: Galvanized steel metal Height of Robot: 2.7m Height of Plexiglas boundary: 2.5m
LED Specifications	Brand: MC-E Cree Xlamp Inc. Half viewing angle: 60º
Number of LEDs	6
Receiver Field of View	35 degrees
Receiver area	1 cm^2

Resulting Channel Impulse Responses are shown for LED1 to LED6 in Figure 19 to Figure 24. Figure 25 provides the combined channel impulse responses from all LEDs.
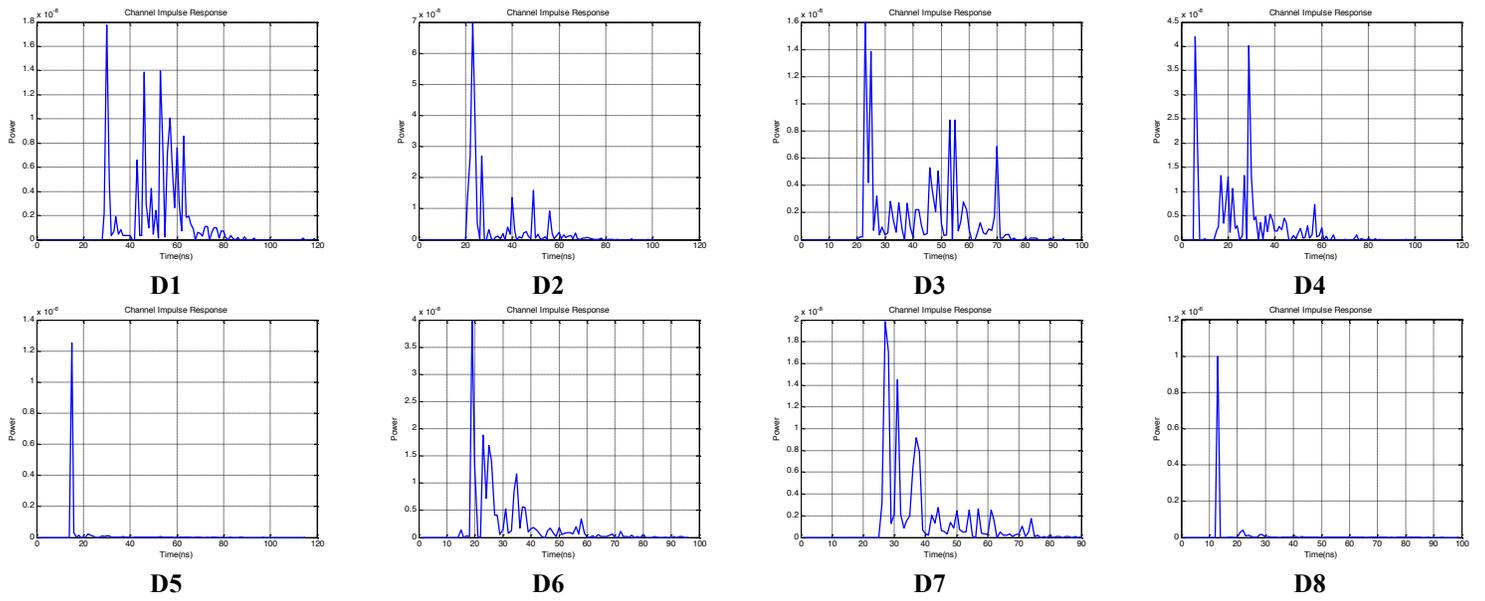
Figure 19. Channel impulse responses of LED1 to D1-D8
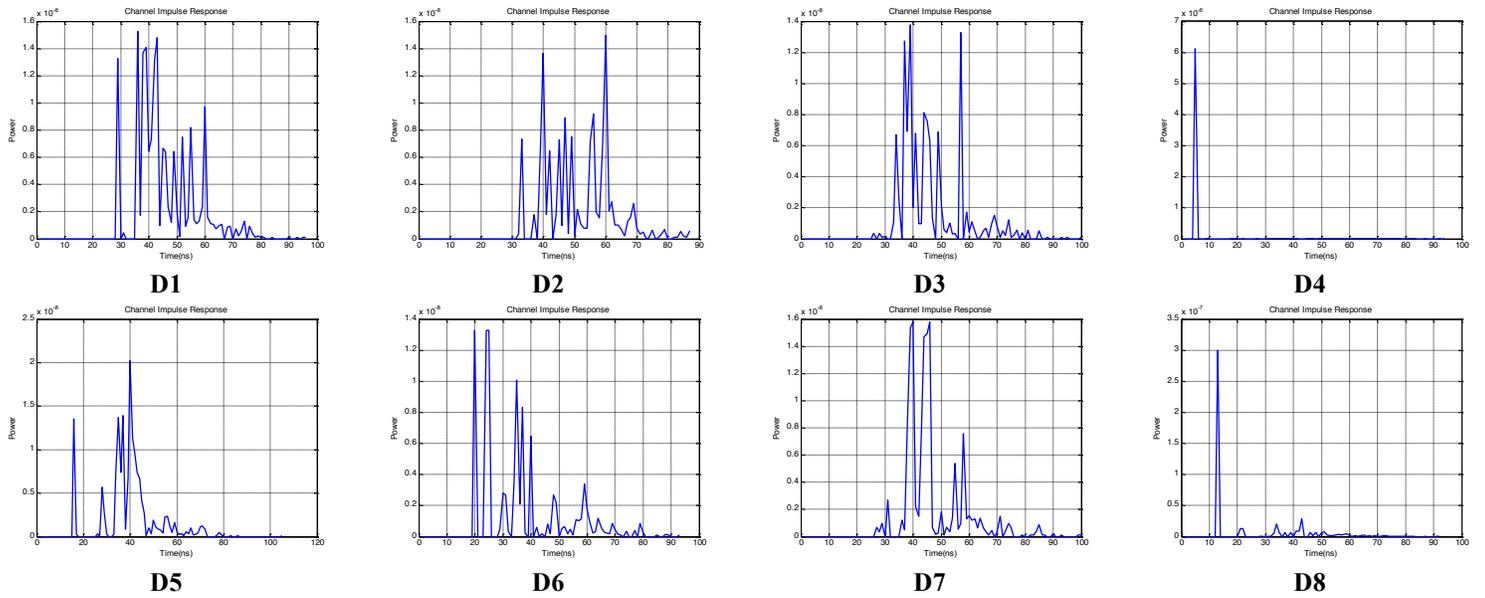
Figure 20. Channel impulse responses of LED2 to D1-D8
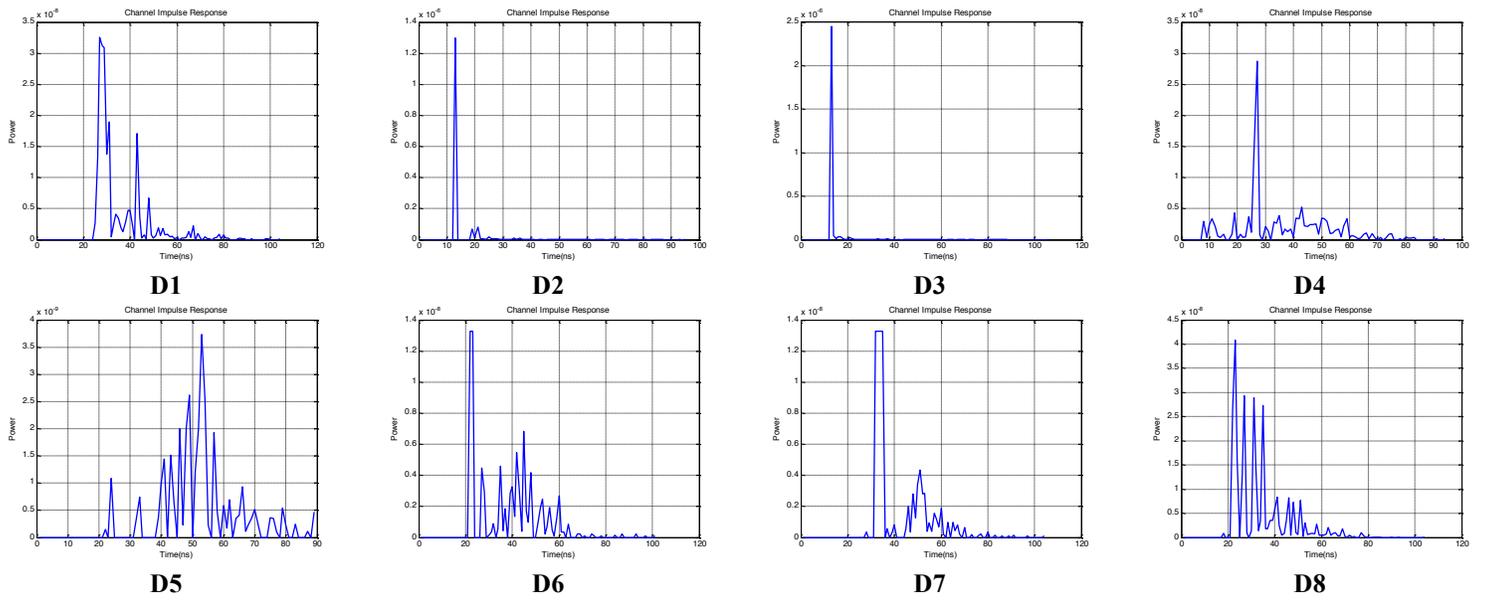
Figure 21. Channel impulse responses of LED3 to D1-D8
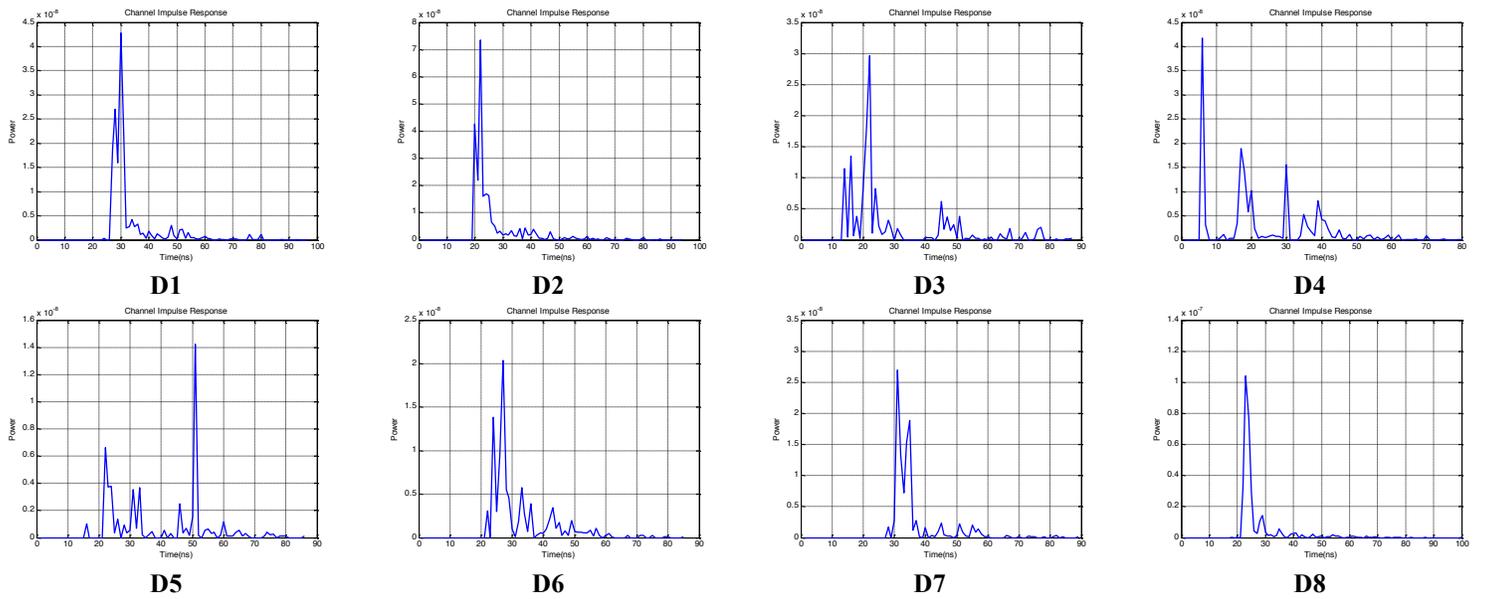
Figure 22. Channel impulse responses of LED4 to D1-D8
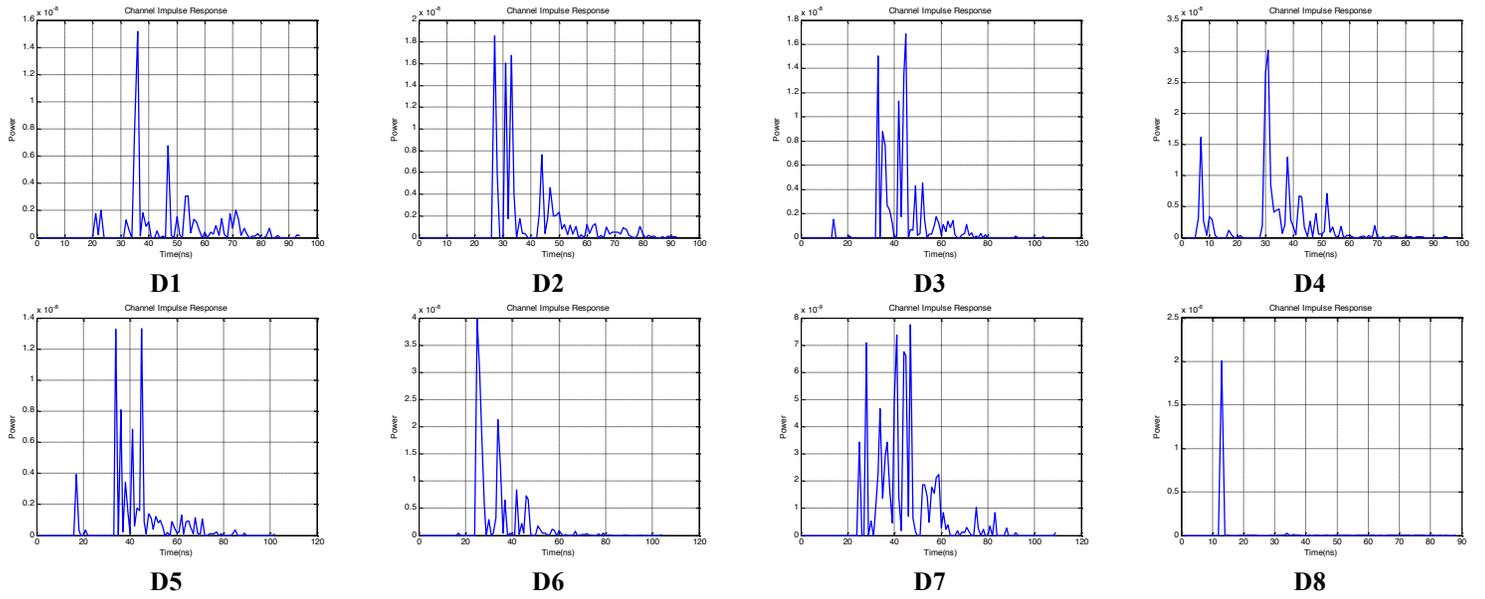
Figure 23. Channel impulse responses of LED5 to D1-D8
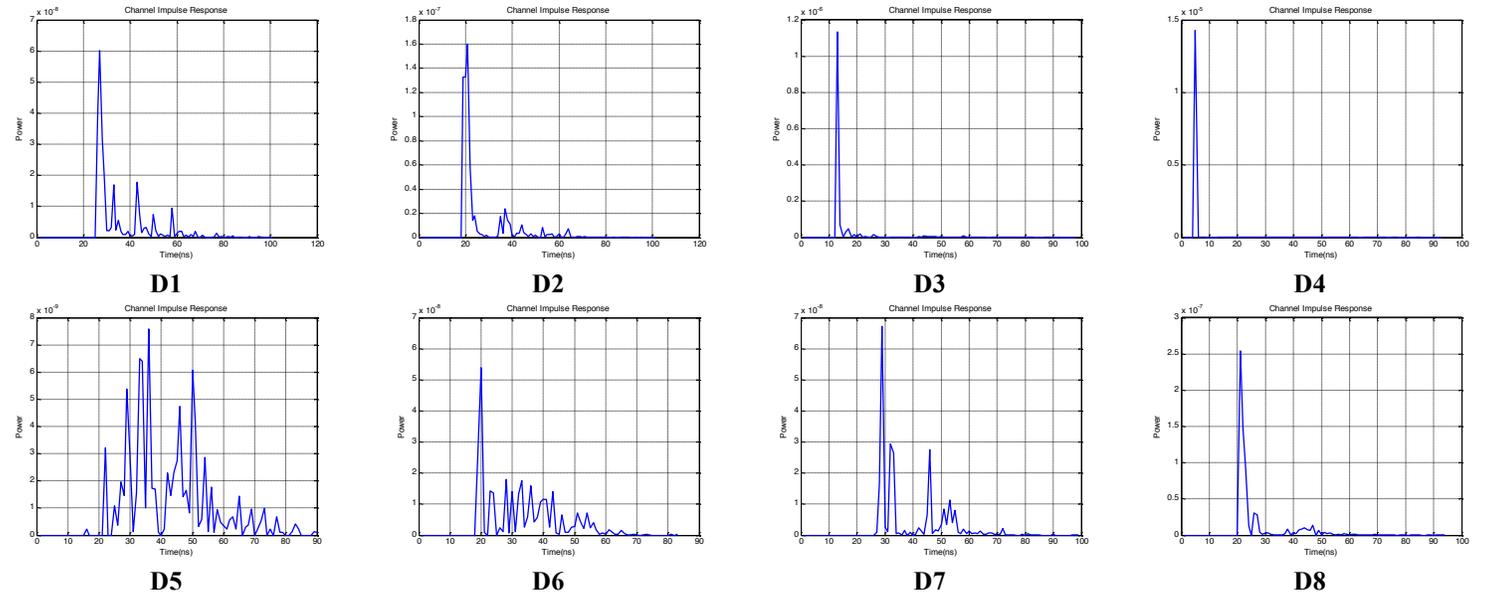
Figure 24. Channel impulse responses of LED6 to D1-D8
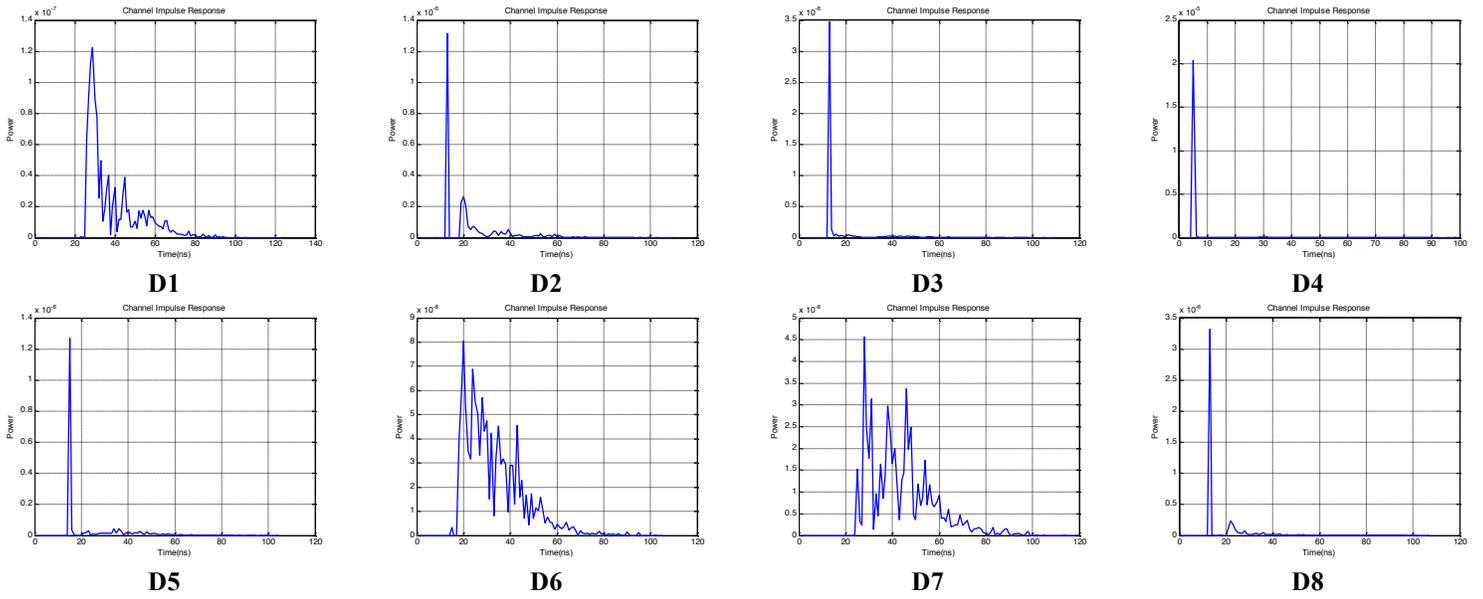
Figure 25. Channel impulse responses of LED1-6 to D1-D8

Regarding channel parameters, **Table 9** and **Table 10** show the results for each LED and **Table 11** shows the combined channel.

Table 9. Channel parameters of LED1-LED3 with respect to D1-D8

TX-RX		$T_{97\%}$ (ns)	t_{RMS} (ns)	H_0
LED1	**D1**	75	12.88	1.45×10^{-7}
	D2	64	13.48	2.71×10^{-7}
	D3	70	15.93	1.16×10^{-7}
	D4	58	15.56	2.55×10^{-7}
	D5	38	7.52	1.45×10^{-6}
	D6	63	12.82	1.92×10^{-7}
	D7	71	12.71	1.20×10^{-7}
	D8	43	9.12	1.19×10^{-6}
LED2	**D1**	69	10.62	1.73×10^{-7}
	D2	71	10.80	1.30×10^{-7}
	D3	73	11.04	1.17×10^{-7}
	D4	5	5.45	6.27×10^{-6}
	D5	68	11.50	1.57×10^{-7}
	D6	69	14.73	1.01×10^{-7}
	D7	73	10.22	1.37×10^{-7}
	D8	64	17.05	4.92×10^{-7}

	D1	67	11.37	2.19×10^{-7}
	D2	36	7.82	1.59×10^{-6}
	D3	29	6.19	2.73×10^{-6}
LED3	**D4**	68	15.65	1.42×10^{-7}
	D5	79	11.97	3.30×10^{-8}
	D6	62	13.73	8.89×10^{-8}
	D7	67	11.77	8.84×10^{-8}
	D8	63	11.77	2.83×10^{-7}

Table 10. Channel parameters of LED4-LED6 with respect to D1-D8

TX-RX		$T_{97\%}$ (ns)	t_{RMS} (ns)	H_0
	D1	60	9.84	1.70×10-7
	D2	58	10.53	2.53×10-7
	D3	75	15.86	1.40×10-7
LED4	**D4**	55	14.78	1.65×10-7
	D5	67	14.74	5.43×10-8
	D6	56	10.09	9.77×10-8
	D7	57	8.44	1.07×10-7
	D8	53	8.23	3.19×10-7
	D1	75	14.95	6.39×10-8
	D2	74	13.70	1.05×10-7
	D3	65	10.14	1.08×10-7
LED5	**D4**	58	14.44	1.73×10-7
	D5	70	12.34	7.22×10-8
	D6	57	10.20	1.77×10-7
	D7	75	11.99	8.43×10-8
	D8	34	6.15	2.09×10-6
	D1	66	12.46	2.64×10-7
	D2	59	11.48	6.73×10-7
	D3	47	9.23	1.44×10-6
LED6	**D4**	5	3.87	1.44×10-5
	D5	72	13.12	8.73×10-8
	D6	6	11.97	3.13×10-7
	D7	65	11.78	2.43×10-7
	D8	53	10.51	6.90×10-7

Table 11. Channel parameters of LED1-6 with respect to D1-D8

TX-RX		$T_{97\%}$ (ns)	t_{RMS} (ns)	H_0
	D1	70	13.48	1.16×10^{-6}

	D2	58	13.33	2.99×10^{-6}
	D3	52	11.68	4.46×10^{-6}
LED1-6	**D4**	29	6.79	2.15×10^{-5}
(Covering 360º)	**D5**	60	14.36	1.94×10^{-6}
	D6	62	12.54	1.22×10^{-6}
	D7	75	13.66	5.69×10^{-7}
	D8	51	11.00	4.67×10^{-6}

References

[1] The IEEE P802.15.7r1 Short-Range Optical Wireless Communications Task Group Project Authorization Request (PAR): https://mentor.ieee.org/802.15/dcn/15/15-15-0064-00-0007-p802-15-7-revision-par-approved-2014-12-10.pdf

[2] Technical Considerations Document: https://mentor.ieee.org/802.15/dcn/15/15-15-0492-05-007a-technical-considerations-document.docx

[3] Miramirkhani, F., Uysal, M., Panayirci, E.: Novel channel models for visible light communications. SPIE Photonics West, Broadband Access Communication Technologies IX, February 7-12, (2015)

[4] Miramirkhani, F., Uysal, M.: Channel modeling and characterization for visible light communications. IEEE Photon. J., under submission, (2015)

[5] Zemax® 13 Release 2, Radiant Zemax® LLC. www.radiantzemax.com/zemax

[6] Ghassemlooy, Z., Popoola, W., Rajbhandari, S.: Optical Wireless Communications. Boca Raton, FL, USA: Taylor & Francis, (2012)

[7] IEEE 15-15-0685-00-007a "LiFi Reference Channel Models: Office, Home, Manufacturing Cell

[8] Uysal, M., et.al "Channel modeling for visible light communications " https://mentor.ieee.org/802.15/dcn/15/15-15-0352-02-007a-channel-modeling-for-visible-light-communications.pptx

[9] Uysal, M., et.al "Lifi reference channel models office home hospital" https://mentor.ieee.org/802.15/dcn/15/15-15-0514-01-007a-lifi-reference-channel-models-office-home-hospital.pptx

[10] Uysal, M., et.al "Lifi Channel models office home manufacturing cell" https://mentor.ieee.org/802.15/dcn/15/15-15-0685-00-007a-lifi-reference-channel-models-office-home-manufacturing-cell.pdf

Appendix

The file P802.15-15-747r1 provides MATLAB files, which are explained in this document.

In the file, each folder includes mat files for each receiver defined in each scenario.
The time resolution (time spacing) of all CIRs are 1 ns.
Distance Units are Millimeters.

Folders in the zip file:

%% Folder "Scenario 1"

1) This folder includes the CIRs for open office room and open office with cubicles. Number of CIRs (corresponds to test points) for each case are 24 such as D1-D24.

2) Coordinates of test points are as follows:

D1:(3400,2500,1700)   D5:(3400,-2500,1700)   D9:(3400,-7500,1700)
D13:(1950,-200,950)   D17:(-2050,-5700,950)   D21:(-5900,0,1100)
D2:(-200,2500,1700)   D6:(-200,-2500,1700)   D10:(-200,-7500,1700)
D14:(-2050,-200,950)   D18:(-6050,-5700,950)   D22:(2100,-5500,1100)
D3:(-3800,2500,1700)   D7:(-3800,-2500,1700)   D11:(-3800,-7500,1700)
D15:(-6050,-200,950)   D19:(2100,0,1100)   D23:(-1900,-5500,1100)
D4:(-7400,2500,1700)   D8:(-7400,-2500,1700)   D12:(-7400,-7500,1700)
D16:(1950,-5700,950)   D20:(-1900,0,1100)   D24:(-5900,-5500,1100)

3) Coordinates of luminaries are as follows:

S1:(-5250,5950,3000)   S5:(-5250,4250,3000)   S9:(-5250,2550,3000)
S13:(-5250,850,3000)   S17:(-5250,-850,3000)   S21:(-5250,-2550,3000)
S25:(-5250,-4250,3000)   S29:(-5250,-5950,3000)   S2:(-1750,5950,3000)
S6:(-1750,4250,3000)   S10:(-1750,2550,3000)   S14:(-1750,850,000)
S18:(-1750,-850,3000)   S22:(-1750,-2550,3000)   S26:(-1750,-4250,3000)
S30:(-1750,-5950,3000)   S3:(1750,5950,3000)   S7:(1750,4250,3000)
S11:(1750,2550,3000)   S15:(1750,850,3000)   S19:(1750,-850,3000)
S23:(1750,-2550,3000)   S27:(1750,-4250,3000)   S31:(1750,-5950,3000)
S4:(5250,5950,3000)   S8:(5250,4250,3000)   S12:(5250,2550,3000)
S16:(5250,850,3000)   S20:(5250,-850,3000)   S24:(5250,-2550,3000)
S28:(5250,-4250,3000)   S32:(5250,-5950,3000)

4) Specifications of detector:
FOV: 85 degrees
Area: 1 cm^2

5) Specifications of luminary:
Brand: LR24-38SKA35 Cree Inc
Half Viewing Angle: 40 degrees

%% Folder "Scenario 2"

1) This folder includes the CIRs for office room with secondary light. Number of CIRs (corresponds to test points) are 3 such as:

   * Ceiling Light (Source) To Desk Light (Relay) Receiver
   * Ceiling Light (Source) To Destination
   * Desk Light (Relay) Transmitter To Destination

2) Coordinates of test points are as follows:

Destination:(-1190,1350,880)
Desk Light (Relay) Receiver:(-1260,1280,1500)   Tilt angles in X, Y, Z: (45,225,0)---Towards the source

3) Coordinates of luminaries are as follows:

Ceiling Light (Source):(0,0,3000)
Desk Light (Relay) Transmitter:(-1190,1350,1330)
Tilt angles in X, Y, Z: (0,219,0)---Towards destination

4) Specifications of detector:
FOV: 85 degrees
Area: 1 cm^2

5) Specifications of luminary:
Brand: LR24-38SKA35 Cree Inc
Half Viewing Angle: 40 degrees

%% Reference Channel Model: "Scenario 3"

1) This file includes the CIRs for home environment. Number of CIRs (corresponds to test points) are 8 such as D1-D8.

2) Coordinates of test points are as follows:

D1:(600,-1000,600)   D5:(-200,1500,900)
D2:(-2000,-2000,1700)   D6:(-1000,1850,900)
D3:(2000,2000,1700)   D7:(-1000,1150,900)
D4:(-1800,1500,900)   D8:(1700,-1800,1100)

3) Coordinates of luminaries are as follows:

S1:(-2500,2500,3000)   S5:(0,0,3000)
S2:(0,2500,3000)   S6:(2500,0,3000)
S3:(2500,2500,3000)   S7:(-2500,-2500,3000)
S4:(-2500,0,3000)   S8:(0,-2500,3000)
S9:(2500,-2500,3000)

4) Specifications of detector:
FOV: 85 degrees
Area: 1 cm^2

5) Specifications of luminary:
Brand: CR6-800L Cree Inc
Half Viewing Angle: 40 degrees

%% Folder "Scenario 4"

1) This folder includes the CIRs for one manufacturing cell. Labels and Number of CIRs are as follows:

   "Individually"------48: For LEDi-Dj   i=1:6 & j=1:8
   "Simultaneously"----8: For LED(1-6)-Dj

2) Coordinates of test points are as follows:

D1:(-2810,-3594,2500)   D5:(2984,4042,2500)
D2:(0,-3594,2500)   D6:(-310,4040,2500)
D3:(2810,-3594,2500)   D7:(-2509,5645,2500)
D4:(2370,500,2500)   D8:(-2510,1025,2500)

3) Coordinates of LEDs are as follows:

S1:(1170,-10,2080)   S4:(1200,-100,2050)
S2:(1200,-45,2190)   S5:(1125,-100,2130)
S3:(1230,-150,2140)   S6:(1270,-45,2105)

4) Specifications of detector:
FOV: 35 degrees
Area: 1 cm^2

5) Specifications of LEDs:
Brand: MC-E Cree Xlamp Inc
Half Viewing Angle: 60 degrees

List of Contributors

Murat Uysal	Ozyegin University
Tuncer Baykas	Istanbul Medipol University
Farshad Miramirkhani (	Ozyegin University
Volker Jungnickel	Fraunhofer Heinrich Hertz Institute
Nikola Serafimovski	pureLiFi
Dominic Schulz	Fraunhofer Heinrich Hertz Institute
Yeong Min Jang	Kookmin University
Richard Roberts	Intel
Yu Zeng	China Telecom
Mitsuaki Oshima	Panasonic
Rojan Chitrakar	Panasonic
Jaesang Cha	SNUST
Soo-Young Chang	SYCA
Trang Nguyen Van	Kookmin University
Md. Shareef Ifthekhar	Kookmin University
Nam Tuan Le	Kookmin University
Shuzo Kato	Tohoku University
Mohamad Arif Hussein	Kookmin University
Hideki Aoyama	Panasonic
Shoichi Kitazawa	ATR