

**IEEE P802.11  
Wireless LANs**

<b>IEEE 802.11bb Reference Channel Models for Indoor Environments</b>				
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### Abstract

**This contribution proposes 802.11bb reference channel models for indoor environments.**

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## 1. Definitions

<b>PHY</b>	Physical Layer
<b>MAC</b>	Media Access Control
<b>LC</b>	Light Communications
<b>SAP</b>	Service Access Point
<b>HCF</b>	Hybrid Coordination Function
<b>OBSS</b>	Overlapping Basic Service Set
<b>CFP</b>	Call for Proposal
<b>OWC</b>	Optical Wireless Communication
<b>CIR</b>	Channel Impulse Response
<b>VLC</b>	Visible Light Communication
<b>RMS</b>	Root Mean Square
<b>LED</b>	Light Emmiting Diode
<b>FOV</b>	Field of View
<b>TCD</b>	Technical Considerations Document

## 2. Introduction

This amendment specifies a new physical layer (PHY) layer and modifications to the IEEE 802.11 Media Access Control (MAC) that enable operation of wireless light communications (LC). This amendment specifies a PHY that provides:

- 1) Uplink and downlink operations in 380 nm to 5,000 nm band.
- 2) All modes of operation achieve minimum single-link throughput of 10 Mb/s and at least one mode of operation that achieves single-link throughput of at least 5 Gb/s, as measured at the MAC data service access point (SAP).
- 3) Interoperability among solid state light sources with different modulation bandwidths.

This amendment specifies changes to the IEEE 802.11 MAC that are limited to the following:

- 1) Hybrid coordination function (HCF) channel access.
- 2) Overlapping basic service set (OBSS) detection and coexistence.
- 3) Existing power management modes of operation (excluding new modes), and modifications to other clauses necessary to support these changes.

The purpose of this standard is to provide wireless connectivity for fixed, portable, and moving stations within a local area. This standard also offers regulatory bodies a means of standardizing access to one or more frequency bands for the purpose of local area communication. The main goal of this document is to provide channel models to allow a fair comparison of different PHY submitted to TGbb in response to the Call for Proposals (CFP).

The most reliable channel modeling approach for optical wireless communication (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 802.11bb 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 (CIRs).

The remainder of the document is organized as follow. Sections 3 presents the channel modeling methodology. Sections 4 to 8 include scenarios considered by TGbb. Appendix contains Matlab instructions for the simulation of CIRs.

### **3. Channel Modeling Methodology**

A realistic visible light communication (VLC) channel model should take into account 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 come up with more realistic VLC channel models, a new modeling approach based on ray tracing is used [1]-[6]. This chapter provides an overview of this approach and presents some new results for various configurations.

The proposed approach in [1] is based on Zemax<sup>®</sup>; a commercially available optical and illumination design software [7]. The simulation environment is created in Zemax<sup>®</sup> and enables us to specify the geometry of the environment, the objects within as well as the specifications of the light sources and the photodiodes used respectively as transmitters and receivers. For a given number of rays and the number of reflections, the non-sequential ray tracing tool of Zemax<sup>®</sup> calculates the detected power and path lengths from source to detector for each ray. This information is then imported into Matlab<sup>®</sup> and the corresponding CIR for that environment is obtained through proper normalizations. Figure 1 illustrates the process. We express the CIR as [1]

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

where  $P_i$  is the optical power of the  $i$ th ray,  $\tau_i$  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 several channel parameters such as channel DC gain, path loss, root mean square (RMS) delay spread and mean excess delay. Channel DC gain ( $H_0$ ) is one of the most important features of a VLC channel, as it determines the achievable signal-to-noise ratio for a fixed transmitter power and is calculated as [1]

$$H_0 = \int_0^{\infty} h(t) dt \quad (2)$$

The path loss can be then expressed as [8]

$$PL = -10 \log_{10} \left( \int_0^{\infty} h(t) dt \right). \quad (3)$$

The time dispersion parameters of channel, RMS delay spread and mean excess delay, are respectively given by [1]

$$\tau_{RMS} = \sqrt{\frac{\int_0^{\infty} (t - \tau_0)^2 h(t) dt}{\int_0^{\infty} h(t) dt}} \quad (4)$$

$$\tau_0 = \frac{\int_0^{\infty} t \times h(t) dt}{\int_0^{\infty} h(t) dt} \quad (5)$$

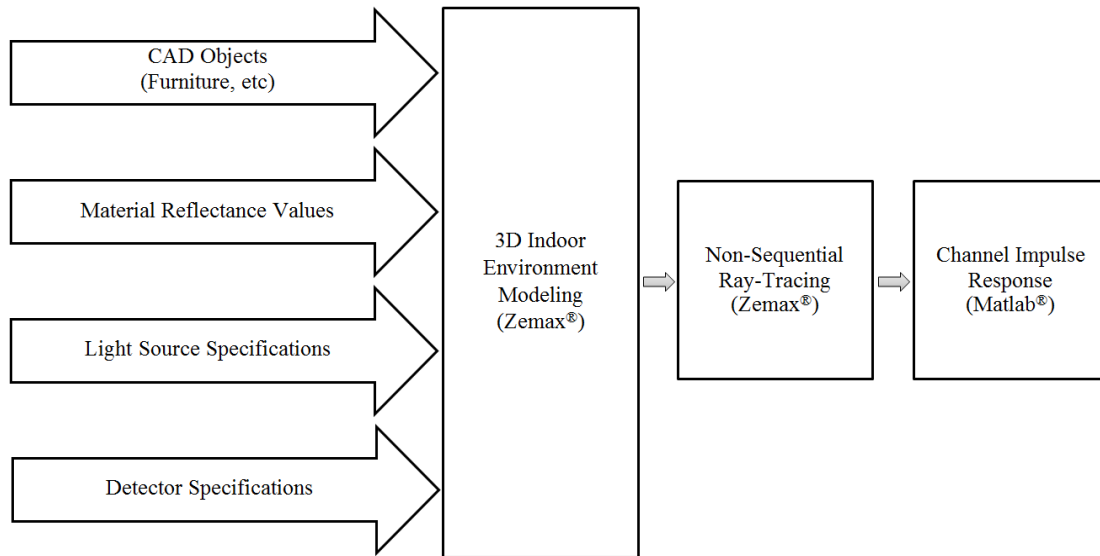


Fig. 1. Channel modeling methodology

#### 4. Scenario Empty Room

We consider a room with a size of 6 m × 6 m × 3 m as illustrated in Fig. 2 with plaster ceiling/walls and pinewood floor. We assume nine luminaires on the ceiling with equidistance spacing. These are commercially available light emitting diodes (LEDs) (Cree® CR6-800L) with 40° half viewing angle. The optical power for each luminaire is 11 Watts. This yields an average illumination level of 153 lux which satisfies typical illumination levels for home environment [9]. The simulation parameters are provided in Table 1. Fig. 3 illustrates arrangement of luminaires in empty room, emission pattern of each luminary, simulated illumination levels in Zemax and illumination level contours in Matlab.

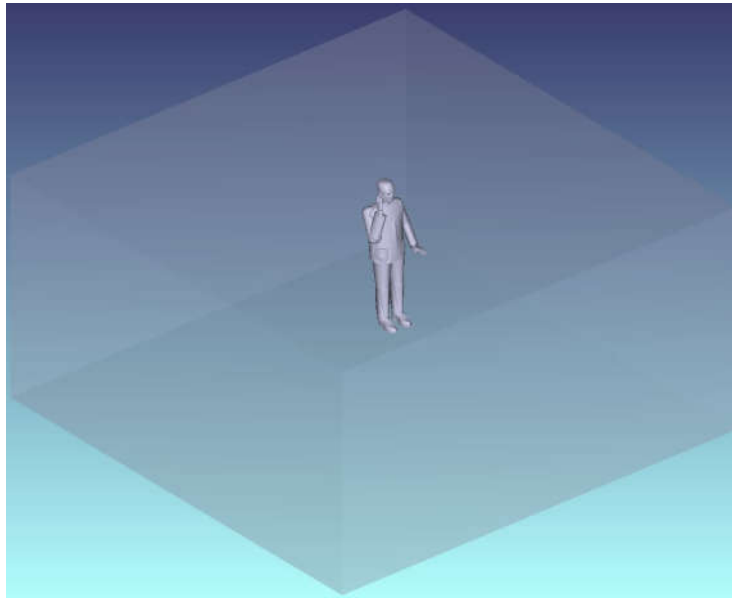


Fig. 2. Room under consideration

Table 1. Simulation parameters for empty room

<b>Room size</b>	6 m × 6 m × 3 m
<b>Materials</b>	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
<b>Objects specifications</b>	Cell phone: Black gloss paint (5.5 cm × 10.5 cm × 0.5 cm) Human body: <ul style="list-style-type: none"> <li>▪ Shoes: Black gloss paint</li> <li>▪ Head &amp; Hands: Absorbing</li> <li>▪ Clothes: Cotton</li> </ul>
<b>Luminaire Specifications</b>	Brand: CR6-800L Cree Inc., Half viewing angle: 40°
<b>Number of luminaires</b>	9
<b>Number of PDs</b>	7
<b>Receiver area</b>	1 cm <sup>2</sup>



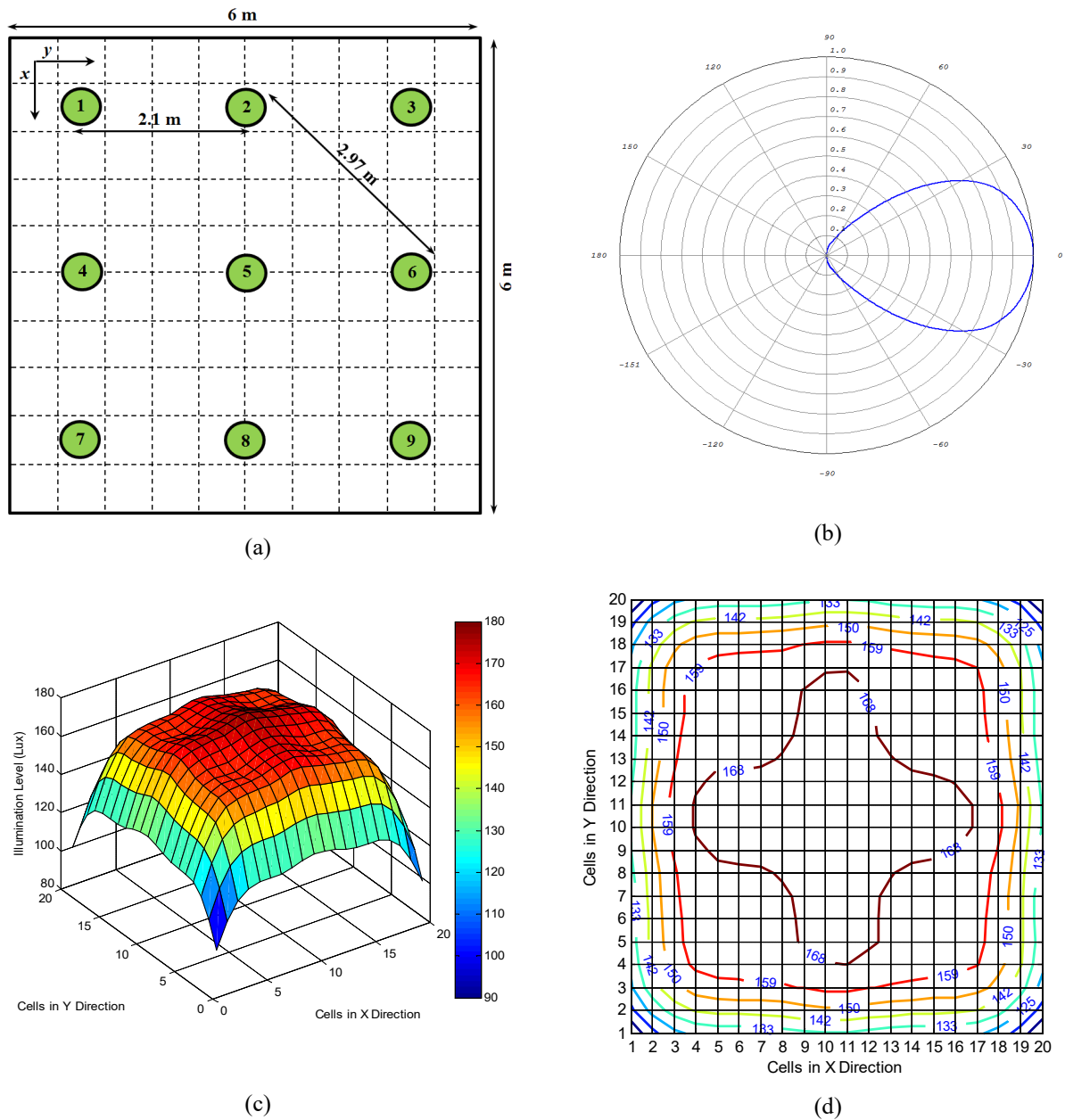


Fig. 3. (a) Arrangement of luminaires (b) emission pattern of each luminaire (c) simulated illumination levels in Zemax and (d) illumination level contours in Matlab

We consider a user with a height of 1.8 m and model the human body as a CAD object (see Fig. 4.a) with absorbing property. The cell phone has a size of  $5.5 \text{ cm} \times 10.5 \text{ cm} \times 0.5 \text{ cm}$  and is equipped with a single photodetector. The user holds the phone in his hand next to his ear with  $45^\circ$  rotation upward the ceiling and at a height of 1.8 m. We consider seven potential locations for the photodetectors denoted as  $D_n$ ,  $n = 1, \dots, 7$  (see Fig. 4.b).  $D_1, \dots, D_5$  are placed on the top edge of the cell phone oriented toward the ceiling.  $D_6$  and  $D_7$  are placed on the top two round corners of the cell phone oriented toward the ceiling and floor, respectively. The field of view (FOV) and the area of each detector are  $85^\circ$  and  $1 \text{ cm}^2$ , respectively.

Non-sequential ray tracing features of Zemax<sup>®</sup> are used to calculate the detected power and path lengths from source to detector for each ray. These are then imported Matlab to obtain the CIR. To further investigate the effects of user locations, we consider 100 cells with equidistant

spacing of 0.6 m in x and y directions. The user is assumed to be standing in the middle of the cell. Let  $h_i(t)$  denote the individual optical CIR between the  $i$ th luminary and a given location of the photodetector. The combined optical CIR is given by  $h(t) = \sum_{i=1}^9 h_i(t)$ . The path loss can be then calculated as (3).

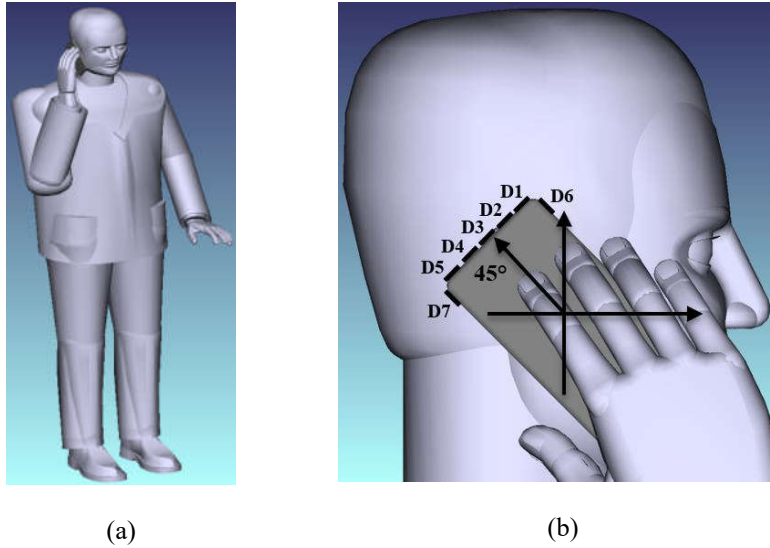


Fig. 4. (a) Human model and (b) location/orientation of PDs on the cell phone

As an example, we consider ten locations for the user denoted as  $P_{1,3}$ ,  $P_{2,8}$ ,  $P_{3,1}$ ,  $P_{4,4}$ ,  $P_{5,9}$ ,  $P_{6,5}$ ,  $P_{7,2}$ ,  $P_{8,7}$ ,  $P_{9,10}$ , and  $P_{10,6}$  (i.e., indicated with yellow colored squares in Fig. 5). The CIRs in these sample locations as seen by the photodetector D5 are presented in Fig. 6.

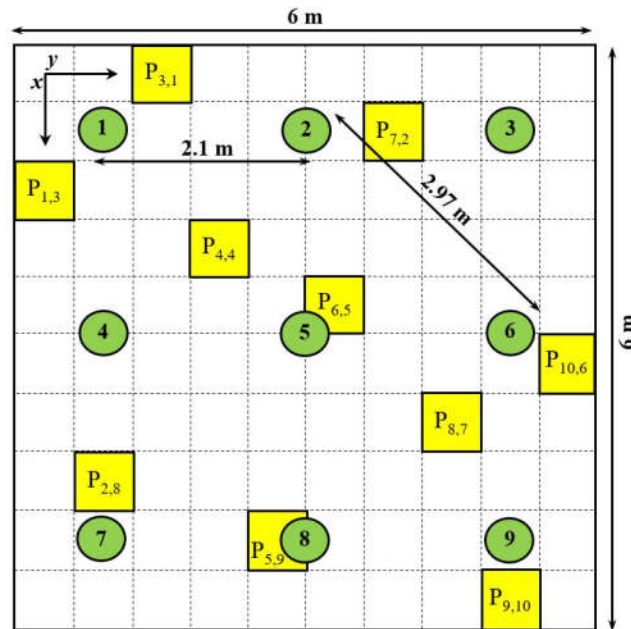
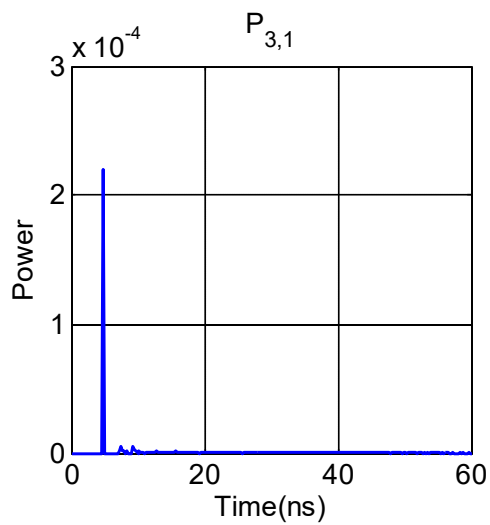
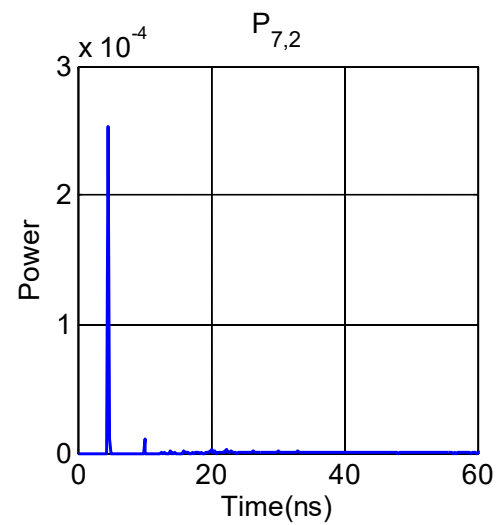


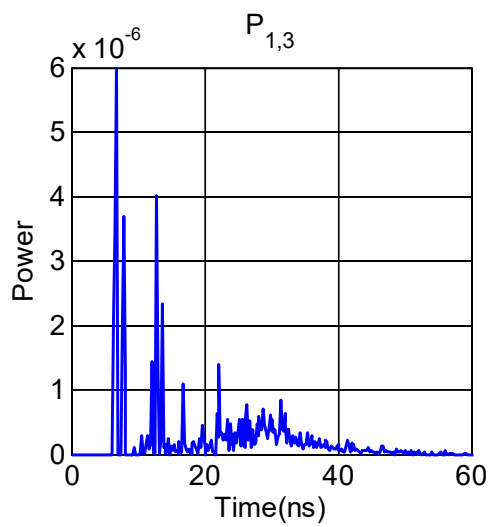
Fig. 5. Sample locations of the user



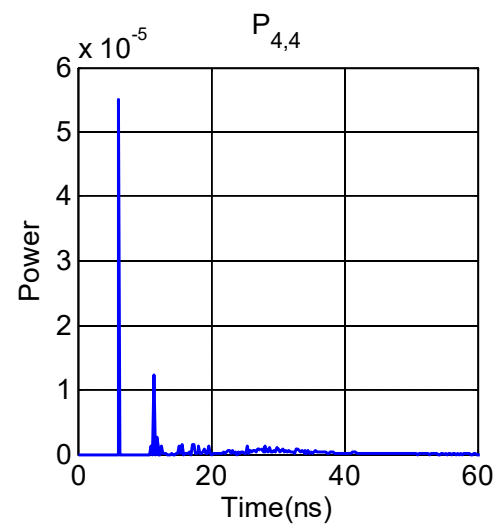
(a)



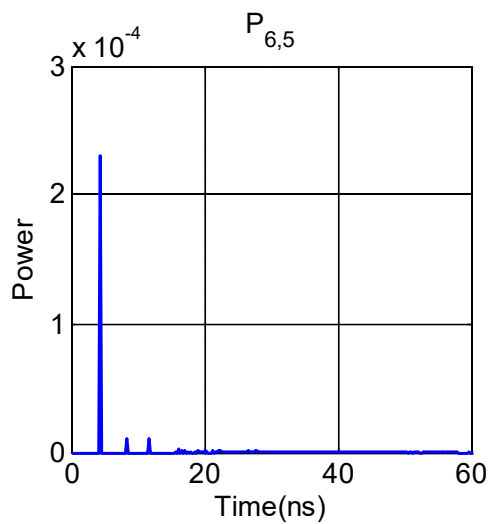
(b)



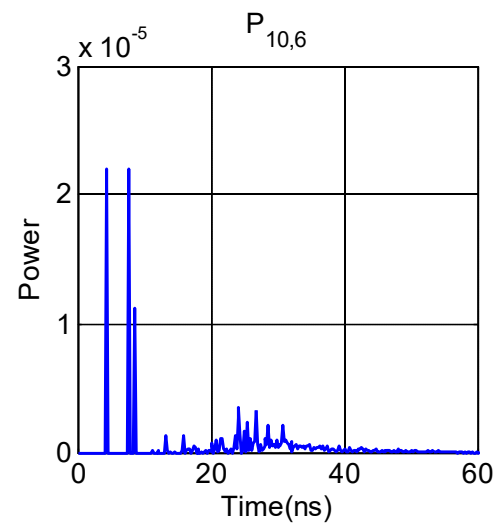
(c)



(d)



(e)



(f)

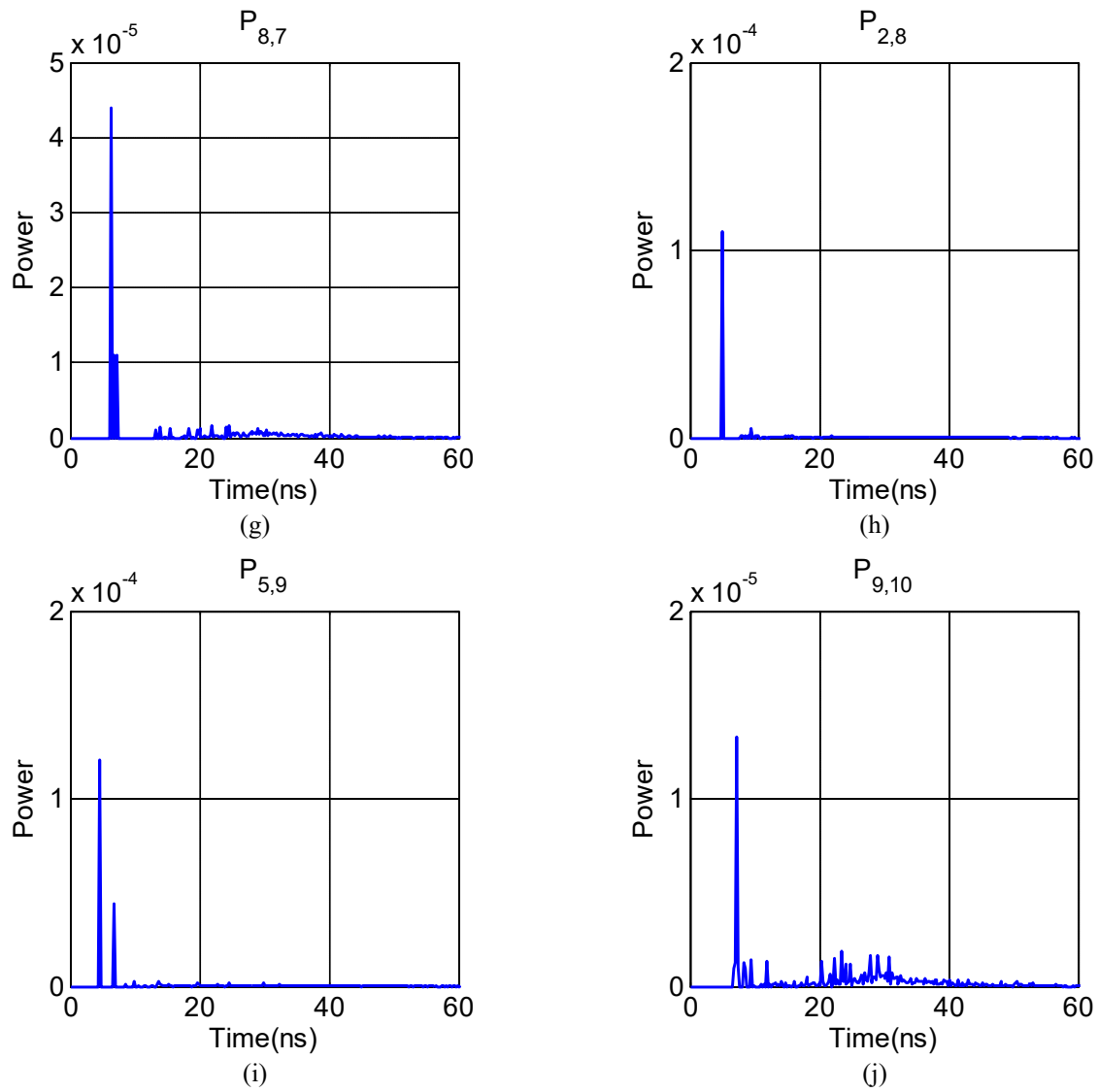


Fig. 6. Sample CIRs as seen by photodetector D5

The frequency response of the optical channel can be further obtained through the Fourier transform, i.e.,

$$H(f) = F[h(t)] = \int_{-\infty}^{\infty} h(t) e^{-j2\pi t} dt \quad (6)$$

The sample optical channel responses are presented in Fig. 7.

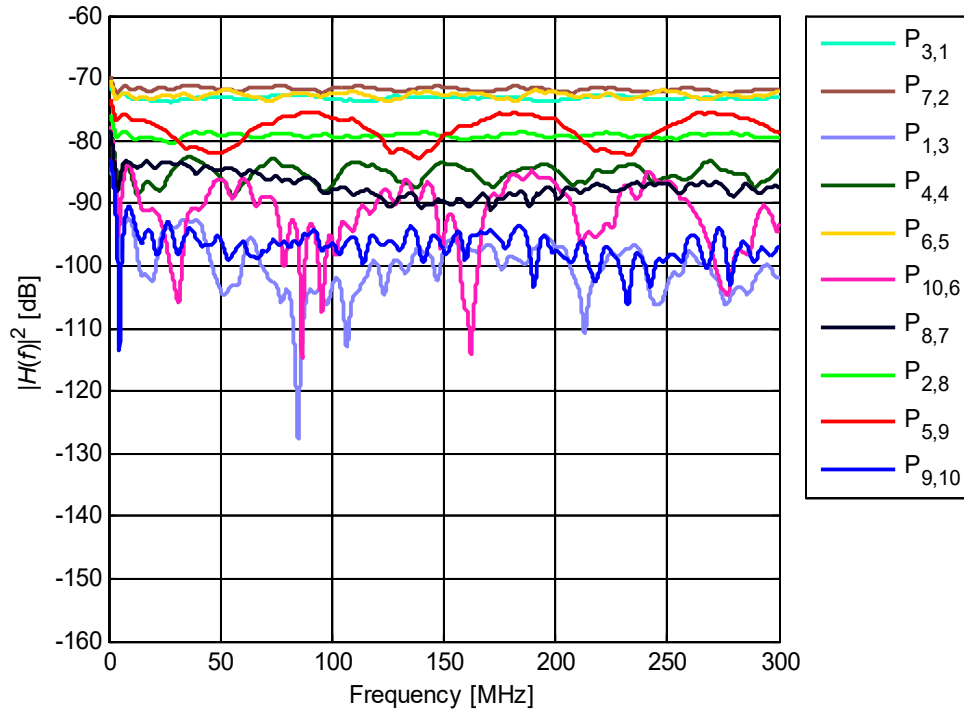


Fig. 7. Sample optical channel responses as seen by photodetector D5

In addition to the multipath propagation environment, the effects of LED sources should be further taken into account in the channel modelling. Two frequency response models for the LED can be assumed as [10], [11]

$$H_{\text{LED}}(f) = \frac{1}{1 + j f / f_{\text{cut-off}}} \quad (7)$$

$$H_{\text{LED}}(f) = e^{-\ln(\sqrt{2}) \left( \frac{f}{f_{\text{cut-off}}} \right)^2} \quad (8)$$

where  $f_{\text{cut-off}}$  is the LED cut-off frequency. Fig. 8 presents these two models assuming different cut-off frequencies of 5 MHz, 10 MHz, 15 MHz and 20 MHz.

The *effective* channel frequency response (taking into account the LED characteristics) can be then expressed as  $H_{\text{eff}}(f) = H_{\text{LED}}(f)H(f)$  where  $H(f)$  denotes the frequency response of VLC channel.

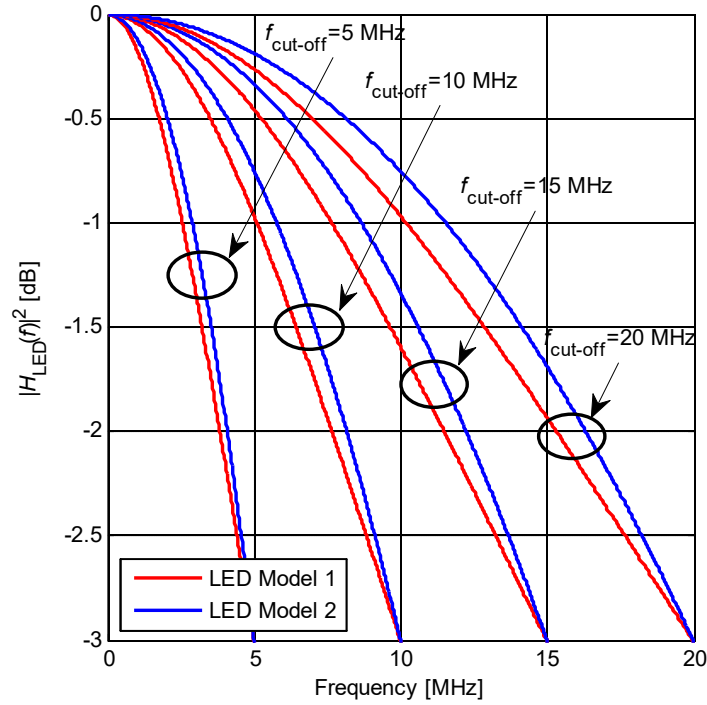
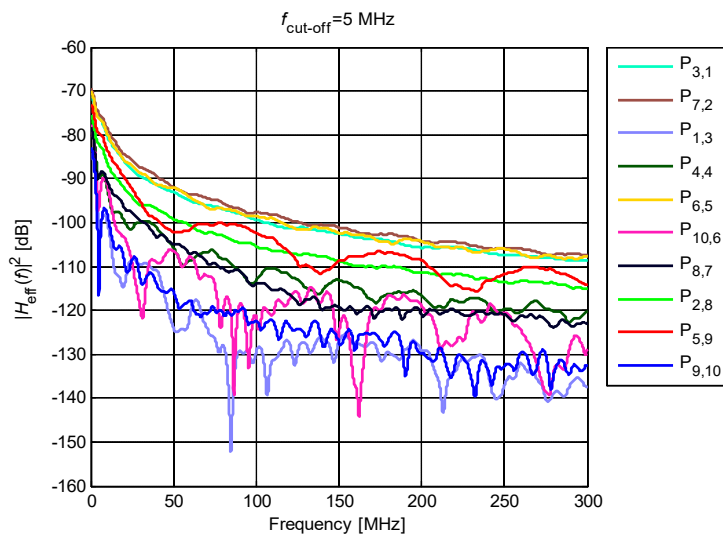


Fig. 8. Frequency response of LED based on (7) and (8) assuming different cut-off frequencies of 5 MHz, 10 MHz, 15 MHz and 20 MHz

The sample effective channel responses as seen by photodetector D5 are illustrated in Fig. 9 assuming LED model in (7) with a cut-off frequencies of  $f_{cut-off} = 5$  MHz, 10 MHz, 15 MHz and 20 MHz. It is observed that the low-pass characteristics of LED result in some attenuation towards higher frequencies. It is also observed that in the effective channel responses of  $P_{1,3}$ ,  $P_{10,6}$  and  $P_{9,10}$ , frequency selectivity is more pronounced. It is a result of the fact that these locations are close to the walls (see Fig. 5) and therefore more reflected rays are received (see corresponding CIRs in Fig. 6). In the rest of this document, the LED model in (7) with cut-off frequency of 20 MHz is considered.



(a)

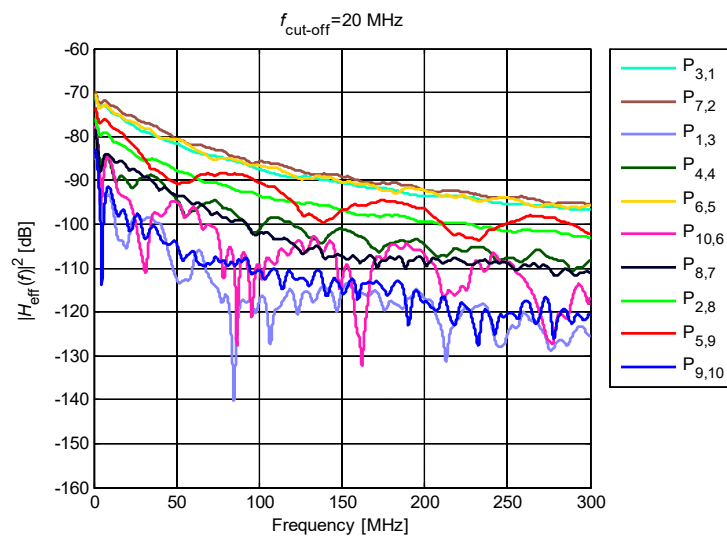
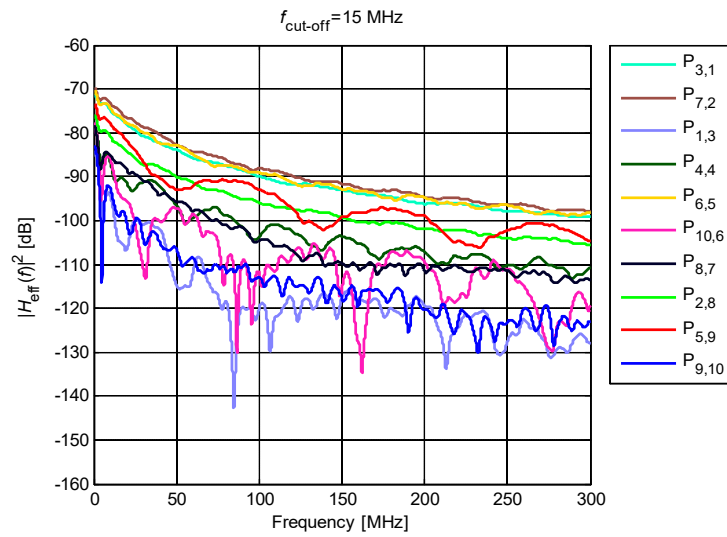
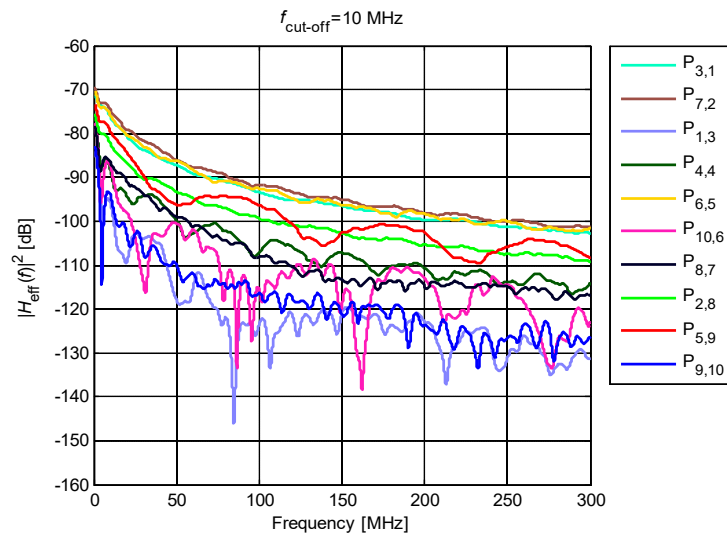
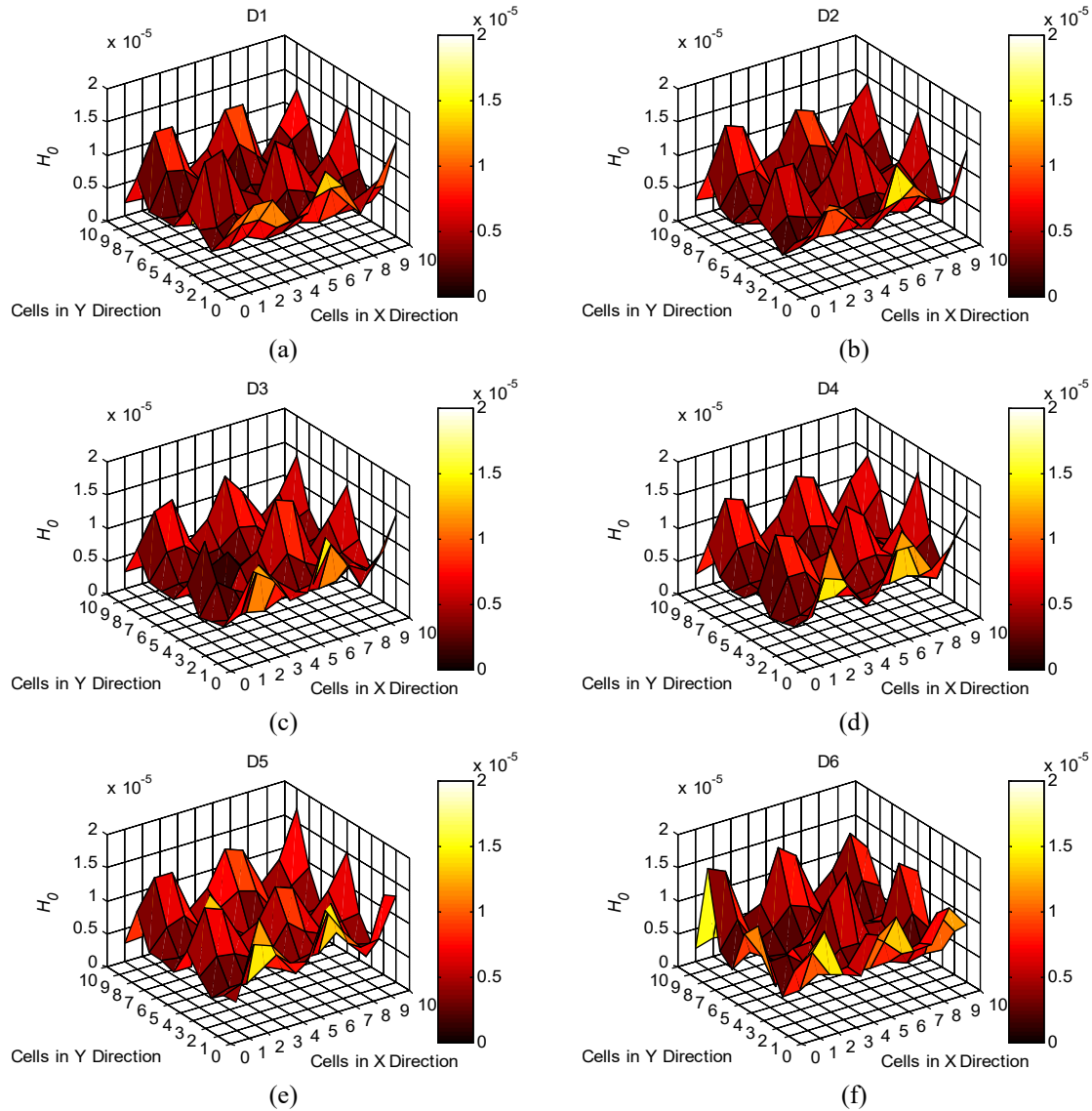


Fig. 9. Sample effective channel responses as seen by photodetector D5

In Fig. 10, we illustrate the spatial distribution of channel gain as seen by the individual photodetectors  $D_n$ ,  $n=1, \dots, 7$ . It is observed that as user moves within the room, the spatial distributions of channel gain seen by the photodetectors  $D1, \dots, D6$  follow the sinusoidal pattern in  $x$  and  $y$  directions. In other words, the maximum signal strength (i.e., maximum value of channel gain) occurs when human moves under the luminaire and vice versa. On the other hand, the spatial distribution of channel gain seen by the photodetector  $D7$  is almost flat (i.e., the same channel gain for all cells). This is due to this fact that this detector is oriented toward the floor and cannot see the received rays from luminaires. Table 2 presents the average channel gains and RMS delay spreads over different cells for  $D1, D2, D3, D4, D5, D6$  and  $D7$ .





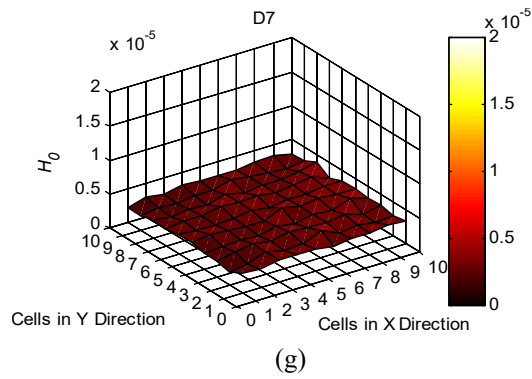


Fig. 10. Spatial distributions of path loss as seen by the individual photodetectors  $D_n$ ,  $n = 1, \dots, 7$

Table 2. Channel parameters for empty room

	$\tau_{RMS}$ (ns)	$H_0$
<b>D1</b>	13.92	$6.00 \times 10^{-6}$
<b>D2</b>	14.10	$6.08 \times 10^{-6}$
<b>D3</b>	14.07	$6.33 \times 10^{-6}$
<b>D4</b>	14.09	$6.89 \times 10^{-6}$
<b>D5</b>	14.10	$7.19 \times 10^{-6}$
<b>D6</b>	14.06	$6.25 \times 10^{-6}$
<b>D7</b>	13.22	$3.05 \times 10^{-6}$

In Fig. 11, we present the channel gains versus cell number for D1, D2, D3, D4, D5, D6 and D7.

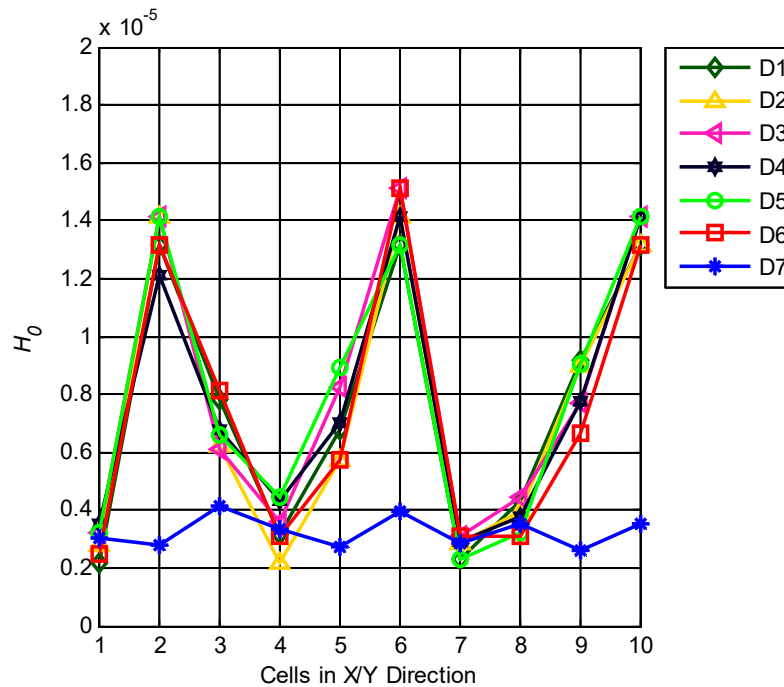


Fig. 11. Channel gain versus cell number as seen by the individual photodetectors  $D_n$ ,  $n = 1, \dots, 7$

In Fig. 12, we present the cumulative distribution function (CDF) of path loss as seen by the individual photodetectors  $D_n$ ,  $n = 1, \dots, 7$ . This gives the probability that path loss will take less than or equal to a specific value. It is observed from Fig. 12 that D1, D2, D3, D4, D5 and D6 have similar path loss values in the range of 51.95 dB-52.94 dB. In comparison to them, D7 has about 2.2 dB-3.2 dB more path loss on average since there is no LOS component.

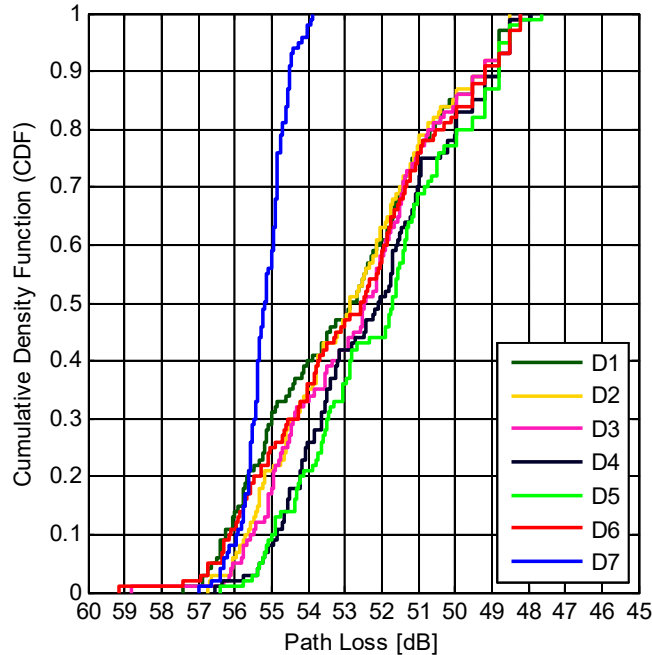


Fig. 12. CDF of path loss as seen by the individual photodetectors  $D_n$ ,  $n = 1, \dots, 7$

## 5. Scenario Enterprise-Conference Room

We consider a conference room where ten users sit around a table (see Fig. 13). The user (photodetector) locations are denoted as  $D_n$ ,  $n = 1, 2, \dots, 10$ . The FOV and the area of the detector are  $85^\circ$  and  $1 \text{ cm}^2$ , respectively. For standing persons (D1 and D10), the cell phone is held in their hand next to their ear and the detector is located on the top edge of the phone with  $45^\circ$  rotation upward the ceiling and at a height of 1.8 m (see Fig. 13.c). For sitting persons (D2, D3, D4, D5, D6, D7, D8, D9), the cell phone is held in their hand over their stomach. The detector is located on the top edge of the phone with  $45^\circ$  rotation upward the ceiling and at a height of 1.1 m (see Fig. 13.c). Details on the floor, ceiling, walls, objects and users within the environment are provided in Table 3.

There are 10 LED luminaires each with 46 watt. These are denoted as  $S_m$ ,  $m = 1, 2, \dots, 10$  (see Fig. 13.b). The LED luminaires used in simulations are commercially available from Cree (LR24-38SKA35). Fig. 14 illustrates emission pattern of each luminaire, simulated illumination levels in Zemax and illumination level contours in Matlab.

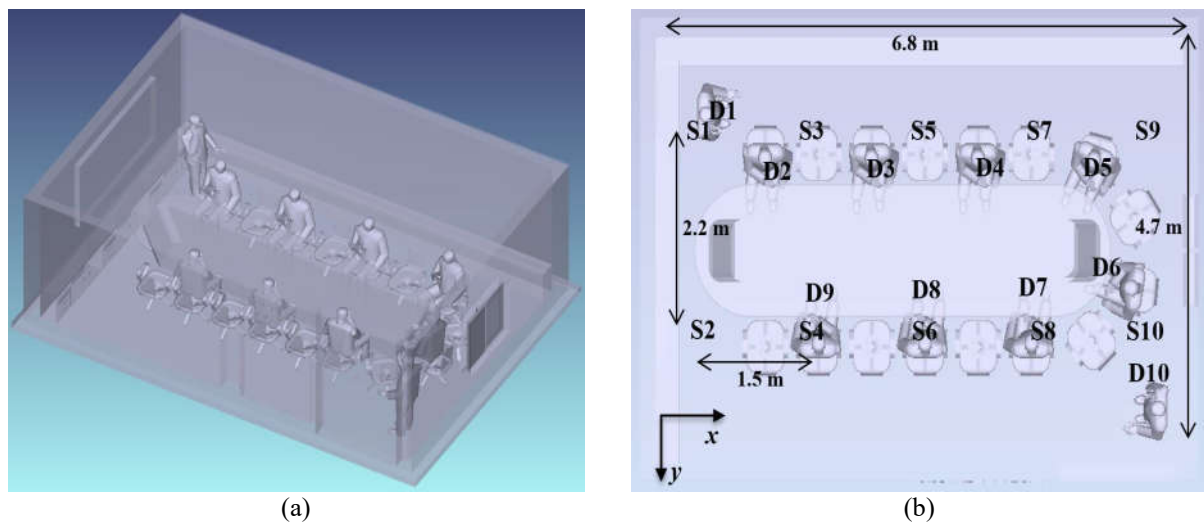


Fig. 13. Conference room under consideration

Table 3. Simulation parameters for conference room

<b>Room size</b>	6.8 m × 4.7 m × 3 m
<b>Materials</b>	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
<b>Objects specifications</b>	Windows: Glass, Monitor: Glass, Chairs: Black gloss paint, Table: Pinewood, Storage cupboard: Aluminum metal, Cell phone: Black gloss paint (5.5 cm × 10.5 cm × 0.5 cm) Human body: <ul style="list-style-type: none"> <li>▪ Shoes: Black gloss paint</li> <li>▪ Head &amp; Hands: Absorbing</li> <li>▪ Clothes: Cotton</li> </ul>
<b>Luminaire Specifications</b>	Brand: LR24-38SKA35 Cree Inc., Half viewing angle: 40°
<b>Number of luminaires</b>	10
<b>Number of PDs</b>	10
<b>Receiver area</b>	1 cm <sup>2</sup>

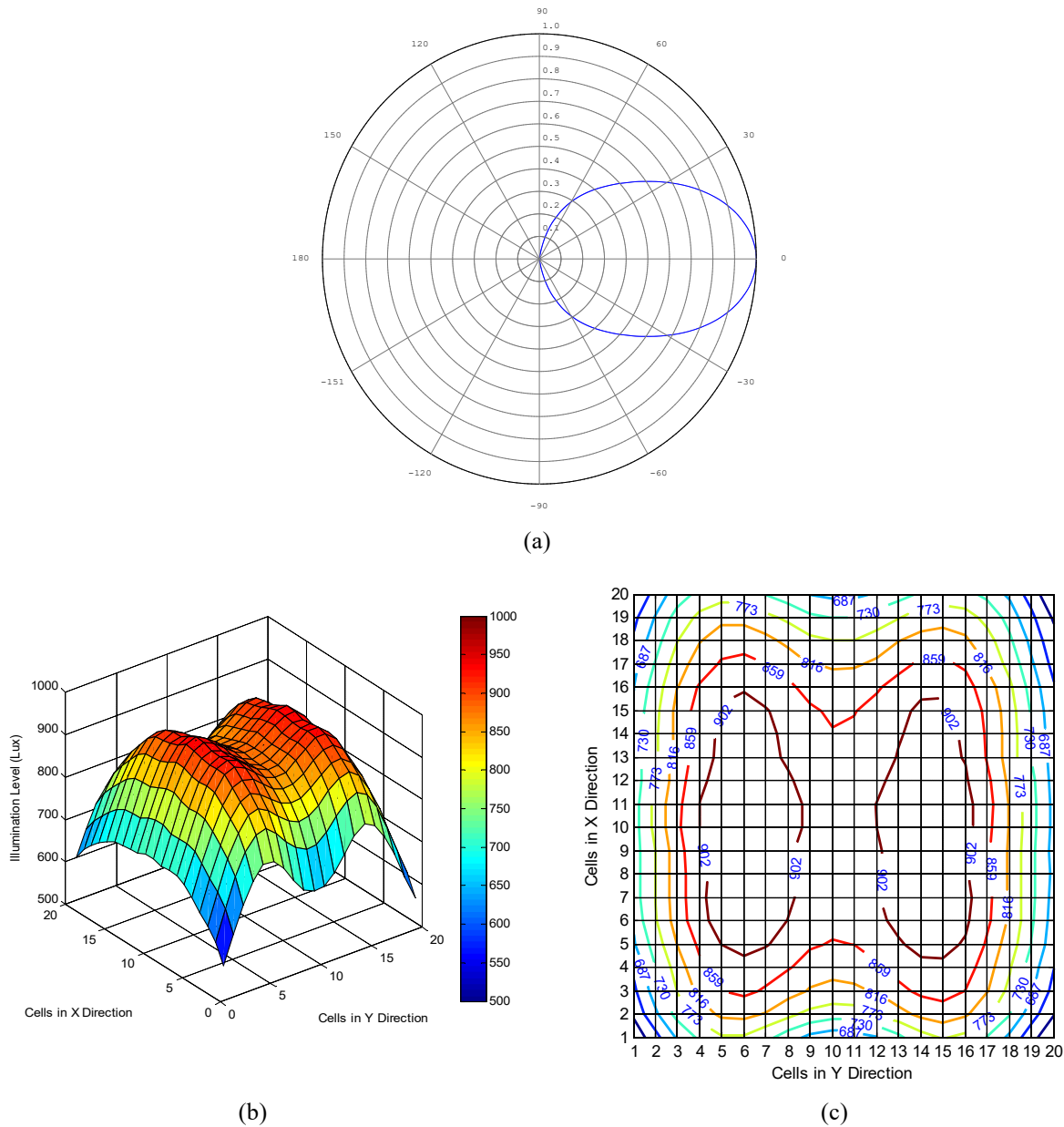


Fig. 14. (a) Emission pattern of each luminaire (b) simulated illumination levels in Zemax and (c) illumination level contours in Matlab

Based on the described simulation scenario above, we present the optical and effective channel responses in Fig. 15. The channel DC gain and RMS delay spreads are also obtained and provided in Table 4.

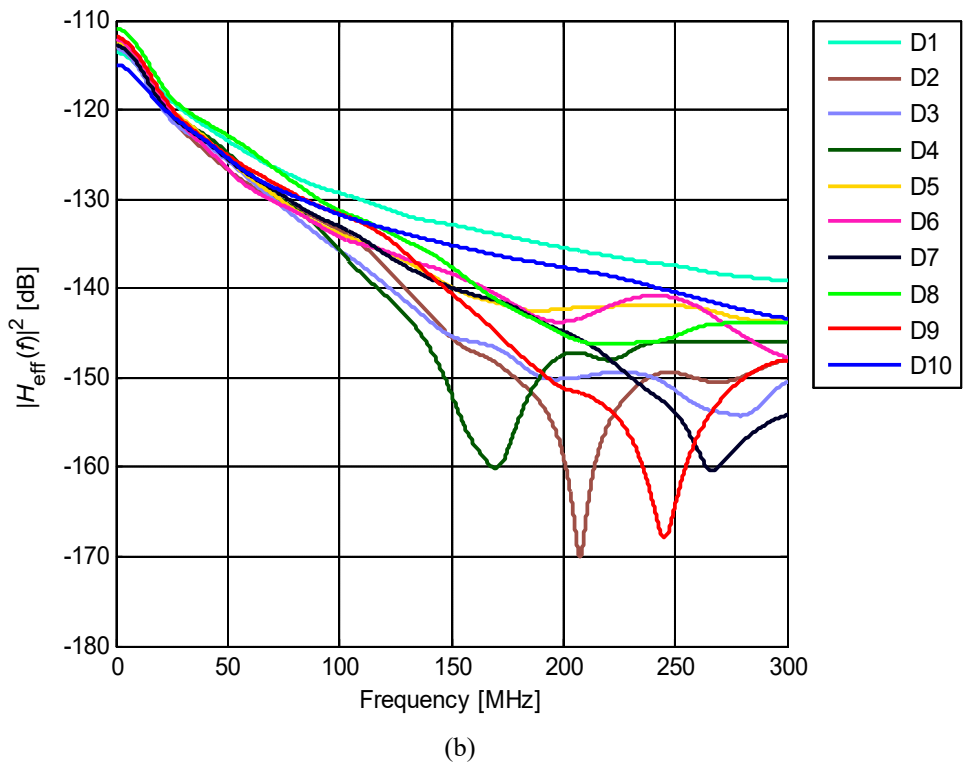
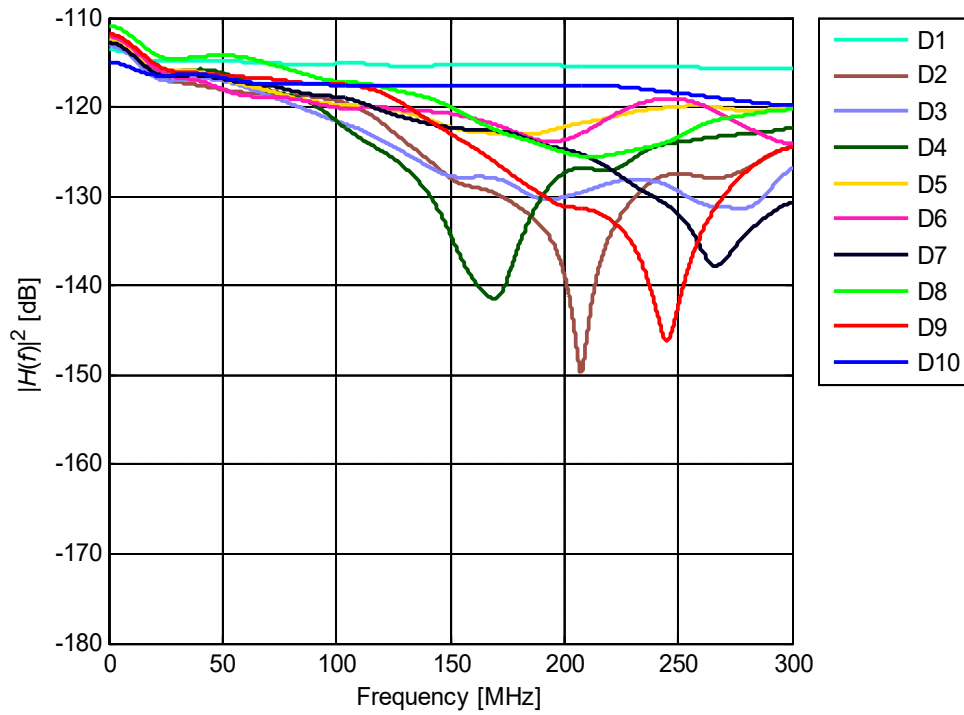


Fig. 15. (a) Optical channel responses and (b) effective channel responses

Table 4. Channel parameters for conference room

		$\tau_{RMS}$ (ns)	$H_0$			$\tau_{RMS}$ (ns)	$H_0$
S1	D1	8.24	$8.23 \times 10^{-5}$	S6	D1	9.98	$5.37 \times 10^{-7}$
	D2	10.35	$1.49 \times 10^{-5}$		D2	11.26	$8.09 \times 10^{-6}$
	D3	12.31	$4.61 \times 10^{-6}$		D3	10.70	$1.57 \times 10^{-5}$
	D4	12.93	$1.77 \times 10^{-6}$		D4	10.63	$1.57 \times 10^{-5}$
	D5	12.40	$1.00 \times 10^{-6}$		D5	11.44	$6.57 \times 10^{-6}$
	D6	10.76	$1.96 \times 10^{-6}$		D6	11.86	$8.01 \times 10^{-6}$
	D7	11.79	$1.86 \times 10^{-6}$		D7	11.89	$1.02 \times 10^{-5}$
	D8	11.68	$3.65 \times 10^{-6}$		D8	10.04	$2.89 \times 10^{-5}$
	D9	10.40	$1.03 \times 10^{-5}$		D9	11.64	$1.10 \times 10^{-5}$
	D10	9.17	$2.78 \times 10^{-7}$		D10	11.45	$1.19 \times 10^{-6}$
S2	D1	9.90	$3.90 \times 10^{-6}$	S7	D1	9.91	$3.10 \times 10^{-7}$
	D2	10.29	$1.44 \times 10^{-5}$		D2	13.02	$1.41 \times 10^{-6}$
	D3	11.35	$5.82 \times 10^{-6}$		D3	12.35	$6.26 \times 10^{-6}$
	D4	11.80	$2.32 \times 10^{-6}$		D4	10.38	$2.31 \times 10^{-5}$
	D5	11.45	$1.35 \times 10^{-6}$		D5	10.14	$2.16 \times 10^{-5}$
	D6	11.37	$1.74 \times 10^{-6}$		D6	10.95	$1.31 \times 10^{-5}$
	D7	12.75	$1.56 \times 10^{-6}$		D7	10.57	$1.85 \times 10^{-5}$
	D8	12.66	$3.05 \times 10^{-6}$		D8	11.20	$1.10 \times 10^{-5}$
	D9	11.22	$8.84 \times 10^{-6}$		D9	11.71	$4.99 \times 10^{-6}$
	D10	9.42	$3.56 \times 10^{-7}$		D10	10.98	$1.17 \times 10^{-6}$
S3	D1	10.99	$2.48 \times 10^{-6}$	S8	D1	10.26	$2.37 \times 10^{-7}$
	D2	9.90	$2.76 \times 10^{-5}$		D2	12.20	$2.87 \times 10^{-6}$
	D3	10.66	$1.67 \times 10^{-5}$		D3	11.62	$6.58 \times 10^{-6}$
	D4	12.87	$4.40 \times 10^{-6}$		D4	10.66	$1.67 \times 10^{-5}$
	D5	12.61	$1.43 \times 10^{-6}$		D5	10.73	$1.52 \times 10^{-5}$
	D6	11.83	$3.56 \times 10^{-6}$		D6	9.83	$2.72 \times 10^{-5}$
	D7	12.14	$3.94 \times 10^{-6}$		D7	9.90	$3.01 \times 10^{-5}$
	D8	11.28	$9.68 \times 10^{-6}$		D8	11.89	$9.58 \times 10^{-6}$
	D9	10.40	$1.79 \times 10^{-5}$		D9	12.87	$3.23 \times 10^{-6}$
	D10	10.74	$5.36 \times 10^{-7}$		D10	10.28	$4.61 \times 10^{-6}$
S4	D1	10.43	$8.61 \times 10^{-7}$	S9	D1	9.66	$3.39 \times 10^{-7}$
	D2	10.72	$1.61 \times 10^{-5}$		D2	10.58	$8.50 \times 10^{-7}$
	D3	10.71	$1.38 \times 10^{-5}$		D3	12.73	$2.74 \times 10^{-6}$
	D4	11.96	$5.96 \times 10^{-6}$		D4	11.90	$6.80 \times 10^{-6}$
	D5	12.15	$2.64 \times 10^{-6}$		D5	10.14	$2.18 \times 10^{-5}$
	D6	12.51	$3.30 \times 10^{-6}$		D6	11.45	$8.90 \times 10^{-6}$
	D7	13.80	$2.44 \times 10^{-6}$		D7	10.58	$1.14 \times 10^{-5}$
	D8	11.86	$9.34 \times 10^{-6}$		D8	11.01	$5.70 \times 10^{-6}$
	D9	9.83	$2.94 \times 10^{-5}$		D9	11.05	$2.75 \times 10^{-6}$
	D10	10.80	$3.93 \times 10^{-7}$		D10	10.46	$2.94 \times 10^{-6}$
S5	D1	10.75	$7.29 \times 10^{-7}$	S10	D1	9.67	$2.20 \times 10^{-7}$
	D2	12.73	$5.96 \times 10^{-6}$		D2	11.33	$2.12 \times 10^{-6}$
	D3	10.24	$2.62 \times 10^{-5}$		D3	11.64	$3.50 \times 10^{-6}$
	D4	10.69	$1.91 \times 10^{-5}$		D4	10.93	$8.11 \times 10^{-6}$
	D5	12.36	$5.85 \times 10^{-6}$		D5	9.99	$1.75 \times 10^{-5}$
	D6	11.55	$7.32 \times 10^{-6}$		D6	10.16	$2.03 \times 10^{-5}$
	D7	11.19	$1.06 \times 10^{-5}$		D7	11.42	$9.72 \times 10^{-6}$
	D8	10.36	$1.93 \times 10^{-5}$		D8	12.72	$2.96 \times 10^{-6}$
	D9	10.89	$1.23 \times 10^{-5}$		D9	11.09	$1.11 \times 10^{-6}$
	D10	10.53	$6.72 \times 10^{-7}$		D10	8.38	$6.02 \times 10^{-5}$

## 6. Scenario Enterprise-Office with Secondary Light

According to technical considerations document (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” [12]. 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. Fig. 16 illustrates the office and the simulation parameters are provided in Table 5.

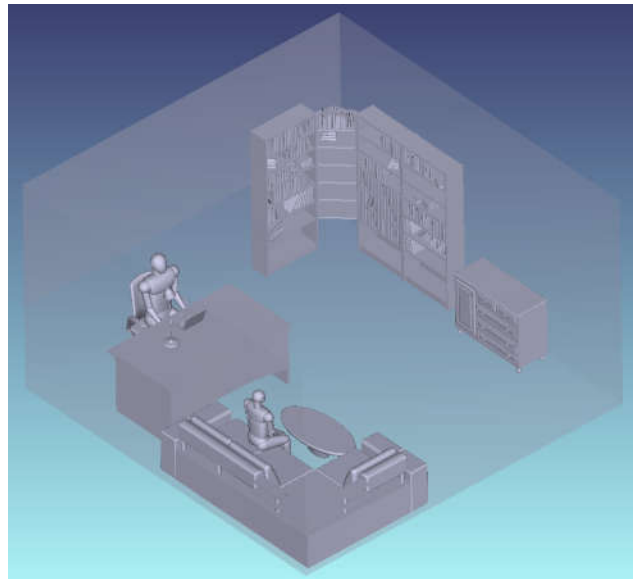


Fig. 16. Office room under consideration

Table 5. Simulation parameters for office room with secondary light

<b>Room size</b>	5 m × 5 m × 3 m
<b>Materials</b>	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
<b>Objects</b>	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
<b>Objects specifications</b>	Desk: Pinewood (Typical height of 0.88 m), Chair: Black gloss paint, Laptop: Black gloss paint, Desk light: Black gloss paint, Library: Pinewood, Window: Glass, Couch: Cotton, Coffee table: Pinewood Human body: <ul style="list-style-type: none"> <li>▪ Shoes: Black gloss paint</li> <li>▪ Head &amp; Hands: Absorbing</li> <li>▪ Clothes: Cotton</li> </ul>
<b>Luminaire Specifications</b>	Brand: LR24-38SKA35 Cree Inc., Half viewing angle: 40°
<b>Number of luminaires</b>	1 on the ceiling, 1 for the desk light
<b>Receiver area</b>	1 cm <sup>2</sup>

Fig. 17 illustrates arrangement of luminaires in office room, emission pattern of each luminaire, simulated illumination levels in Zemax and illumination level contours in Matlab.

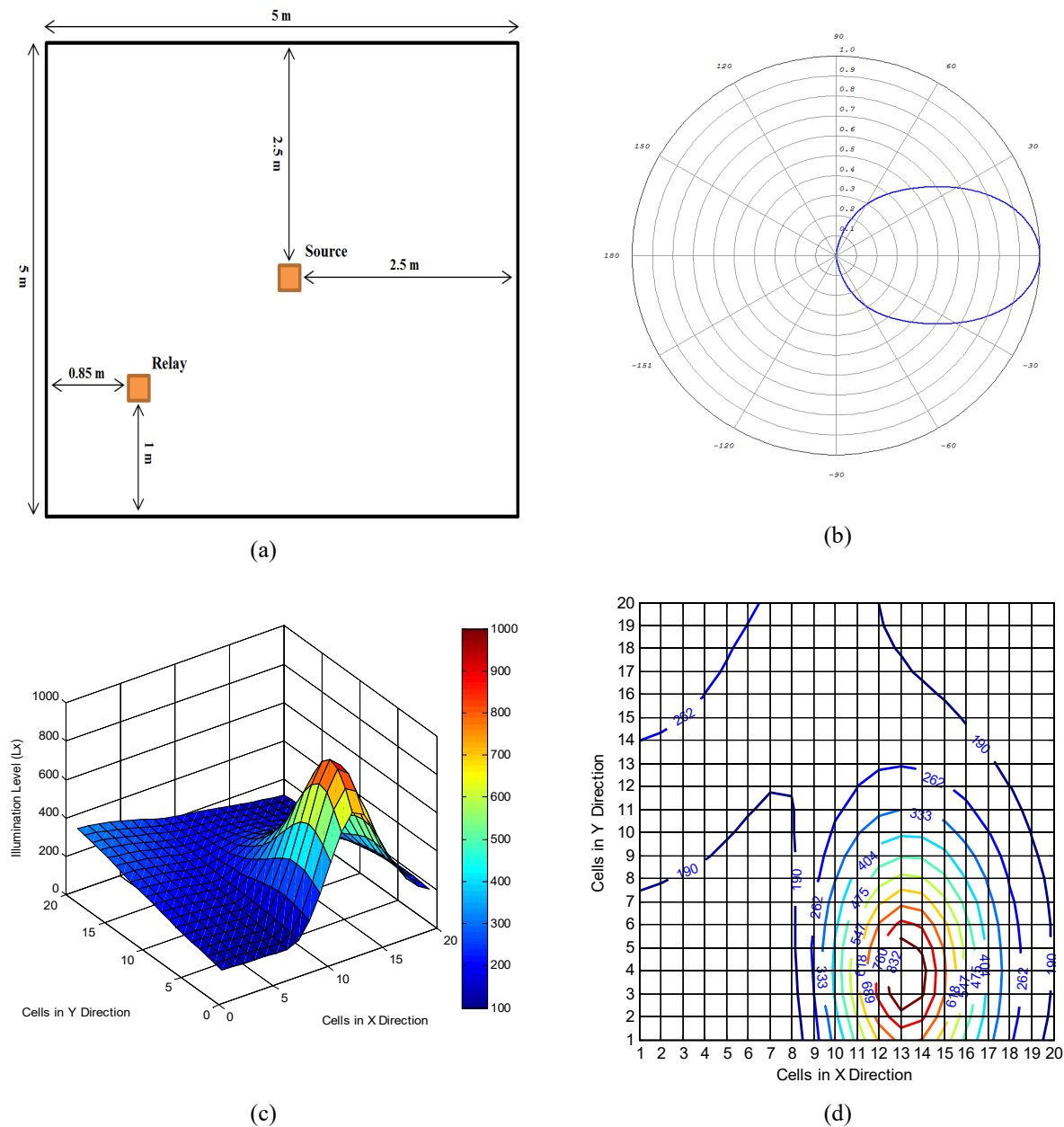
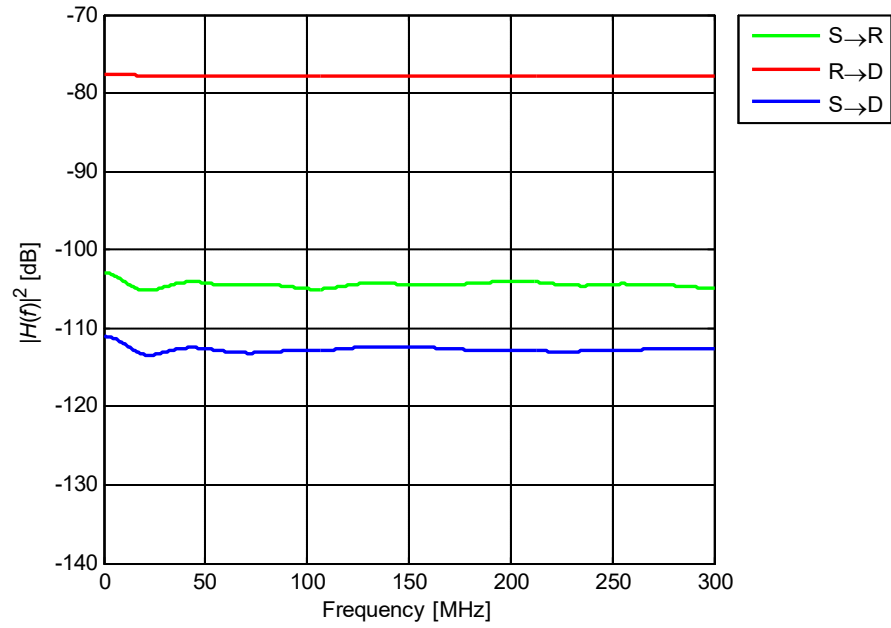


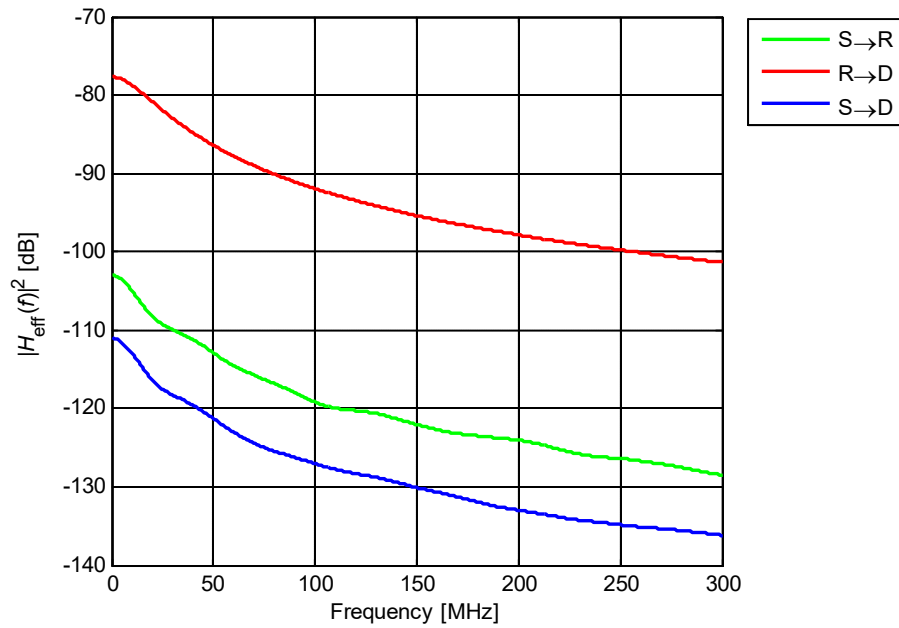
Fig. 17. (a) Arrangement of luminaires (b) emission pattern of each luminaire (c) simulated illumination levels in Zemax and (d) illumination level contours in Matlab

Two test points are chosen. Location D 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 R is on the top of desk light at a height of 1.5 m with 45° rotation toward the source on the ceiling. Based on the described simulation scenario above, we present the optical and effective channel responses in Fig. 18. The channel DC gain and RMS delay spreads are also obtained and provided in Table 6.





(a)



(b)

Fig. 18. (a) Optical channel responses and (b) effective channel responses for S→R, R→D and S→D

Table 6. Channel parameters for office room with secondary light

	$\tau_{RMS}$ (ns)	$H_0$
<b>S→R</b>	11.52	$2.84 \times 10^{-5}$
<b>R→D</b>	8.07	$5.21 \times 10^{-4}$
<b>S→D</b>	11.11	$1.12 \times 10^{-5}$

## 7. Scenario Residential

In this scenario a living room is considered with table, chairs, couch, coffee table as shown in Fig. 19. The simulation parameters are provided in Table 7.

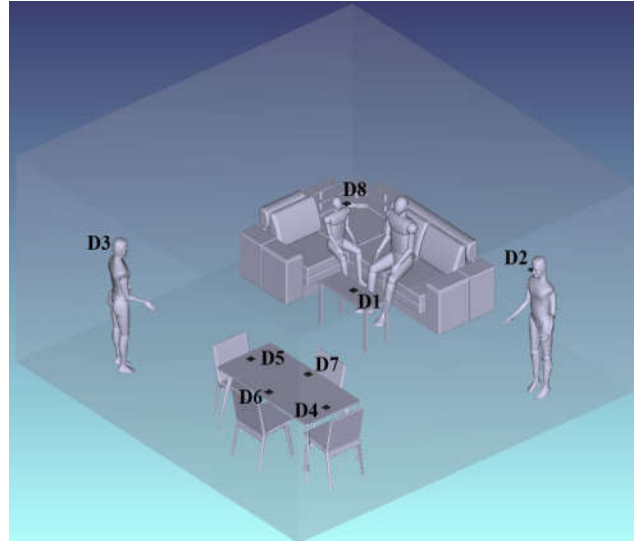


Fig. 19. Home environment

Table 7. Simulation parameters for home environment

<b>Room size</b>	6 m × 6 m × 3 m
<b>Materials</b>	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
<b>Objects</b>	Table with 4 chairs, Couch, Coffee table, 4 human bodies
<b>Object Specifications</b>	Tables: Wooden with size of 2 m × 1 m × 0.9 m, Chairs: Wooden matched with table, Couch: Cotton, Coffee table: Glass Human body: <ul style="list-style-type: none"> <li>▪ Shoes: Black gloss paint</li> <li>▪ Head &amp; Hands: Absorbing</li> <li>▪ Clothes: Cotton</li> </ul>
<b>Luminaire Specifications</b>	Brand: CR6-800L Cree Inc., Half viewing angle: 40°
<b>Number of luminaires</b>	9
<b>Receiver area</b>	1 cm <sup>2</sup>

Arrangement of luminaires in home, emission pattern of each luminaire, simulated illumination levels in Zemax and Illumination levelcontours in Matlab are shown in Fig. 20.

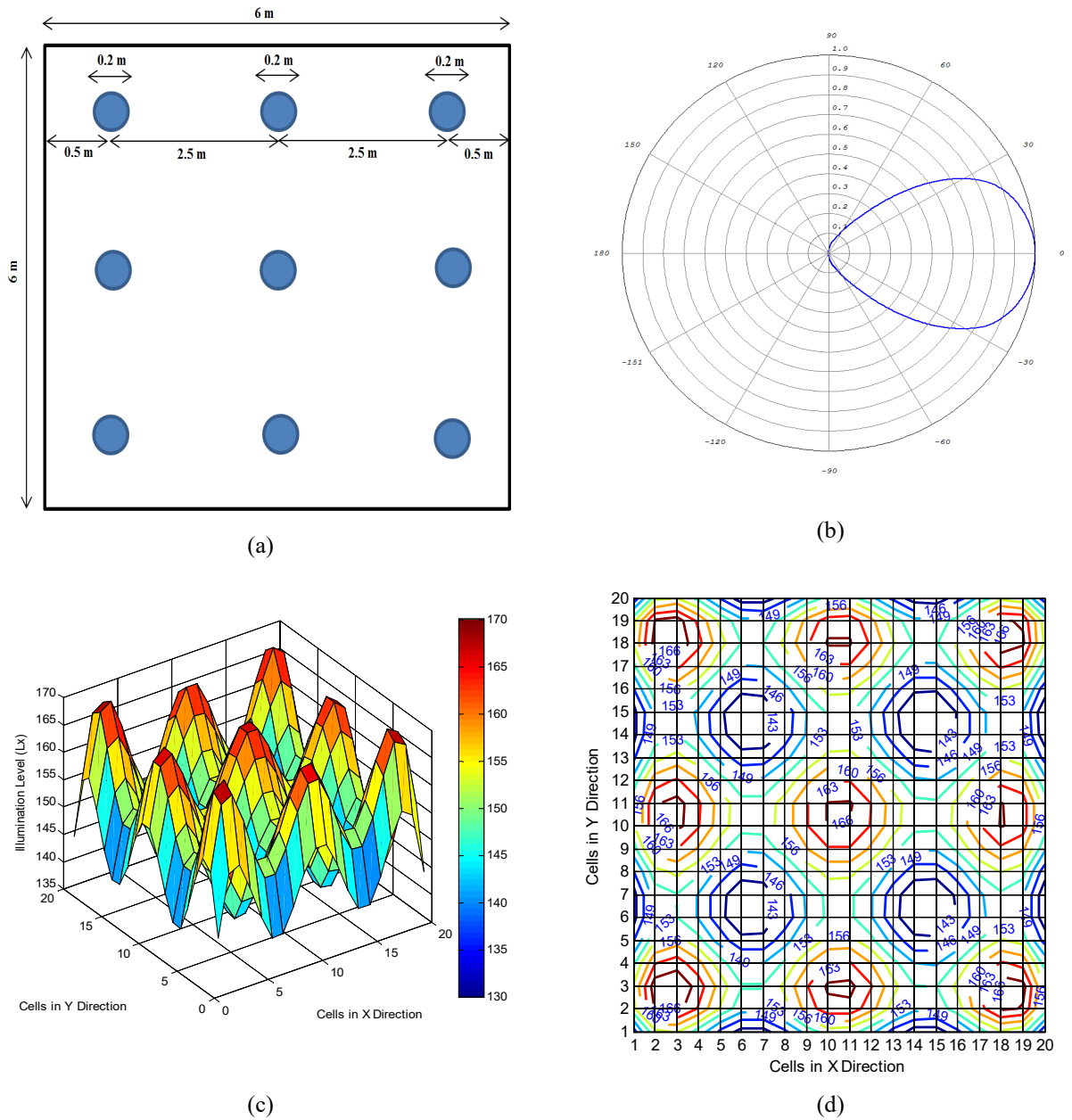
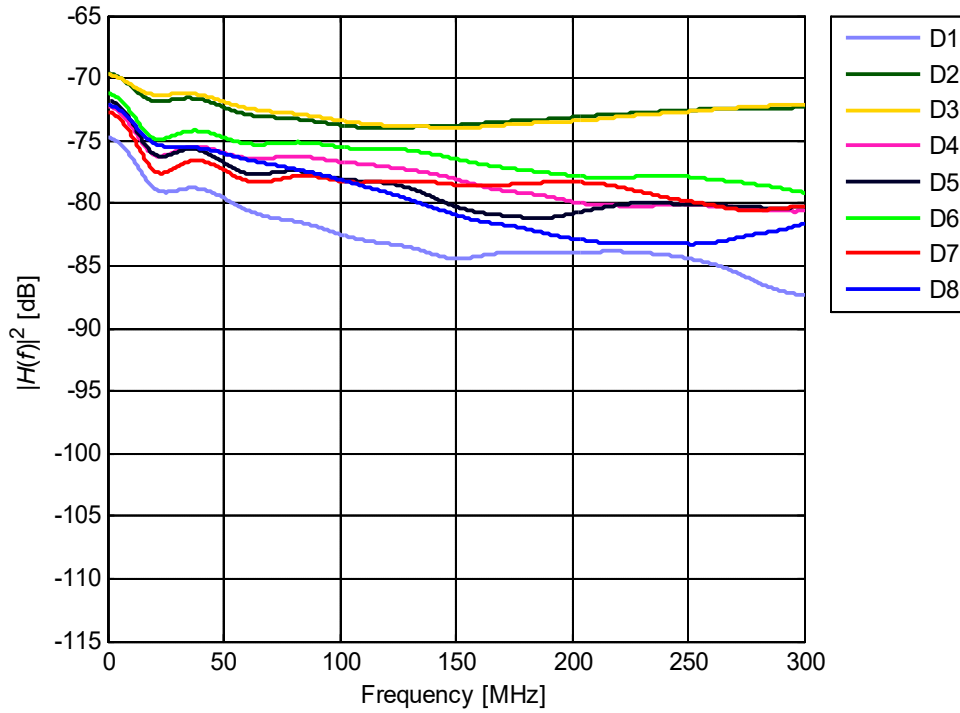
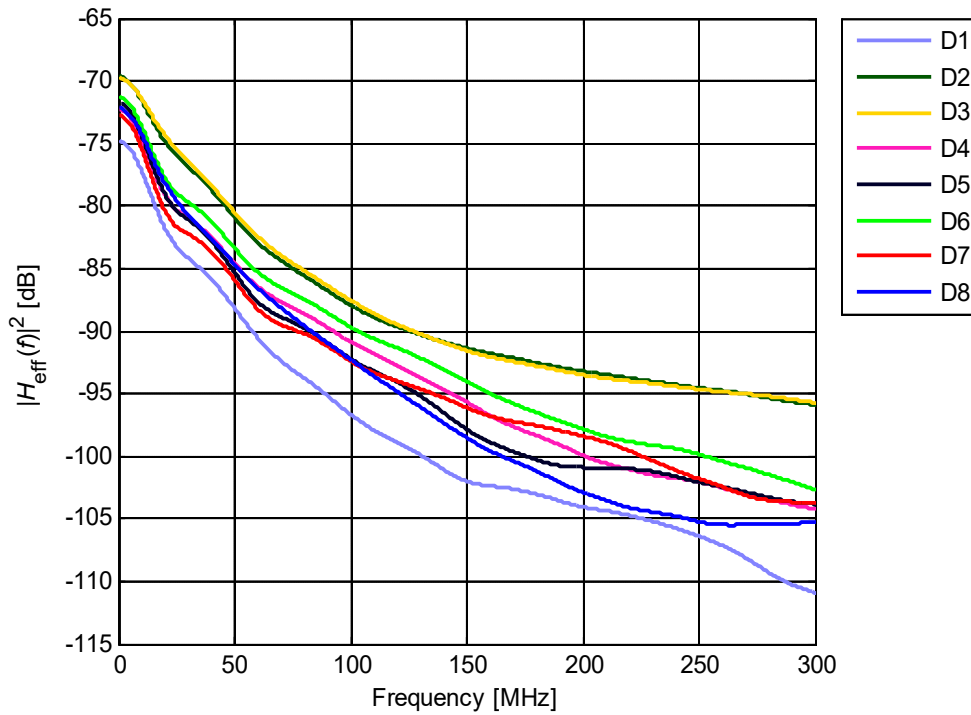


Fig. 20. (a) Arrangement of luminaires (b) emission pattern of each luminaire (c) simulated illumination levels in Zemax and (d) illumination level contours in Matlab

Based on the described simulation scenario above, we present the optical and effective channel responses in Fig. 21. The channel DC gain and RMS delay spreads are also obtained and provided in Table 8.



(a)



(b)

Fig. 21. (a) Optical channel responses and (b) effective channel responses for home environment

Table 8. Channel parameters for home environment

	$\tau_{RMS}$ (ns)	$H_0$
<b>D1</b>	12.49	$6.75 \times 10^{-6}$
<b>D2</b>	11.50	$1.22 \times 10^{-5}$
<b>D3</b>	10.72	$1.20 \times 10^{-5}$
<b>D4</b>	12.70	$9.03 \times 10^{-6}$
<b>D5</b>	12.90	$9.56 \times 10^{-6}$
<b>D6</b>	12.48	$1.01 \times 10^{-5}$
<b>D7</b>	13.01	$8.55 \times 10^{-6}$
<b>D8</b>	11.88	$9.13 \times 10^{-6}$

## 8. Scenario Industrial Wireless

The last scenario considered by this document is for a manufacturing cell with two robots in a factory environment as shown in Fig. 22. Locations of the transmitters and receivers are provided in Fig. 23 and 24 respectively.

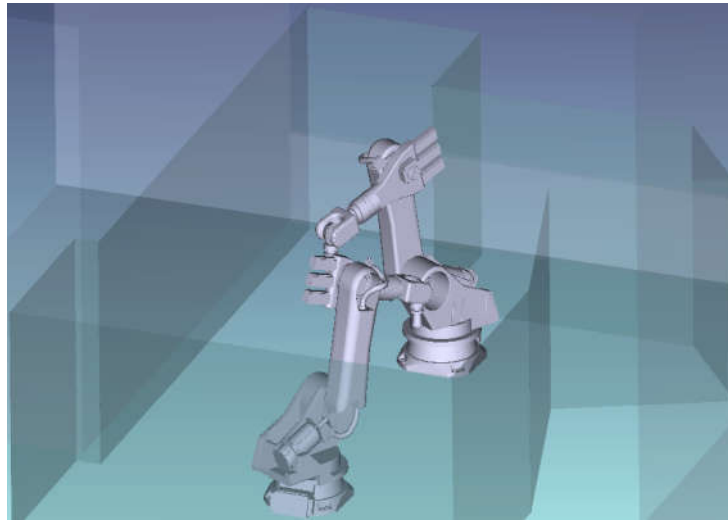


Fig. 22. Manufacturing cell

Table 9. Simulation parameters for manufacturing cell

<b>Room size</b>	8.03 m $\times$ 9.45 m $\times$ 6.8 m
<b>Materials</b>	Walls: Concrete, aluminum metal, and Plexiglas (PMMA), Ceiling: Aluminum metal, Floor: Concrete
<b>Objects</b>	Two robots
<b>Object Specifications</b>	Robot: Galvanized steel metal, Height of Robot: 2.7 m Height of Plexiglas boundary: 2.5 m
<b>LED Specifications</b>	Brand: MC-E Cree Xlamp Inc., Half viewing angle: 60°
<b>Number of LEDs</b>	6
<b>Receiver area</b>	1 cm <sup>2</sup>

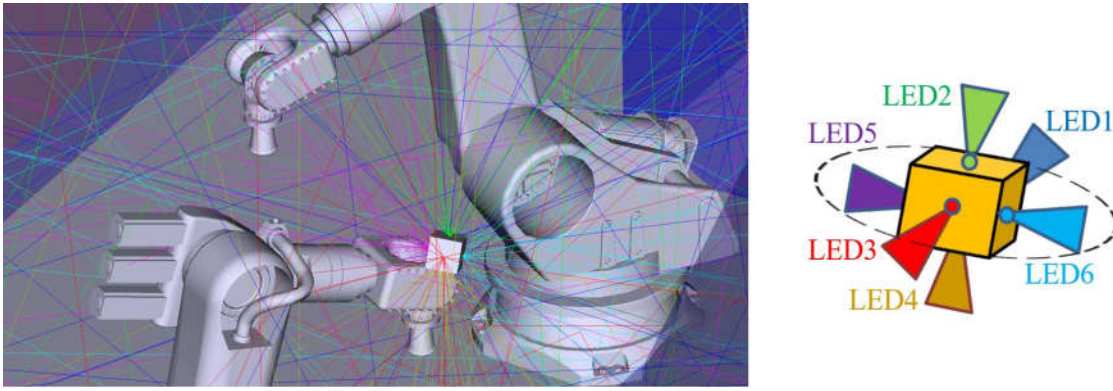


Fig. 23. Location of transmitters

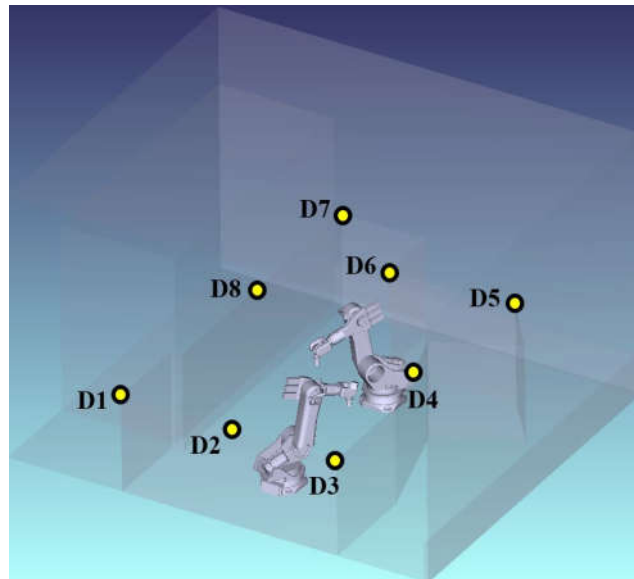


Fig. 24. Location of receivers

Based on the described simulation scenario above, we present the individual and overall optical and effective channel responses in Figs. 25 and 26. The channel DC gain and RMS delay spreads for individual and overall effective responses are obtained and respectively provided in Tables 10 and 11.

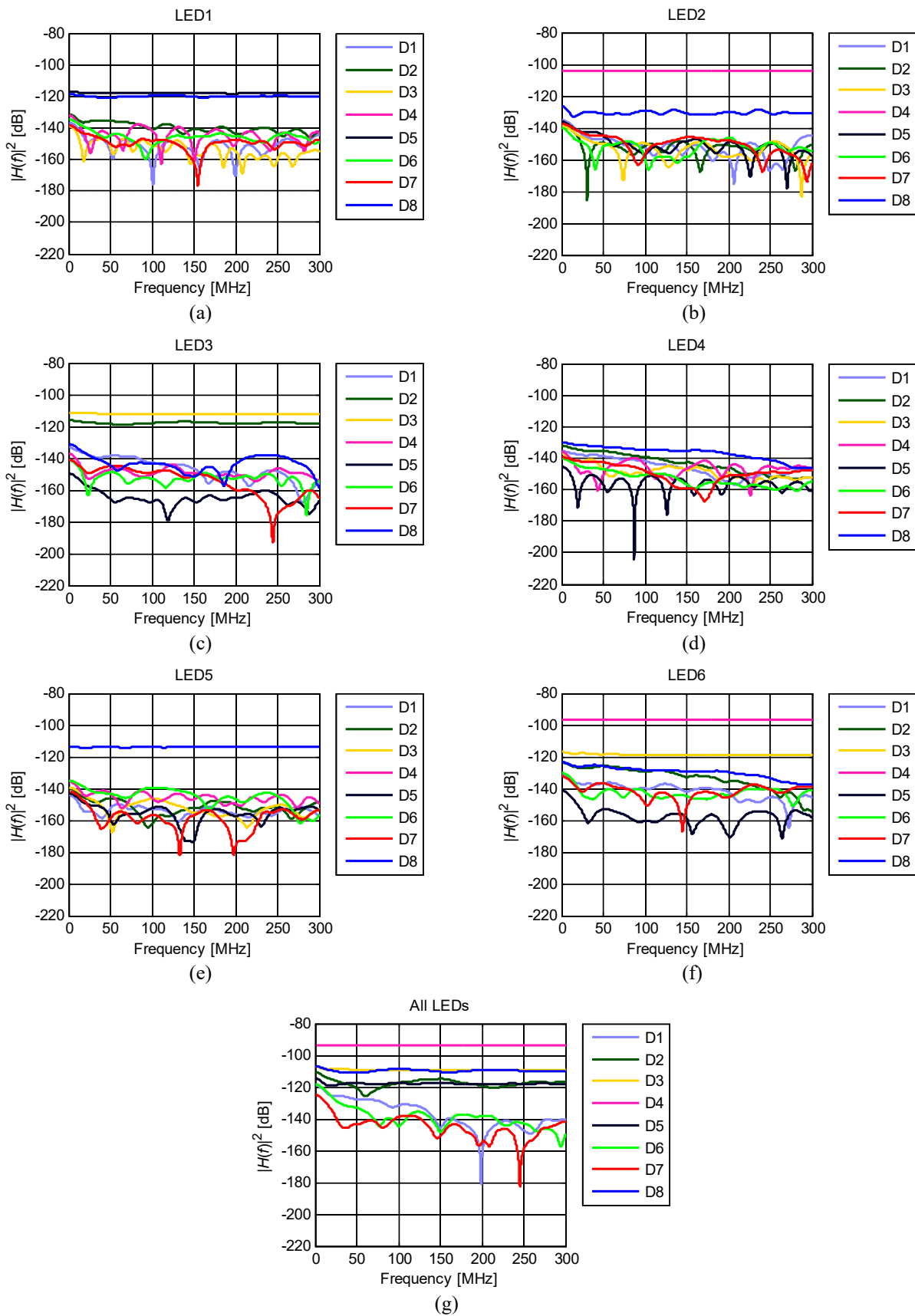


Fig. 25. Individual and overall optical channel responses for manufacturing cell

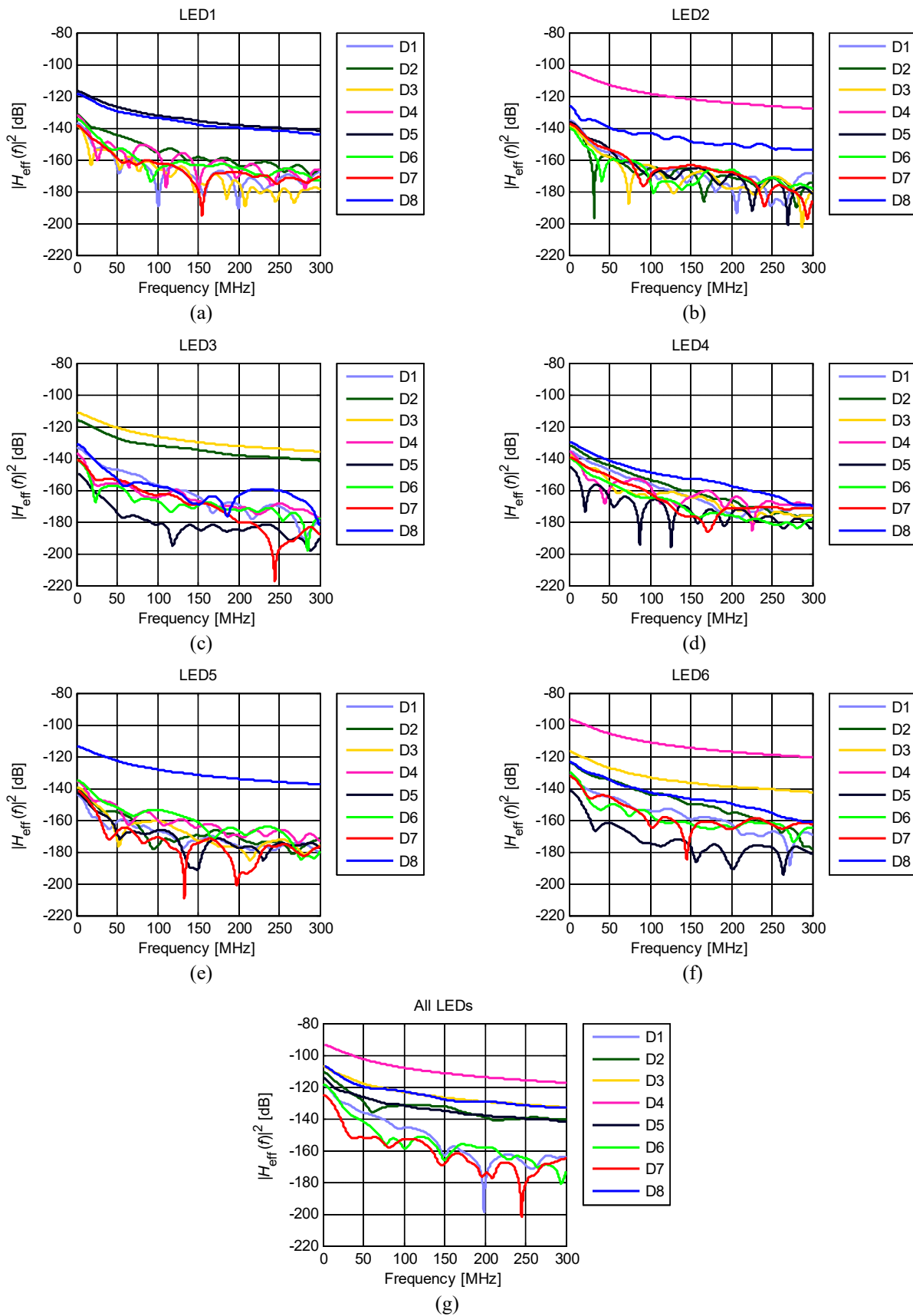


Fig. 26. Individual and overall effective channel responses for manufacturing cell



Table 10. Channel parameters for individual responses in manufacturing cell

		$\tau_{RMS}$ (ns)	$H_0$			$\tau_{RMS}$ (ns)	$H_0$
<b>LED1</b>	<b>D1</b>	15.20	$5.81 \times 10^{-7}$	<b>LED4</b>	<b>D1</b>	12.71	$6.79 \times 10^{-7}$
	<b>D2</b>	15.68	$1.08 \times 10^{-6}$		<b>D2</b>	13.23	$1.01 \times 10^{-6}$
	<b>D3</b>	17.84	$4.64 \times 10^{-7}$		<b>D3</b>	17.82	$5.61 \times 10^{-7}$
	<b>D4</b>	17.53	$1.01 \times 10^{-6}$		<b>D4</b>	16.81	$6.60 \times 10^{-7}$
	<b>D5</b>	10.96	$5.79 \times 10^{-6}$		<b>D5</b>	16.81	$2.17 \times 10^{-7}$
	<b>D6</b>	15.13	$7.67 \times 10^{-7}$		<b>D6</b>	12.92	$3.90 \times 10^{-7}$
	<b>D7</b>	15.03	$4.82 \times 10^{-7}$		<b>D7</b>	11.66	$4.29 \times 10^{-7}$
	<b>D8</b>	12.11	$4.77 \times 10^{-6}$		<b>D8</b>	11.48	$1.27 \times 10^{-6}$
<b>LED2</b>	<b>D1</b>	13.29	$6.94 \times 10^{-7}$	<b>LED5</b>	<b>D1</b>	16.99	$2.55 \times 10^{-7}$
	<b>D2</b>	13.51	$5.21 \times 10^{-7}$		<b>D2</b>	15.89	$4.21 \times 10^{-7}$
	<b>D3</b>	13.66	$4.68 \times 10^{-7}$		<b>D3</b>	12.96	$4.32 \times 10^{-7}$
	<b>D4</b>	9.64	$2.50 \times 10^{-5}$		<b>D4</b>	16.52	$6.92 \times 10^{-7}$
	<b>D5</b>	14.03	$6.30 \times 10^{-7}$		<b>D5</b>	14.77	$2.88 \times 10^{-7}$
	<b>D6</b>	16.79	$4.05 \times 10^{-7}$		<b>D6</b>	13.00	$7.10 \times 10^{-7}$
	<b>D7</b>	13.00	$5.47 \times 10^{-7}$		<b>D7</b>	14.48	$3.37 \times 10^{-7}$
	<b>D8</b>	18.82	$1.96 \times 10^{-6}$		<b>D8</b>	10.08	$8.34 \times 10^{-6}$
<b>LED3</b>	<b>D1</b>	13.93	$8.78 \times 10^{-7}$	<b>LED6</b>	<b>D1</b>	14.81	$1.05 \times 10^{-6}$
	<b>D2</b>	11.16	$6.35 \times 10^{-6}$		<b>D2</b>	13.98	$2.68 \times 10^{-6}$
	<b>D3</b>	10.09	$1.09 \times 10^{-5}$		<b>D3</b>	12.19	$5.75 \times 10^{-6}$
	<b>D4</b>	17.59	$5.70 \times 10^{-7}$		<b>D4</b>	8.84	$5.78 \times 10^{-5}$
	<b>D5</b>	14.66	$1.32 \times 10^{-7}$		<b>D5</b>	15.39	$3.48 \times 10^{-7}$
	<b>D6</b>	15.94	$3.55 \times 10^{-7}$		<b>D6</b>	14.40	$1.25 \times 10^{-6}$
	<b>D7</b>	14.29	$3.53 \times 10^{-7}$		<b>D7</b>	14.24	$9.74 \times 10^{-7}$
	<b>D8</b>	14.24	$1.13 \times 10^{-6}$		<b>D8</b>	13.19	$2.75 \times 10^{-6}$

Table 11. Channel parameters for overall responses in manufacturing cell

		$\tau_{RMS}$ (ns)	$H_0$
<b>All LEDs</b>	<b>D1</b>	15.66	$7.78 \times 10^{-7}$
	<b>D2</b>	15.52	$1.99 \times 10^{-6}$
	<b>D3</b>	14.13	$2.96 \times 10^{-6}$
	<b>D4</b>	10.45	$1.43 \times 10^{-5}$
	<b>D5</b>	16.42	$1.29 \times 10^{-6}$
	<b>D6</b>	14.85	$8.15 \times 10^{-7}$
	<b>D7</b>	15.83	$3.78 \times 10^{-7}$
	<b>D8</b>	13.58	$3.10 \times 10^{-6}$

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## Appendix

```

close all
clear all
clc

%% LED and Channel Parameters
f_cut_off = 20e+6; % Cut-off frequency of LED
t = 0:1e-9:200*1e-9; % Time duration of channel impulse response (CIR)

%% Associated CIR
load('Run1')

%% Frequency Responses of Different LED Models
f = linspace(0,300e+6,5000);
j = sqrt(-1);
H_LED = 1./(1+j*f/f_cut_off); % "LED Model 1"
% H_LED = exp((-log(sqrt(2)))*(f/f_cut_off).^2)); % "LED Model 2"
H_VLC = zeros(1,length(f));

%% Frequency Response of Optical CIR
count = 1;
for fx = f
    for t = 1:length(averun2)
        H_VLC(1,count) = H_VLC(1,count) + averun2(t)*exp(-sqrt(-1)*2*pi*fx*(t-1)/1e+9);
    end
    count = count + 1;
end

figure (1)
plot(f/1e+6,pow2db(abs(H_VLC).^2),'linewidth',2)
grid on
xlabel('Frequency [MHz]')
ylabel('| \itH\rm(\itf\rm) |^{2} [dB]')

%% Frequency Response of Effective CIR
H_VLCeff(1,:) = H_VLC(1,:).*H_LED;

figure (2)
plot(f/1e+6,pow2db(abs(H_VLCeff).^2),'linewidth',2)
grid on
xlabel('Frequency [MHz]')
ylabel('| \itH\rm_{eff}\rm(\itf\rm) |^{2} [dB]')

%% Effective CIR in Time Domain
z=1;
f_cut_off = 20e+6; % Cut-off frequency of LED
t = 0:1e-9:200*1e-9; % Time duration of channel impulse response (CIR)

% "LED Model 1" in time domain
dummy = exp(-f_cut_off*(2*pi)*t);
LED_Model_1_Response = dummy/norm(dummy);

averun2 = conv(averun2,LED_Model_1_Response);
averun1 = 1:length(averun2);

```

```

averun2=averun2';
averun1=averun1';

% Effective CIR
filename = ['Run' num2str(z) '.mat'];
save(filename, 'averun1', 'averun2');

```

## This is the instruction for using the “IEEE 802.11bb Reference Channel Models for Indoor Environments”

### 802.11bbChannels.mat File Instruction

This file includes the samples of channel impulse response (CIR). The variables of this file are as follows:

“averun1”: Represents the “time” samples in nanosecond. The time resolution (time spacing) of these CIRs is 1 ns.

“averun2”: Represents the “power” samples in Watt.

\*Units are Millimeters.

### Simulation Scenario Empty Room

1) This file includes the CIRs for empty room with dimensions 6 m × 6 m × 3 m. We consider 100 cells (i.e., 10 × 10 cells) with equidistant spacing of 0.6 m in  $x$  and  $y$  directions. We consider a user with a height of 1.8 m who holds the phone in his hand next to his ear with 45° rotation upward the ceiling and at a height of 1.65 m. The cell phone is equipped with a single photodetector (PD). We consider seven possible locations (D1-D7) for the photodetectors.

2) The CIRs given in this file are impulse responses from all luminaires to each PD on the phone (i.e., “Overall CIRs”). The “Optical CIRs” and “Effective CIRs” represent the CIRs without and with the effect of LED response, respectively. The “LED Model 1” with cut-off frequency of 20 MHz is considered.

3) Additional information such as simulation parameters, rotation, 3D locations and channel parameters of these test points can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, “IEEE 802.11bb Reference Channel Models for Indoor Environments”, doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

4) Coordinates of test points depends on the location of the user within the room.

5) Coordinates of luminaires are as follows:

S1:(2100, 2100, 3000)	S2:(2100, 0, 3000)	S3:(2100, -2100, 3000)
S4:(0, 2100, 3000)	S5:(0, 0, 3000)	S6:(0, -2100, 3000)
S7:(-2100, 2100, 3000)	S8:(-2100, 0, 3000)	S9:(-2100, -2100, 3000)

6) Specifications of detectors and luminaires can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, “IEEE 802.11bb Reference Channel Models for Indoor Environments”, doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

1) Specifications of detector:

Number of PDs: 7

FOV: 85 degrees

Area: 1 cm<sup>2</sup>

2) Specifications of luminaire:

Number of luminaires: 9

Brand: Cree CR6-800L

Half Viewing Angle: 40 degrees

Input Power: 11 W

---

### Simulation Scenario Enterprise-Conference Room

1) This file includes the CIRs for a conference room with dimensions 6.8 m × 4.7 m × 3 m where ten users sit around a table. We consider ten possible locations for the PDs. For standing persons (D1 and D10), the cell phone is held in their hand next to their ear and the detector is located on the top edge of the phone with 45° rotation upward the ceiling and at a height of 1.8 m. For sitting persons (D2, D3, D4, D5, D6, D7, D8, D9), the cell phone is held in their hand over their stomach and the detector is located on the top edge of the phone with 45° rotation upward the ceiling and at a height of 1.1 m.

2) The CIRs given in this file are from each luminaire to each PD (i.e., “Individual CIRs”) and from all luminaires to each PD (i.e., “Overall CIRs”). The “Optical CIRs” and “Effective CIRs” represent the CIRs without and with the effect of LED response, respectively. The “LED Model 1” with cut-off frequency of 20 MHz is considered.

3) Additional information such as simulation parameters, rotation, 3D locations and channel parameters of these test points can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, “IEEE 802.11bb Reference Channel Models for Indoor Environments”, doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

4) Coordinates of test points are as follows:

D1:(-1398, -2880, 273)

D2:(-688, -2025, -307)

D3:(-688, -625, -307)

D4:(-688, 775, -307)

D5:(-665, 2190, -307)

D6:(470, 2386, -312)

D7:(735, 1330, -308)

D8:(735, -70, -308)

D9:(735, -1470, -308)

D10:(1699, 3070, 272)

5) Coordinates of luminaires are as follows:

S1:(-1050, -3100, 3000)	S2:(1150, -3100, 3000)	S3:(-1050, -1600, 3000)
S4:(1150, -1600, 3000)	S5:(-1050, -100, 3000)	S6:(1150, -100, 3000)
S7:(-1050, 1400, 3000)	S8:(1150, 1400, 3000)	S9:(-1050, 2900, 3000)
S10:(1150, 2900, 3000)		

6) Specifications of detectors and luminaires can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, "IEEE 802.11bb Reference Channel Models for Indoor Environments", doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

1) Specifications of detector:

Number of PDs: 10  
FOV: 85 degrees  
Area: 1 cm<sup>2</sup>

2) Specifications of luminaire:

Number of luminaires: 10  
Brand: Cree LR24-38SKA35  
Half Viewing Angle: 40 degrees  
Input Power: 46 W

---

### Simulation Scenario Enterprise-Office with Secondary Light

1) This file includes the CIRs for an office environment with dimensions 5 m \* 5 m \* 3 m and with two light sources. The first one is the main light source at the ceiling (S) and the other one is mounted on the desk to provide task lighting (R).

2) The CIRs given in this file are as follows:

- \* Ceiling Light (S) to Desk Light (R) Receiver
- \* Desk Light (R) Transmitter to Destination (D)
- \* Ceiling Light (S) to Destination (D)

The "Optical CIRs" and "Effective CIRs" represent the CIRs without and with the effect of LED response, respectively. The "LED Model 1" with cut-off frequency of 20 MHz is considered.

3) Additional information such as simulation parameters, rotation, 3D locations and channel parameters of these test points can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, "IEEE 802.11bb Reference Channel Models for Indoor Environments", doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

4) Coordinates of test points are as follows:

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

5) Coordinates of luminaires are as follows:

Ceiling Light (S):(0, 0, 3000)

Desk Light (R) Transmitter:(-1190, 1350, 1330)

Tilt angles in X, Y, Z:(0, 219, 0), toward the destination

6) Specifications of detectors and luminaires can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, "IEEE 802.11bb Reference Channel Models for Indoor Environments", doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

1) Specifications of detector:

FOV: 85 degrees

Area: 1 cm<sup>2</sup>

2) Specifications of luminaire:

Brand: Cree LR24-38SKA35

Half Viewing Angle: 40 degrees

Input Power: 52 W

---

### Simulation Scenario Residential

1) This file includes the CIRs for a living room with dimensions 6 m × 6 m × 3 m. Four persons are present in the room, two sitting on the couch and two standing. The detector on the coffee table (D1) is at a height of 0.6 m with 45° rotation toward the person sitting on the couch. For two persons in a standing position who hold a cell phone in their hand next to their ear, the detectors (D2-D3) are located on the phone (i.e., the detector is at a height of 1.7 m with 45° rotation). The detectors on the dinner table (D4-D7) are at a height of 0.9 m. For a person who sits on the couch and holds a cell phone in their hand next to their ear, the detector (D8) is located on the phone at a height of 1.1 m with 45° rotation.

2) The CIRs given in this file are from each luminaire to each PD (i.e., "Individual CIRs") and from all luminaires to each PD (i.e., "Overall CIRs"). The "Optical CIRs" and "Effective CIRs" represent the CIRs without and with the effect of LED response, respectively. The "LED Model 1" with cut-off frequency of 20 MHz is considered.

3) Additional information such as simulation parameters, rotation, 3D locations and channel parameters of these test points can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, "IEEE 802.11bb Reference Channel Models for Indoor Environments", doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

4) Coordinates of test points are as follows:

D1:(600, -1000, 600)

D2:(-2000, -2000, 1700)

D3:(2000, 2000, 1700)

D4:(-1800, 1500, 900)

D5:(-200, 1500, 900)

D6:(-1000, 1850, 900)

D7:(-1000, 1150, 900)

D8:(1700, -1800, 1100)

5) Coordinates of luminaries are as follows:

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

6) Specifications of detectors and luminaires can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, “IEEE 802.11bb Reference Channel Models for Indoor Environments”, doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

1) Specifications of detector:

Number of PDs: 8  
FOV: 85 degrees  
Area: 1 cm<sup>2</sup>

2) Specifications of luminaire:

Number of luminaires: 9  
Brand: Cree CR6-800L  
Half Viewing Angle: 40 degrees  
Input Power: 12 W

---

### Simulation Scenario Industrial Wireless

1) This file includes the CIRs for a manufacturing cell with dimensions 8.03 m × 9.45 m × 6.8 m. Six LED transmitters are located at the head of the robotic arm that has the shape of a cube. Each face of the cube is equipped with one transmitter, ensuring 360° coverage.

2) The CIRs given in this file are from each LED to each PD (i.e., “Individual CIRs”) and from all LEDs to each PD (i.e., “Overall CIRs”). The “Optical CIRs” and “Effective CIRs” represent the CIRs without and with the effect of LED response, respectively. The “LED Model 1” with cut-off frequency of 20 MHz is considered.

3) Additional information such as simulation parameters, rotation, 3D locations and channel parameters of these test points can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, “IEEE 802.11bb Reference Channel Models for Indoor Environments”, doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

4) Coordinates of test points are as follows:

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



5) Coordinates of LEDs are as follows:

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

6) Specifications of detectors and LEDs can be found at:

M. Uysal, F. Miramirkhani, T. Baykas, N. Serafimovski, and V. Jungnickel, "IEEE 802.11bb Reference Channel Models for Indoor Environments", doc: IEEE 11-18-1236-01-00bb, July 2018. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-1236-01-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf>

1) Specifications of detector:

Number of PDs: 8

FOV: 35 degrees

Area: 1 cm<sup>2</sup>

\* All detectors rotated toward the robot arms

2) Specifications of LEDs:

Number of LEDs: 6

Brand: Cree MC-E Xlamp

Half Viewing Angle: 60 degrees

Input Power: 1 W