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Wireless LANs

IEEE 802.11bb Reference Channel Models for Indoor Environments				
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Abstract

This contribution proposes 802.11bb reference channel models for indoor envirionments.

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1. **Definitions**

PHY	Physical Layer
MAC	Media Access Control
LC	Light Communications
SAP	Service Access Point
HCF	Hybrid Coordination Function
OBSS	Overlapping Basic Service Set
CFP	Call for Proposal
OWC	Optical Wireless Communication
CIR	Channel Impulse Response
VLC	Visible Light Communication
RMS	Root Mean Square
LED	Light Emmiting Diode
FOV	Field of View
TCD	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 9 include scenarios considered by TGbb. Appendix contains Matlab instructions for the simulation of CIRs.

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

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[®]; a commercially available optical and illumination design software [7]. The simulation environment is created in Zemax[®] 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[®] calculates the detected power and path lengths from source to detector for each ray. This information is then imported into Matlab[®] and the corresponding CIR for that environment is obtained through proper normalizations. Figure 1 illustrates the process. We express the CIR as [1]

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

where P_i is the optical power of the ith ray, τ_i is the propagation time of the ith 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]

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

The path loss can be then expressed as [8]

$$PL = -10\log_{10}\left(\int_{0}^{\infty} h(t)\,dt\right). \tag{3}$$

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

$$\tau_{RMS} = \sqrt{\frac{\int_{0}^{\infty} (t-\tau_0)^2 h(t)\,dt}{\int_{0}^{\infty} h(t)\,dt}} \tag{4}$$

$$\tau_0 = \frac{\int_{0}^{\infty} t \times h(t)\,dt}{\int_{0}^{\infty} h(t)\,dt} \tag{5}$$
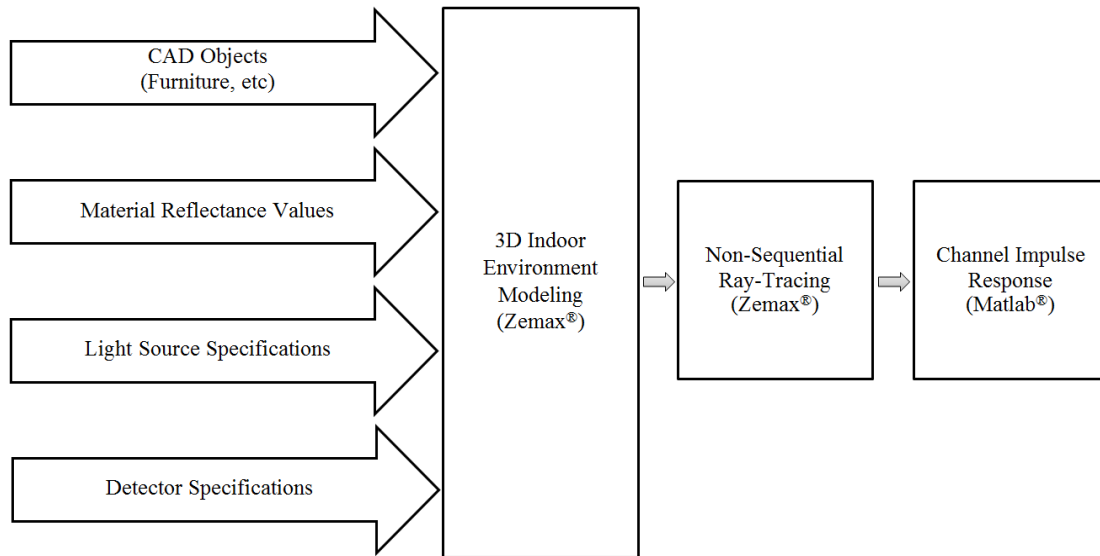
Fig. 1. Channel modeling methodology

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 emmiting diodes (LEDs) (Cree® CR6-800L) with 40º half viewing angle. The optical power for each luminaire is 11 W. 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 luminaire, simulated illumination levels in Zemax and illumination level contours in Matlab.
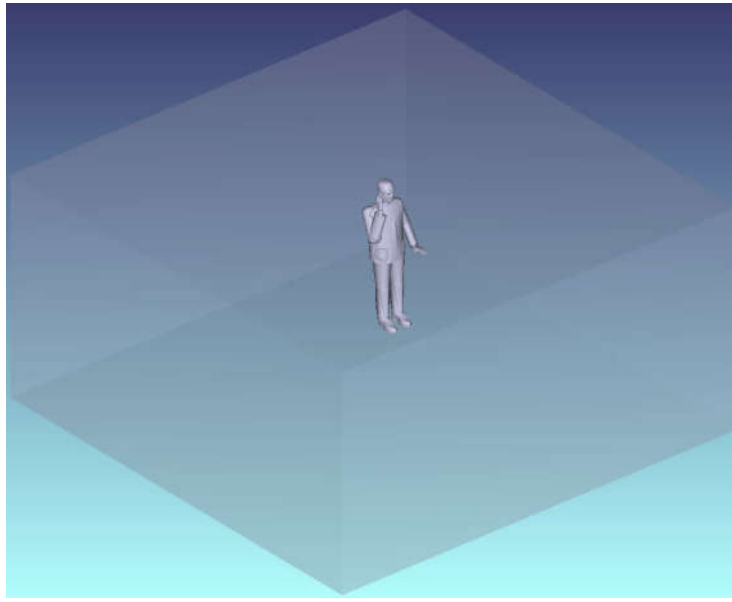
Fig. 2. Empty room under consideration

Table 1. Simulation parameters for empty room

Room size	6 m × 6 m × 3 m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood

Objects specifications	Cell phone: Black gloss paint (5.5 cm × 10.5 cm × 0.5 cm)
	Human body:
	  ▪ Shoes: Black gloss paint
	  ▪ Head & Hands: Absorbing
	  ▪ Clothes: Cotton

Luminaire specifications	Brand: Cree CR6-800L, Half viewing angle: 40º, Number of luminaires: 9, Power per each luminaire: 11 W
Receiver specifications	Number of PDs: 7, Receiver area: 1 cm^2, FOV: 85º

(a)

(b)

(c)

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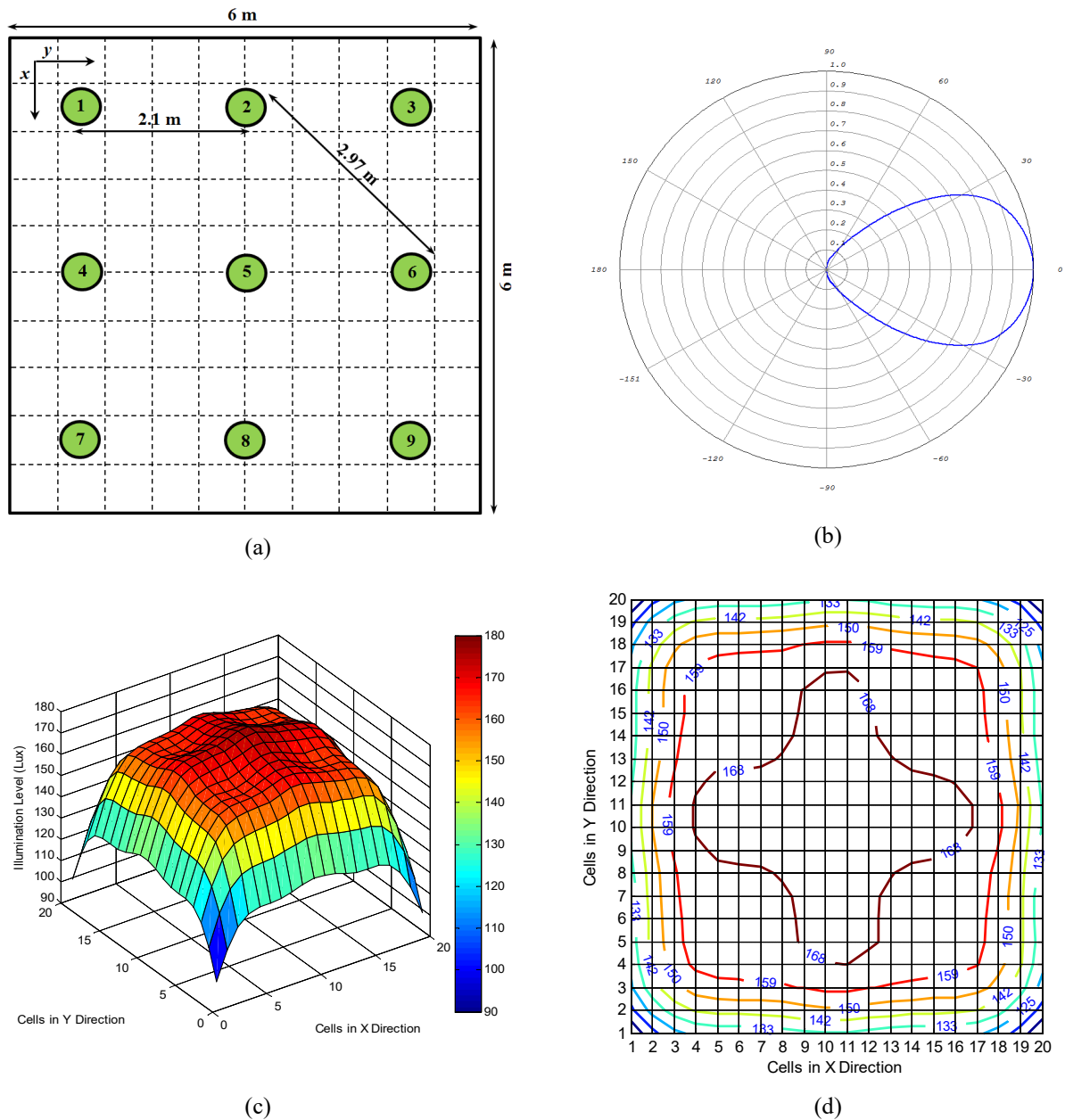
Fig. 3. (a) Arrangement of luminaires, (b) emission pattern of each luminaire, (c) simulated illumination levels in Zemax and (d) illumination level contours in Matlab for empty room

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 cm × 10.5 cm × 0.5 cm and is equipped with a single photodetector. The user holds the phone in his hand next to his ear with 45° rotation upward the ceiling and at a height of 1.8 m. We consider seven potential locations for the photodetectors denoted as D_n, $n = 1,...,7$ (see Fig. 4.b). D1,…,D5 are placed on the top edge of the cell phone oriented toward the ceiling. D6 and D7 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° and 1 cm^2, respectively.

Non-sequential ray tracing features of Zemax$^®$ 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 ith luminaire 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).

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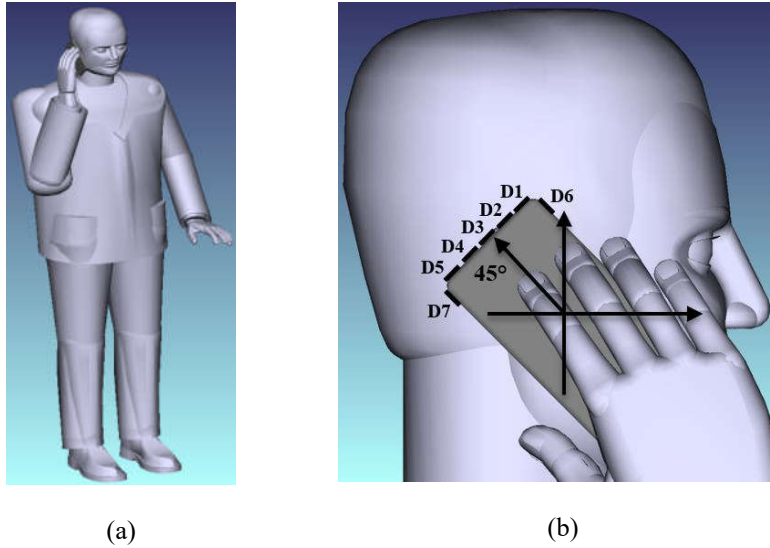
Fig. 4. (a) Human model and (b) location/orientation of PDs on the cell phone

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.
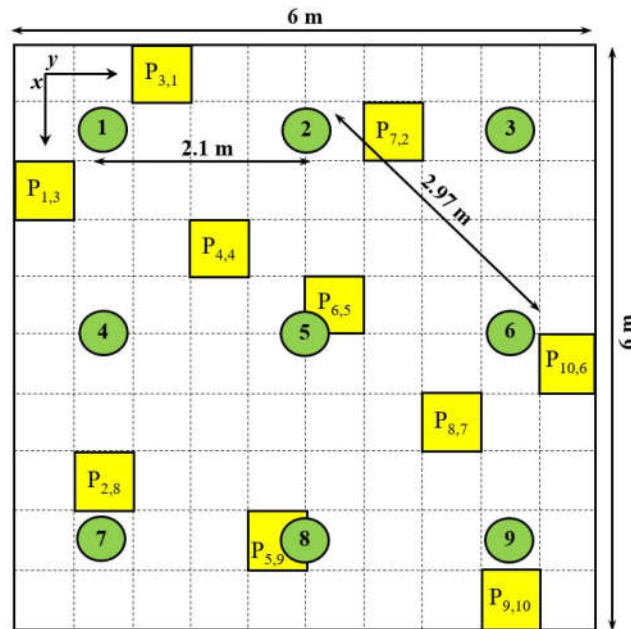
Fig. 5. Sample locations of the user
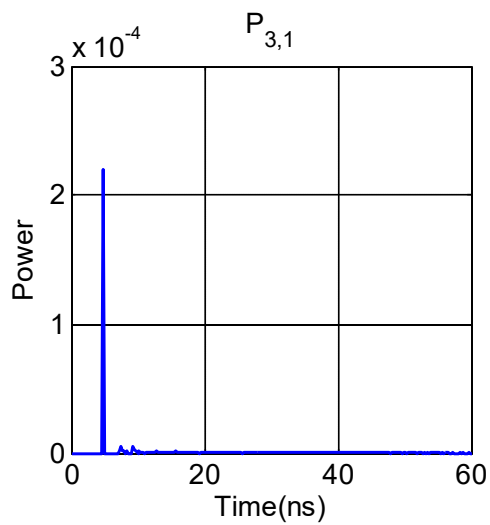
(a)
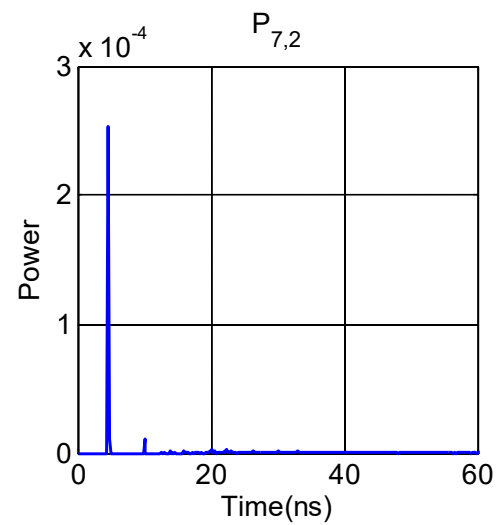
(b)
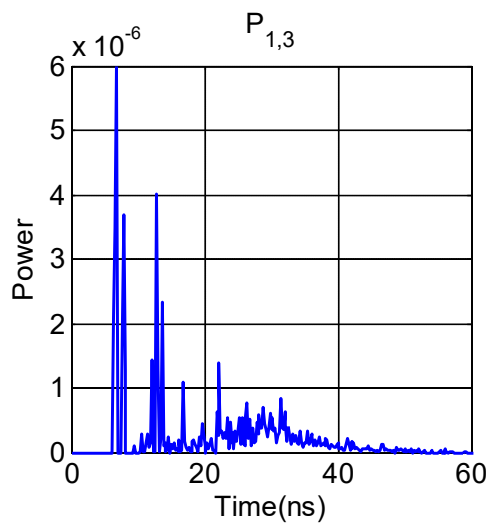
(c)
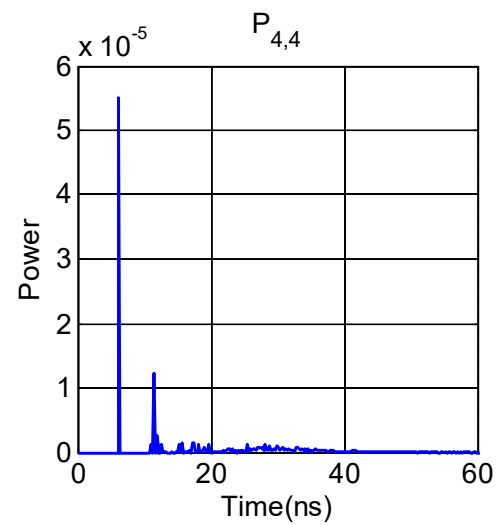
(d)
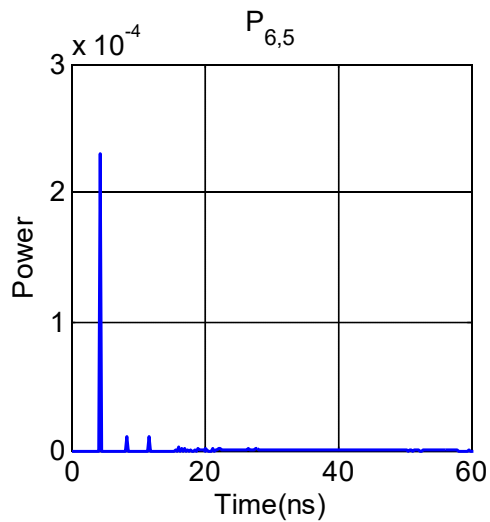
(e)
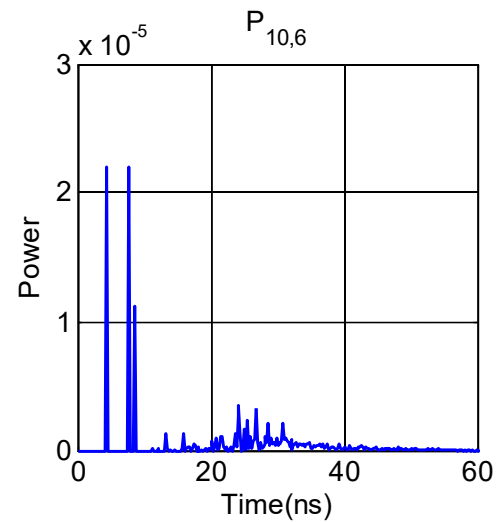
(f)
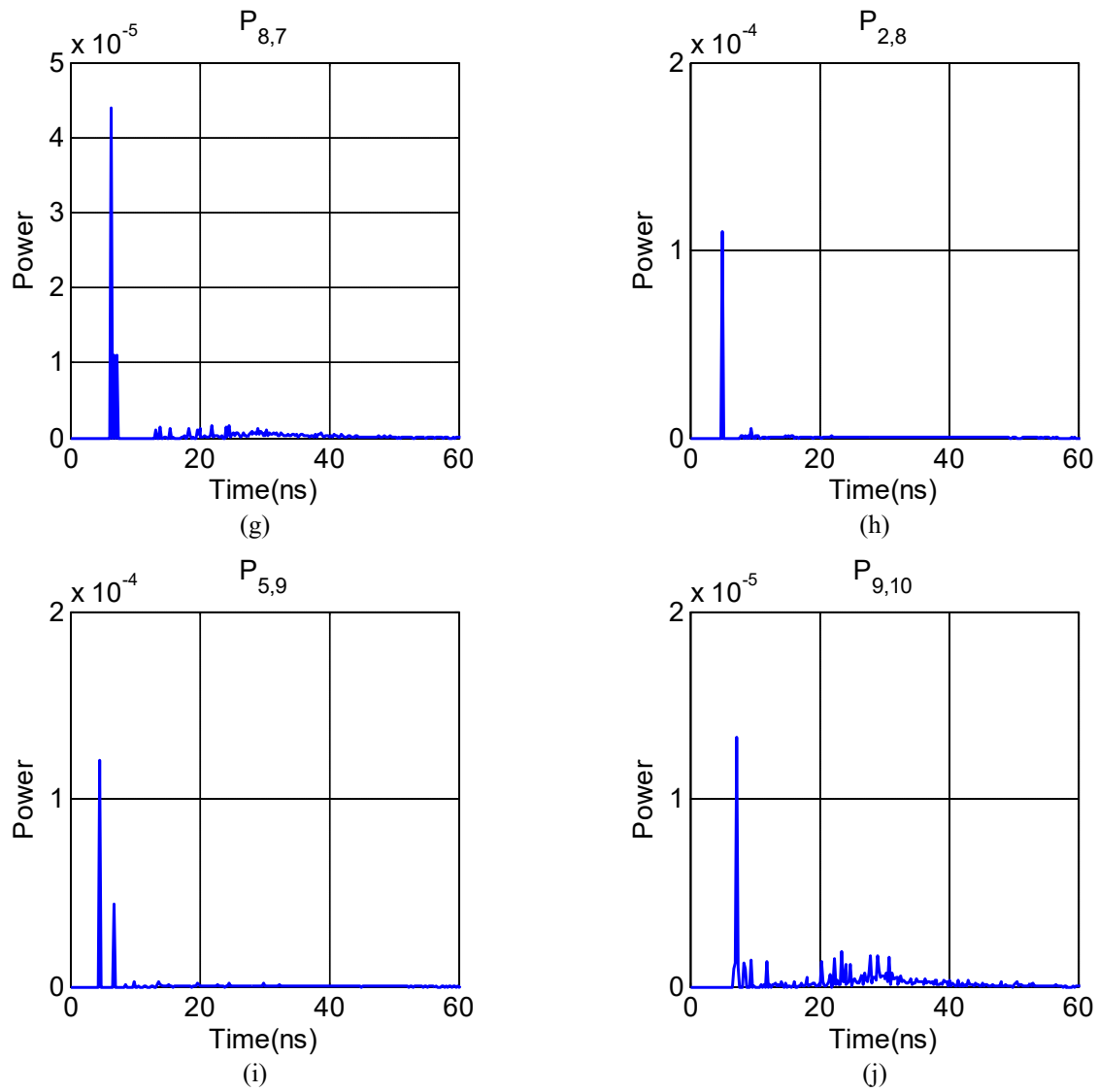
Fig. 6. Sample CIRs as seen by photodetector D5

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

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

The sample optical channel responses are presented in Fig. 7.
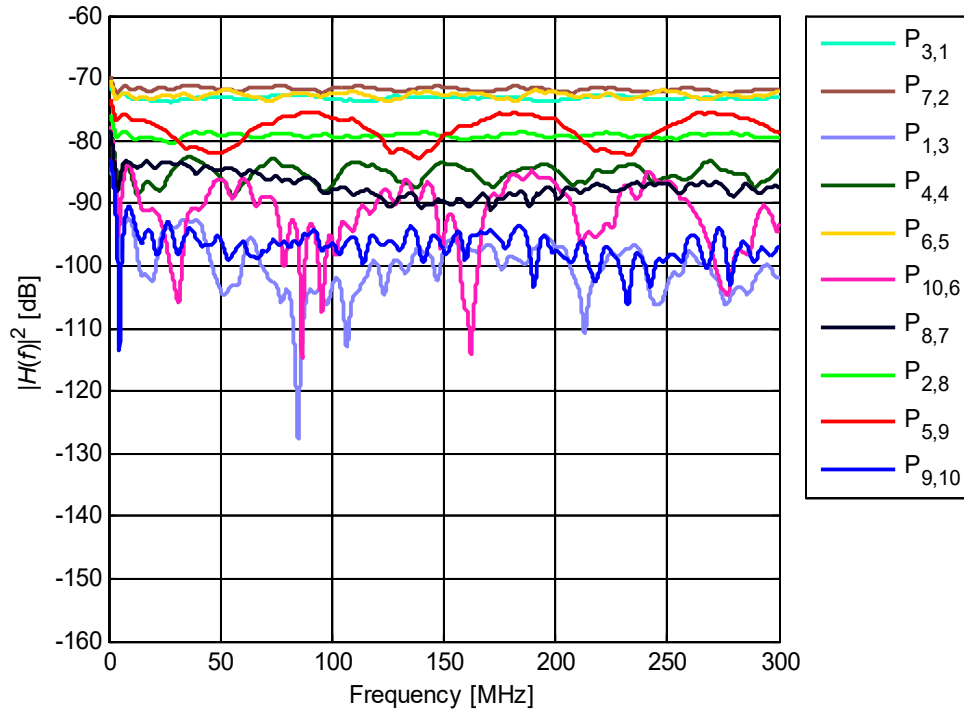
Fig. 7. Sample optical channel responses as seen by photodetector D5

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]

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

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

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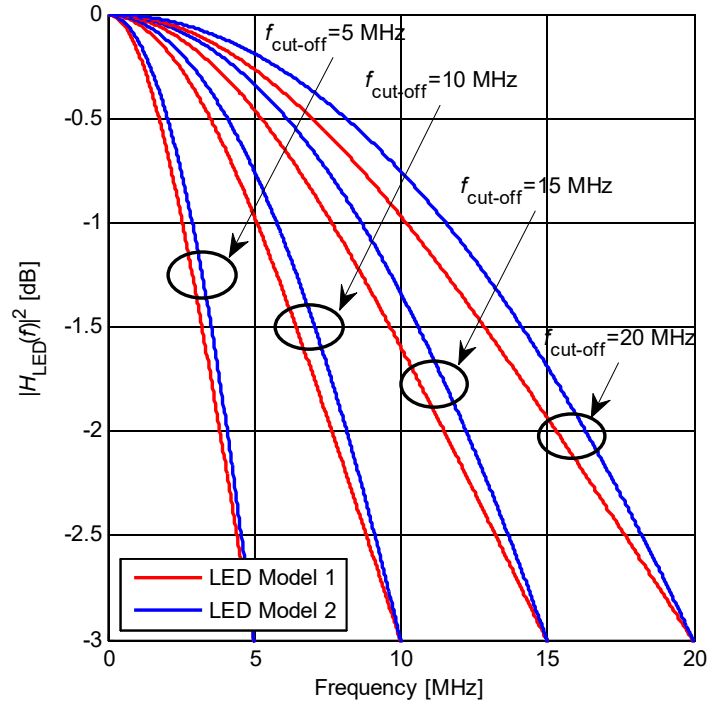
Fig. 8. Frequency response of LED based on (7) and (8) assuming cut-off frequencies of 5 MHz, 10 MHz, 15 MHz and 20 MHz

The sample effective channel responses as seen by photodetector D5 are illustrated in Fig. 9 assuming LED model in (7) with 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.
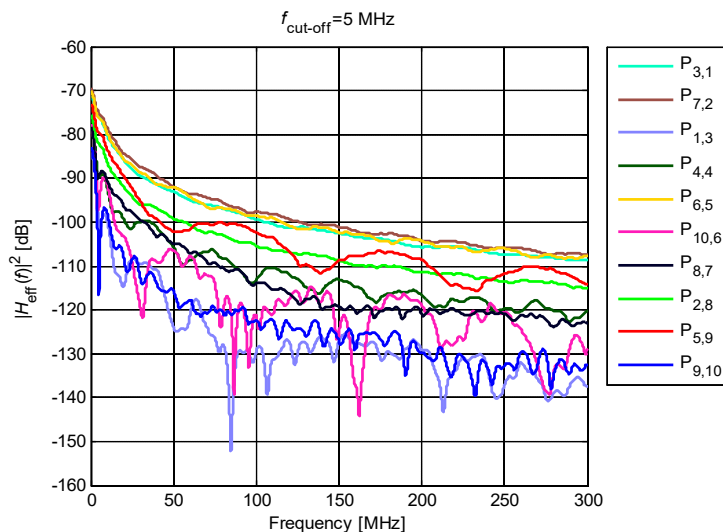
(a)
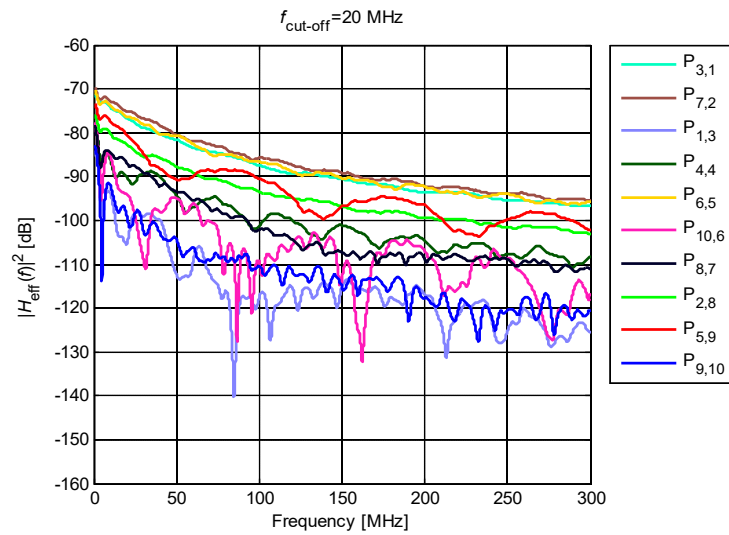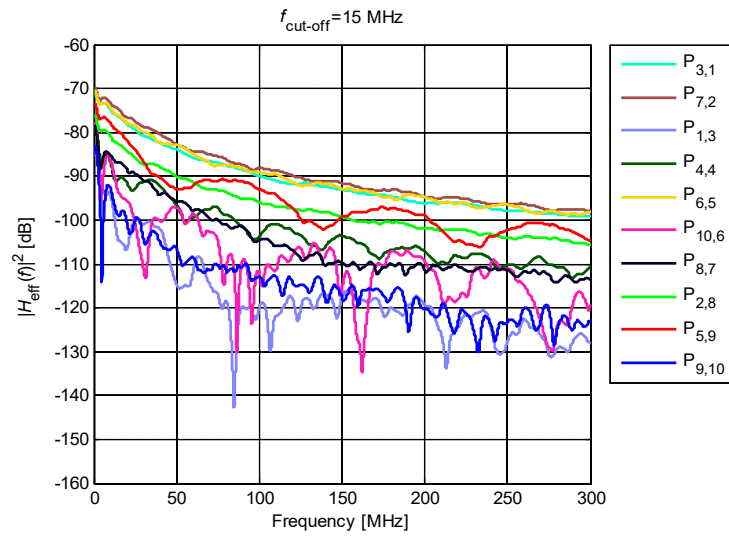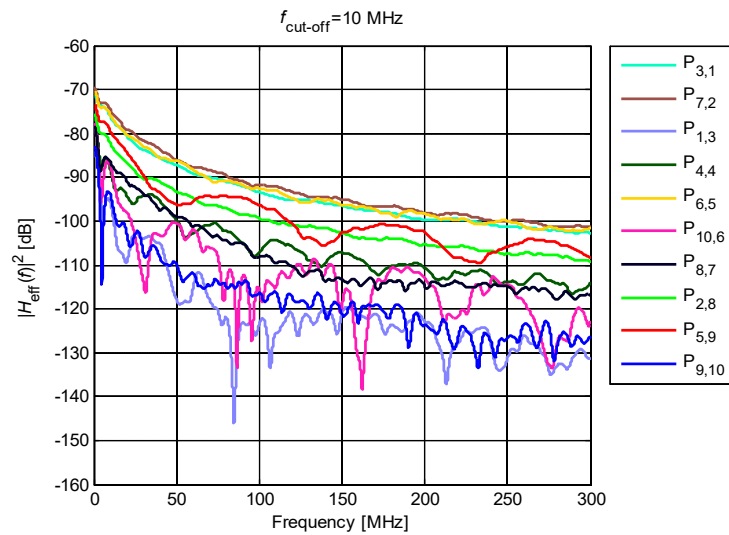
Fig. 9. Sample effective channel responses as seen by photodetector D5 assuming cut-off frequencies of (a) 5 MHz, (b) 10 MHz, (c) 15 MHz and (d) 20 MHz

In Fig. 10, we illustrate the spatial distribution of channel gain as seen by the individual photodetectors D_n, $n = 1,...,7$. It is observed that as user moves within the room, the spatial distributions of channel gain seen by the photodetectors $D_1,...,D_6$ 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 D_7 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 D_1, D_2, D_3, D_4, D_5, D_6 and D_7.

(a)

(b)

(c)

(d)

(e)

(f)

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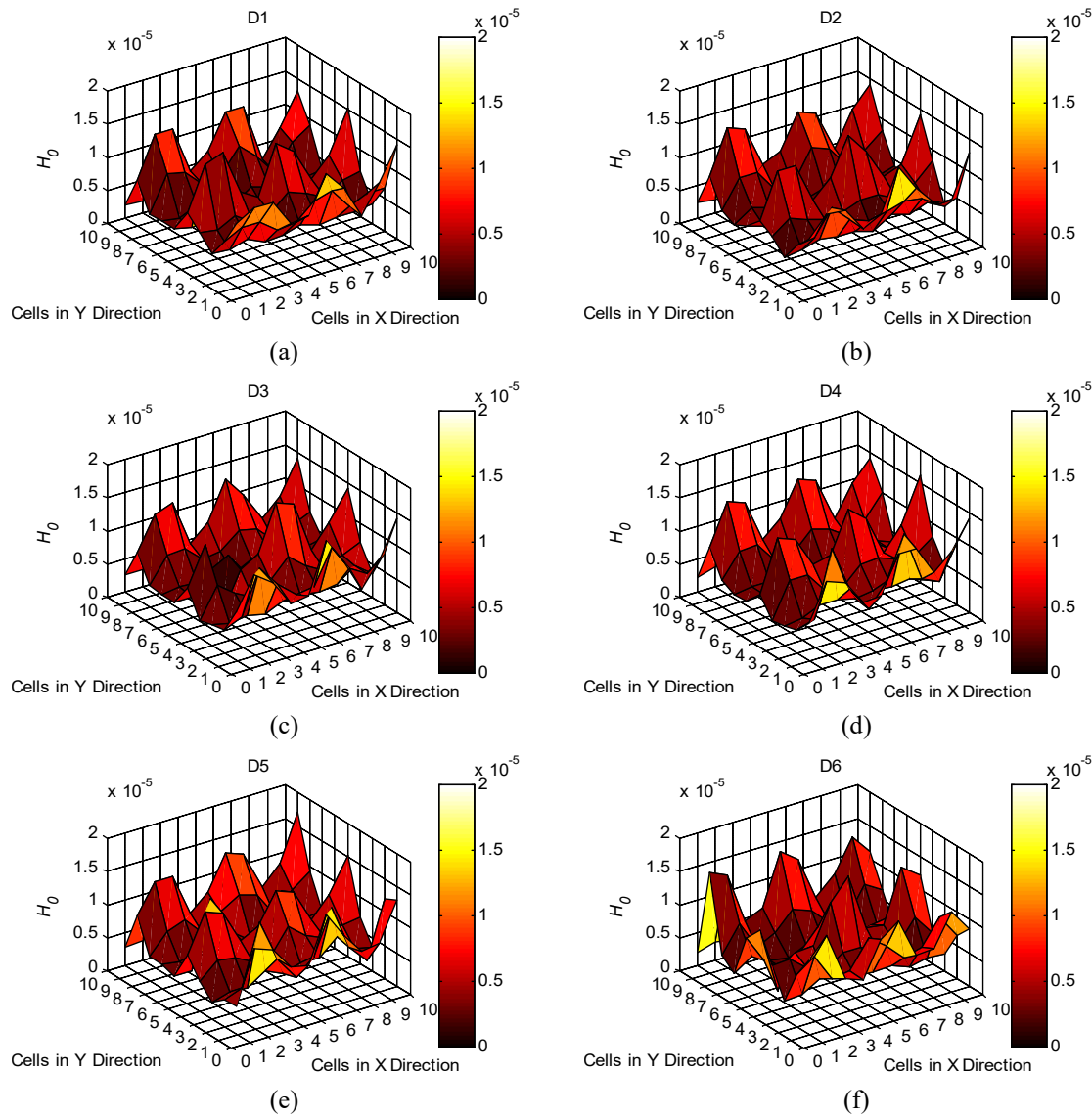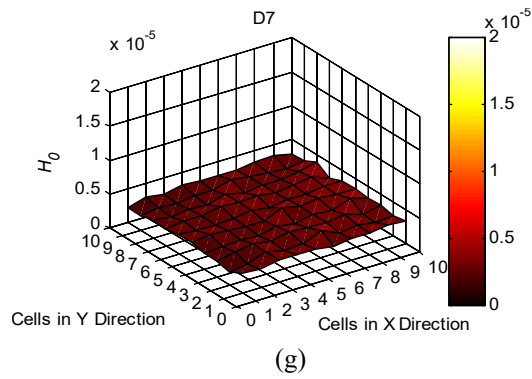
Fig. 10. Spatial distributions of path loss as seen by the individual photodetectors D_n, $n = 1,...,7$

Table 2. Channel parameters for empty room

	τ_{RMS} (ns)	H_0
D1	13.92	6.00×10^{-6}
D2	14.10	6.08×10^{-6}
D3	14.07	6.33×10^{-6}
D4	14.09	6.89×10^{-6}
D5	14.10	7.19×10^{-6}
D6	14.06	6.25×10^{-6}
D7	13.22	3.05×10^{-6}

In Fig. 11, we present the channel gains versus cell number for D1, D2, D3, D4, D5, D6 and D7.
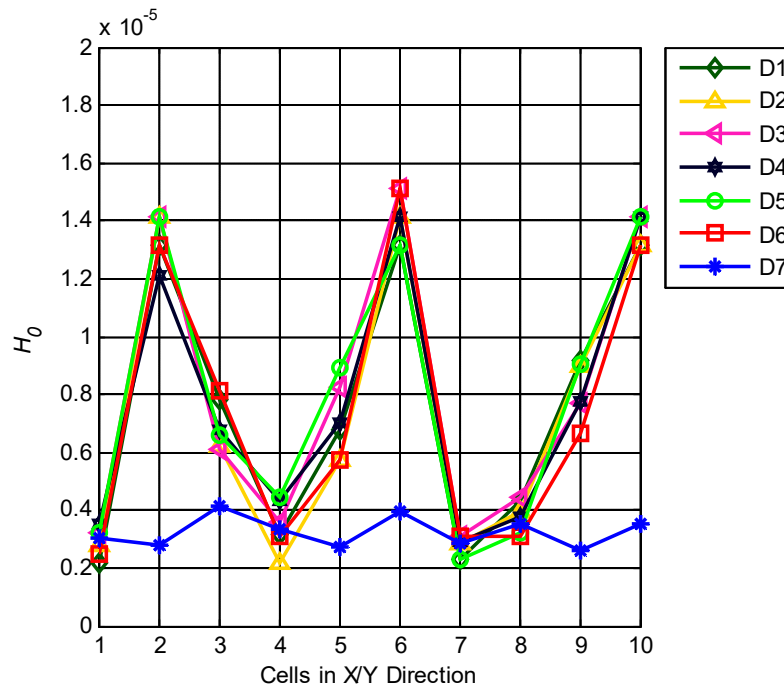
Fig. 11. Channel gain versus cell number as seen by the individual photodetectors D_n, $n = 1,...,7$

In Fig. 12, we present the cumulative distribution function (CDF) of path loss as seen by the individual photodetectors D_n, $n = 1,...,7$. 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.
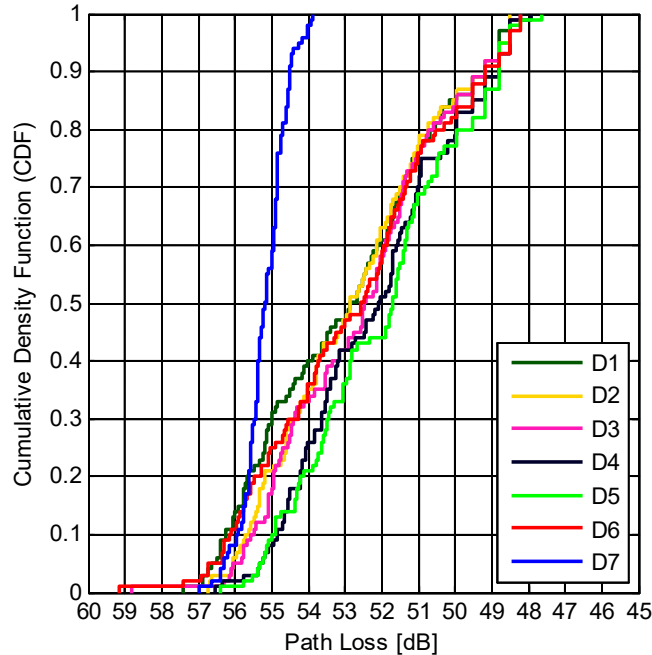
Fig. 12. CDF of path loss as seen by the individual photodetectors D_n, $n = 1,...,7$

5. Scenario Enterprise-Conference Room

We consider a conference room where ten users sit around a table (see Fig. 13.a). The user (photodetector) locations are denoted as D_n, $n = 1,2,…,10$. The FOV and the area of the detector are 85° and 1 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 45º 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 45º 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 W. These are denoted as S_m, $m = 1,2,…,10$ (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.

(a)

(b)

(c)
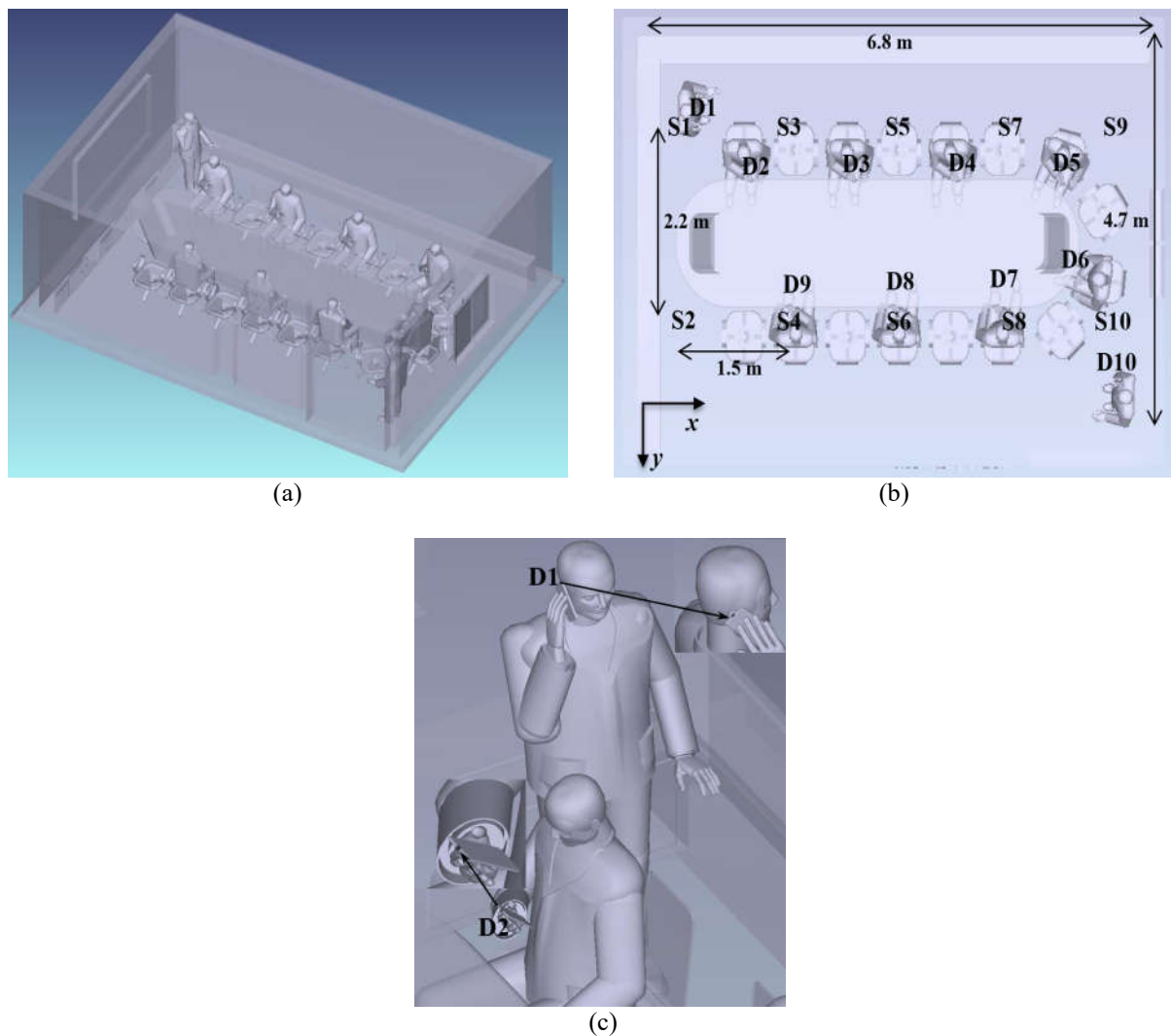
Fig. 13. Conference room under consideration

Table 3. Simulation parameters for conference room

Room size	6.8 m × 4.7 m × 3 m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
Objects specifications	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: ▪ Shoes: Black gloss paint ▪ Head & Hands: Absorbing ▪ Clothes: Cotton
Luminaire specifications	Brand: Cree LR24-38SKA35, Half viewing angle: 40º, Number of luminaires: 10, Power per each luminaire: 46 W
Receiver specifications	Number of PDs: 10, Receiver area: 1 cm^2, FOV: 85º

(a)

(b)

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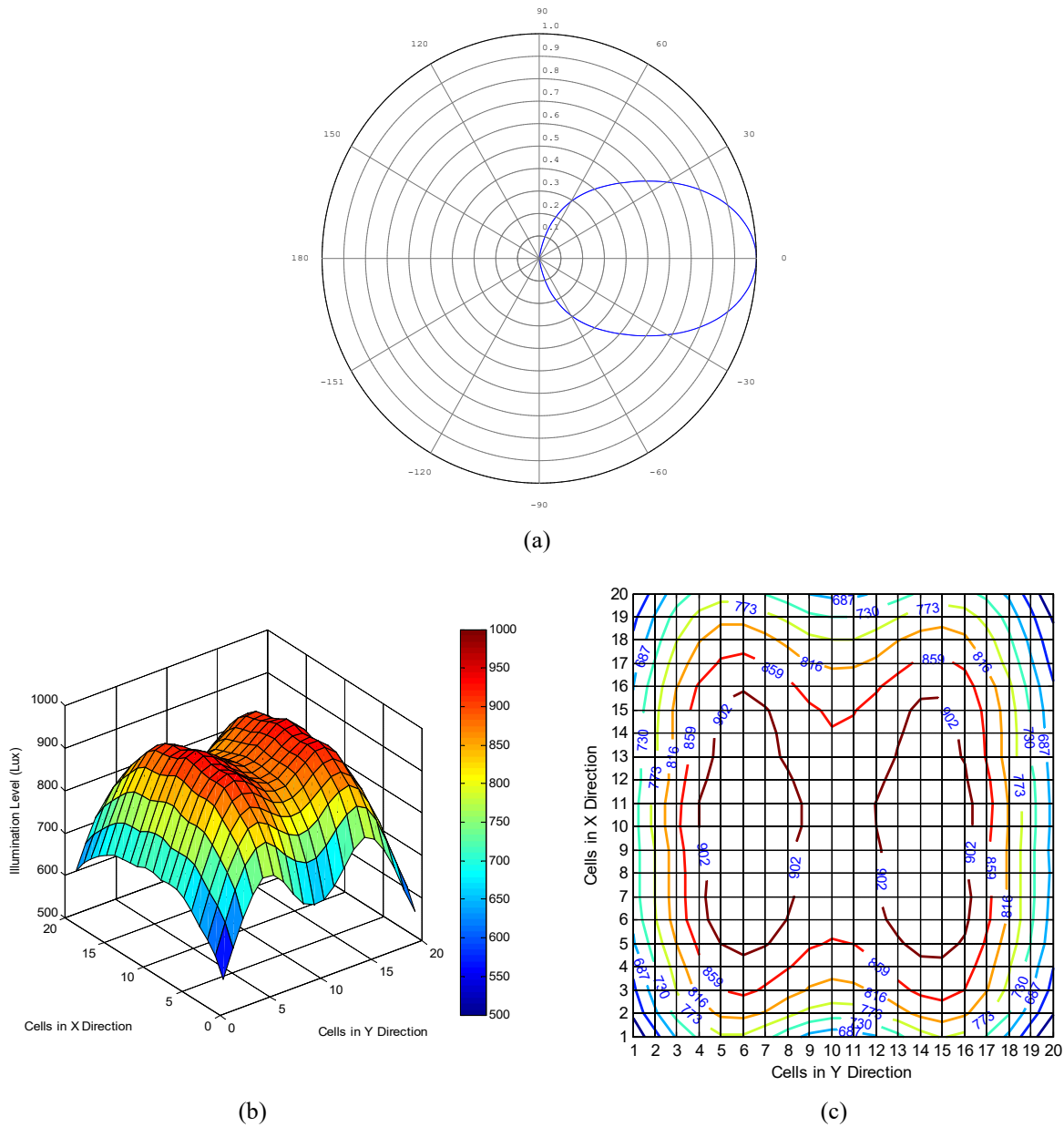
Fig. 14. (a) Emission pattern of each luminaire, (b) simulated illumination levels in Zemax and (c) illumination level contours in Matlab for conference room

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.

(a)

(b)

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

Table 4. Channel parameters for conference room

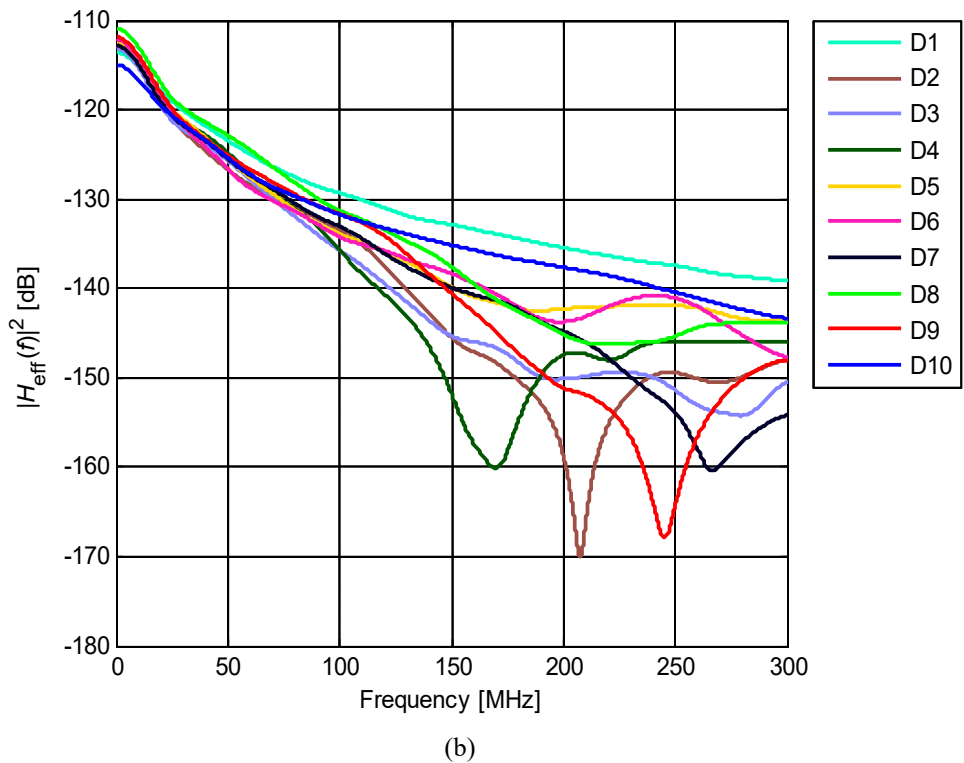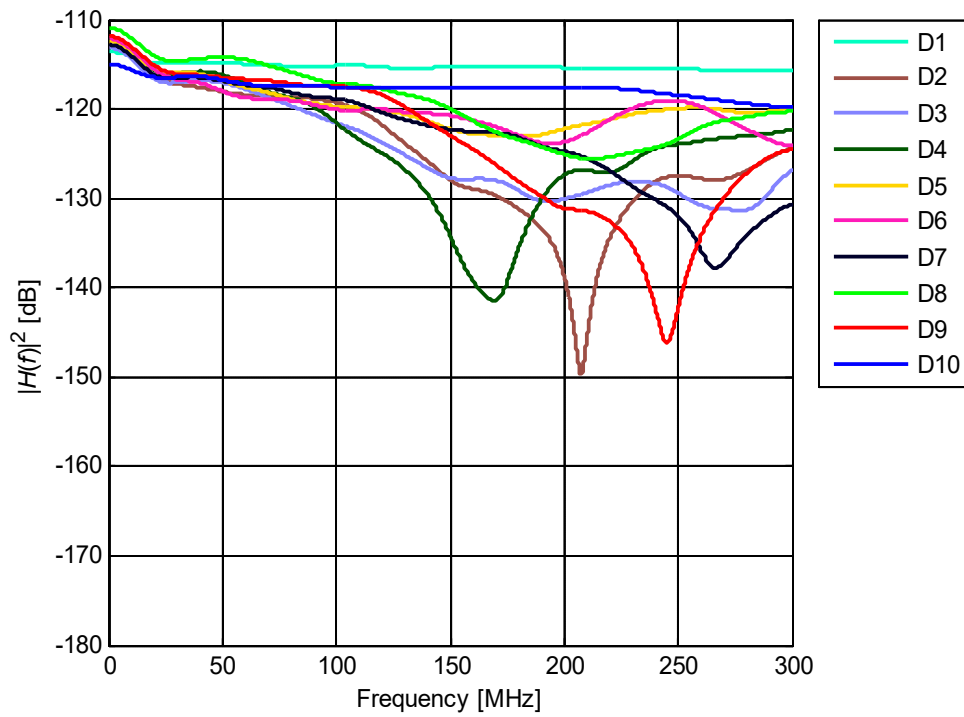|		τ_{RMS} (ns)	H_0			τ_{RMS} (ns)	H_0
S1	**D1**	8.24	8.23×10^{-5}	**S6**	**D1**	9.98	5.37×10^{-7}
	D2	10.35	1.49×10^{-5}		**D2**	11.26	8.09×10^{-6}
	D3	12.31	4.61×10^{-6}		**D3**	10.70	1.57×10^{-5}
	D4	12.93	1.77×10^{-6}		**D4**	10.63	1.57×10^{-5}
	D5	12.40	1.00×10^{-6}		**D5**	11.44	6.57×10^{-6}
	D6	10.76	1.96×10^{-6}		**D6**	11.86	8.01×10^{-6}
	D7	11.79	1.86×10^{-6}		**D7**	11.89	1.02×10^{-5}
	D8	11.68	3.65×10^{-6}		**D8**	10.04	2.89×10^{-5}
	D9	10.40	1.03×10^{-5}		**D9**	11.64	1.10×10^{-5}
	D10	9.17	2.78×10^{-7}		**D10**	11.45	1.19×10^{-6}
S2	**D1**	9.90	3.90×10^{-6}	**S7**	**D1**	9.91	3.10×10^{-7}
	D2	10.29	1.44×10^{-5}		**D2**	13.02	1.41×10^{-6}
	D3	11.35	5.82×10^{-6}		**D3**	12.35	6.26×10^{-6}
	D4	11.80	2.32×10^{-6}		**D4**	10.38	2.31×10^{-5}
	D5	11.45	1.35×10^{-6}		**D5**	10.14	2.16×10^{-5}
	D6	11.37	1.74×10^{-6}		**D6**	10.95	1.31×10^{-5}
	D7	12.75	1.56×10^{-6}		**D7**	10.57	1.85×10^{-5}
	D8	12.66	3.05×10^{-6}		**D8**	11.20	1.10×10^{-5}
	D9	11.22	8.84×10^{-6}		**D9**	11.71	4.99×10^{-6}
	D10	9.42	3.56×10^{-7}		**D10**	10.98	1.17×10^{-6}
S3	**D1**	10.99	2.48×10^{-6}	**S8**	**D1**	10.26	2.37×10^{-7}
	D2	9.90	2.76×10^{-5}		**D2**	12.20	2.87×10^{-6}
	D3	10.66	1.67×10^{-5}		**D3**	11.62	6.58×10^{-6}
	D4	12.87	4.40×10^{-6}		**D4**	10.66	1.67×10^{-5}
	D5	12.61	1.43×10^{-6}		**D5**	10.73	1.52×10^{-5}
	D6	11.83	3.56×10^{-6}		**D6**	9.83	2.72×10^{-5}
	D7	12.14	3.94×10^{-6}		**D7**	9.90	3.01×10^{-5}
	D8	11.28	9.68×10^{-6}		**D8**	11.89	9.58×10^{-6}
	D9	10.40	1.79×10^{-5}		**D9**	12.87	3.23×10^{-6}
	D10	10.74	5.36×10^{-7}		**D10**	10.28	4.61×10^{-6}
S4	**D1**	10.43	8.61×10^{-7}	**S9**	**D1**	9.66	3.39×10^{-7}
	D2	10.72	1.61×10^{-5}		**D2**	10.58	8.50×10^{-7}
	D3	10.71	1.38×10^{-5}		**D3**	12.73	2.74×10^{-6}
	D4	11.96	5.96×10^{-6}		**D4**	11.90	6.80×10^{-6}
	D5	12.15	2.64×10^{-6}		**D5**	10.14	2.18×10^{-5}
	D6	12.51	3.30×10^{-6}		**D6**	11.45	8.90×10^{-6}
	D7	13.80	2.44×10^{-6}		**D7**	10.58	1.14×10^{-5}
	D8	11.86	9.34×10^{-6}		**D8**	11.01	5.70×10^{-6}
	D9	9.83	2.94×10^{-5}		**D9**	11.05	2.75×10^{-6}
	D10	10.80	3.93×10^{-7}		**D10**	10.46	2.94×10^{-6}
S5	**D1**	10.75	7.29×10^{-7}	**S10**	**D1**	9.67	2.20×10^{-7}
	D2	12.73	5.96×10^{-6}		**D2**	11.33	2.12×10^{-6}
	D3	10.24	2.62×10^{-5}		**D3**	11.64	3.50×10^{-6}
	D4	10.69	1.91×10^{-5}		**D4**	10.93	8.11×10^{-6}
	D5	12.36	5.85×10^{-6}		**D5**	9.99	1.75×10^{-5}
	D6	11.55	7.32×10^{-6}		**D6**	10.16	2.03×10^{-5}
	D7	11.19	1.06×10^{-5}		**D7**	11.42	9.72×10^{-6}
	D8	10.36	1.93×10^{-5}		**D8**	12.72	2.96×10^{-6}
	D9	10.89	1.23×10^{-5}		**D9**	11.09	1.11×10^{-6}
	D10	10.53	6.72×10^{-7}		**D10**	8.38	6.02×10^{-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.
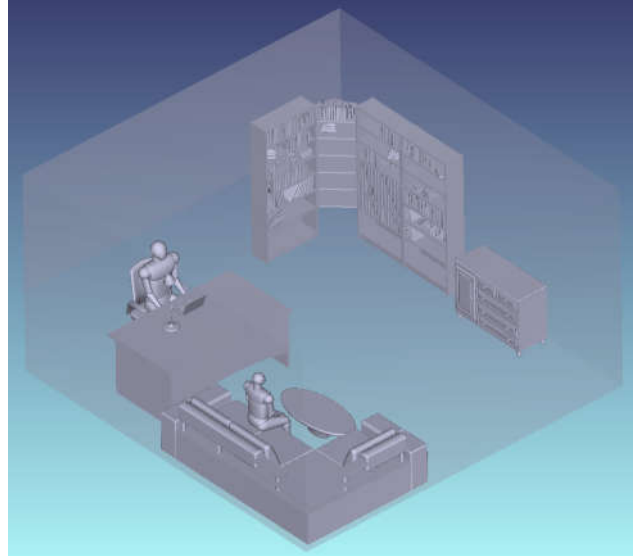
Fig. 16. Office room under consideration

Table 5. Simulation parameters for office room

Room size	5 m × 5 m × 3 m
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 0.88 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: ▪ Shoes: Black gloss paint ▪ Head & Hands: Absorbing ▪ Clothes: Cotton
Luminaire specifications	Brand: Cree LR24-38SKA35, Half viewing angle: 40º, Number of luminaires: 1 on the ceiling, 1 for the desk light, Power per each luminaire: 52 W
Receiver specifications	Number of PDs: 1 next to the laptop, 1 for the desk light, Receiver area: 1 cm^2, FOV: 85º

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.

(a)

(b)

(c)

(d)
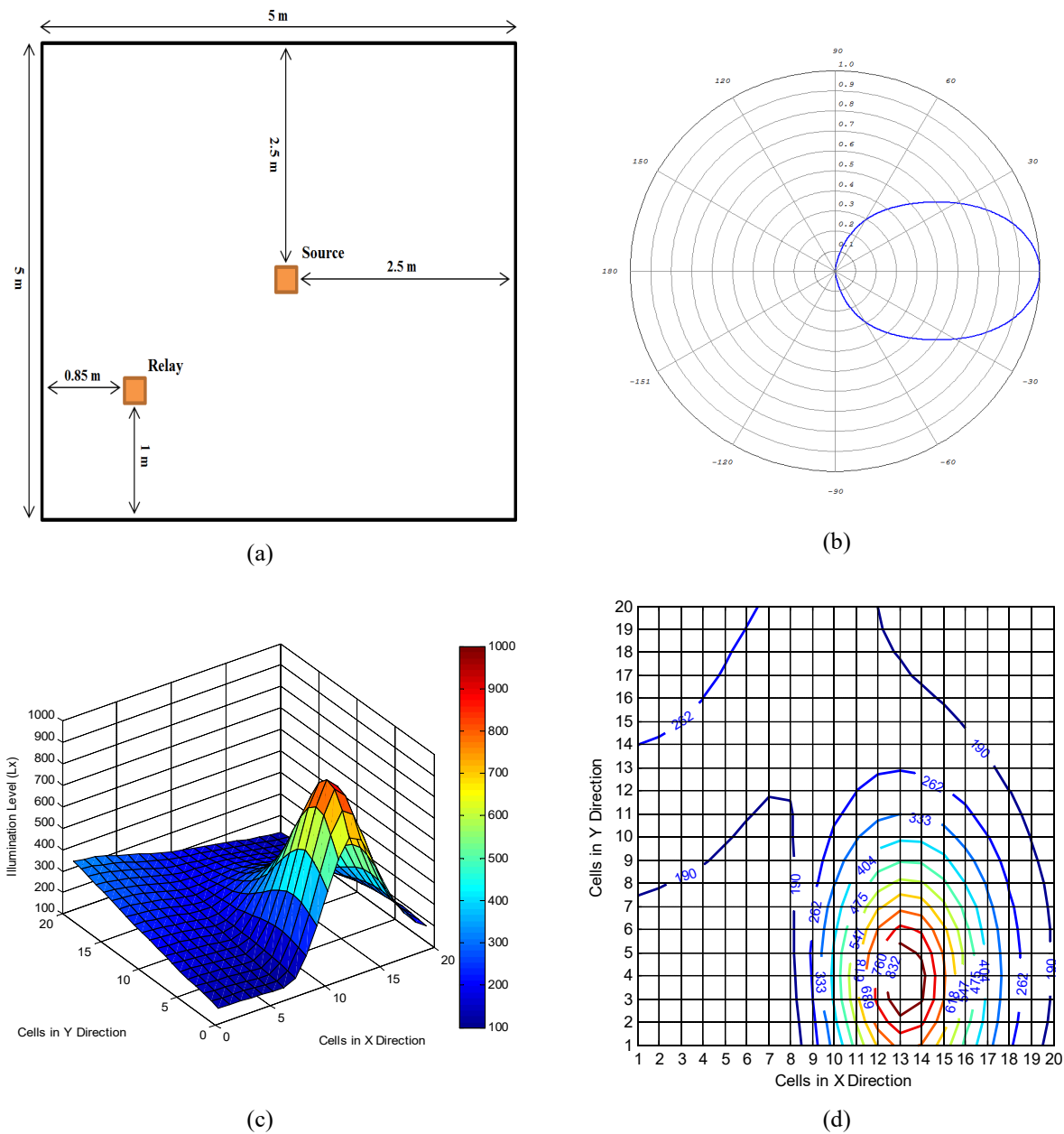
Fig. 17. (a) Arrangement of luminaires, (b) emission pattern of each luminaire, (c) simulated illumination levels in Zemax and (d) illumination level contours in Matlab for office room with secondary light

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 45º 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.
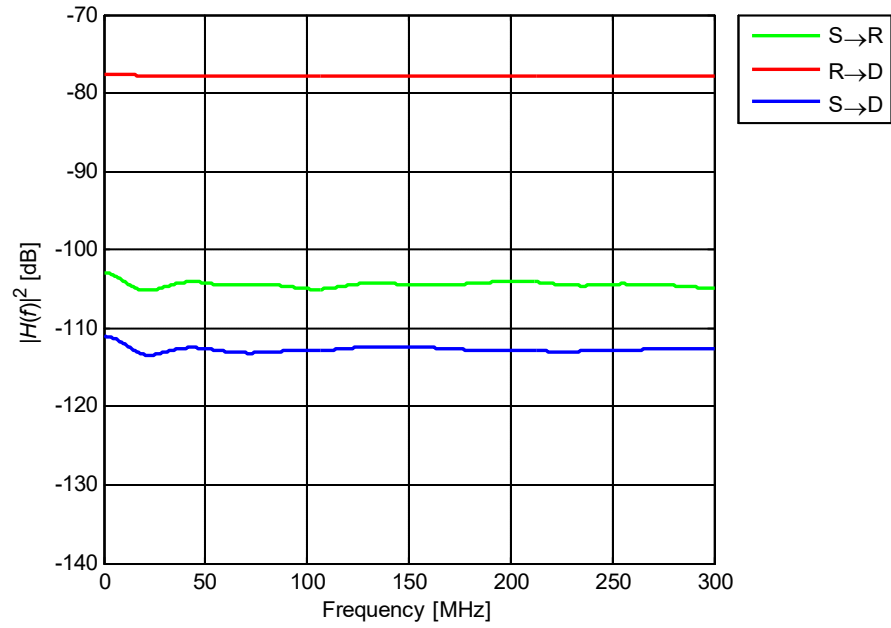
(a)
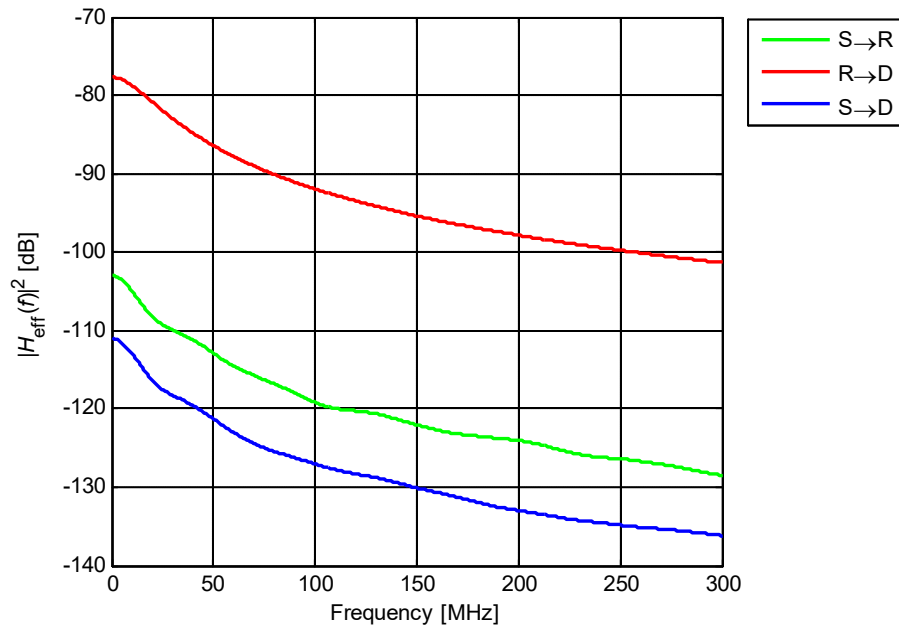
(b)

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

	τ_{RMS} (ns)	H_0
S→R	11.52	2.84×10^{-5}
R→D	8.07	5.21×10^{-4}
S→D	11.11	1.12×10^{-5}

7. Scenario Hospital Ward

We consider a hospital emergency room with beds, reception desk and large diagnostic instruments such as MRI, CT scan, surgical equipment, etc (see Fig. 19). The photodetector locations are denoted as Dn, n = 1, 2, …, 16. The FOV and the area of the detector are 85° and 1 cm^2, respectively. Details on the floor, ceiling, walls, objects and users within the environment are provided in Table 7.

There are 16 LED luminaires each with 19 W. The LED luminaires used in simulations are commercially available from Cree (CR14-40L-HE). Fig. 20 illustrates arrangement of luminaires in hospital ward, emission pattern of each luminaire, simulated illumination levels in Zemax and illumination level contours in Matlab.

Fig. 19. Hospital ward under consideration

Table 7. Simulation parameters for hospital ward

| Room size	8 m × 8 m × 3 m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
Objects	4 beds, Ultrasound instrument, Reception desk, 2 human bodies
Object specifications	Bed: size of 2 m × 1 m × 1 m with metal frames, Reception desk: Pinewood, Ultrasound instrument: Aluminum metal Human body: ▪ Shoes: Black gloss paint ▪ Head & Hands: Absorbing ▪ Clothes: Cotton
Luminaire specifications	Brand: Cree CR14-40L-HE, Half viewing angle: 54º, Number of luminaires: 16, Power per each luminaire: 19 W
Receiver specifications	Number of PDs: 16, Receiver area: 1 cm^2, FOV: 85º

(a)

(b)
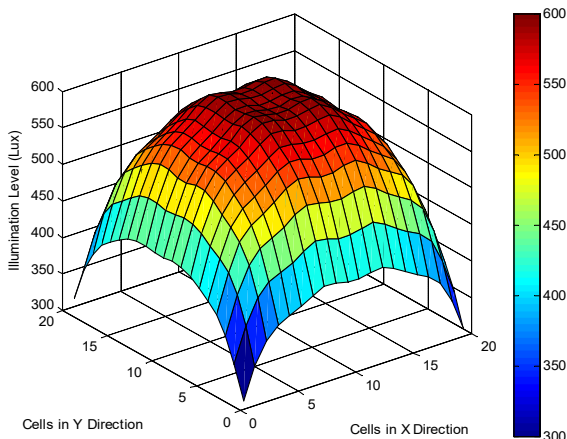
(c)
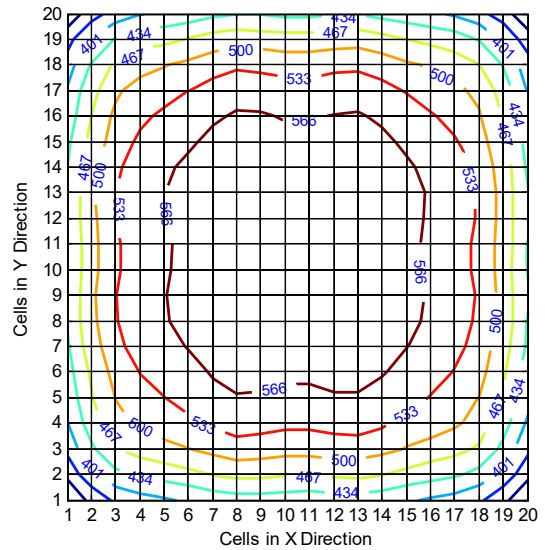
(d)

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 for hospital ward

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.
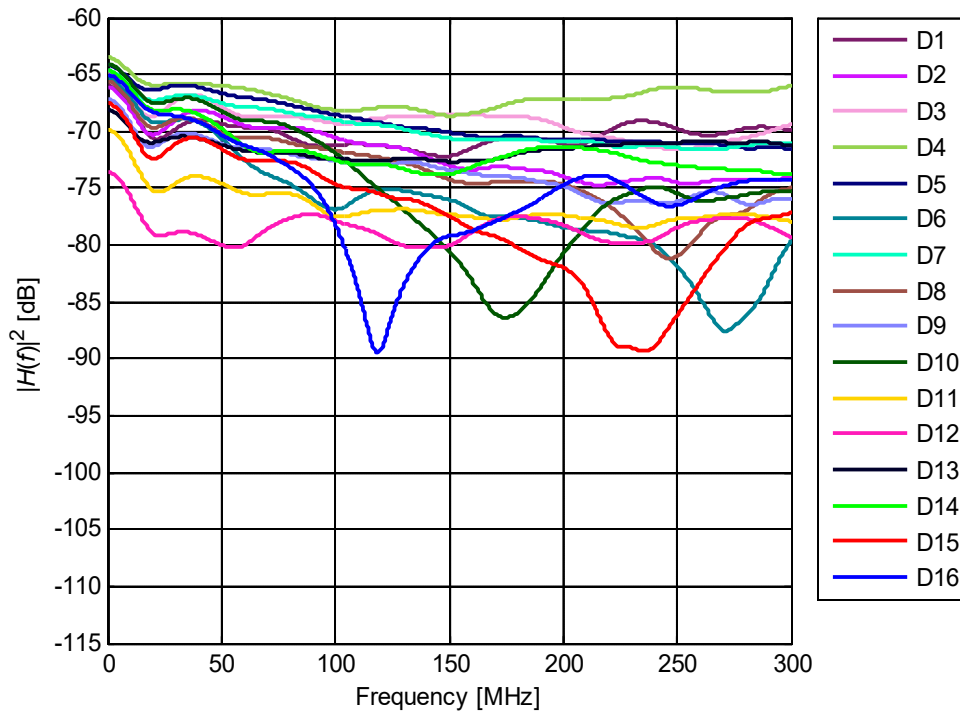
(a)
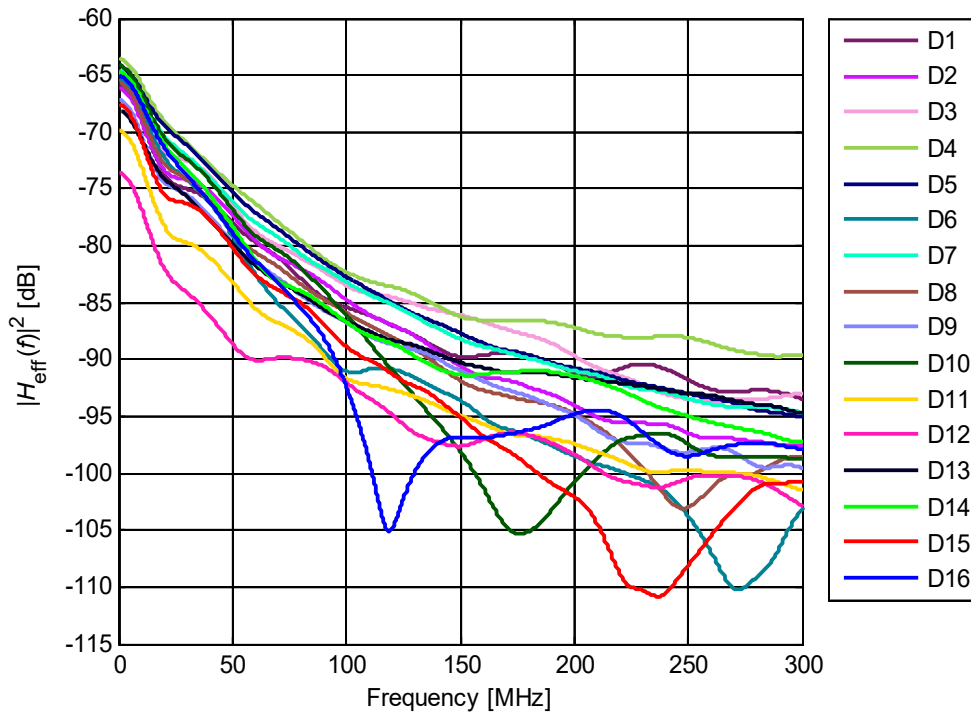
(b)

Fig. 21. (a) Optical channel responses and (b) effective channel responses for hospital ward

Table 8. Channel parameters for hospital ward

	τ_{RMS} (ns)	H_0		τ_{RMS} (ns)	H_0
D1	13.61	6.60×10^{-6}	**D9**	14.24	5.76×10^{-6}
D2	13.75	6.51×10^{-6}	**D10**	13.02	8.19×10^{-6}
D3	13.75	7.57×10^{-6}	**D11**	14.30	4.23×10^{-6}
D4	12.53	8.79×10^{-6}	**D12**	14.26	2.75×10^{-6}
D5	12.55	8.15×10^{-6}	**D13**	13.40	5.17×10^{-6}
D6	13.24	7.09×10^{-6}	**D14**	13.00	7.68×10^{-6}
D7	12.80	7.70×10^{-6}	**D15**	14.22	5.52×10^{-6}
D8	13.71	6.88×10^{-6}	**D16**	12.93	7.35×10^{-6}

8. <u>Scenario Residential</u>

In this scenario a living room is considered with table, chairs, couch, coffee table as shown in Fig. 22. Details on the floor, ceiling, walls, objects and users within the environment are provided in Table 9.
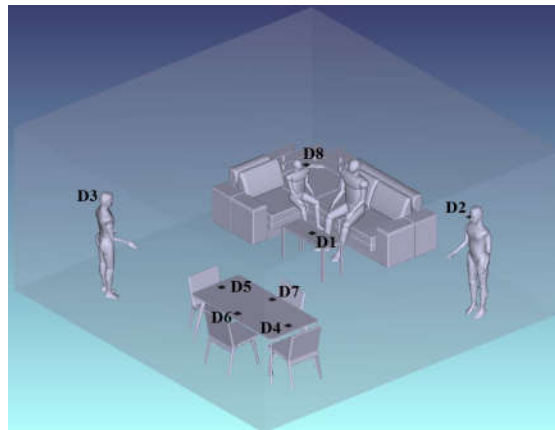
Fig. 22. Home environment

Table 9. Simulation parameters for home environment

Room size	6 m × 6 m × 3 m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
Objects	Table with 4 chairs, Couch, Coffee table, 4 human bodies
Object specifications	Tables: Wooden with size of 2 m × 1 m × 0.9 m, Chairs: Wooden matched with table, Couch: Cotton, Coffee table: Glass Human body: ▪ Shoes: Black gloss paint ▪ Head & Hands: Absorbing ▪ Clothes: Cotton
Luminaire specifications	Brand: Cree CR6-800L, Half viewing angle: 40º, Number of luminaires: 9, Power per each luminaire: 12 W
Receiver specifications	Number of PDs: 8, Receiver area: 1 cm², FOV: 85º

Arrangement of luminaires in home, emission pattern of each luminaire, simulated illumination levels in Zemax and Illumination levelcontours in Matlab are shown in Fig. 23.
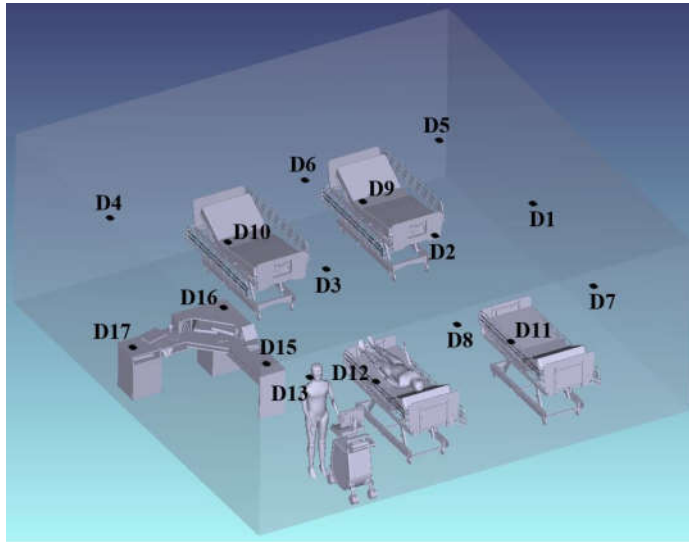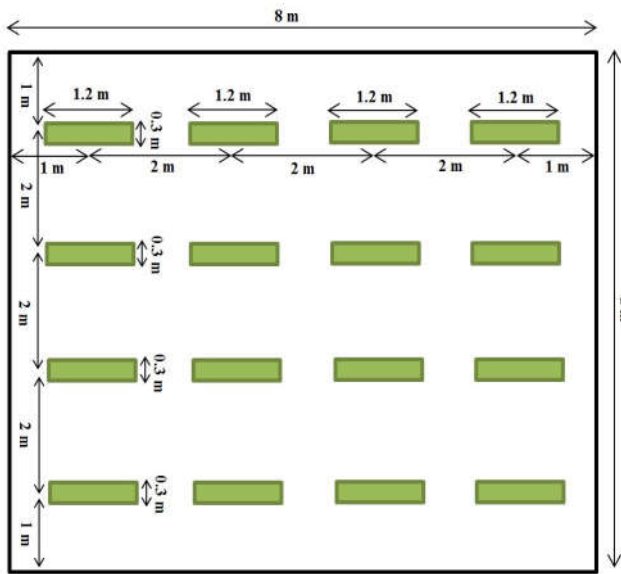

(a)

(b)

(c)

(d)
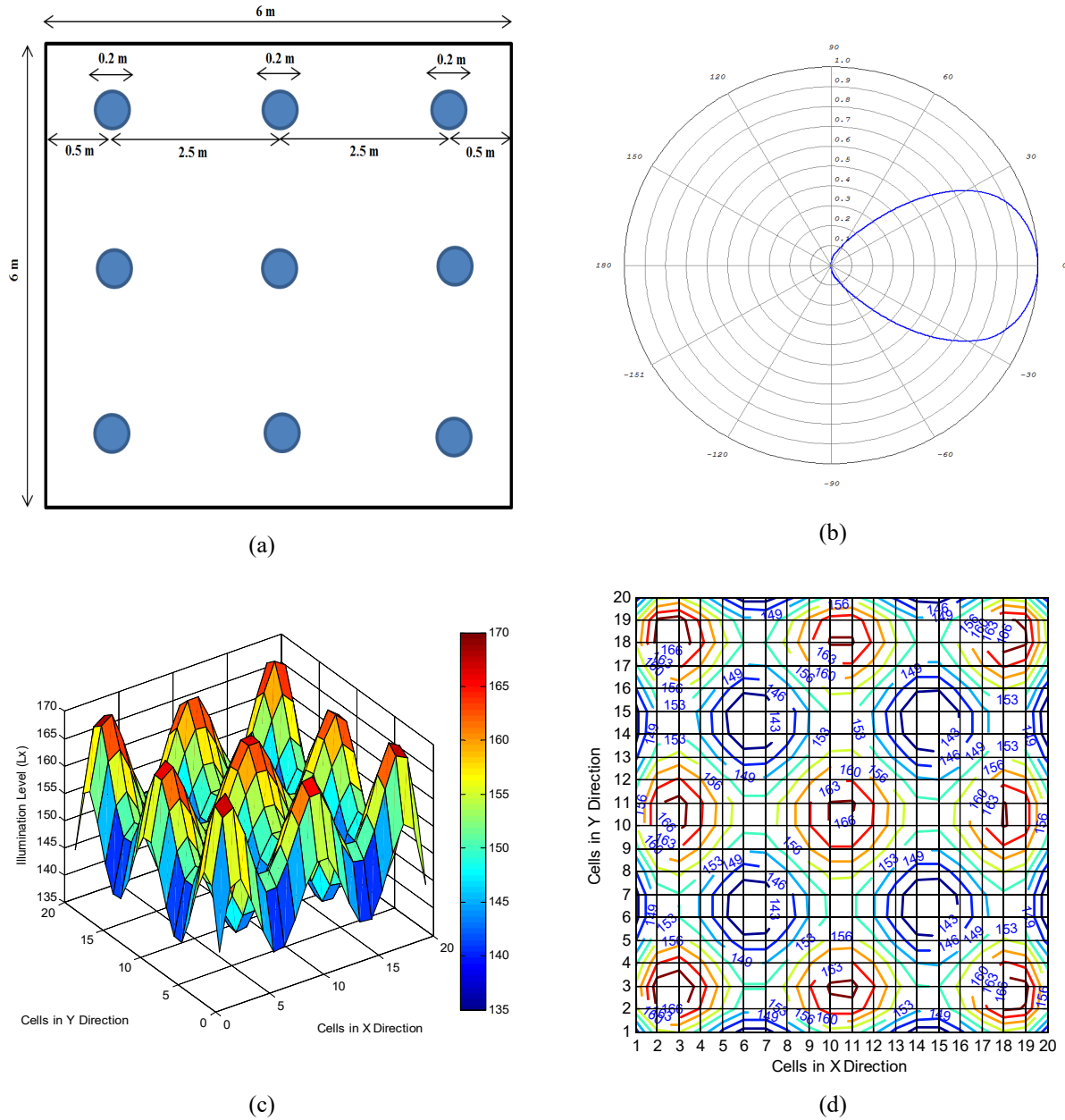
Fig. 23. (a) Arrangement of luminaires, (b) emission pattern of each luminaire, (c) simulated illumination levels in Zemax and (d) illumination level contours in Matlab for home environment
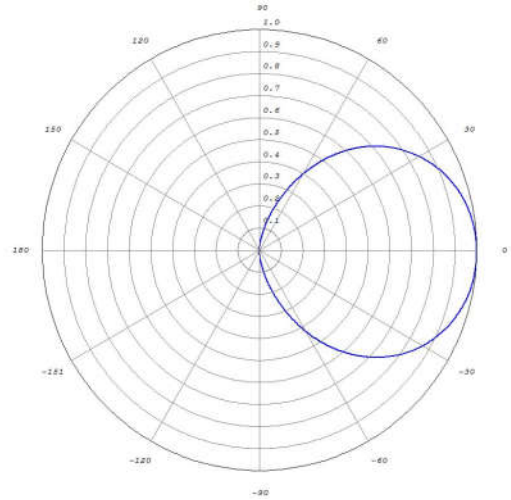
Based on the described simulation scenario above, we present the optical and effective channel responses in Fig. 24. The channel DC gain and RMS delay spreads are also obtained and provided in Table 10.
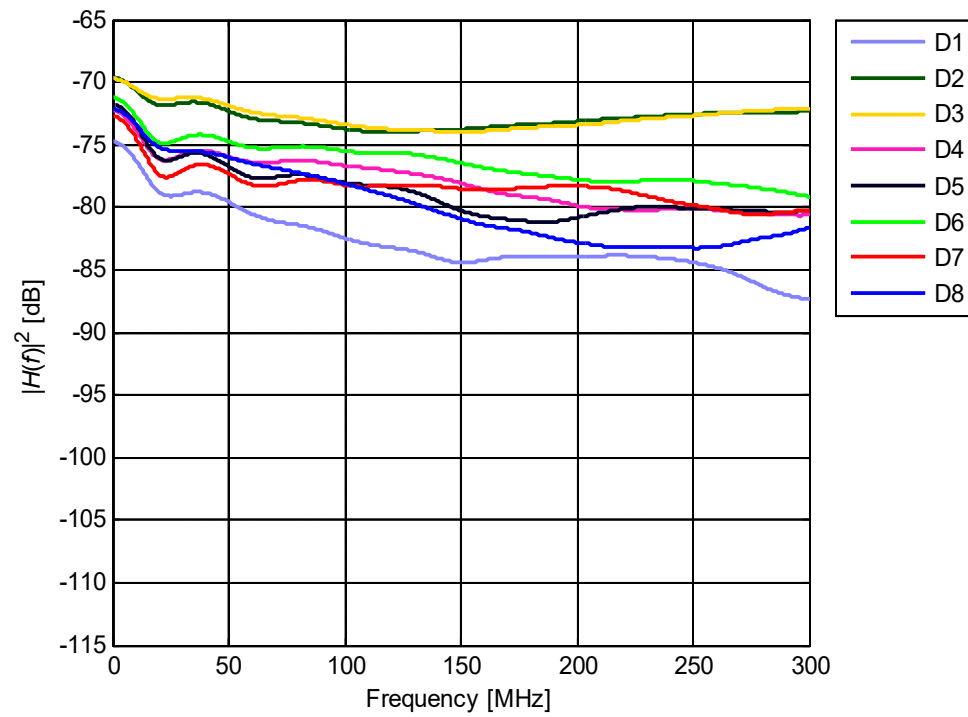
(a)
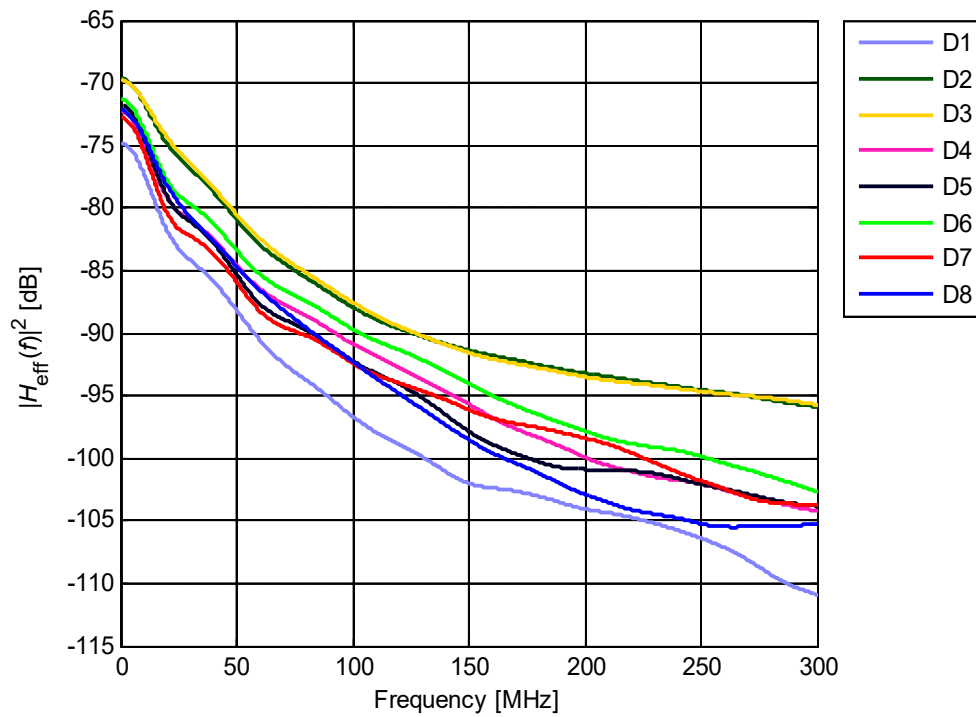
(b)

Fig. 24. (a) Optical channel responses and (b) effective channel responses for home environment

Table 10. Channel parameters for home environment

	τ_{RMS} (ns)	H_0
D1	12.49	6.75×10^{-6}
D2	11.50	1.22×10^{-5}
D3	10.72	1.20×10^{-5}
D4	12.70	9.03×10^{-6}
D5	12.90	9.56×10^{-6}
D6	12.48	1.01×10^{-5}
D7	13.01	8.55×10^{-6}
D8	11.88	9.13×10^{-6}

9. 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. 25. The specific materials for floor, ceiling, walls, and objects within the environment can be found in Table 11. Locations of the transmitters and receivers are also provided in Figs. 26 and 27 respectively.
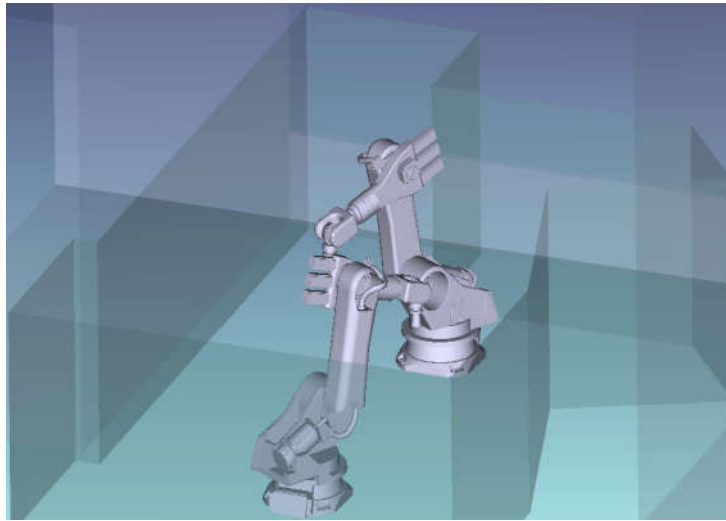
Fig. 25. Manufacturing cell

Table 11. Simulation parameters for manufacturing cell

|	
Room size	8.03 m × 9.45 m × 6.8 m
Materials	Walls: Concrete, aluminum metal, and Plexiglas (PMMA), Ceiling: Aluminum metal, Floor: Concrete
Objects	Two robots
Object specifications	Robot: Galvanized steel metal, Height of Robot: 2.7 m, Height of Plexiglas boundary: 2.5 m
LED specifications	Brand: Cree MC-E Xlamp, Half viewing angle: 60º, Number of LEDs: 6, Power per each luminaire: 1 W
Receiver specifications	Number of PDs: 8, Receiver area: 1 cm², FOV: 85º
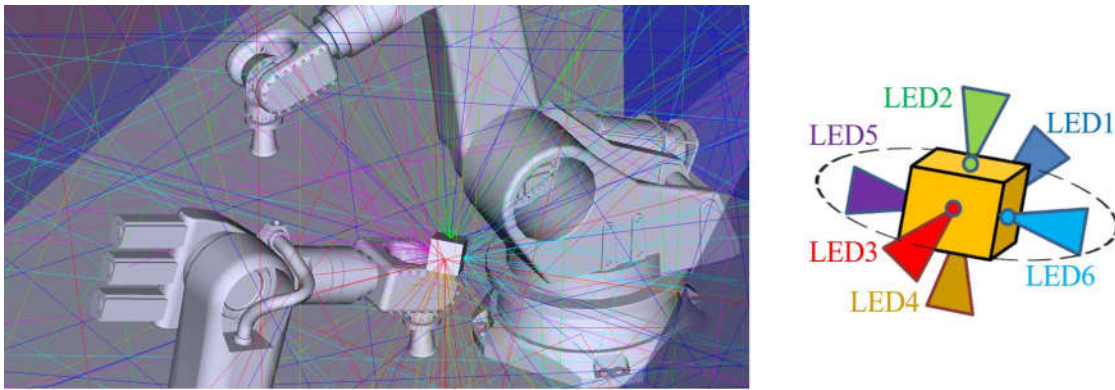
Fig. 26. Location of transmitters
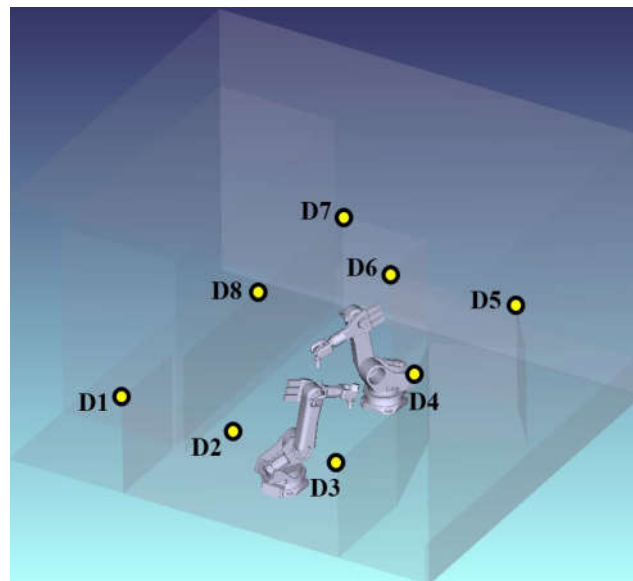

Fig. 27. Location of receivers

Based on the described simulation scenario above, we present the individual and overall optical and effective channel responses in Figs. 28 and 29. The channel DC gain and RMS delay spreads for individual and overall effective responses are obtained and respectively provided in Tables 12 and 13.
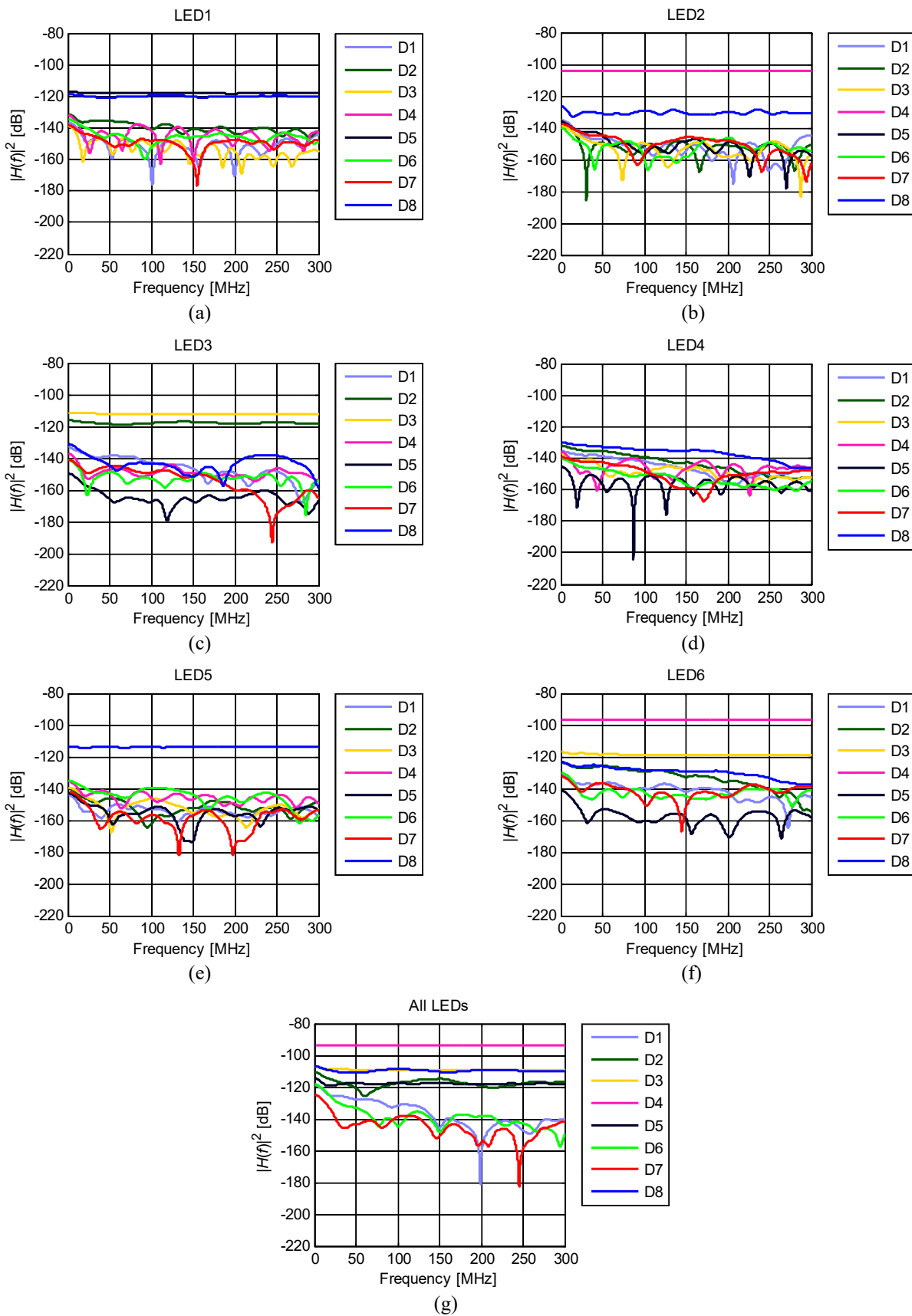
Fig. 28. Individual and overall optical channel responses for manufacturing cell
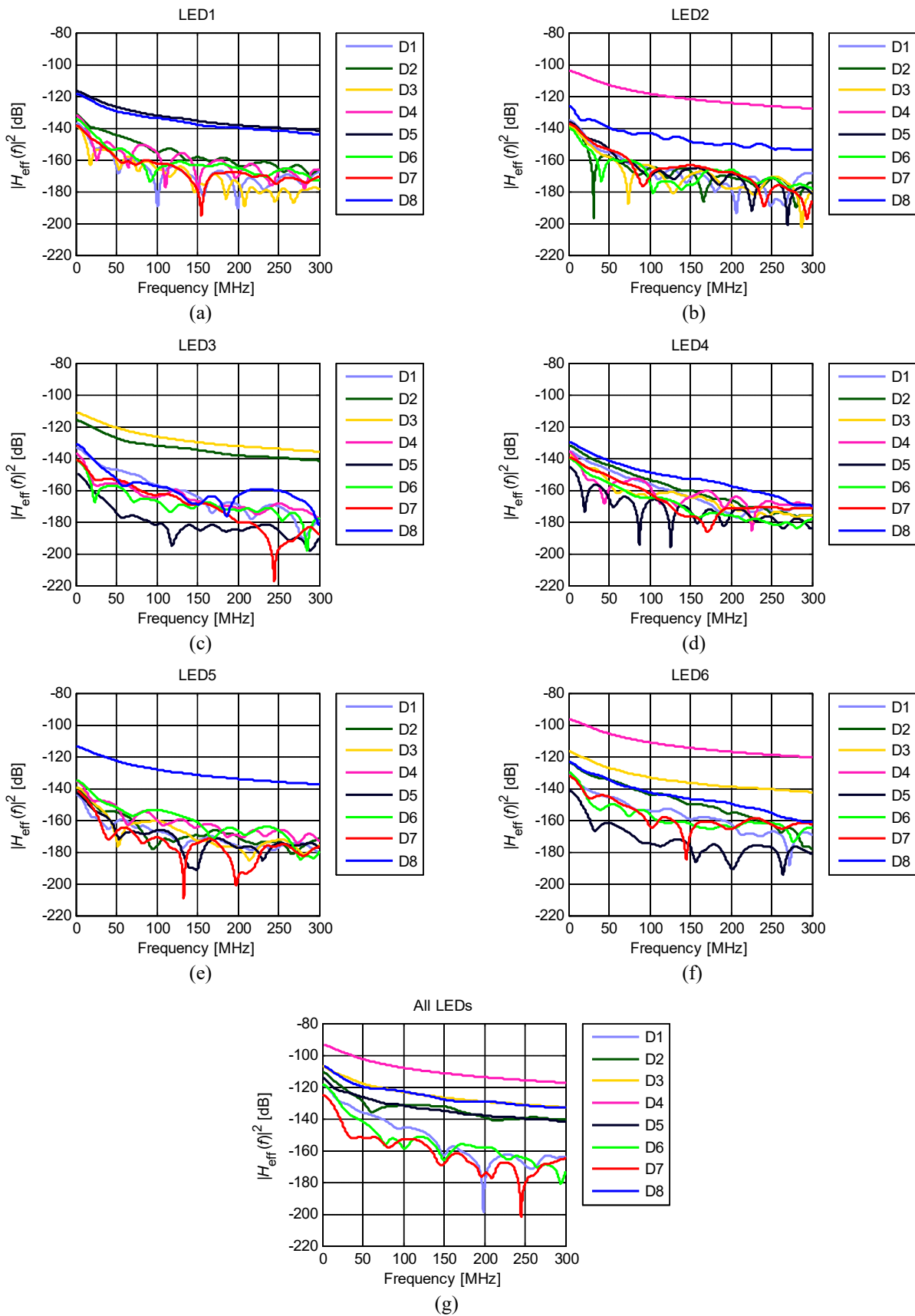
Fig. 29. Individual and overall effective channel responses for manufacturing cell

Table 12. Channel parameters of individual responses for manufacturing cell

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

Table 13. Channel parameters for overall responses in manufacturing cell

		τ_{RMS} (ns)	H_0
All LEDs	**D1**	15.66	7.78×10^{-7}
	D2	15.52	1.99×10^{-6}
	D3	14.13	2.96×10^{-6}
	D4	10.45	1.43×10^{-5}
	D5	16.42	1.29×10^{-6}
	D6	14.85	8.15×10^{-7}
	D7	15.83	3.78×10^{-7}
	D8	13.58	3.10×10^{-6}

Acknowledgement

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Appendix

```matlab
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)

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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^2

    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, and T. Baykas, "IEEE 802.11bb Channel Model for Conference Room Environment", doc.: IEEE 11-18-1365-00-00bb, July 2018. [Online]. Available: https://mentor.ieee.org/802.11/dcn/18/11-18-1365-00-00bb-ieee-802-11bb-channel-model-for-conference-room-environment.docx

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^2

   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^2

   2) Specifications of luminaire:
     Brand: Cree LR24-38SKA35
     Half Viewing Angle: 40 degrees
     Input Power: 52 W

Simulation Scenario Hospital Ward

1) This file includes the CIRs for a hospital emergency room with dimensions 8 m × 8 m × 3 m with beds, reception desk and large diagnostic instruments such as MRI, CT scan, surgical equipment, etc.

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) Coordinates of test points are as follows:

D1:(2500, 0, 1700)	D2:(500, 0, 1700)	D3:(-1500, 0, 1700)
D4:(-3800, 3000, 1700)	D5:(2000, 2500, 1700)	D6:(-500, 2500, 1700)
D7:(2000, -2500, 1700)	D8:(-500, -2500, 1700)	D9:(600, 2500, 1000)
D10:(-1900, 2500, 1000)	D11:(600, -2500, 1000)	D12:(-1900, -2500, 1000)
D13:(-3400, -2800, 1700)	D14:(-3000, -700, 800)	D15:(-3000, 700, 1030)
D16:(-4650, 700, 800)		

4) Coordinates of luminaires are as follows:

S1:(3000, 3000, 3000)	S2:(3000, 1000, 3000)	S3:(3000, -1000, 3000)
S4:(3000, -3000, 3000)	S5:(1000, 3000, 3000)	S6:(1000, 1000, 3000)
S7:(1000, -1000, 3000)	S8:(1000, -3000, 3000)	S9:(-1000, 3000, 3000)
S10:(-1000, 1000, 3000)	S11:(-1000, -1000, 3000)	S12:(-1000, -3000, 3000)
S13:(-3000, 3000, 3000)	S14:(-3000, 1000, 3000)	S15:(-3000, -1000, 3000)
S16:(-3000, -3000, 3000)		

5) Specifications of detectors and luminaires are as follows:

   1) Specifications of detector:
     Number of PDs: 16
     FOV: 85 degrees
     Area: 1 cm^2

   2) Specifications of luminaire:
     Number of luminaires: 16
     Brand: Cree CR14-40L-HE
     Half Viewing Angle: 54 degrees
     Input Power: 19 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 luminaires 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^2

    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^2
 * 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