Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: LiFi Reference Channel Models: Office, Home, Manufacturing Cell

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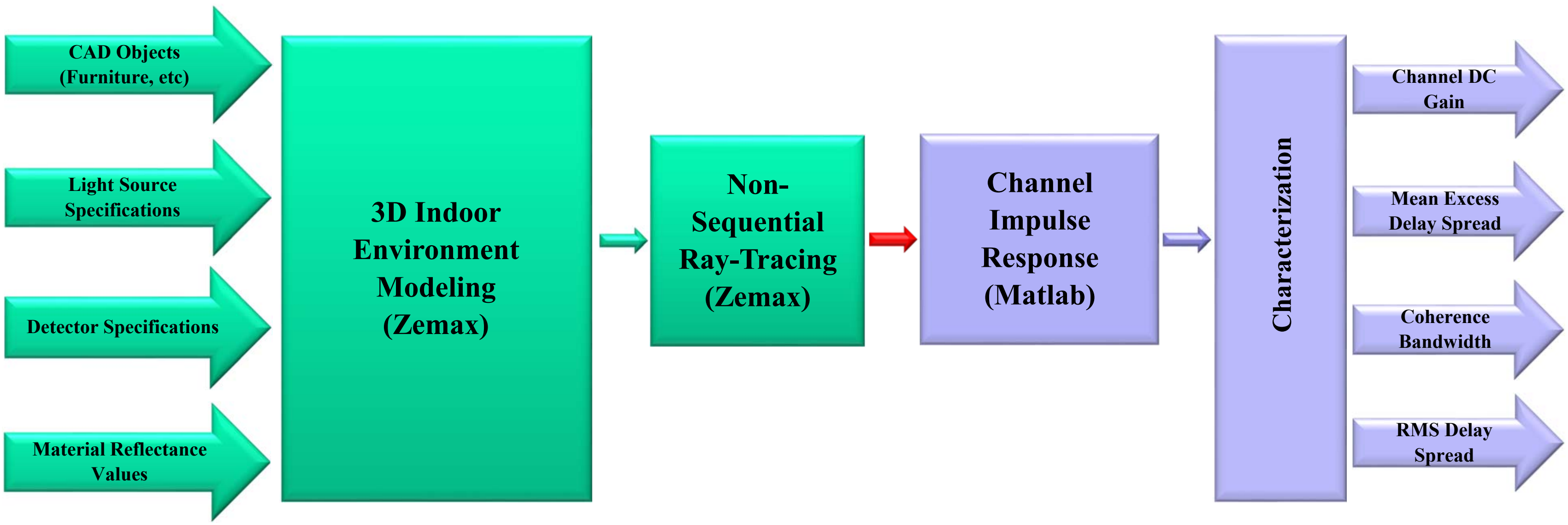
Abstract: In response to «Call for Proposals for OWC Channel Models» issued by 802.15.7r1, this contribution proposes LiFi reference channel models for indoor environments such as office, home and manufacturing cell.
Purpose: To introduce reference channel models for the evaluation of different PHY proposals.

LiFi Reference Channel Models: Office, Home, Manufacturing Cell

Outline

- Introduction
  - Overview of Channel Modeling Methodology
- Scenarios under Consideration: Office, Home, Manufacturing Cell
  - Modeling of Indoor Environment
  - Source Modeling
  - Illumination Level Requirements
  - Channel Impulse Responses (CIR)
- Conclusions

Overview of Channel Modeling Methodology



- A flexible and efficient method for realistic VLC channel modeling
  - Wavelength dependency
  - Realistic light sources
  - Effect of objects within the environment and types of surface (coating) materials

See IEEE 15-15-0352-00-007a “Channel Modeling for Visible Light Communications” for additional details

Characterization of CIR

Channel Parameters	Definition
Channel DC Gain	$H_0 = \int_{-\infty}^{\infty} h(t)\,dt$
Mean Excess Delay Spread	$\tau_0 = \dfrac{\int_0^{\infty} t \times h(t)\,dt}{\int_0^{\infty} h(t)\,dt}$
RMS Delay Spread	$\tau_{RMS} = \sqrt{\dfrac{\int_0^{\infty} (t-\tau_0)^2 h(t)\,dt}{\int_0^{\infty} h(t)\,dt}}$
Truncation Time ($T_{97\%}$)	$\int_0^{T_{97\%}} h(t)\,dt = 0.97 \int_0^{\infty} h(t)\,dt$
Frequency Correlation Function	$H(\Delta f) = \int_{-\infty}^{\infty} h(t) e^{-j2\pi\Delta f t}\,dt$
Coherence Bandwidth (Correlation level of 0.9)	$B_{0.9} = \min(\Delta f)\ \text{such that} \left\|H(\Delta f)\right\| = 0.9$
Channel Transfer Function	$H(f) = \int_{-\infty}^{\infty} h(t) e^{-j2\pi f t}\,dt$

Overview of Channel Modeling Methodology

- Creation of 3D indoor environment in Zemax involves the selection of
  - Room size and shape
  - CAD objects within the environment (furniture etc)
  - Position and type of transmitters and receivers
  - Type and properties of materials (walls, floor, ceiling, objects etc)
- The Zemax non-sequential ray-tracing tool generates an output file, which includes all the data about rays such as the detected power and path lengths for each ray.
- The data from Zemax output file is imported to MATLAB and using these information, the CIR is expressed as

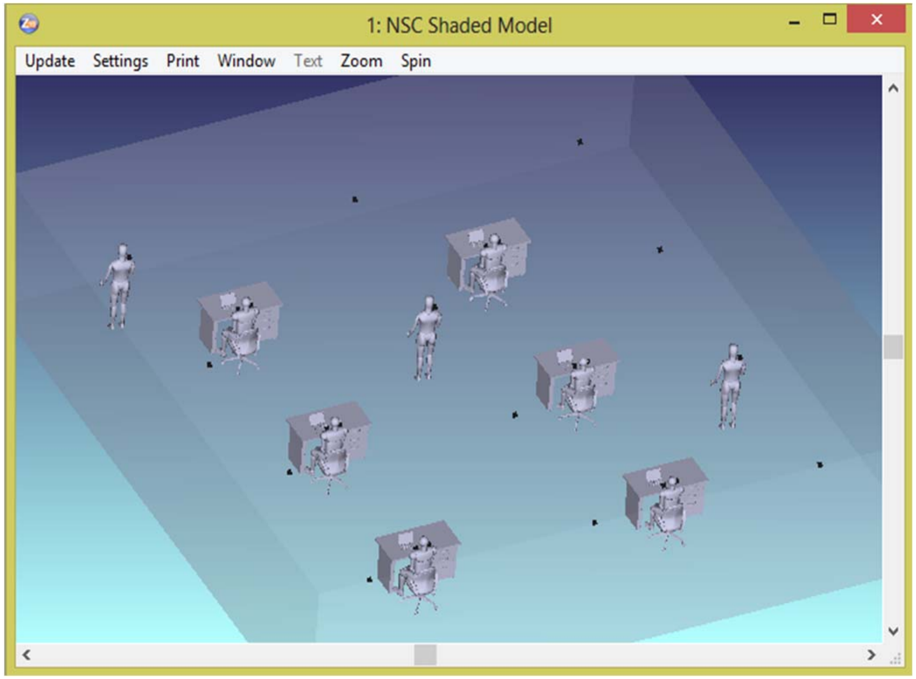
$$h(t) = \sum_{i=1}^{N_r} P_i \delta(t - \tau_i)$$

P_i = the power of the ith ray
τ_i = the propagation time of the ith ray
$\delta(t)$ = the Dirac delta function
N_r = the number of rays received at the detector

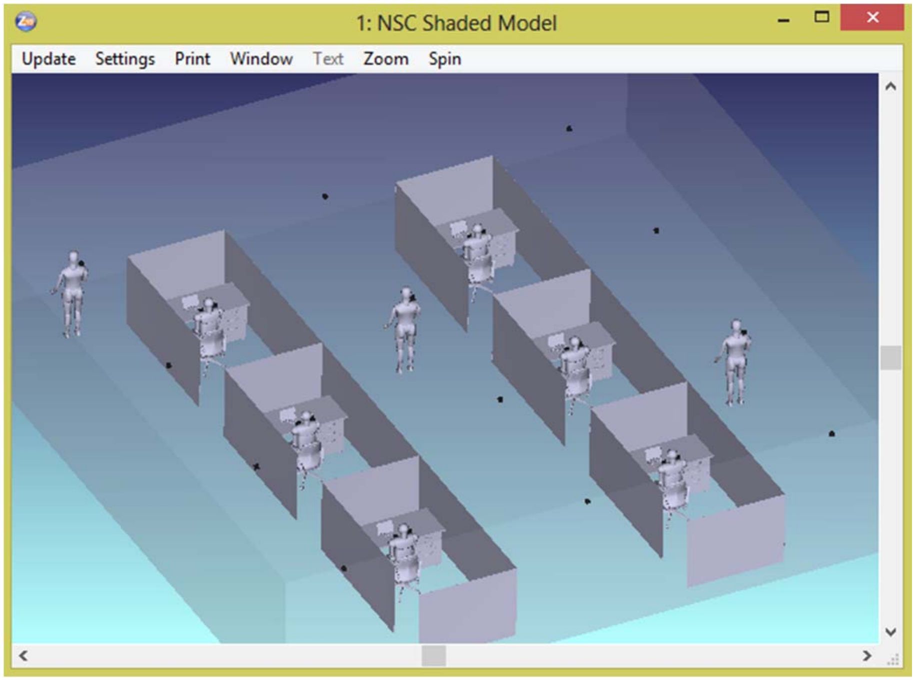
Scenario 1: Office

- Typical office places include furniture (e.g., desk, chairs, cubicles etc), various equipments (e.g., computers, printers etc) and personnel.

Open Office



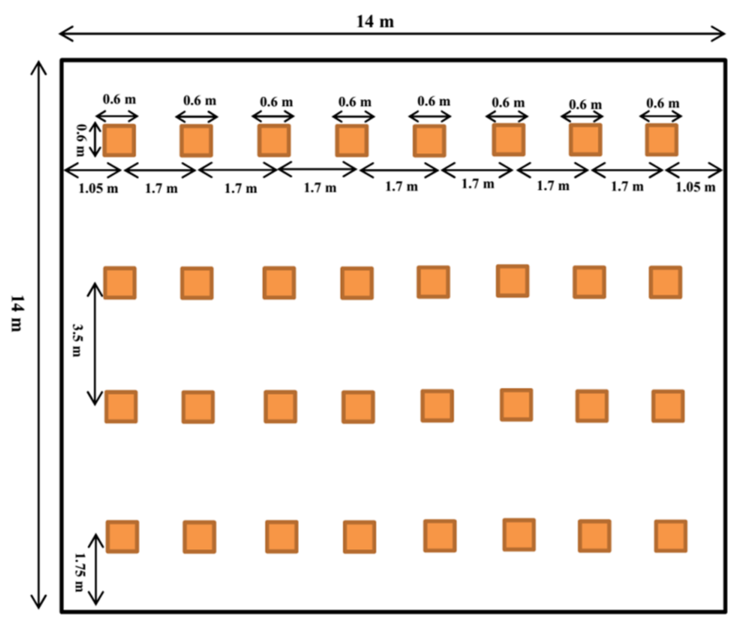
Office With Cubicles



Simulation Parameters

Room size	14m × 14m × 3m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
Objects	6 desks and a chair paired with each desk 6 laptops on each desk 6 cubicles (optional) 9 human bodies
Objects specifications	Cubicles: Plaster Desk: Pinewood (Typical height of 0.85m) Chair: Pinewood Laptop: Black gloss paint Human body: ▪ Shoes: Black gloss paint ▪ Head & Hands: Absorbing ▪ Clothes: Cotton
Luminary Specifications	Brand: LR24-38SKA35 Cree Inc. Half viewing angle: 40^o
Number of luminaries	32
Receiver area	1 cm^2

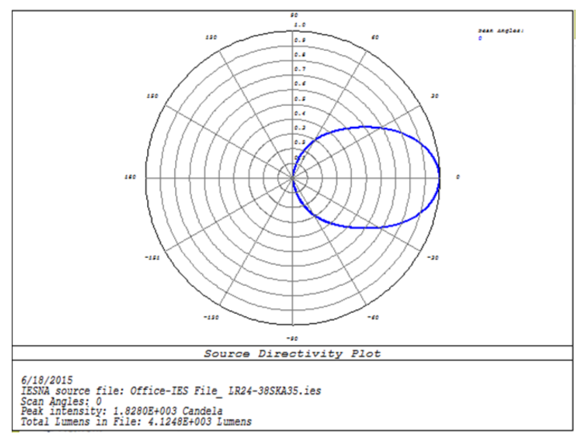
Location of Luminaries (Transmitters)



Arrangement of luminaries

$$\text{Uniformity} = \frac{\text{Min Lux}}{\text{Average Lux}}$$

Delivered light output from each luminary	3504 lumens
Average of illumination level	533 lx
Uniformity of illumination	0.5211

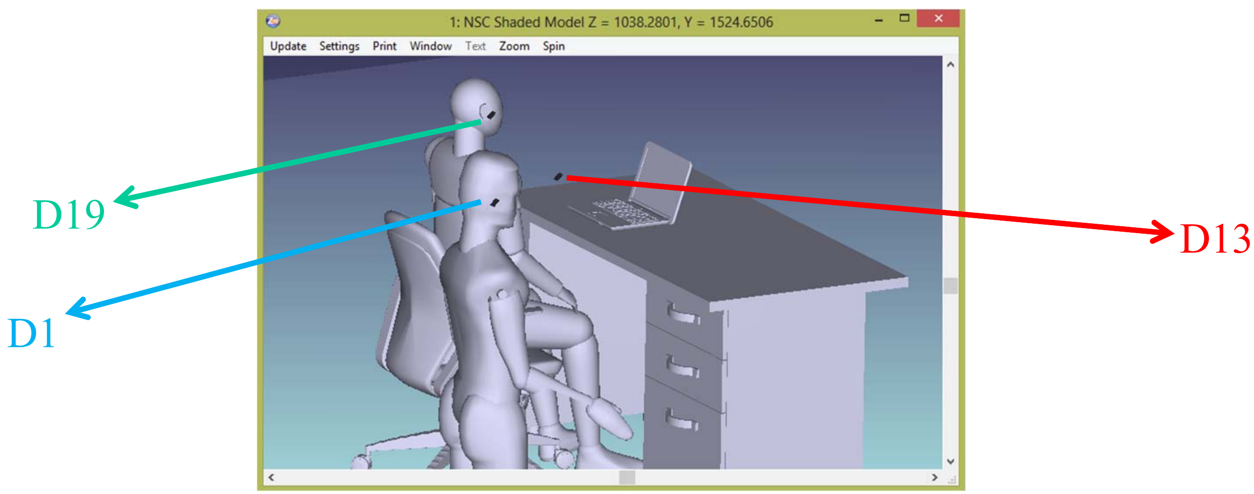


Emission pattern of each luminary

Location of Test Points (Receivers)

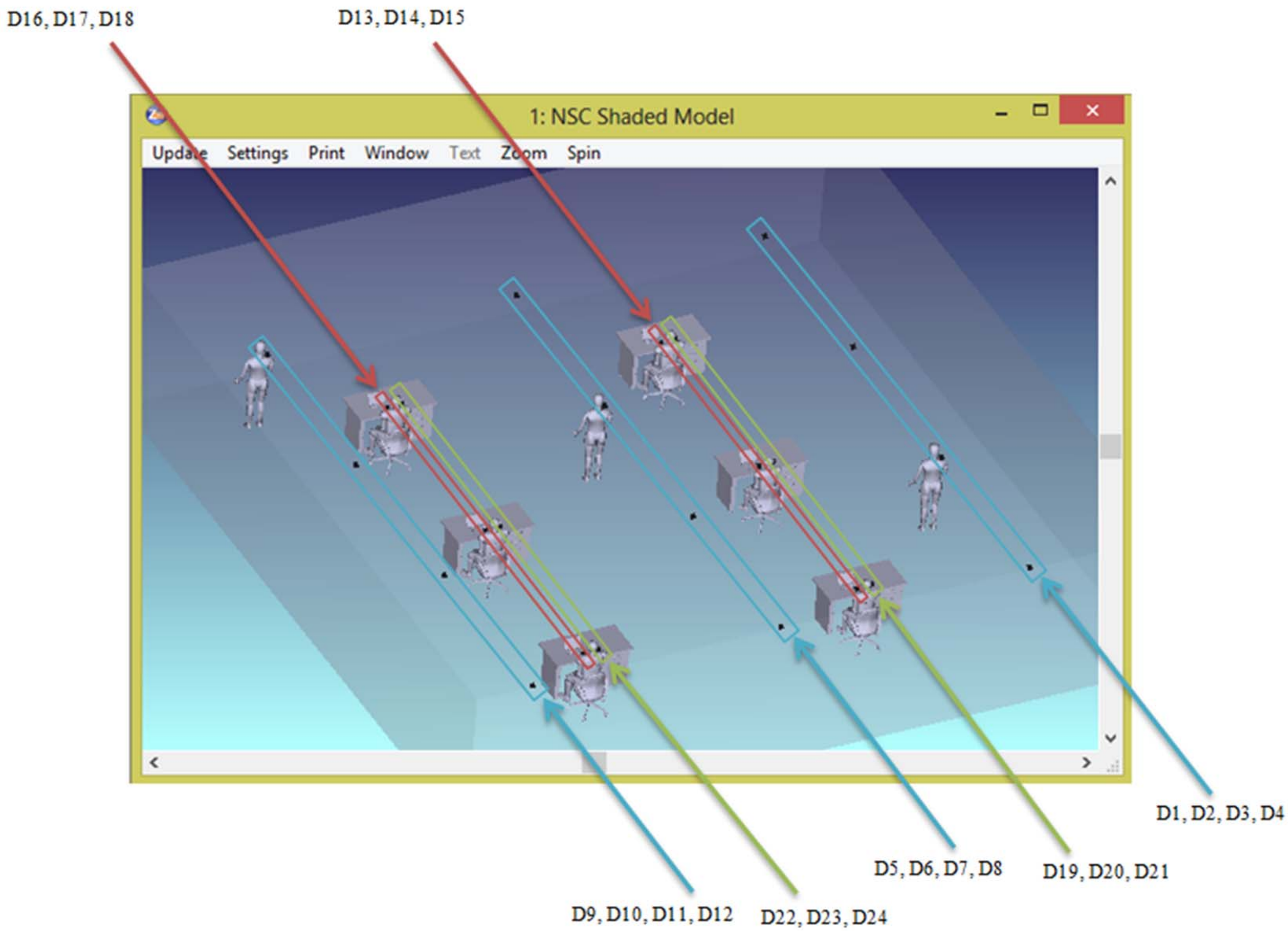
- 24 test points are chosen which are categorized into three groups:

In the corridors at a height of 1.7m with 45° rotation (e.g., people who stand with a cell phone in hand)	D1-D12
On the top of chairs at a height of 0.95m with 45° rotation (i.e., people with a cell phone in hand)	D13-D18
On the top of chairs at a height of 1.1m with 45° rotation (e.g., people who sit with a cell phone in hand to his/her ear)	D19-D24

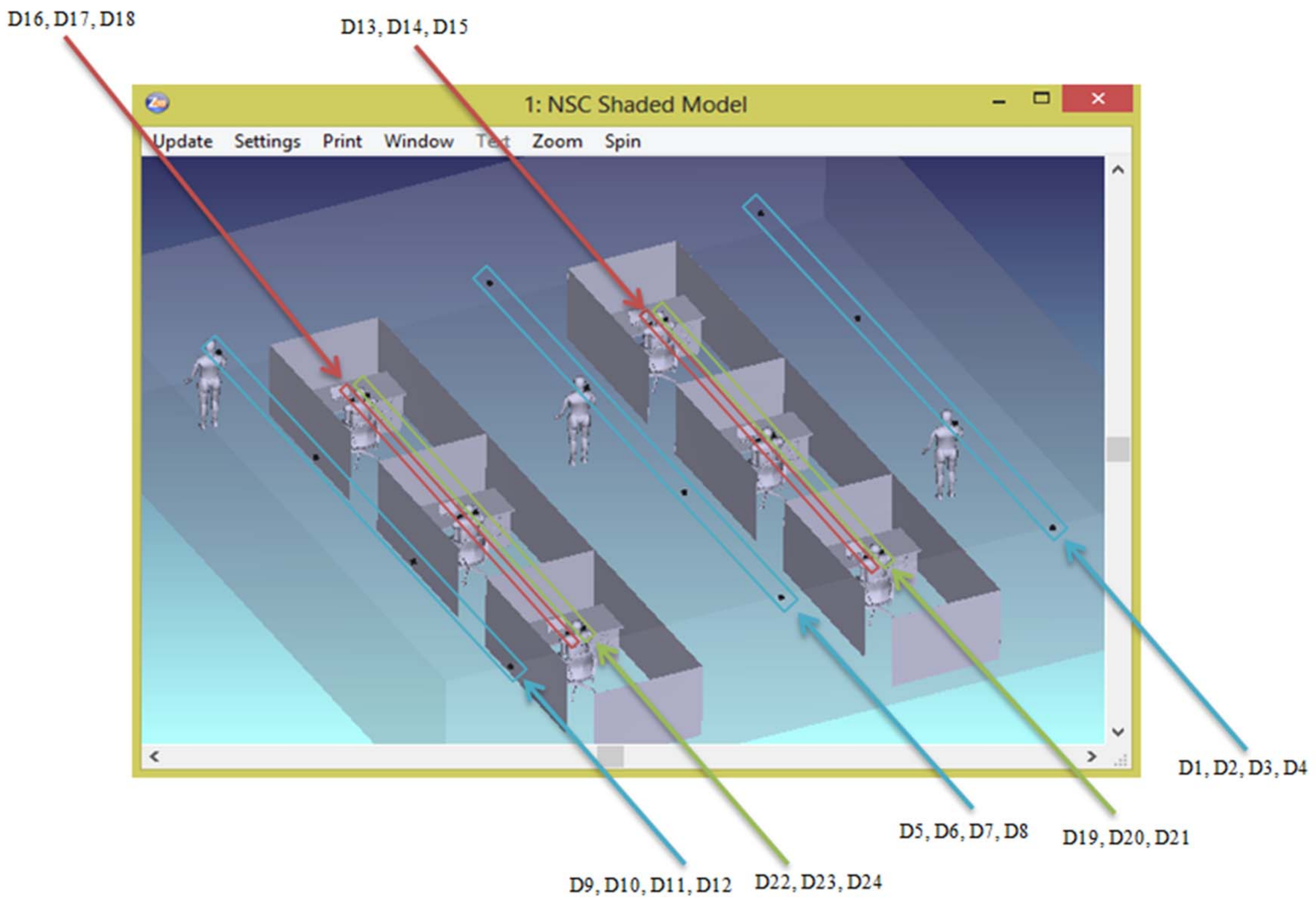


Location and rotation of test points

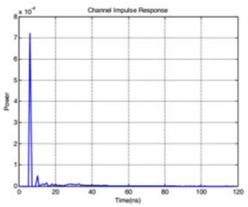
Test Points (Open Office)



Test Points (Office with Cubicles)



CIR Results (Open Office)



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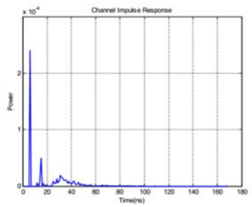

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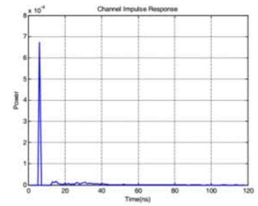

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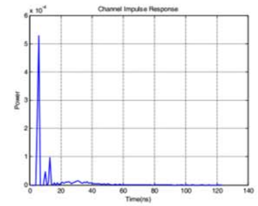

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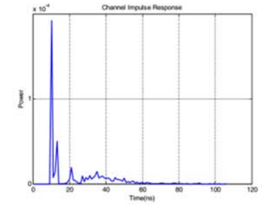

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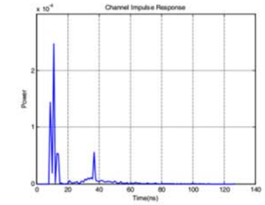

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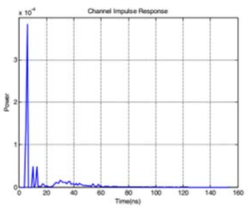

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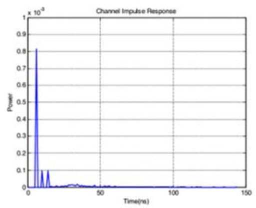

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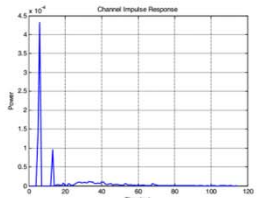

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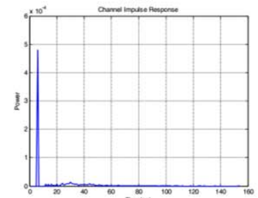

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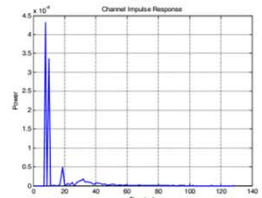

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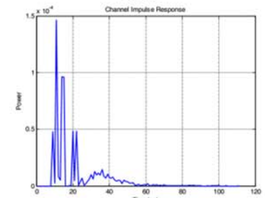

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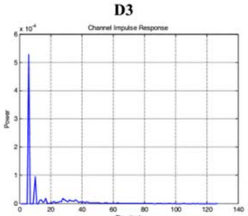

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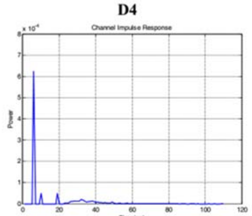

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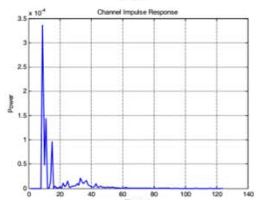

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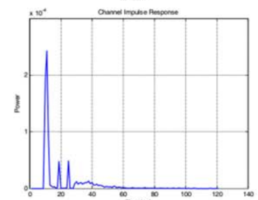

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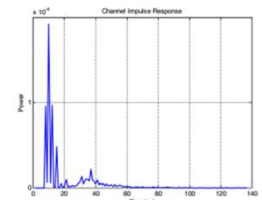

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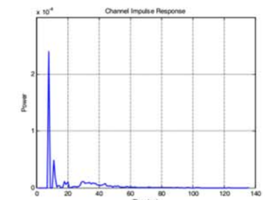

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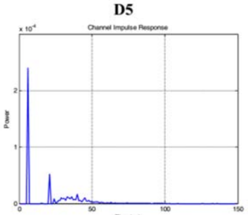

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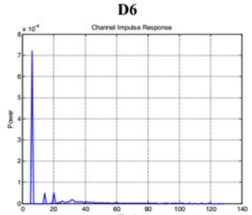

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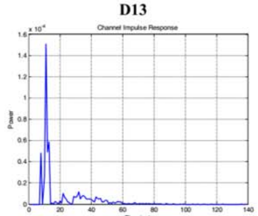

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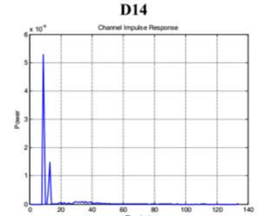

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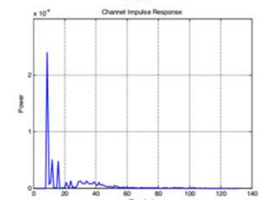

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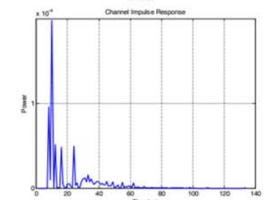


D24

Channel Characteristics

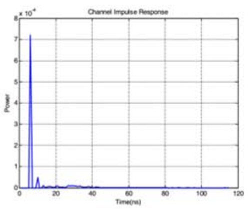
	$T_{97\%}$ (ns)	τ_{RMS} (ns)	H_0
D1	48	13.30	1.00×10^{-3}
D2	56	17.04	5.26×10^{-4}
D3	57	17.15	9.22×10^{-4}
D4	55	14.98	1.26×10^{-3}
D5	51	14.73	9.06×10^{-4}
D6	51	15.38	9.96×10^{-4}
D7	61	18.80	5.19×10^{-4}
D8	56	15.95	1.06×10^{-3}
D9	51	13.99	9.29×10^{-4}
D10	48	13.84	1.20×10^{-3}
D11	63	17.24	9.21×10^{-4}
D12	61	17.85	7.08×10^{-4}
D13	50	13.15	8.74×10^{-4}
D14	53	13.97	8.45×10^{-4}
D15	58	15.79	5.16×10^{-4}
D16	48	12.39	9.03×10^{-4}
D17	58	16.23	4.96×10^{-4}
D18	53	14.63	7.41×10^{-4}
D19	49	12.99	1.05×10^{-3}
D20	52	13.65	7.09×10^{-4}
D21	55	15.41	6.57×10^{-4}
D22	57	16.15	5.15×10^{-4}
D23	57	16.11	5.84×10^{-4}
D24	60	15.95	6.75×10^{-4}
Ave	54.5	15.27	8.13×10^{-4}

$$48 \le T_{97\%} \le 63$$
$$12.39\,\text{ns} \le \tau_{RMS} \le 18.80\,\text{ns}$$
$$4.96\times10^{-4} \le H_0 \le 1.26\times10^{-3}$$

- The effects of human shadowing are considered.
- With respect to open office room without human bodies,
  - Channel DC gain decreases (avg. 10.4%). This decrease is a result of the presence of human bodies. The rays hit the human body and decay more rapidly than those rays in open office.
  - RMS delay spread decreases (avg. 4.1%). Since the rays cannot pass through human body, delay spread values are smaller.

The CIRs for the same environments without human bodies can be found at
IEEE 15-15-0514-00-007a “LiFi Reference Channel Models: Office, Home, Hospital”

CIR Results (Office with Cubicles)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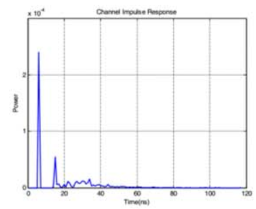
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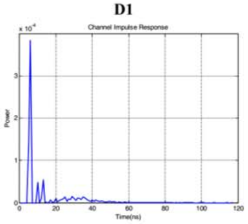
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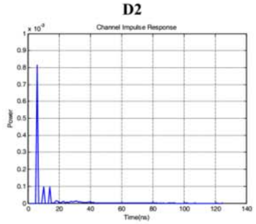
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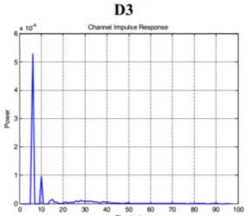
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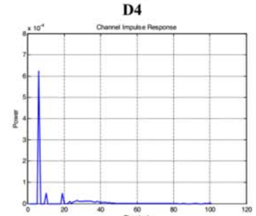
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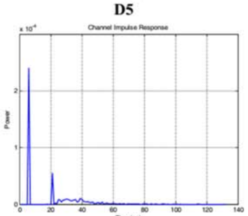
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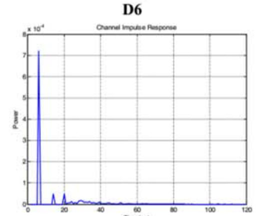
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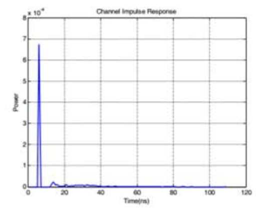
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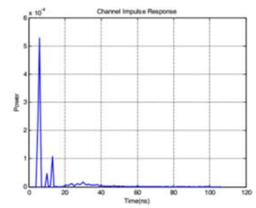
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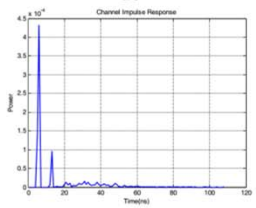
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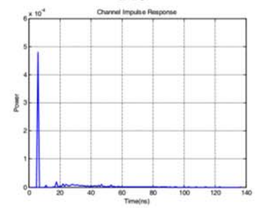
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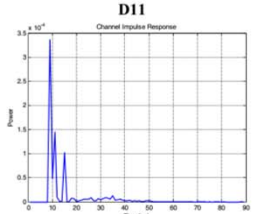
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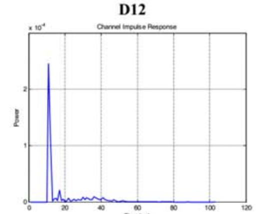
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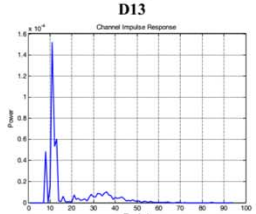
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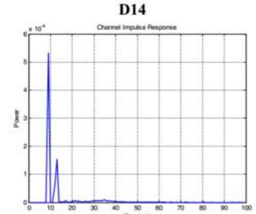
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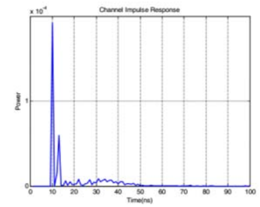
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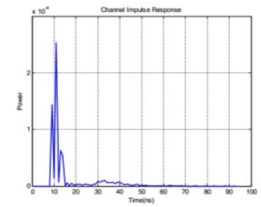
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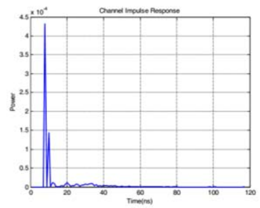
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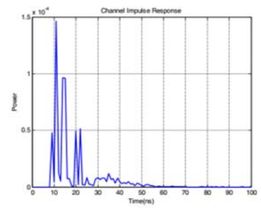
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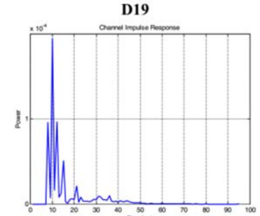
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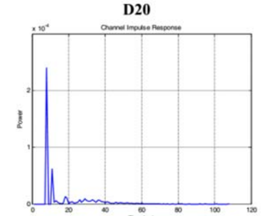
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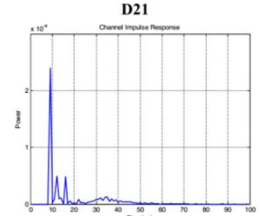
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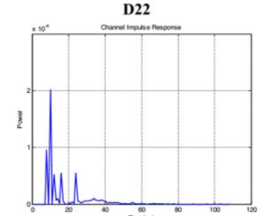

D24

Channel Characteristics

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

$$39 \le T_{97\%} \le 57$$

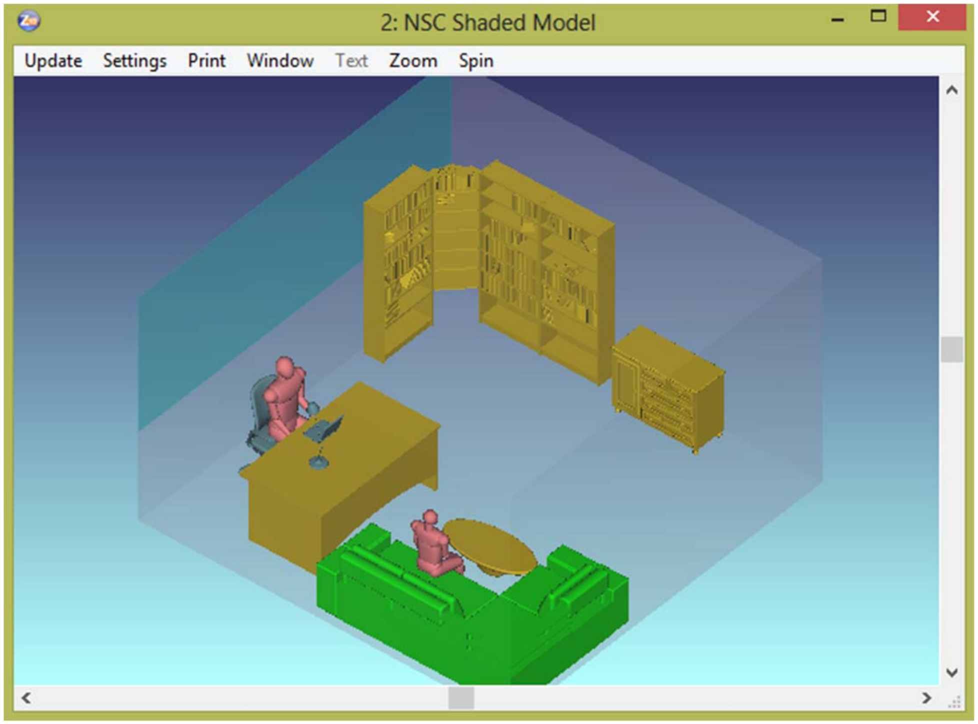
$$9.44\,\text{ns} \le \tau_{RMS} \le 17.08\,\text{ns}$$

$$4.12\times10^{-4} \le H_0 \le 1.22\times10^{-3}$$

- With respect to previous case (i.e., open office with human bodies)
  - Channel DC gain decreases (avg. 7.6%). This decrease is a result of the presence of cubicles. The rays within cubicles hit the cubicle walls and decay more rapidly than those rays in open office.
  - RMS delay spread decreases (avg. 16.9%). Since the rays cannot pass through cubicle walls, delay spread values are smaller.

Scenario 2: Office with Secondary Light

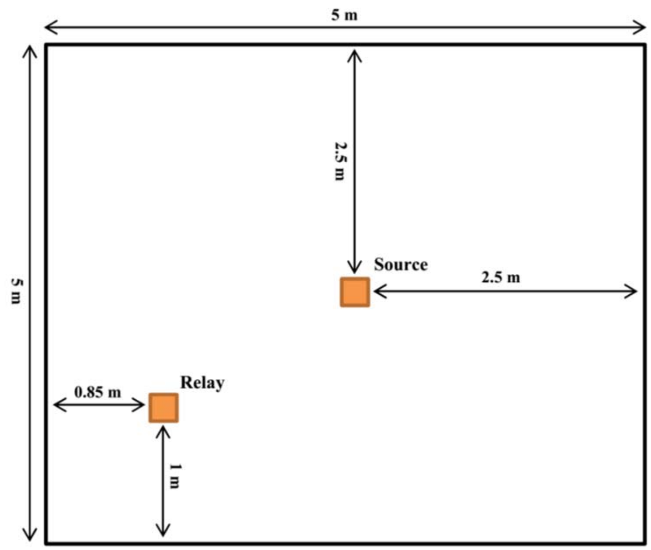
- In this office environment, there are two light sources; one of them is the main light source at the ceiling and the other one is mounted on the desk to provide task lighting.



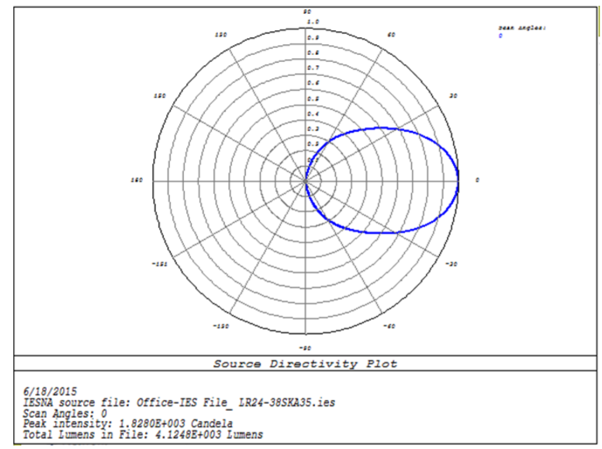
Simulation Parameters

Room size	5m × 5m × 3m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
Objects	1 desk and a chair paired with desk 1 laptop on the desk, 1 desk light on the desk, 1 library 1 couch, 1 coffee table, window, 2 human bodies
Objects specifications	Desk: Pinewood (Typical height of 0.88m) Chair: Black gloss paint, Laptop: Black gloss paint Desk light: Black gloss paint, Library: Pinewood, Window: Glass Couch: Cotton, Coffee table: Pinewood Human body: ▪ Shoes: Black gloss paint ▪ Head & Hands: Absorbing ▪ Clothes: Cotton
Luminary Specifications	Brand: LR24-38SKA35 Cree Inc. Half viewing angle: 40º
Number of luminaries	1 on the ceiling 1 for the desk light
Receiver area	1 cm^2

Location of Luminaries (Transmitters)



Arrangement of luminaries



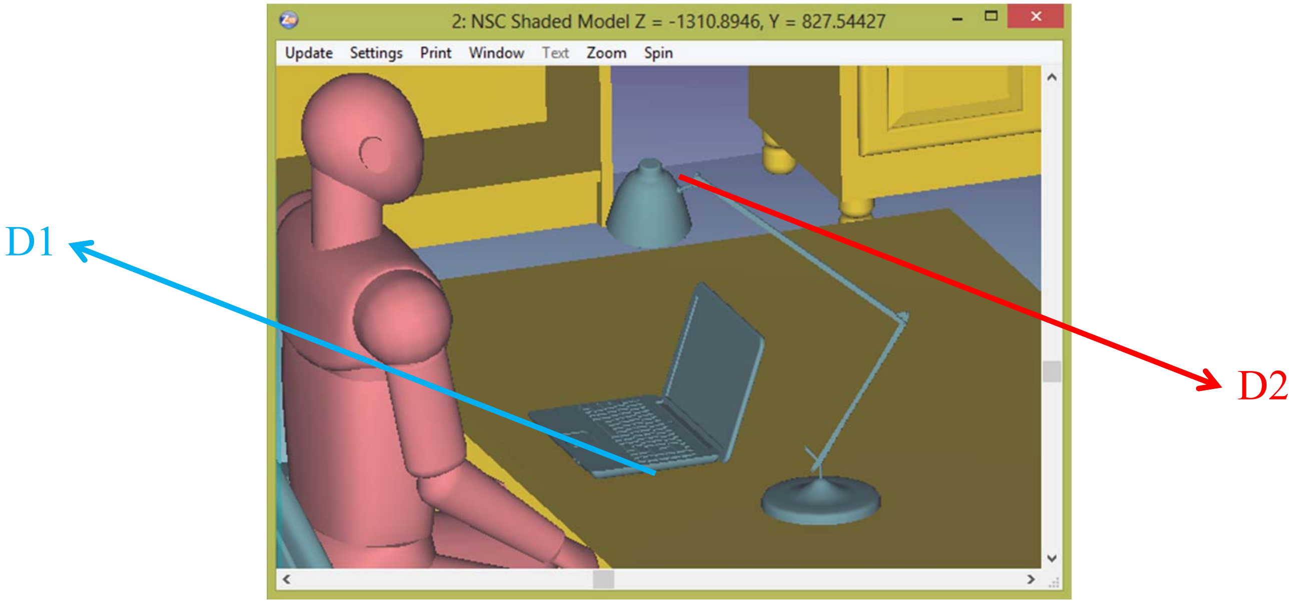
Emission pattern of luminary

Delivered light output	3796 lumens
Average of illumination level	270 lx
Uniformity of illumination	0.4409

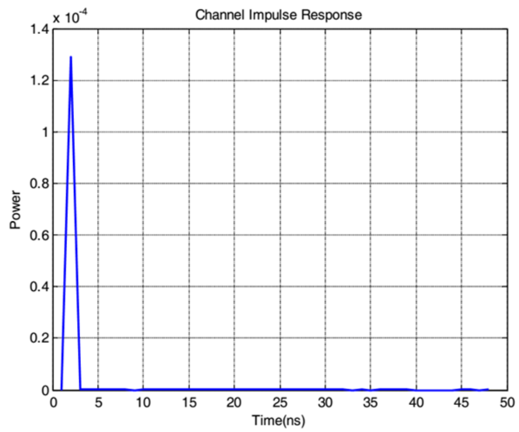
Location of Test Points (Receivers)

- 2 test points are chosen:

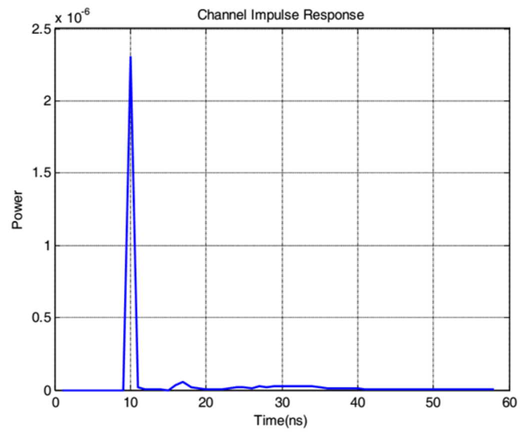
On the desk next to the laptop at a height of 0.88 m (e.g., a USB-type device connected to laptop)	D1
On the top of desk light at a height of 1.5m with 45º rotation toward the source on the ceiling	D2



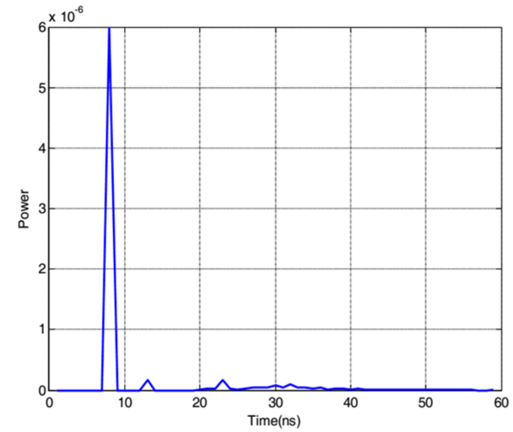
CIR Results & Channel Characteristics



Relay Transmitter To Destination



Source To Destination

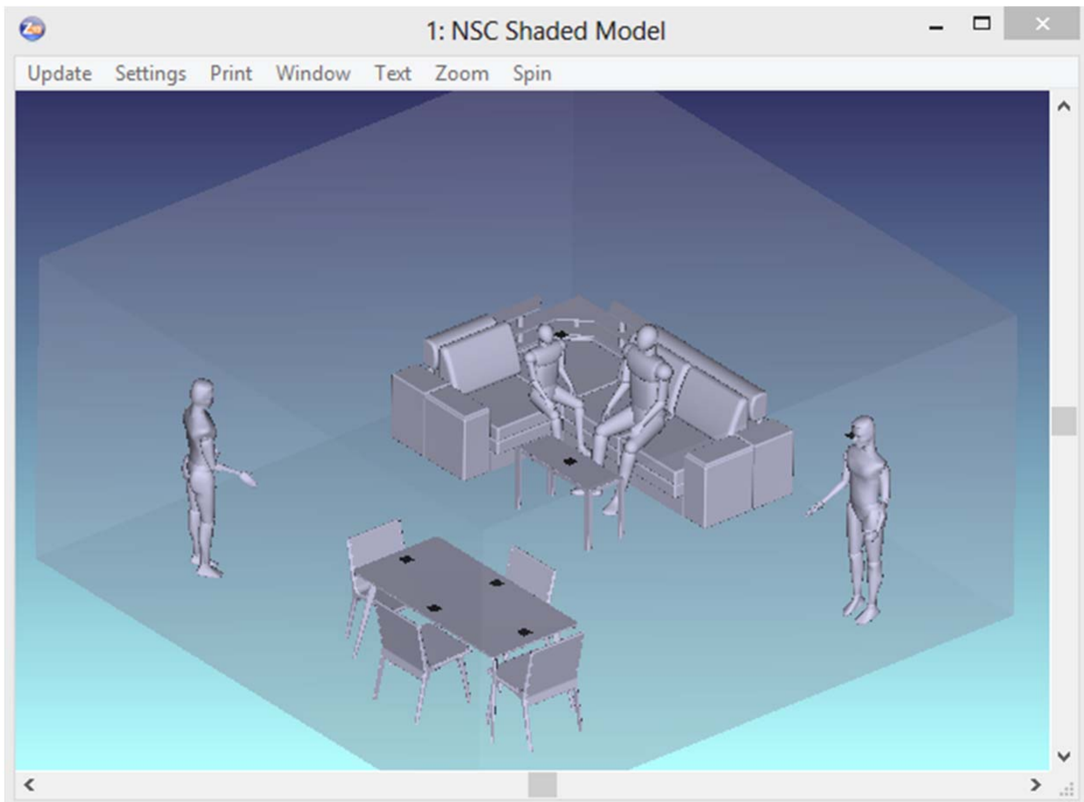


Source To Relay Receiver

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

Scenario 3: Home

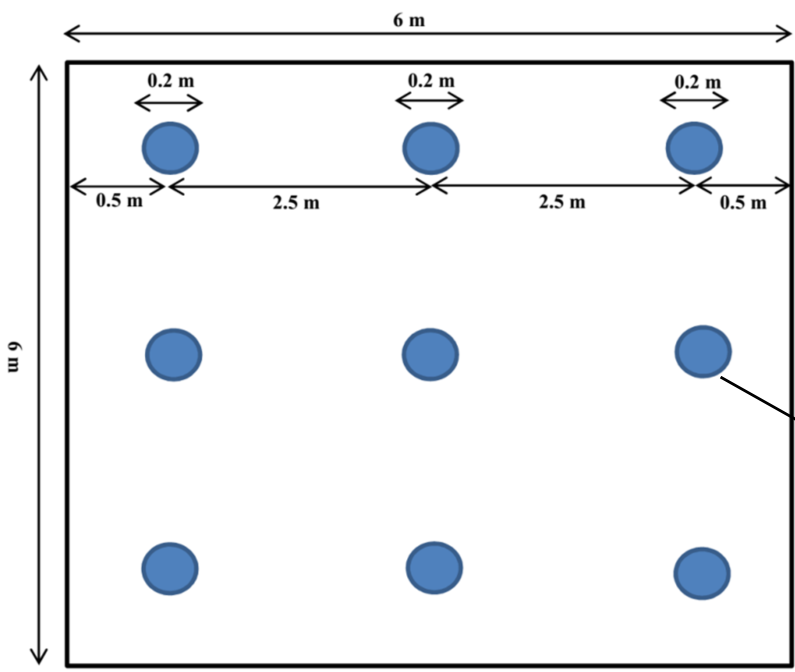
- We consider a living room with table, chairs, couch, coffee table and human bodies.



Simulation Parameters

Room size	6m × 6m × 3m
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 2m × 1m × 0.9m Chairs: Wooden matched with table Couch: Cotton Coffee table: Glass Human body: ▪ Shoes: Black gloss paint ▪ Head & Hands: Absorbing ▪ Clothes: Cotton
Luminary Specifications	Brand: CR6-800L Cree Inc. Half viewing angle: 40º
Number of luminaries	9
Receiver area	1 cm^2

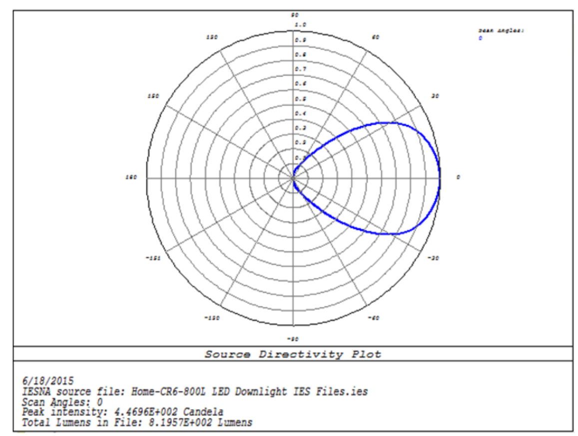
Location of Luminaries (Transmitters)



Arrangement of luminaries

$$\text{Uniformity}=\frac{\text{Min Lux}}{\text{Average Lux}}$$

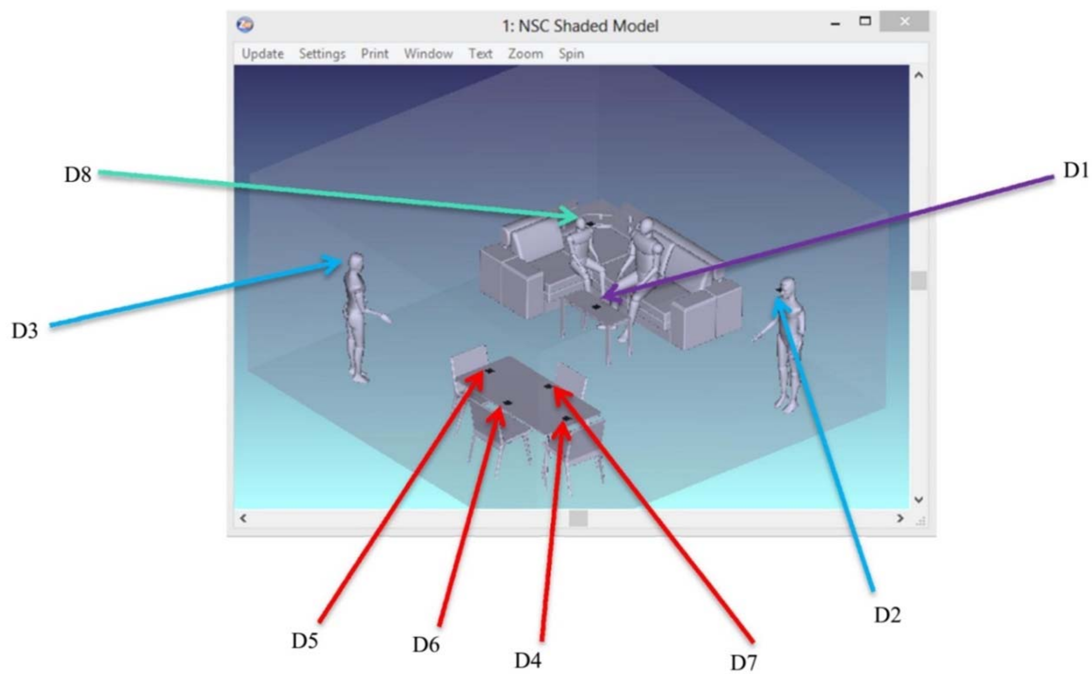
Delivered light output from each luminary	804 lumens
Average of illumination level	153 lx
Uniformity of illumination	0.9068



Emission pattern of luminary

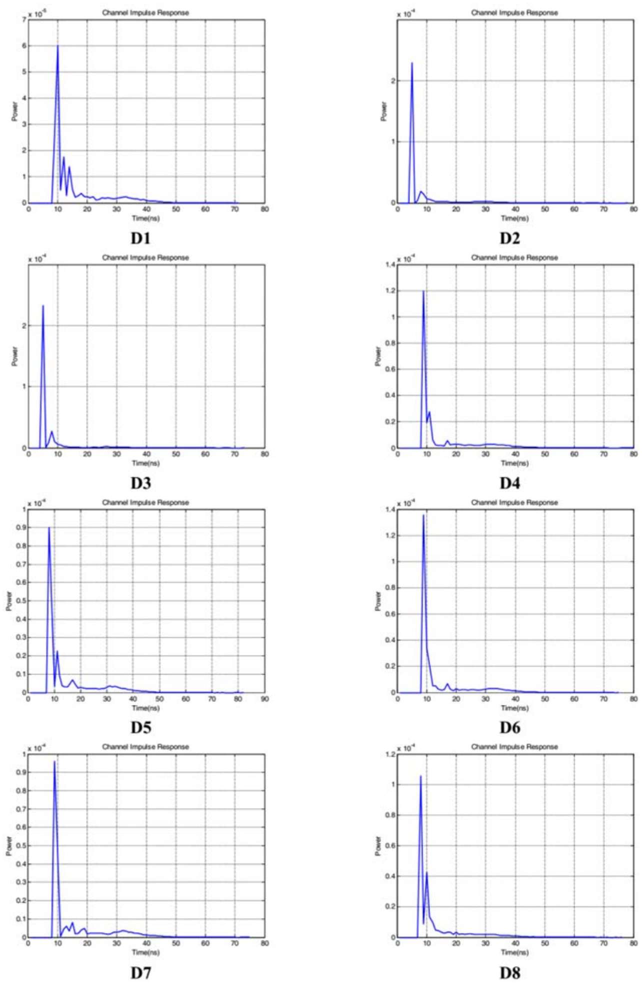
Location of Test Points (Receivers)

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



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

CIR Results & Channel Characteristics



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

$$31 \leq T_{97\%} \leq 41$$

$$7.19\,\text{ns} \leq \tau_{RMS} \leq 10.30\,\text{ns}$$

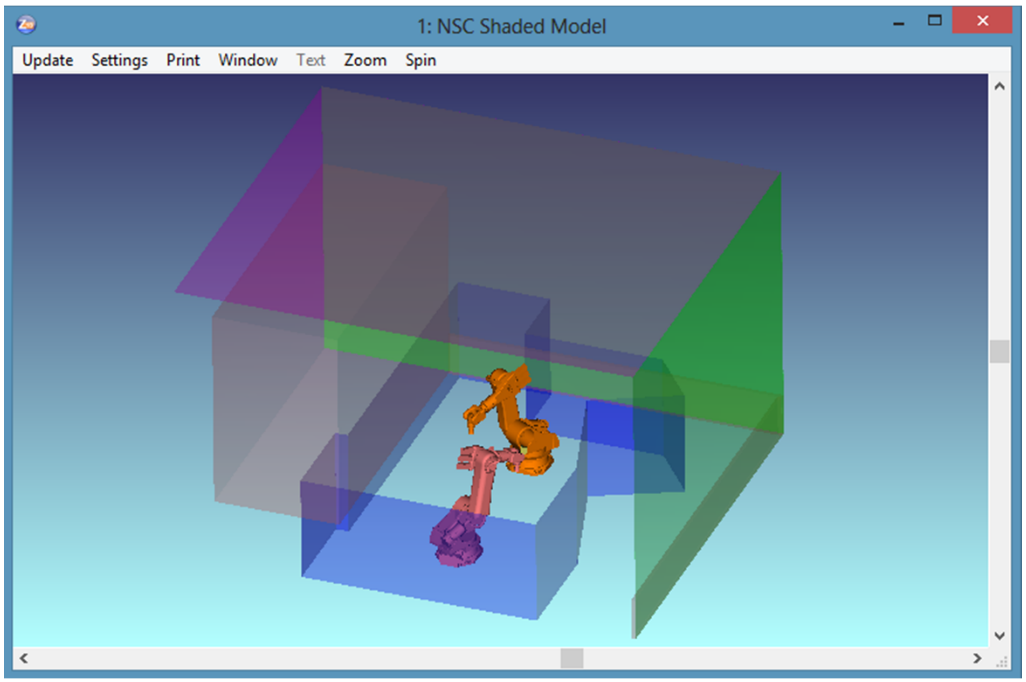
$$1.82\times10^{-4} \leq H_0 \leq 3.31\times10^{-4}$$

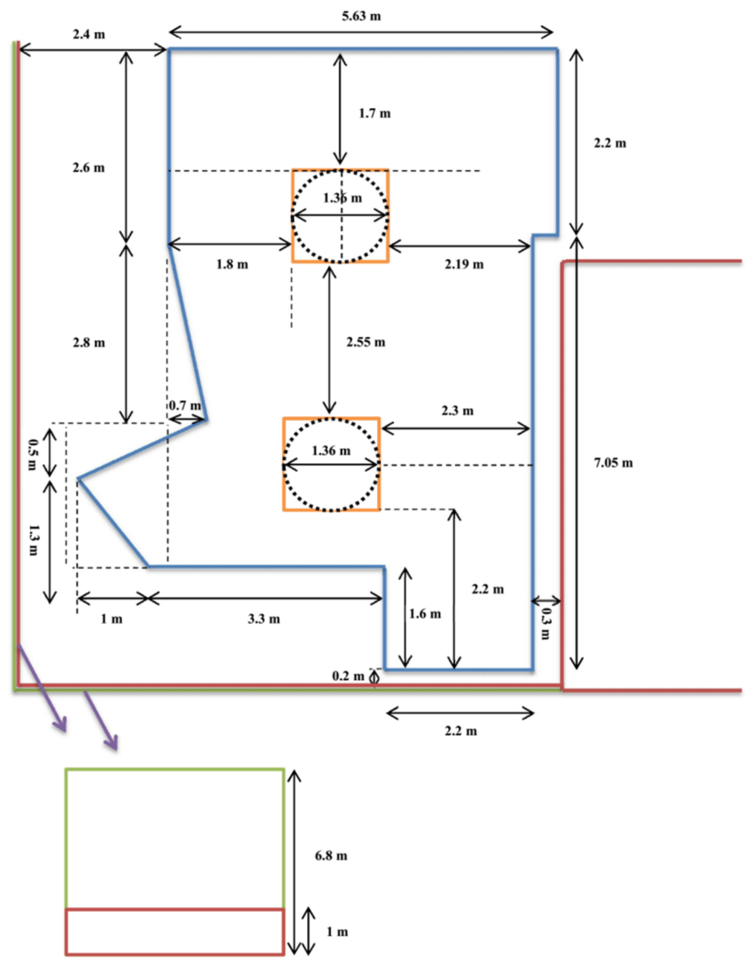
- With respect to home scenario without human bodies
  - RMS delay spread ↓ (avg. 7.2%)
  - Channel DC gain ↓ (avg. 9%)

The CIRs for the same environment without human bodies can be found at IEEE 15-15-0514-00-007a “LiFi Reference Channel Models: Office, Home, Hospital”

Scenario 4: Manufacturing Cell

- We consider a manufacturing cell with two robots.



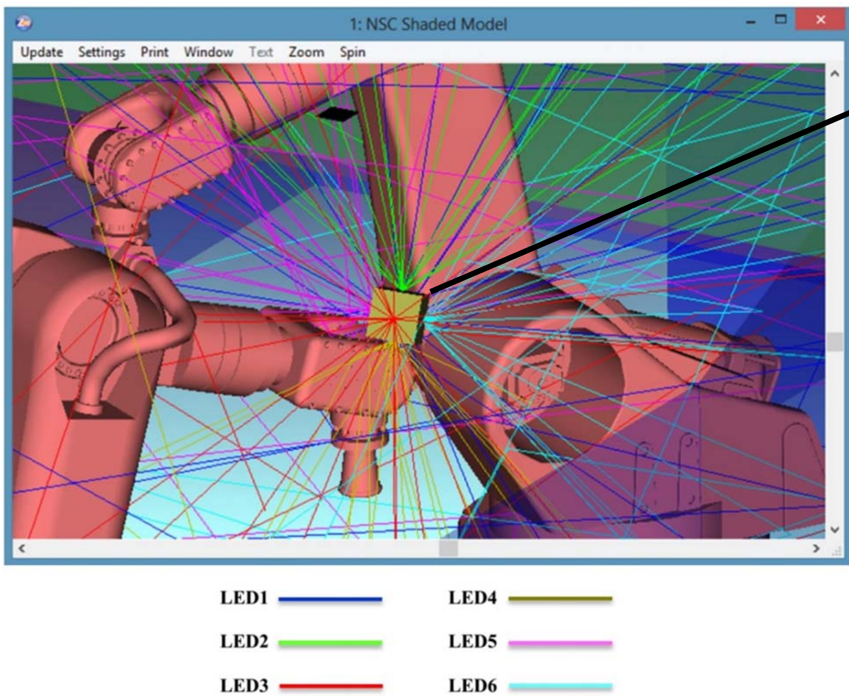


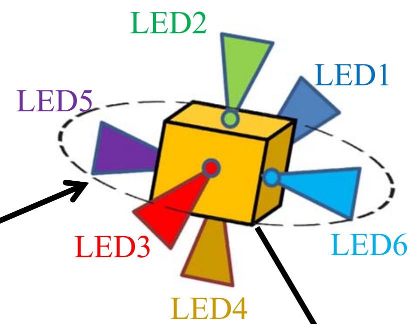
Simulation Parameters

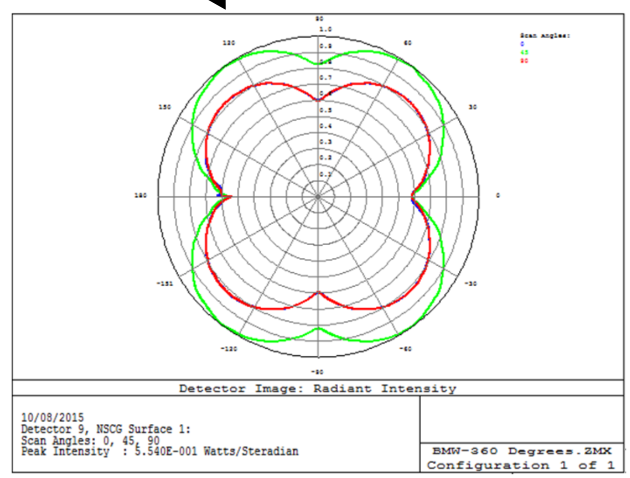
Room size	8.03m × 9.45m × 6.8m (See p.18 for exact layout)
Materials	Red Walls: Concrete Green Walls: Aluminum metal Blue Walls: Plexiglas (PMMA) Ceiling: Aluminum metal Floor: Concrete
Objects	Two robots
Object Specifications	Robot: Galvanized steel metal Height of Robot: 2.7m Height of Plexiglas boundary: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

Location of Luminaries (Transmitters)

- 6 transmitters are located at the head of the robot, arranged on the six sides of a cube to cover 360º.



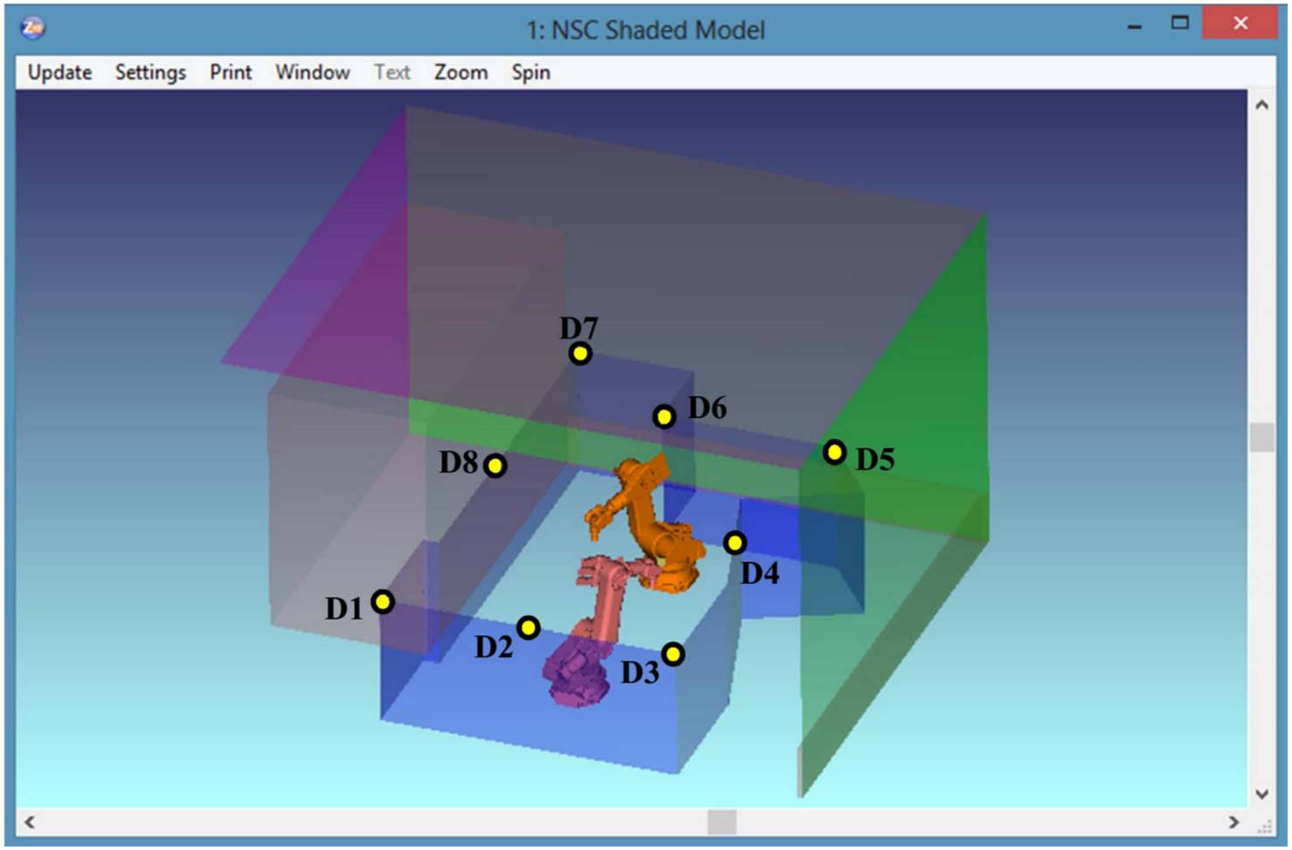




Emission pattern of six LEDs which cover 360º

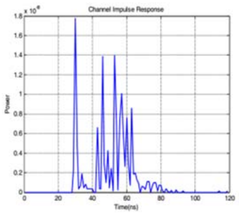
Location of Test Points (Receivers)

- Test points are considered on the top of the Plexiglas boundary which are looking in the direction of the robots.

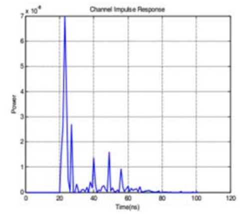


CIR Results (Manufacturing Cell)

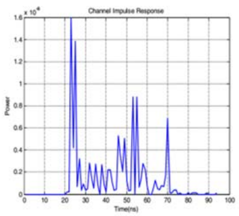
LED1



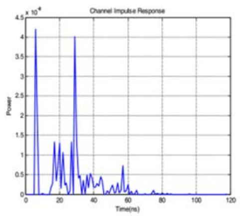
D1



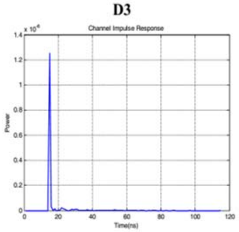
D2



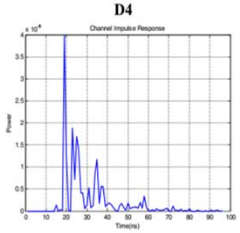
D3



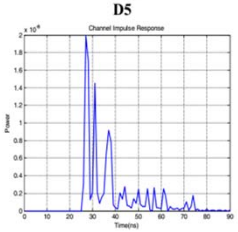
D4



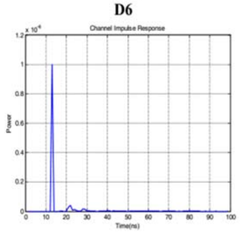
D5



D6

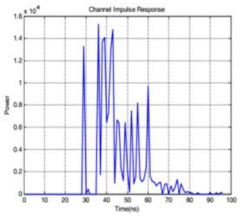


D7

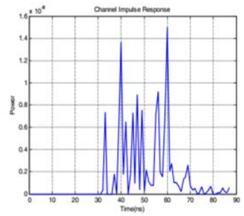


D8

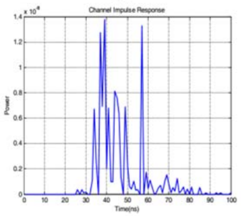
LED2



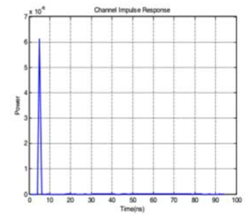
D1



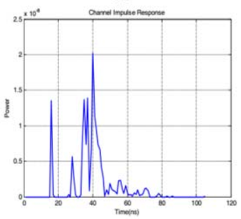
D2



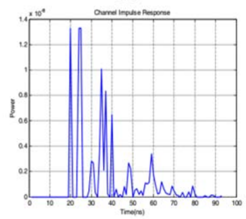
D3



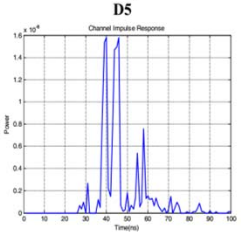
D4



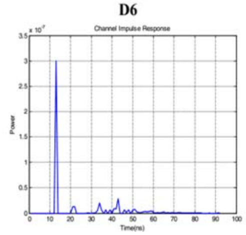
D5



D6

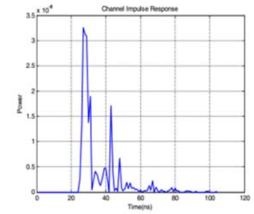


D7

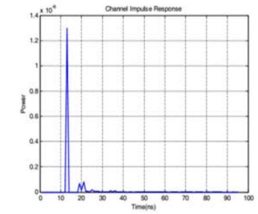


D8

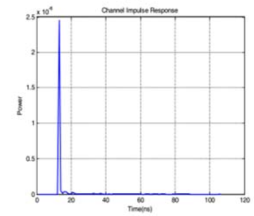
LED3



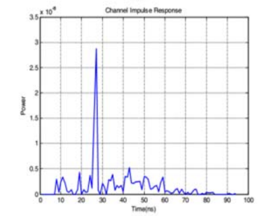
D1



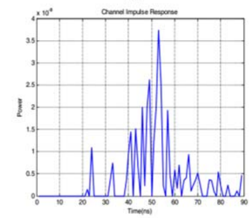
D2



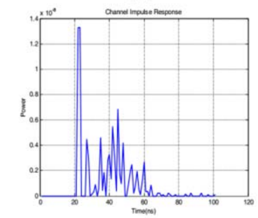
D3



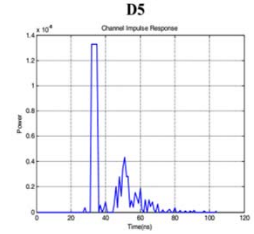
D4



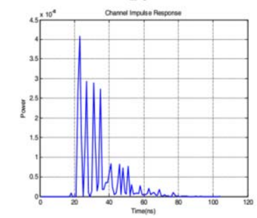
D5



D6



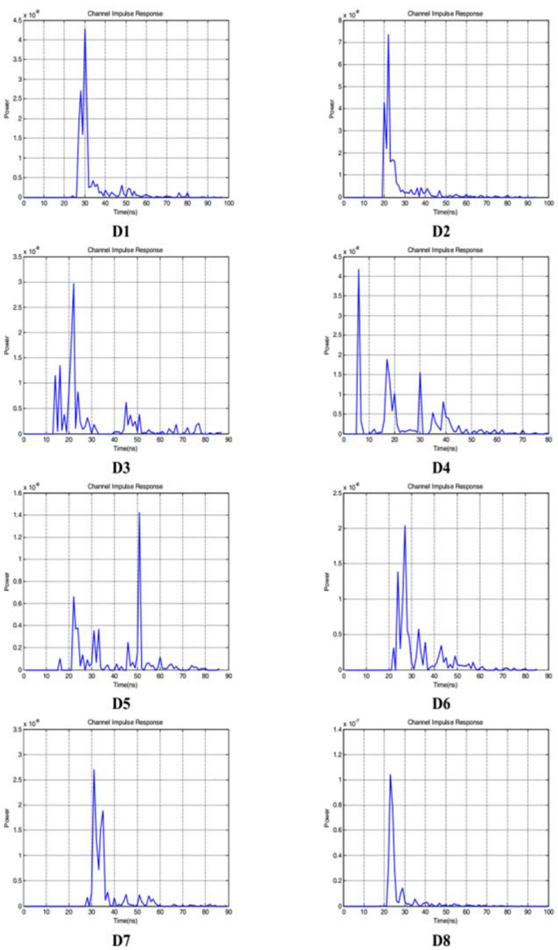
D7



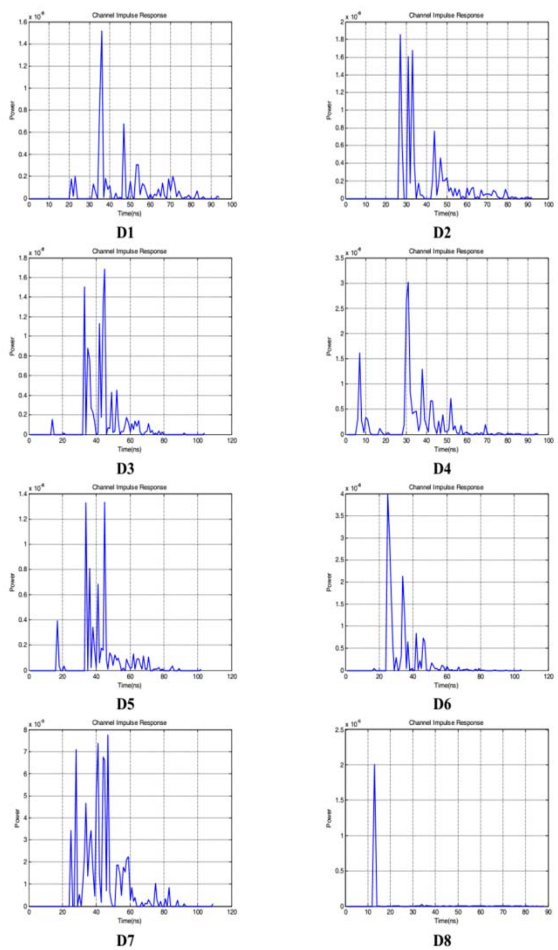
D8

CIR Results (Manufacturing Cell)

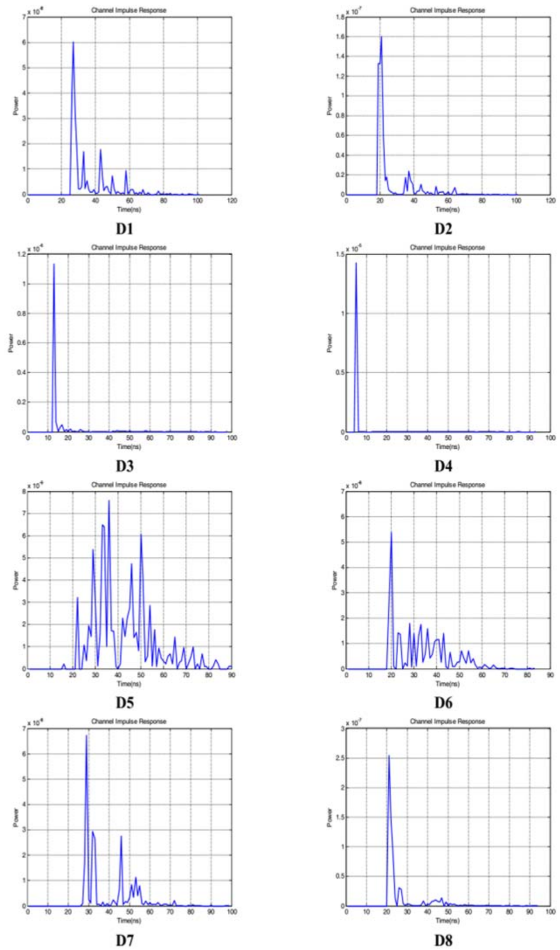
LED4



LED5

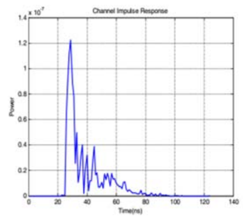


LED6

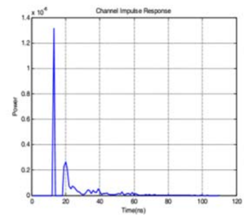


CIR Results (Manufacturing Cell)

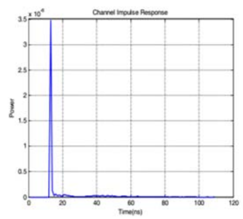
LED1-6 (all are active)



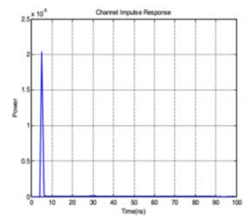
D1



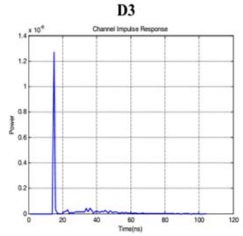
D2



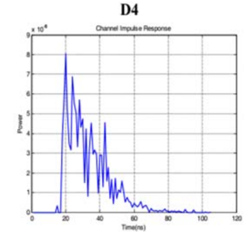
D3



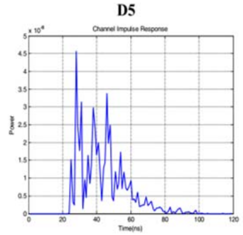
D4



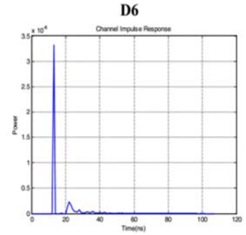
D5



D6



D7



D8

Channel Characteristics

TX-RX		$T_{97\%}$ (ns)	τ_{RMS} (ns)	H_0
LED1	D1	75	12.88	1.45×10^{-7}
	D2	64	13.48	2.71×10^{-7}
	D3	70	15.93	1.16×10^{-7}
	D4	58	15.56	2.55×10^{-7}
	D5	38	7.52	1.45×10^{-6}
	D6	63	12.82	1.92×10^{-7}
	D7	71	12.71	1.20×10^{-7}
	D8	43	9.12	1.19×10^{-6}
LED2	D1	69	10.62	1.73×10^{-7}
	D2	71	10.80	1.30×10^{-7}
	D3	73	11.04	1.17×10^{-7}
	D4	5	5.45	6.27×10^{-6}
	D5	68	11.50	1.57×10^{-7}
	D6	69	14.73	1.01×10^{-7}
	D7	73	10.22	1.37×10^{-7}
	D8	64	17.05	4.92×10^{-7}
LED3	D1	67	11.37	2.19×10^{-7}
	D2	36	7.82	1.59×10^{-6}
	D3	29	6.19	2.73×10^{-6}
	D4	68	15.65	1.42×10^{-7}
	D5	79	11.97	3.30×10^{-8}
	D6	62	13.73	8.89×10^{-8}
	D7	67	11.77	8.84×10^{-8}
	D8	63	11.77	2.83×10^{-7}

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

TX-RX		$T_{97\%}$ (ns)	τ_{RMS} (ns)	H_0
LED1-6 (Covering 360º)	D1	70	13.48	1.16×10^{-6}
	D2	58	13.33	2.99×10^{-6}
	D3	52	11.68	4.46×10^{-6}
	D4	29	6.79	2.15×10^{-5}
	D5	60	14.36	1.94×10^{-6}
	D6	62	12.54	1.22×10^{-6}
	D7	75	13.66	5.69×10^{-7}
	D8	51	11.00	4.67×10^{-6}

Conclusions

- In response to «Call for Proposals for OWC Channel Models» issued by 802.15.7r1, this contribution proposes LiFi reference channel models for office, home and manufacturing cells.
- Our results are extended versions of the previous contribution where the effects of human presence are further considered.
- All CIRs will be made available as .m files for public use.

Appendix

- This table represents the recommended illumination levels for different environments.

Environment/Activity	Illumination (lux, lumen/m^2)
Public area with dark surroundings	20-50
Simple orientation for short visits	50-100
Working areas where visual tasks are only occasionally performed	100-150
Warehouse, Homes, Theaters, Archives	150
Easy office work, Classes	250
Normal office work, PC work, Study library, Groceries, Show rooms, Laboratories	500
Supermarkets, Mechanical workshops, Office landscapes	750
Normal drawing work, Detailed mechanical workshops, Operation theaters	1000
Detailed drawing work, Very detailed mechanical works	1500-2000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2000-5000
Performance of very prolonged and exacting visual tasks	5000-10000
Performance of very special visual tasks of extremely low contrast and small size	10000-20000

http://www.engineeringtoolbox.com/light-level-rooms-d_708.html

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