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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Source: Murat Uysal (Ozyegin University), Farshad Miramirkhani (Ozyegin University), Tuncer Baykas (Istanbul Medipol University), Nikola Serafimovski (pureLiFi Ltd.), and Volker Jungnickel (Fraunhofer HHI)

Address: Ozyegin University, Nisantepe Mh. Orman Sk. No:34-36 Çekmekoy 34794 Istanbul, Turkey
Voice: +90 (216) 5649329, Fax: +90 (216) 5649450, E-Mail: murat.uysal@ozyegin.edu.tr

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.
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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

<table>
<thead>
<tr>
<th>Channel Parameters</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channel DC Gain</strong></td>
<td>[ H_0 = \int_{-\infty}^{\infty} h(t) , dt ]</td>
</tr>
<tr>
<td><strong>Mean Excess Delay Spread</strong></td>
<td>[ \tau_0 = \frac{\int_0^{\infty} t \times h(t) , dt}{\int_0^{\infty} h(t) , dt} ]</td>
</tr>
<tr>
<td><strong>RMS Delay Spread</strong></td>
<td>[ \tau_{RMS} = \sqrt{\frac{\int_0^{\infty} (t - \tau_0)^2 h(t) , dt}{\int_0^{\infty} h(t) , dt}} ]</td>
</tr>
<tr>
<td><strong>Truncation Time (T_{97%})</strong></td>
<td>[ \int_0^{\infty} h(t) , dt = 0.97 \int_0^{\infty} h(t) , dt ]</td>
</tr>
<tr>
<td><strong>Frequency Correlation Function</strong></td>
<td>[ H(\Delta f) = \int_{-\infty}^{\infty} h(t) e^{-j2\pi\Delta f} , dt ]</td>
</tr>
<tr>
<td><strong>Coherence Bandwidth</strong></td>
<td>[ B_{0.9} = \min (\Delta f) \text{ such that }</td>
</tr>
<tr>
<td><strong>Channel Transfer Function</strong></td>
<td>[ H(f) = \int_{-\infty}^{\infty} h(t) e^{-j2\pi f} , dt ]</td>
</tr>
</tbody>
</table>
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 \(i\)th ray
- \(\tau_i\) = the propagation time of the \(i\)th 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

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

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

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

Arrangement of luminaries

Emission pattern of each luminary
Location of Test Points (Receivers)

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

<table>
<thead>
<tr>
<th>Location Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the corridors at a height of 1.7m with 45° rotation (e.g., people who stand with a cell phone in hand)</td>
<td>D1-D12</td>
</tr>
<tr>
<td>On the top of chairs at a height of 0.95m with 45° rotation (i.e., people with a cell phone in hand)</td>
<td>D13-D18</td>
</tr>
<tr>
<td>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)</td>
<td>D19-D24</td>
</tr>
</tbody>
</table>

Location and rotation of test points
Test Points (Open Office)
Test Points (Office with Cubicles)
CIR Results (Open Office)
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”

---

<table>
<thead>
<tr>
<th>D1</th>
<th>48</th>
<th>13.30</th>
<th>1.00×10⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>56</td>
<td>17.04</td>
<td>5.26×10⁻⁴</td>
</tr>
<tr>
<td>D3</td>
<td>57</td>
<td>17.15</td>
<td>9.22×10⁻⁴</td>
</tr>
<tr>
<td>D4</td>
<td>55</td>
<td>14.98</td>
<td>1.26×10⁻⁴</td>
</tr>
<tr>
<td>D5</td>
<td>51</td>
<td>14.73</td>
<td>9.06×10⁻⁴</td>
</tr>
<tr>
<td>D6</td>
<td>51</td>
<td>15.38</td>
<td>9.66×10⁻⁴</td>
</tr>
<tr>
<td>D7</td>
<td>61</td>
<td>18.80</td>
<td>5.19×10⁻⁴</td>
</tr>
<tr>
<td>D8</td>
<td>56</td>
<td>15.95</td>
<td>1.06×10⁻³</td>
</tr>
<tr>
<td>D9</td>
<td>51</td>
<td>13.99</td>
<td>9.29×10⁻⁴</td>
</tr>
<tr>
<td>D10</td>
<td>48</td>
<td>13.84</td>
<td>1.20×10⁻³</td>
</tr>
<tr>
<td>D11</td>
<td>63</td>
<td>17.24</td>
<td>9.21×10⁻⁴</td>
</tr>
<tr>
<td>D12</td>
<td>61</td>
<td>17.85</td>
<td>7.08×10⁻⁴</td>
</tr>
<tr>
<td>D13</td>
<td>50</td>
<td>13.15</td>
<td>8.74×10⁻⁴</td>
</tr>
<tr>
<td>D14</td>
<td>53</td>
<td>13.97</td>
<td>8.45×10⁻⁴</td>
</tr>
<tr>
<td>D15</td>
<td>58</td>
<td>15.79</td>
<td>5.16×10⁻⁴</td>
</tr>
<tr>
<td>D16</td>
<td>48</td>
<td>12.39</td>
<td>9.03×10⁻⁴</td>
</tr>
<tr>
<td>D17</td>
<td>58</td>
<td>16.23</td>
<td>4.96×10⁻⁴</td>
</tr>
<tr>
<td>D18</td>
<td>53</td>
<td>14.63</td>
<td>7.41×10⁻⁴</td>
</tr>
<tr>
<td>D19</td>
<td>49</td>
<td>12.99</td>
<td>1.05×10⁻³</td>
</tr>
<tr>
<td>D20</td>
<td>52</td>
<td>13.65</td>
<td>7.09×10⁻⁴</td>
</tr>
<tr>
<td>D21</td>
<td>55</td>
<td>15.41</td>
<td>6.57×10⁻⁴</td>
</tr>
<tr>
<td>D22</td>
<td>57</td>
<td>16.15</td>
<td>5.15×10⁻⁴</td>
</tr>
<tr>
<td>D23</td>
<td>57</td>
<td>16.11</td>
<td>5.84×10⁻⁴</td>
</tr>
<tr>
<td>D24</td>
<td>60</td>
<td>15.95</td>
<td>6.75×10⁻⁴</td>
</tr>
<tr>
<td>Ave</td>
<td>54.5</td>
<td>15.27</td>
<td>8.13×10⁻⁴</td>
</tr>
</tbody>
</table>
CIR Results (Office with Cubicles)
Channel Characteristics

- 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.

<table>
<thead>
<tr>
<th></th>
<th>(T_{97%}) (ns)</th>
<th>(\tau_{\text{RMS}}) (ns)</th>
<th>(H_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>41</td>
<td>11.26</td>
<td>9.55\times10^4</td>
</tr>
<tr>
<td>D2</td>
<td>53</td>
<td>15.38</td>
<td>5.03\times10^4</td>
</tr>
<tr>
<td>D3</td>
<td>50</td>
<td>14.41</td>
<td>8.85\times10^4</td>
</tr>
<tr>
<td>D4</td>
<td>44</td>
<td>11.98</td>
<td>1.22\times10^4</td>
</tr>
<tr>
<td>D5</td>
<td>46</td>
<td>12.91</td>
<td>8.32\times10^4</td>
</tr>
<tr>
<td>D6</td>
<td>47</td>
<td>14.04</td>
<td>9.54\times10^4</td>
</tr>
<tr>
<td>D7</td>
<td>57</td>
<td>17.08</td>
<td>4.77\times10^4</td>
</tr>
<tr>
<td>D8</td>
<td>54</td>
<td>14.75</td>
<td>1.06\times10^4</td>
</tr>
<tr>
<td>D9</td>
<td>42</td>
<td>11.39</td>
<td>8.87\times10^4</td>
</tr>
<tr>
<td>D10</td>
<td>46</td>
<td>12.47</td>
<td>1.14\times10^4</td>
</tr>
<tr>
<td>D11</td>
<td>50</td>
<td>14.60</td>
<td>9.19\times10^4</td>
</tr>
<tr>
<td>D12</td>
<td>54</td>
<td>15.90</td>
<td>6.92\times10^4</td>
</tr>
<tr>
<td>D13</td>
<td>41</td>
<td>10.02</td>
<td>8.00\times10^4</td>
</tr>
<tr>
<td>D14</td>
<td>46</td>
<td>11.88</td>
<td>5.33\times10^4</td>
</tr>
<tr>
<td>D15</td>
<td>47</td>
<td>12.39</td>
<td>4.91\times10^4</td>
</tr>
<tr>
<td>D16</td>
<td>39</td>
<td>9.44</td>
<td>8.89\times10^4</td>
</tr>
<tr>
<td>D17</td>
<td>47</td>
<td>12.60</td>
<td>4.12\times10^4</td>
</tr>
<tr>
<td>D18</td>
<td>43</td>
<td>10.71</td>
<td>6.78\times10^4</td>
</tr>
<tr>
<td>D19</td>
<td>43</td>
<td>10.88</td>
<td>7.51\times10^4</td>
</tr>
<tr>
<td>D20</td>
<td>46</td>
<td>10.71</td>
<td>6.67\times10^4</td>
</tr>
<tr>
<td>D21</td>
<td>44</td>
<td>10.74</td>
<td>6.45\times10^4</td>
</tr>
<tr>
<td>D22</td>
<td>51</td>
<td>13.62</td>
<td>4.73\times10^4</td>
</tr>
<tr>
<td>D23</td>
<td>49</td>
<td>13.24</td>
<td>5.54\times10^4</td>
</tr>
<tr>
<td>D24</td>
<td>47</td>
<td>12.15</td>
<td>6.24\times10^4</td>
</tr>
<tr>
<td>Ave</td>
<td>46.95</td>
<td>12.68</td>
<td>7.51\times10^4</td>
</tr>
</tbody>
</table>

39 \leq T_{97\%} \leq 57

9.44 \text{ ns} \leq \tau_{\text{RMS}} \leq 17.08 \text{ ns}

4.12 \times 10^{-4} \leq H_0 \leq 1.22 \times 10^{-3}
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

<table>
<thead>
<tr>
<th><strong>Room size</strong></th>
<th>5m × 5m × 3m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td>Walls: Plaster, Ceiling: Plaster, Floor: Pinewood</td>
</tr>
<tr>
<td><strong>Objects</strong></td>
<td>1 desk and a chair paired with desk</td>
</tr>
<tr>
<td></td>
<td>1 laptop on the desk, 1 desk light on the desk, 1 library</td>
</tr>
<tr>
<td></td>
<td>1 couch, 1 coffee table, window, 2 human bodies</td>
</tr>
<tr>
<td><strong>Objects specifications</strong></td>
<td>Desk: Pinewood (Typical height of 0.88m)</td>
</tr>
<tr>
<td></td>
<td>Chair: Black gloss paint, Laptop: Black gloss paint</td>
</tr>
<tr>
<td></td>
<td>Desk light: Black gloss paint, Library: Pinewood, Window: Glass</td>
</tr>
<tr>
<td></td>
<td>Couch: Cotton, Coffee table: Pinewood</td>
</tr>
<tr>
<td></td>
<td>Human body:</td>
</tr>
<tr>
<td></td>
<td>- Shoes: Black gloss paint</td>
</tr>
<tr>
<td></td>
<td>- Head &amp; Hands: Absorbing</td>
</tr>
<tr>
<td></td>
<td>- Clothes: Cotton</td>
</tr>
<tr>
<td><strong>Luminary Specifications</strong></td>
<td>Brand: LR24-38SKA35 Cree Inc.</td>
</tr>
<tr>
<td></td>
<td>Half viewing angle: 40°</td>
</tr>
<tr>
<td><strong>Number of luminaries</strong></td>
<td>1 on the ceiling</td>
</tr>
<tr>
<td></td>
<td>1 for the desk light</td>
</tr>
<tr>
<td><strong>Receiver area</strong></td>
<td>1 cm²</td>
</tr>
</tbody>
</table>
Location of Luminaries (Transmitters)

Arrangement of luminaries

Emission pattern of luminary

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivered light output</td>
<td>3796</td>
</tr>
<tr>
<td>Average of illumination level</td>
<td>270 lx</td>
</tr>
<tr>
<td>Uniformity of illumination</td>
<td>0.4409</td>
</tr>
</tbody>
</table>
Location of Test Points (Receivers)

- 2 test points are chosen:

<table>
<thead>
<tr>
<th>Location Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>On the desk next to the laptop at a height of 0.88 m (e.g., a USB-type device connected to laptop)</td>
<td>D1</td>
</tr>
<tr>
<td>On the top of desk light at a height of 1.5 m with 45º rotation toward the source on the ceiling</td>
<td>D2</td>
</tr>
</tbody>
</table>
CIR Results & Channel Characteristics

<table>
<thead>
<tr>
<th></th>
<th>$T_{97%}$ (ns)</th>
<th>$\tau_{RMS}$ (ns)</th>
<th>$H_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desk Light (Relay) Transmitter To Destination</td>
<td>2</td>
<td>1.37</td>
<td>1.30×10^{-4}</td>
</tr>
<tr>
<td>Ceiling Light (Source) To Destination</td>
<td>35</td>
<td>7.76</td>
<td>2.81×10^{-6}</td>
</tr>
<tr>
<td>Ceiling Light (Source) To Desk Light (Relay) Receiver</td>
<td>35</td>
<td>8.32</td>
<td>7.13×10^{-6}</td>
</tr>
</tbody>
</table>
Scenario 3: Home

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

<table>
<thead>
<tr>
<th>Room size</th>
<th>6m × 6m × 3m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Walls: Plaster, Ceiling: Plaster, Floor: Pinewood</td>
</tr>
<tr>
<td>Objects</td>
<td>Table with 4 chairs, Couch, Coffee table, 4 human bodies</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Object Specifications</th>
<th>Tables: Wooden with size of 2m × 1m × 0.9m, Chairs: Wooden matched with table, Couch: Cotton, Coffee table: Glass, Human body:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>▪ Shoes: Black gloss paint, Head &amp; Hands: Absorbing, Clothes: Cotton</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Luminary Specifications</th>
<th>Brand: CR6-800L Cree Inc., Half viewing angle: 40º</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of luminaries</td>
<td>9</td>
</tr>
<tr>
<td>Receiver area</td>
<td>1 cm²</td>
</tr>
</tbody>
</table>
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

September 2015
Location of Test Points (Receivers)

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

<table>
<thead>
<tr>
<th>Location Description</th>
<th>Test Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>On the coffee table at a height of 0.6 m with 45° rotation</td>
<td>D1</td>
</tr>
<tr>
<td>Next to the wall at a height of 1.7 m (e.g., standing people) with 45° rotation</td>
<td>D2-D3</td>
</tr>
<tr>
<td>On the table at a height of 0.9 m</td>
<td>D4-D7</td>
</tr>
<tr>
<td>On the top of couch at height of 1.1 m (e.g., sitting people) with 45° rotation</td>
<td>D8</td>
</tr>
</tbody>
</table>
CIR Results & Channel Characteristics

<table>
<thead>
<tr>
<th>ID</th>
<th>$T_{97%}$ (ns)</th>
<th>$\tau_{RMS}$ (ns)</th>
<th>$H_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>40</td>
<td>9.64</td>
<td>$1.82 \times 10^{-4}$</td>
</tr>
<tr>
<td>D2</td>
<td>33</td>
<td>8.30</td>
<td>$3.31 \times 10^{-4}$</td>
</tr>
<tr>
<td>D3</td>
<td>31</td>
<td>7.19</td>
<td>$3.26 \times 10^{-4}$</td>
</tr>
<tr>
<td>D4</td>
<td>40</td>
<td>9.90</td>
<td>$2.44 \times 10^{-4}$</td>
</tr>
<tr>
<td>D5</td>
<td>40</td>
<td>10.16</td>
<td>$2.58 \times 10^{-4}$</td>
</tr>
<tr>
<td>D6</td>
<td>39</td>
<td>9.62</td>
<td>$2.74 \times 10^{-4}$</td>
</tr>
<tr>
<td>D7</td>
<td>41</td>
<td>10.30</td>
<td>$2.31 \times 10^{-4}$</td>
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<tr>
<td>D8</td>
<td>37</td>
<td>8.83</td>
<td>$2.47 \times 10^{-4}$</td>
</tr>
<tr>
<td>Ave</td>
<td>37.62</td>
<td>9.24</td>
<td>$2.61 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- $31 \leq T_{97\%} \leq 41$
- $7.19\,\text{ns} \leq \tau_{RMS} \leq 10.30\,\text{ns}$
- $1.82 \times 10^{-4} \leq H_0 \leq 3.31 \times 10^{-4}$

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

<table>
<thead>
<tr>
<th>Room size</th>
<th>8.03m × 9.45m × 6.8m (See p.18 for exact layout)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Red Walls: Concrete</td>
</tr>
<tr>
<td></td>
<td>Green Walls: Aluminum metal</td>
</tr>
<tr>
<td></td>
<td>Blue Walls: Plexiglas (PMMA)</td>
</tr>
<tr>
<td></td>
<td>Ceiling: Aluminum metal</td>
</tr>
<tr>
<td></td>
<td>Floor: Concrete</td>
</tr>
<tr>
<td>Objects</td>
<td>Two robots</td>
</tr>
<tr>
<td>Object Specifications</td>
<td>Robot: Galvanized steel metal</td>
</tr>
<tr>
<td></td>
<td>Height of Robot: 2.7m</td>
</tr>
<tr>
<td></td>
<td>Height of Plexiglas boundary: 2.5m</td>
</tr>
<tr>
<td>LED Specifications</td>
<td>Brand: MC-E Cree Xlamp Inc.</td>
</tr>
<tr>
<td></td>
<td>Half viewing angle: 60º</td>
</tr>
<tr>
<td>Number of LEDs</td>
<td>6</td>
</tr>
<tr>
<td>Receiver area</td>
<td>1 cm²</td>
</tr>
</tbody>
</table>
Location of Luminaries (Transmitters)

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

Emission pattern of six LEDs which cover 360°
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

LED2

LED3
CIR Results (Manufacturing Cell)

LED4

LED5

LED6
CIR Results (Manufacturing Cell)

LED1-6 (all are active)
## Channel Characteristics

<table>
<thead>
<tr>
<th>TX-RX</th>
<th>$T_{97%}$ (ns)</th>
<th>$\tau_{RMS}$ (ns)</th>
<th>$H_0$</th>
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<tr>
<td><strong>LED1</strong></td>
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<td>15.93</td>
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<td>D4</td>
<td>58</td>
<td>15.56</td>
<td>$2.55 \times 10^{-7}$</td>
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<tr>
<td>D5</td>
<td>38</td>
<td>7.52</td>
<td>$1.45 \times 10^{-6}$</td>
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<tr>
<td>D6</td>
<td>63</td>
<td>12.82</td>
<td>$1.92 \times 10^{-7}$</td>
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<tr>
<td>D7</td>
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<td>12.71</td>
<td>$1.20 \times 10^{-7}$</td>
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<tr>
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<td>9.12</td>
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<td><strong>LED2</strong></td>
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</table>

<table>
<thead>
<tr>
<th>TX-RX</th>
<th>$T_{97%}$ (ns)</th>
<th>$\tau_{RMS}$ (ns)</th>
<th>$H_0$</th>
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<tbody>
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<tr>
<td>D8</td>
<td>53</td>
<td>10.51</td>
<td>$6.90 \times 10^{-7}$</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Environment/Activity</th>
<th>Illumination (lux, lumen/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public area with dark surroundings</td>
<td>20-50</td>
</tr>
<tr>
<td>Simple orientation for short visits</td>
<td>50-100</td>
</tr>
<tr>
<td>Working areas where visual tasks are only occasionally performed</td>
<td>100-150</td>
</tr>
<tr>
<td>Warehouse, Homes, Theaters, Archives</td>
<td>150</td>
</tr>
<tr>
<td>Easy office work, Classes</td>
<td>250</td>
</tr>
<tr>
<td>Normal office work, PC work, Study library, Groceries, Show rooms, Laboratories</td>
<td>500</td>
</tr>
<tr>
<td>Supermarkets, Mechanical workshops, Office landscapes</td>
<td>750</td>
</tr>
<tr>
<td>Normal drawing work, Detailed mechanical workshops, Operation theaters</td>
<td>1000</td>
</tr>
<tr>
<td>Detailed drawing work, Very detailed mechanical works</td>
<td>1500-2000</td>
</tr>
<tr>
<td>Performance of visual tasks of low contrast and very small size for prolonged periods of time</td>
<td>2000-5000</td>
</tr>
<tr>
<td>Performance of very prolonged and exacting visual tasks</td>
<td>5000-10000</td>
</tr>
<tr>
<td>Performance of very special visual tasks of extremely low contrast and small size</td>
<td>10000-20000</td>
</tr>
</tbody>
</table>

Acknowledgments

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