Visible Light Wireless Communications

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1. Introduction
2. LEDs and photo diodes
3. VLC characteristics
4. MIMO, OFDM, QCM, DCM in VLC
5. VLC with lighting constraints
6. Outdoor VLC, VLC attocells
7. Concluding remarks
Introduction

LEDs and photo diodes

VLC characteristics

MIMO, OFDM, QCM, DCM in VLC

VLC with lighting constraints

Outdoor VLC, VLC attocells

Concluding remarks
Optical wireless communication (OWC)

- promising complementary technology for RF communication (RFC) technology
- information conveyed via **optical radiation in free space**
- wavelengths of interest
  - infrared to ultraviolet
  - includes **visible light** wavelengths (380 to 780 nm)

Visible light communication (VLC)

- communications using **visible light spectrum**
- abundant VLC spectrum (~ 300 THz bandwidth)
- multi-gigabit rates over short distances
- LEDs as transmitters and **photo diodes (PD)** as receivers
VLC: Pros and Cons

- **Pros**
  - low power, low cost devices (LEDs, PDs)
  - no spectrum cost
  - no RF radiation issues
  - inherent security in closed-room applications
  - simultaneous data transmission and lighting
    - VLC technology rides along with efficient white LED lighting technology
  - MIMO and OFDM techniques
    - improve spectral efficiency and performance

- **Cons**
  - channel itself!
    - ambient light/interference from other light sources
    - alignment between Tx and Rx
    - scattering and multipath dispersion (ISI)
  - no/low mobility
VLC is not that new!

- **1879**: ‘photophone’ by Alexander G. Bell
  - Analog voice transceiver
  - Transmitter: a mirror controls the amount of light reflected from a source
  - Receiver: a photocell connected to a speaker

OWC and VLC in recent days

- **1980**
  - infrared remote controls (analog)
- **1993**
  - infrared data transfer in mobiles, laptops, etc.
  - standards body: IrDA (9.6-128 Kbps).
- **IEEE 802.15c**
  - low power, high data rate systems in satellites, portable devices, etc.
- **VLCC**: Visible Light Communication Consortium
- **VLC for home networks**
  - hOME Gigabit Access (OMEGA) project
- **IEEE 802.15.7**
  - VLC PHY, up to 96 Mbps
- **LiFi and attocells**
VLC implementations/applications

High speed

Mobile to Mobile (100Mbps, Samsung)
Tx, Rx (~30Mbps, Univ. of Oxford)
LED array (~1Gbps, Keio Univ.)

Low speed

Music broadcasting (6Mbps, Univ. of Oxford)
Infra to Mobile (10Mbps, Tamura Inc.)
Sign board (10Mbps, Samsung)
Infra to Mobile (LAN) (4Mbps, Samsung)

Audio transmission (100kbps, Hongkong Univ.)
Infra to Mobile, VLCC (Keio Univ., NEC, Toshiba, Sony, Matsushita, Casio etc.) (4.8kbps, illuminations, visible light ID, sign board, applications based on JEITA)

Source: www.ieee802.org/15

Introduction
LEDs and photo diodes
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Concluding remarks
**VLC implementations/applications**

LEDs and photo diodes
Why LEDs?

E cient lighting using white LEDs

Lumen: SI unit of luminous 
ux (luminous power)

example LED specs: 5 lumens, 90 lumens, 160 lumens

Lumens/Watt: unit of luminous e cacy

Tungsten incandescent lamp: 15 lumens/watt (6W for 90lm)

Halogen lamp: 20 lumens/watt (4.5W for 90lm)

Mercury vap our lamp: 50 lumens/watt (1.8W for 90lm)

Fluo rescent lamp: 60 lumens/watt (1.5W for 90lm)

LED lamp: 90 lumens/watt (1W for 90lm)

High pressure so dium vap our lamp: 117 lumens/watt (0.77W for 90lm)

Lo w pressure so dium vap our lamp: 150 lumens/watt (0.6W for 90lm)

Energy saving lamps have high luminous e cacy

Theoretical max. for white LED (with phosphorescence mixing): 250 lm/W

Recent claims on white LEDs: 100 to 160 lm/W

examples commercial white LED spec: 90 lm/W, 120 lm/W

Target for 2020: 200 lm/W

claimed to have been reached! 208 lm/W LED (prototyp e)
• Efficient lighting using white LEDs
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*Why LEDs?*

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- LEDs and photo diodes

**VLC characteristics**
- MIMO, OFDM, QCM, DCM in VLC

**VLC with lighting constraints**
- Outdoor VLC, VLC attocells

**Concluding remarks**

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Economical power source: white LEDs

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- Target for 2020: **200 lm/W**
  - claimed to have been breached! **208 lm/W** LED (prototype)
Why LEDs?

- Lighting arrangement in Golden Jubilee Seminar Hall, ECE

- Off-stage
  - 32 bulbs (20 W bulbs previously; now replaced with 5 W LED bulbs)

- On-stage
  - 6 bulbs (60 W bulbs previously; now replaced with 18 W LED bulbs)
LEDs

• **Luminous intensity (LI):**
  • Luminous power radiated by a point light source in a particular direction per unit solid angle
  • SI unit of LI: Candela (Lumens/Steradian); cd (lm/sr)

![Image source: Wikipedia](image)

• Solid angle (in steradians) of a cone with apex angle $\theta$ (in degrees) = $2\pi(1 - \cos \frac{\theta}{2})$, i.e., $\text{cd} = \text{lm}/(2\pi(1 - \cos \frac{\theta}{2}))$

• **Examples of white LED spec:**
  • Luminous flux = 90 lm; luminous intensity = 59 cd
    $\Rightarrow \theta = 81.5^\circ$ (viewing angle at 50% power; half-power angle)
  • Luminous intensity = 59 cd; $\theta = 55^\circ$
    $\Rightarrow$ Luminous flux = 41.8 lm
  • Luminous intensity = 11200 mcd (11.2 cd); $\theta = 45^\circ$
    $\Rightarrow$ Luminous flux = 5.35 lm
**Luminous intensity (LI):**

- Two LEDs with same luminous flux of 0.2 lumens
- Left LED’s solid angle is $15^\circ$.
  \[ \text{LI} = 3.7 \text{ cd} \]
- Right LED’s solid angle is $30^\circ$.
  \[ \text{LI} = 0.9 \text{ cd} \]
- Left LED produces a smaller, brighter spot

Image source: Internet
**LEDs**

- **Illuminance:**
  - measure of how much luminous power is incident on a given area
  - **brightness:** subjective impression of illuminance
  - SI unit of illuminance: **Lux** (lx)
  - Lux: Lumens per square meter (lm/m²)
  - illuminance varies inversely with square of the distance from the source in free-space line of sight
  - Luminous flux (lumens) = Illuminance (lx) × 4πr²
    - (r: distance from source in meters)

- **Example:**
  - 243 lumens light source
    - 5 feet = 800 fc
    - 10 feet = 200 fc
    - 20 feet = 50 fc
  - 1.5 meters = 8600 lux
    - 3 meters = 2150 lux
    - 6 meters = 535 lux

*Image source: Internet*
• **Color temperature:**
  • different shades of white

  • ‘yellowish white’ (warm white): 2700° K
  • ‘bluish white’ (cool white): 6000° K

*Image source: Internet*
• **Color rendering index (CRI):**
  - a measure of a light source’s ability to show object colors ‘realistically’ (or ‘naturally’) compared to a familiar reference source, either incandescent light or daylight
  - **Max. value is 100**
  - Lower CRI values
    ⇒ some colors may appear unnatural when illuminated by the light source (LED) in question
  - **Example CRI values:**
    - 70-80 (cool LED); 80-90 (warm/neutral LED)

• **Switching speed (rise/fall times):**
  - typ. tens of nsec
  - switch LED for the following reasons:
    - to meet **illumination constraints (dimming)**
      - consider human eye’s response characteristics
    - to achieve **data communication**
      - consider photo detector’s response characteristics
    - to achieve both dimming control and communication simultaneously
• **White LED spectrum:**
  - Emitted wavelengths of a white LED include peaks in **blue** (450-470 nm) and **yellow** (570-590 nm) regions (**solid curve**)
  - Interpreted as white light by the human eye
    - Relative light sensitivity of human eye is shown (**dotted curve**)

![Image source: Internet](image-source-url)

• **Half-power semi-angle, $\Phi_{1/2}$:**

![Image source: Internet](image-source-url)
Generalized Lambertian radiation pattern of LED

- $n$ is the mode number of the radiating lobe given by
  \[
  n = \frac{-\ln(2)}{\ln \cos \Phi_{\frac{1}{2}}}, \quad \Phi_{\frac{1}{2}} \text{ is half-power semi-angle}
  \]

- Mode number specifies the directionality of the source
  - larger the mode number, higher is the directionality
  - $n = 1$ corresponds to a traditional Lambertian source
- **Generalized Lambertian radiation pattern**
**Flicker**

- Fluctuation of the brightness of light (as perceived by human eye)
- LEDs are switched for the purposes of
  1. communication (using intensity modulation, e.g., OOK/PAM)
  2. dimming control (e.g., PWM)
- Human eye won’t perceive flicker frequency > 200 Hz
- No perceived flicker as long as the signaling rate is > 200 Hz (i.e., one signaling interval < 5 ms)
- Communication signaling rates are often much higher than 200 Hz
- So VLC using intensity modulation is not a major source of flicker
• **Photo diode**
  - Semiconductor (e.g., Si, Ge) device that converts light into current (may contain optical filters, built-in lenses)

• **Key specifications**
  - **Responsivity:** Amperes/Watt
    - ratio of the generated photo current to incident light power
  - **Response/rise time ($t_r$):**
    - determined by resistance and capacitance of the photo diode and external circuitry (typ. tens of nsec)
    - determines the bandwidth available for signal modulation ($f_{bw}$) and thus data transmission
  - **Modulation signal bandwidth:**
    - $f_{bw} = \frac{0.35}{t_r}$; e.g., $t_r = 50$ ns $\Rightarrow f_{bw} = 7$ MHz
  - **Field of view (FOV):** angle (e.g., 85°)
    - only the rays coming within FOV create response
VLC characteristics
**RFC vs VLC**

- **RF communication**
  - **Transmitter**
    - Tx RF chain (up converter, power amplifier), *Tx antenna*
  - **Receiver**
    - Rx antenna, Rx RF chain (low noise amplifier, down converter)

- **VLC**
  - **Transmitter**
    - LED
    - Tx data by *intensity modulating (IM)* the LED
  - **Receiver**
    - Photo detector
    - Rx data by *direct detection (DD)*

- **LEDs/PDs with fast switching times**
  - rise and fall times typ. tens of nsec
IM/DD channel

- **VLC Tx-Rx**

![Diagram showing IM/DD channel with Source bits, Intensity modulation, LED, PD, Direct Detection, and Sink bits.](diagram.png)

**IM/DD channel**

- Modeled using Poisson processes to account for the quantum nature of light.
- The channel output (i.e., the detected number of photons) is a random variable with a Poisson distribution with a parameter that corresponds to the expected received intensity level.

**Signal independent noise**

- Originates from background radiation from other light sources (day/ambient light, fluorescent lamps, etc.) and electronics in the receiver (thermal noise).

**Signal dependent noise**

- High-brightness LEDs where the randomness in the signal itself cannot be neglected.
• **VLC Tx-Rx**

![VLC Tx-Rx Diagram]

• **IM/DD channel**
  - Modeled using Poisson processes to account for the quantum nature of light
    - channel output (i.e., the detected number of photons) is a r. v. which has a Poisson distribution with parameter $\lambda$
    - $\lambda$ corresponds to the expected received intensity level
  - Signal independent noise
    - originates from background radiation from other light sources (day/ambient light, fluorescent lamps, etc.) and electronics in the receiver (thermal noise)
  - Signal dependent noise
    - high-brightness LEDs where the randomness in the signal itself can not be neglected
**Poisson channel** (memoryless, discrete-time)

- Derived from photon-counting (hence the Poisson nature)
- Input: r.v $\Lambda \geq 0$
- Output: discrete r.v $X$ drawn from Poisson distribution with parameter $\Lambda + \lambda_0$, i.e., $X \sim \mathcal{P}(\Lambda + \lambda_0)$

![IM/DD channel model diagram]

- Non-negative term $\lambda_0$:
  - a constant related to ambient light or thermal noise
- Conditional output probability of this channel is

$$p(x|\lambda) = e^{-(\lambda+\lambda_0)} \frac{(\lambda + \lambda_0)^x}{x!}, \quad x \in \mathbb{N}, \quad \lambda \geq 0$$

- Distribution of r.v. $X \sim \mathcal{P}(\lambda)$ for large $\lambda$ approaches a Gaussian distribution $\mathcal{N}(\lambda, \lambda)$

• **VLC Tx-Rx**

![VLC Tx-Rx Diagram]

- **Baseband communication** *(no passband involved)*
- **Signaling**: *positive, real-valued tx. signals*

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VLC channel

- CIR between source $S$ and receiver $R$ at time $t$ is given by
  \[ h(t; S, R) = \sum_{k=0}^{\infty} h^{(k)}(t; S, R) \]
  $h^{(k)}(t)$: response of light undergoing exactly $k$ reflections

**VLC channel**

- $h_{ij}$: LOS channel gain between $j$th LED and $i$th PD is

$$h_{ij} = \frac{n + 1}{2\pi} \cos^n \phi \cos \theta \frac{A}{R^2} \text{rect} \left( \frac{\theta}{\text{FOV}} \right)$$

**Geometry of LED source and photo detector**
MIMO in VLC
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MIMO in VLC

- Multiple LEDs and PDs
- $N_t$: no. of LEDs at Tx; $N_r$: no. of PDs at Rx

Advantages
- high data rates ($N_t$ symbols per channel use)
- gives MIMO gains even under LOS conditions
- induced power imbalance at Tx LEDs helps
A typical indoor VLC configuration

(g) Typical indoor VLC configuration

(h) SNR as a function of receiver position

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- 8 × 8 MIMO VLC system

Source: Internet (Boston Univ.)
• 48-LED array

Source: Internet
• $N_t$ LEDs (transmitter)
• $N_r$ photo detectors (receiver)
• $\mathbf{H}$ denotes the $N_r \times N_t$ VLC MIMO channel matrix

\[
\mathbf{H} = \begin{bmatrix}
    h_{11} & h_{12} & h_{13} & \cdots & h_{1N_t} \\
    h_{21} & h_{22} & h_{23} & \cdots & h_{2N_t} \\
    \vdots & \vdots & \ddots & \vdots & \vdots \\
    h_{N_r1} & h_{N_r2} & h_{N_r3} & \cdots & h_{N_rN_t}
\end{bmatrix}
\]

MIMO channel matrix between LEDs and PDs
Example VLC channel matrices

- **Channel matrix for** \( d_{tx} = 1 \text{m} \)
  - **Channel gain:** High
  - **Channel correlation:** High

\[
H_{d_{tx}=1\text{m}} = \begin{bmatrix}
0.5600 & 0.5393 & 0.5196 & 0.5393 \\
0.5393 & 0.5600 & 0.5393 & 0.5196 \\
0.5196 & 0.5393 & 0.5600 & 0.5393 \\
0.5393 & 0.5196 & 0.5393 & 0.5600 \\
\end{bmatrix} \times 10^{-5}
\]

- **Channel matrix for** \( d_{tx} = 4 \text{m} \)
  - **Channel gain:** Low
  - **Channel correlation:** Low

\[
H_{d_{tx}=4\text{m}} = \begin{bmatrix}
0.9947 & 0.9337 & 0.8782 & 0.9337 \\
0.9337 & 0.9947 & 0.9337 & 0.8782 \\
0.8782 & 0.9337 & 0.9947 & 0.9337 \\
0.9337 & 0.8782 & 0.9337 & 0.9947 \\
\end{bmatrix} \times 10^{-6}
\]
Modulation schemes for VLC

- Transmit signals in VLC must be
  - positive real-valued for intensity modulation of LEDs

- Approaches
  - OOK
  - $M$-PAM with positive signal points
  - $M$-QAM/$M$-PSK with Hermitian symmetry
  - SSK and spatial modulation using multiple LEDs
  - QCM, DCM (Quad-/Dual-LED complex modulation)


**MIMO VLC schemes**

- **Spatial multiplexing (SMP)**
  - $N_t$ LEDs and $N_r$ PDs
  - At any given time, all LEDs are ON
  - $\eta_{smp} = N_t \log_2 M$ bpcu

- **Spatial modulation (SM)**
  - At any given time, any one LED is ON
  - Other $N_t - 1$ LEDs are OFF
  - $\eta_{sm} = \lceil \log_2 N_t \rceil + \log_2 M$ bpcu

- **Space shift keying (SSK)**
  - Special case of SM
  - Only index of active LED conveys information
  - $\eta_{ssk} = \lceil \log_2 N_t \rceil$ bpcu
MIMO VLC schemes

- **Generalized space shift keying (GSSK)**
  - Generalization of SSK
  - $N_a \leq N_t$ active LEDs
  - $\eta_{gssk} = \lceil \log_2 \left( \frac{N_t}{N_a} \right) \rceil \ \text{bpcu}$

- **Generalized spatial modulation (GSM)**
  - Generalization of SM
  - $N_a \leq N_t$ active LEDs
  - $\eta_{gsm} = \lceil \log_2 \left( \frac{N_t}{N_a} \right) \rceil + N_a \lceil \log_2 M \rceil \ \text{bpcu}$

---


MIMO VLC system model

- Each active LED emits an $M$-ary intensity modulation symbol $I_m \in \mathbb{M}$
  - $\mathbb{M}$: set of all possible intensity levels given by
    $$I_m = \frac{2I_p m}{M + 1}, \quad m = 1, 2, \cdots, M, \quad M = |\mathbb{M}|$$

- $\mathbf{x}$: $N_t \times 1$ transmit signal vector; $x_i \in \{\mathbb{M} \cup 0\}$
- $\mathbf{n}$: $N_r \times 1$ noise vector at the receiver; $n_i \sim \mathcal{N}(0, \sigma^2)$
- $\mathbf{n}$: $N_r \times 1$ received signal vector at the receiver
  $$\mathbf{y} = a \mathbf{H} \mathbf{x} + \mathbf{n}$$
  - $a$: responsivity of the PD (amp/Watt)

- Average received SNR
  $$\bar{\gamma} = \frac{a^2 P_r^2}{\sigma^2}, \quad P_r^2 = \frac{1}{N_r} \sum_{i=1}^{N_r} \mathbb{E}[|\mathbf{h}_i \mathbf{x}|^2]$$
  - $\mathbf{h}_i$: $i$th row of $\mathbf{H}$
GSM-MIMO in VLC

GSM-MIMO transmitter for VLC system with $N_t = 4$, $N_a = 2$, $M = 2$
• Intensity levels are $l_1 = \frac{2}{3}$ and $l_2 = \frac{4}{3}$

• We need only 4 activation patterns out of $(\binom{N_t}{N_a}) = \binom{4}{2} = 6$ possible activation patterns

• So the GSM signal set for this example can be chosen as follows:

$$S_{N_t,M}^{N_a} = S_{4,2}^{2} = \begin{cases} 
\begin{bmatrix} \frac{2}{3} \\ \frac{3}{3} \\ 0 \\ 0 \end{bmatrix}, & \begin{bmatrix} \frac{2}{3} \\ \frac{3}{3} \\ 0 \\ 0 \end{bmatrix}, & \begin{bmatrix} \frac{4}{3} \\ \frac{3}{3} \\ 0 \\ 0 \end{bmatrix}, & \begin{bmatrix} \frac{4}{3} \\ \frac{3}{3} \\ 0 \\ 0 \end{bmatrix}, & \begin{bmatrix} 0 \\ 2/3 \\ 0 \\ 0 \end{bmatrix}, & \begin{bmatrix} 0 \\ 2/3 \\ 0 \\ 0 \end{bmatrix}, & \begin{bmatrix} 0 \\ 0 \\ 4/3 \\ 0 \end{bmatrix}, & \begin{bmatrix} 0 \\ 0 \\ 4/3 \\ 0 \end{bmatrix}, & \begin{bmatrix} 0 \\ 0 \\ 0 \\ 4/3 \end{bmatrix}, & \begin{bmatrix} 0 \\ 0 \\ 0 \\ 4/3 \end{bmatrix}, & \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \\
\begin{bmatrix} \frac{2}{3} \\ \frac{4}{3} \\ 2/3 \\ 0 \end{bmatrix}, & \begin{bmatrix} \frac{2}{3} \\ \frac{4}{3} \\ 2/3 \\ 0 \end{bmatrix}, & \begin{bmatrix} 0 \\ \frac{4}{3} \\ 2/3 \\ 0 \end{bmatrix}, & \begin{bmatrix} 0 \\ \frac{4}{3} \\ 2/3 \\ 0 \end{bmatrix}, & \begin{bmatrix} \frac{2}{3} \\ 2/3 \\ \frac{4}{3} \\ 2/3 \end{bmatrix}, & \begin{bmatrix} \frac{2}{3} \\ 2/3 \\ \frac{4}{3} \\ 2/3 \end{bmatrix}, & \begin{bmatrix} 4/3 \\ 0 \\ 2/3 \\ 0 \end{bmatrix}, & \begin{bmatrix} 4/3 \\ 0 \\ 2/3 \\ 0 \end{bmatrix}, & \begin{bmatrix} 4/3 \\ 0 \\ 0 \\ 2/3 \end{bmatrix}, & \begin{bmatrix} 4/3 \\ 0 \\ 0 \\ 2/3 \end{bmatrix}, & \begin{bmatrix} 0 \\ 0 \\ 4/3 \\ 0 \end{bmatrix}, & \begin{bmatrix} 0 \\ 0 \\ 4/3 \\ 0 \end{bmatrix} \\
\end{cases}$$
Maximum likelihood (ML) detection rule is

$$\hat{x} = \arg\min_{x \in \mathbb{S}^{N_a}_{N_t,M}} \left( \frac{a}{\sigma} \| Hx \|^2 - 2y^T Hx \right)$$

Pairwise error probability (PEP) is

$$PEP_{gsm} = Q \left( \frac{a}{2\sigma} \| H(x_2 - x_1) \| \right)$$

Define $L \triangleq |\mathbb{S}^{N_a}_{N_t,M}|$. An upper bound on the BER for ML detection can be obtained using union bound as

$$BER_{gsm} \leq \frac{1}{L} \sum_{i=1}^{L} \sum_{j=1, i \neq j}^{L-1} PEP(x_i \rightarrow x_j | H) \frac{d_H(x_i, x_j)}{\eta_{gsm}}$$

$$= \frac{1}{L} \sum_{i=1}^{L} \sum_{j=1, i \neq j}^{L-1} Q \left( \frac{r}{2\sigma} \| H(x_j - x_i) \| \right) \frac{d_H(x_i, x_j)}{\eta_{gsm}}$$

where $d_H(x_i, x_j)$ is the Hamming distance between the bit mappings corresponding to the signal vectors $x_i$ and $x_j$. 
Indoor VLC - A typical geometric set-up

Figure: Geometric set-up of a typical indoor VLC system
(\(\times\) denotes an LED and \(\bullet\) denotes a PD)

Placement of LEDs and PDs

(a) \(\text{Tx}, N_t = 4\)  (b) \(\text{Rx}, N_r = 4\)  (c) \(\text{Tx}, N_t = 16\)

Outdoor VLC, VLC attocells
Concluding remarks
### System parameters

<table>
<thead>
<tr>
<th>Room</th>
<th>Length (X)</th>
<th>5m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width (Y)</td>
<td>5m</td>
</tr>
<tr>
<td></td>
<td>Height (Z)</td>
<td>3.5m</td>
</tr>
<tr>
<td>Transmitter</td>
<td>Height from the floor</td>
<td>3m</td>
</tr>
<tr>
<td></td>
<td>Elevation</td>
<td>-90°</td>
</tr>
<tr>
<td></td>
<td>Azimuth</td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td>$\Phi_{1/2}$</td>
<td>60°</td>
</tr>
<tr>
<td></td>
<td>Mode number, $n$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$d_{tx}$</td>
<td>0.6m</td>
</tr>
<tr>
<td>Receiver</td>
<td>Height from the floor</td>
<td>0.8m</td>
</tr>
<tr>
<td></td>
<td>Elevation</td>
<td>90°</td>
</tr>
<tr>
<td></td>
<td>Azimuth</td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td>Responsivity, $a$</td>
<td>0.75 Ampere/Watt</td>
</tr>
<tr>
<td></td>
<td>FOV</td>
<td>85°</td>
</tr>
<tr>
<td></td>
<td>$d_{rx}$</td>
<td>0.1m</td>
</tr>
</tbody>
</table>
• LED placements in a $4 \times 4$ square grid
• Different GSM configurations for $\eta = 8 \text{ bpcu}, 5 \text{ bpcu}$

- $\times$ indicates the presence of an LED. $\circ$ indicates the absence of LED.
- Comparison of analytical upper bound and simulated BERs

Figure: GSM with $N_t = 6, 7$, $N_a = 2$, $M = 2, 4$, $\eta_{gsm} = 5, 8$ bpcu.
• Performance of different GSM configurations for fixed $\eta = 8 \text{ bpcu}$

Figure: Comparison of the BER performance of different configurations of GSM with $\eta_{gsm} = 8 \text{ bpcu}$, $N_r = 4$. 
• **Optimum placement of LEDs**

  - The minimum Euclidean distance between any two GSM signal vectors $\mathbf{x}_1$ and $\mathbf{x}_2$ transmitted through $\mathbf{H}$ is given by
    $$d_{H,\text{min}} \triangleq \min_{\mathbf{x}_1, \mathbf{x}_2 \in \mathbb{S}_{N_t,M}^{Na}} ||\mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1)||^2$$

  - Similarly, the average Euclidean distance between any two GSM signal vectors $\mathbf{x}_1$ and $\mathbf{x}_2$ transmitted through $\mathbf{H}$ is
    $$d_{H,\text{avg}} = \frac{1}{{\left| S_{N_t,M}^{Na} \right|}} \sum_{\mathbf{x}_1, \mathbf{x}_2 \in \mathbb{S}_{N_t,M}^{Na}} ||\mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1)||^2$$

  - Choose the placement of the LEDs at the transmitter such that $d_{H,\text{min}}$ and $d_{H,\text{avg}}$ are maximized over all possible placements.
**GSM performance**

<table>
<thead>
<tr>
<th>System</th>
<th>GSM configuration</th>
<th>$d_{H,min}$</th>
<th>$d_{H,avg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$N_t = 4, N_a = 2, M = 8$</td>
<td>$4.623 \times 10^{-17}$</td>
<td>$4.520 \times 10^{-11}$</td>
</tr>
<tr>
<td>2</td>
<td>$N_t = 7, N_a = 2, M = 4$</td>
<td>$1.977 \times 10^{-14}$</td>
<td>$6.601 \times 10^{-11}$</td>
</tr>
<tr>
<td>3</td>
<td>$N_t = 7, N_a = 3, M = 2$</td>
<td>$1.541 \times 10^{-14}$</td>
<td>$6.003 \times 10^{-11}$</td>
</tr>
<tr>
<td>4</td>
<td>$N_t = 12, N_a = 2, M = 2$</td>
<td>$1.346 \times 10^{-16}$</td>
<td>$4.842 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

**Table**: Values of $d_{H,min}$ and $d_{H,avg}$ for different GSM configurations with $\eta_{gsm} = 8$ bpcu.

- Configuration 2 has the largest $d_{H,min}$, $d_{H,avg}$ and hence the best BER performance
• GSM performance as a function of $d_{tx}$ for different SNRs

![Graph showing GSM performance](image)

Figure: GSM with $N_t = 4$, $N_a = 2$, $M = 8$, $\eta_{gsm} = 8$ bpcu.

• Opposing effects of channel correlation and channel chains for increasing $d_{tx}$ results in optimum $d_{tx}$
GSM vs other MIMO techniques

- SMP, GSSK, SM, and GSM with $\eta = 8 \ bpcu$

- **SMP:**
  - $N_t = 4, \ Na = 4, \ M = 4$

- **GSSK:**
  - $N_t = 13, \ Na = 3, \ M = 1$

- **SM:**
  - $N_t = 16, \ Na = 1, \ M = 16$

- **GSM:**
  - $N_t = 7, \ Na = 2, \ M = 4$
GSM vs other MIMO techniques

- Comparison of the BER performance of SMP, GSSK, SM, and GSM for the same $\eta = 8 \text{ bpcu}$, $N_r = 4$

- For the same $\eta = 8 \text{ bpcu}$, GSM performs better (by about 9 dB at $10^{-5}$ BER) compared to SMP, SSK, GSSK, SM
OFDM in VLC
OFDM in VLC

• **OFDM**
  - Popular in wired and wireless RF communications
  - **Attractive in VLC as well**

• **OFDM in RF communications**
  - OFDM signals are in the complex domain
  - Signals can be bipolar

• **OFDM in VLC**
  - VLC transmit signal must be **real and positive**
  - Use **Hermitian symmetry** on information symbols before IFFT to obtain real signals
  - Perform bipolar or unipolar conversion
  - Achieves good performance (3 Gbps single-LED OFDM link has been reported)


OFDM in VLC

Figure: A general single-LED OFDM system model in VLC.
Techniques to generate VLC compatible OFDM signals in the positive real domain:

- **DCO OFDM** (DC-biased optical OFDM)
- **ACO OFDM** (Asymmetrically clipped optical OFDM)
- **Flip OFDM**
- **NDC OFDM** (Non-DC-biased OFDM)
- **CI-NDC OFDM** (Coded Index NDC OFDM)


• \( \frac{N}{2} - 1 \) QAM symbols are modulated per OFDM symbol

• The unipolar OFDM signal \( x_{dc}(t) \) is given by

\[
x_{dc}(t) = x(t) + B_{dc}
\]

where \( x(t) \) is the bipolar OFDM signal

• \( B_{dc} = k \sqrt{\mathbb{E}\{x^2(t)\}} \); define this as a bias of \( 10 \log_{10}(k^2 + 1) \) dB

• The achieved rate in DCO OFDM is given by

\[
\eta_{dco} = \frac{\frac{N}{2} - 1}{N} \log_2 M
\]

\[
\approx \frac{1}{2} \log_2 M \text{ bpcu, for large } N
\]
ACO OFDM

**Transmitter**

- Data in
- QAM modulation & S/P
- Hermitian symmetry mapping
- N-point IFFT
- Clip at zero and transmit positive part
- P/S, D/A
- LED

**Receiver**

- Data out
- QAM demodulation & P/S
- Demapping
- N-point FFT
- A/D, S/P
- PD

**Equation**

\[
\begin{bmatrix}
X_1, X_2, \ldots, X_N
\end{bmatrix}
\]

**Figure Description**

The figure illustrates the process of transmitting and receiving data using asymmetrically clipped optical OFDM (ACOFDM) in an VLC channel. The transmitter section shows the steps from data input to the LED, while the receiver section illustrates the process from receiving the signal to data output.

**Reference**

- $\frac{N}{4}$ QAM symbols are modulated per OFDM symbol
- Only odd subcarriers are used to send information
- All even subcarriers are set to zero
- The unipolar OFDM signal is obtained by clipping the negative signals at zero
- The achieved data rate in ACO OFDM is given by

$$\eta_{aco} = \frac{1}{4} \log_2 M \text{ bpcu}$$
- \( \frac{N}{2} - 1 \) QAM symbols are modulated per OFDM symbol
- The unipolar OFDM signal is obtained by flipping the negative signals
- Two OFDM time slots are used to send one OFDM symbol
- Positive parts are sent on the first slot
- Flipped negative parts are sent on the second slot
- The achieved data rate in flip OFDM is given by
  \[
  \eta_{\text{flip}} = \frac{\frac{N}{2} - 1}{2N} \log_2 M \\
  \approx \frac{1}{4} \log_2 M \quad \text{bpSU, for large } N
  \]
DCO, ACO, flip OFDM performance

Figure: Comparison of the BER performance of ACO OFDM, flip OFDM, and DCO OFDM with 7dB bias for $\eta = 2$ bpcu, $N_t = N_r = 1$. 
DCO OFDM performance for varying DC bias

- Optimum DC bias

**Figure**: BER performance of DCO OFDM as a function of DC bias with $\eta = 2$ bpcu, $M = 16$, and $N_t = N_r = 1$, for SNR = 10, 15, 20, 25 dB.
\[ \eta_{\text{ndc}} = \frac{N-1}{2N} \log_2 M \approx \frac{1}{2} \log_2 M \quad \text{bpcu, for large } N \]

The detector output $y(n)$, $n = 0, 1, 2, \ldots, N - 1$, is

$$|y(n)| = \max_{i=1,2} |z_i(n)|$$

$$\text{sign}\{y(n)\} = \begin{cases} \text{+ve, if } \arg \max_{i=1,2} |z_i(n)| = 1 \\ \text{−ve, if } \arg \max_{i=1,2} |z_i(n)| = 2, \end{cases}$$

where

$$\begin{bmatrix} z_1(n) \\ z_2(n) \end{bmatrix} = \begin{bmatrix} (h_1^T h_1)^{-1} h_1^T y \\ (h_2^T h_2)^{-1} h_2^T y \end{bmatrix},$$

and $h_i$ is the $i$th column of channel matrix $H$, $i = 1, 2$. 
Indexed-NDC OFDM

- **I-NDC OFDM transmitter**

  \[ x(n) = \begin{cases} 
  x^+(n) & \text{if } b(n) = 0 \\
  -x^-(n) & \text{if } b(n) = 1 
  \end{cases} \]

  \[ \hat{b}(n) = \begin{cases} 
  0 & \text{if } y_1(n) > 0 \\
  1 & \text{if } y_1(n) < 0 
  \end{cases} \]

  \[ x(n) = \begin{cases} 
  + & \text{if } \hat{b}(n) = 1 \\
  - & \text{if } \hat{b}(n) = 0 
  \end{cases} \]

- **I-NDC OFDM receiver**

  \[ y(n) = \begin{cases} 
  y_1(n) & \text{if } \hat{b}(n) = 1 \\
  -y_2(n) & \text{if } \hat{b}(n) = 0 
  \end{cases} \]

  \[ \hat{b}(n) = \begin{cases} 
  0 & \text{if } y_3(n) > 0 \\
  1 & \text{if } y_3(n) < 0 
  \end{cases} \]

  \[ x(n) = \begin{cases} 
  + & \text{if } \hat{b}(n) = 1 \\
  - & \text{if } \hat{b}(n) = 0 
  \end{cases} \]
The detector output $y(n)$, $n = 0, 1, 2, \cdots, N - 1$, is

$$|y(n)| = \max_{i=1,2,3,4} |z_i(n)|$$

$$\text{sign}\{y(n)\} = \begin{cases} 
+ve, & \text{if } \arg \max_{i=1,2,3,4} |z_i(n)| = 1 \\
-ve, & \text{if } \arg \max_{i=1,2,3,4} |z_i(n)| = 2 \\
+ve, & \text{if } \arg \max_{i=1,2,3,4} |z_i(n)| = 3 \\
-ve, & \text{if } \arg \max_{i=1,2,3,4} |z_i(n)| = 4, 
\end{cases}$$

where

$$\begin{bmatrix}
z_1(n) \\
z_2(n) \\
z_3(n) \\
z_4(n)
\end{bmatrix} = \begin{bmatrix}
(h_1^T h_1)^{-1} h_1^T y \\
(h_2^T h_2)^{-1} h_2^T y \\
(h_3^T h_3)^{-1} h_3^T y \\
(h_4^T h_4)^{-1} h_4^T y
\end{bmatrix},$$

and $h_i$ is the $i$th column of channel matrix $H$, $i = 1, 2, 3, 4$. 
Performance of NDC OFDM, I-NDC OFDM

- Placement of LEDs

- BLOCK 1: (LED1, LED2)
- BLOCK 2: (LED3, LED4)
Figure: BER performance of I-NDC OFDM and NDC OFDM for $\eta = 4, 5 \text{ bpcu}, N_r = 4$
NDC OFDM and I-NDC OFDM performance

Figure: Reliability of modulation bits and index bits in I-NDC OFDM for $\eta = 4 \text{ bpcu, } N_r = 4$

- Reliability of index bits is poor!
- Use coding for index bits
Coded I-NDC OFDM

- **Cl-NDC OFDM transmitter**

  - Index bits
  - Modulation bits
  - \( rN \lfloor \log_2 N_p \rfloor \) \( \frac{N}{2} \) \( -1 \) \( \log_2 M \)
  - data in
  - 01011.. 1010110001..
  - \( [X_0, X_1, X_2, \cdots, X_{N-1}]^T \)
  - QAM modulation, S/P & Hermitian symmetry mapping
  - N-point IFFT
  - P/S
  - If \( b(n) = 0 \)
  - Polarity separator
  - \(-x^-(n)\)
  - D/A
  - LED 1
  - If \( b(n) = 1 \)
  - Polarity separator
  - \(-x^-(n)\)
  - D/A
  - LED 2

- **Cl-NDC OFDM receiver**

  - \( [Y_0, Y_1, Y_2, \cdots, Y_{N-1}]^T \)
  - Data out
  - Demapping, demodulation & P/S
  - \( y(n) \)
  - N-point FFT
  - SM detector & S/P
  - \( \hat{b}(n) \)
  - Rate-r LDPC/Walsh decoder
  - A/D
  - PD1
  - A/D
  - PD2
  - A/D
  - PD3
  - A/D
  - PD4
CI-NDC OFDM performance

Figure: BER performance of CI-NDC OFDM and NDC OFDM at $\eta = 3.8$ bpcu, $N_r = 4$

- CI-NDC OFDM performs better than NDC OFDM
Quad-LED & dual-LED complex modulation
Quad-LED complex modulation (QCM)

- A complex modulation scheme for VLC
- Uses 4 LEDs (hence the name ‘quad’)
- Does not need Hermitian symmetry
- QCM signaling
  - LEDs are simultaneously intensity modulated by the magnitudes of the real and imaginary parts of a complex symbol
  - Sign information is conveyed through spatial indexing of additional LEDs
- QCM module can serve as a basic building block to bring in the benefits of complex modulation to VLC

Mapping of complex symbol $s = s_I + js_Q$ to LEDs activity in QCM

<table>
<thead>
<tr>
<th>Real part $s_I$</th>
<th>Status of LEDs</th>
<th>Imag. part $s_Q$</th>
<th>Status of LEDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 0$</td>
<td>LED1 emits $</td>
<td>s_I</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>LED2 is OFF</td>
<td></td>
<td>LED4 is OFF</td>
</tr>
<tr>
<td>$&lt; 0$</td>
<td>LED1 is OFF</td>
<td>$&lt; 0$</td>
<td>LED3 is OFF</td>
</tr>
<tr>
<td></td>
<td>LED2 emits $</td>
<td>s_I</td>
<td>$</td>
</tr>
</tbody>
</table>

Example:
- If $s = -3 + j1$, then
  - LED1: OFF; LED2: emits 3;
  - LED3: emits 1; LED4: OFF
  
Corresponding QCM tx. vector is $x = [0 \ 3 \ 1 \ 0]^T$

Note:
- Two LEDs (one among LED1 and LED2, and another one among LED3 and LED4) will be ON simultaneously.
  Other two LEDs will be OFF
• **QCM transmitter**

\[ s = s_I + js_Q \]

Real part

\[ |s_I| \]

Imaginary part

\[ |s_Q| \]

\[ s_I \geq 0 \rightarrow DAC \rightarrow LED 1 \]
\[ s_I < 0 \rightarrow DAC \rightarrow LED 2 \]
\[ s_Q \geq 0 \rightarrow DAC \rightarrow LED 3 \]
\[ s_Q < 0 \rightarrow DAC \rightarrow LED 4 \]

• **QCM receiver**

\[ y_1, y_2, y_3, y_4 \rightarrow ADC \rightarrow QCM detector and demapper \rightarrow \hat{s} \rightarrow QAM/PSK demapper \rightarrow Data bits \]
• Crossover between performance of 4-QAM and 16-QAM
  • due to multiuser detection effect - strong interferer helps
**Effect of varying LED spacing** \( (d_{tx}) \)

- **optimum LED spacing**
  - due to opposing effects of weak channel gain and weak channel correlation for increasing \( d_{tx} \)

![Graph showing QCM performance with varying LED spacing]
QCM with phase rotation

- Rotation of complex modulation symbols
  - known to improve performance in RF wireless
- **Effect of phase rotation in QCM (QCM-PR) in VLC?**

![Graph showing Bit error rate vs Rotation angle (θ) in degrees]

- Phase rotation helps. There is optimum rotation.
• Performance of QCM and QCM-PR (with optimum rotation) as a function of $d_{tx}$
• OFDM signaling along with QCM (QCM-OFDM)
  • $N$ complex symbols drive $N$-point IFFT
  • IFFT output vector (OFDM symbol) drives QCM transmitter block in $N$ channel uses
  • QCM-OFDM signal detection
    • Zero-forcing (ZF), minimum distance (MD) detectors
  • Performance of QCM-OFDM
Performance comparison between QCM, QCM-PR, QCM-OFDM
Achievable rate contours in QCM

- Spatial distribution of received SNR
- Achievable rate (in bpcu) for a given target BER (e.g., $10^{-5}$ BER)
- Percentage area of the room covered vs achieved rate
Dual-LED complex modulation (DCM)

- Exploit representation of complex symbols in polar coordinates
- Adequate to convey only the magnitude and phase of a complex symbol $s = re^{j\phi}$, $r \in \mathbb{R}^+$, $\phi \in [0, 2\pi)$
  - only two LEDs suffice
  - no sign information to convey
- The $2 \times 1$ DCM tx. vector is $x = [r \ \phi]^T$
- DCM transmitter:

- **DCM signal detection**
  - The $N_r \times 1$ received signal vector is
    \[ y = rHx + n \]
  - ML estimate of the transmit vector $x$ is
    \[ \hat{x}_{ML} = \arg\min_{x \in S_D} \| y - rHx \|^2 \]
    $S_D$: DCM signal set (all possible tx. vectors $x$)
  - $\hat{x}_{ML}$ is demapped to corresponding complex symbol $\hat{s}_{ML}$
  - $\hat{s}_{ML}$ is demapped to get corresponding information bits

- **Remark on DCM with $M$-PSK:**
  - Only phase carries information in $M$-PSK (constant $r$)
    - ‘magnitude-LED’ becomes redundant
  - Can be viewed a single-LED scheme with $M$-PAM
  - Both LEDs matter when $M$-symbols undergo some pre-processing (e.g., IFFT in DCM-OFDM)
For small sized QAM (8-QAM), DCM performs better than QCM. For larger sized QAM (16-QAM, 64-QAM), QCM performs better.
## Performance of QCM and DCM

<table>
<thead>
<tr>
<th>Modulation alphabet</th>
<th>DCM</th>
<th>QCM</th>
<th>QCM-PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-QAM</td>
<td>29.2 dB</td>
<td>39.8 dB</td>
<td>39.2 dB</td>
</tr>
<tr>
<td>16-QAM</td>
<td>41.8 dB</td>
<td>40.6 dB</td>
<td>38.6 dB</td>
</tr>
<tr>
<td>32-QAM</td>
<td>45.5 dB</td>
<td>41.8 dB</td>
<td>40 dB</td>
</tr>
<tr>
<td>64-QAM</td>
<td>48.2 dB</td>
<td>43.7 dB</td>
<td>40.2 dB</td>
</tr>
</tbody>
</table>

**Table:** Comparison of $E_b/N_0$ required by DCM, QCM, and QCM-PR to achieve a BER of $10^{-3}$ for different $M$-QAM alphabets.
Performance of QCM-OFDM and DCM-OFDM

- Introduction
- LEDs and photo diodes
- VLC characteristics
- MIMO, OFDM, QCM, DCM in VLC
- VLC with lighting constraints
- Outdoor VLC, VLC attocells
- Concluding remarks

![Graph showing performance comparison between QCM-OFDM and DCM-OFDM](image)

**Bit error rate**

- **N=8, 4-QAM**
- DCM-OFDM, MD detector
- DCM-OFDM, ZF detector
- QCM-OFDM, MD detector
- QCM-OFDM, ZF detector

**Eb/No in dB**

- 5 10 15 20 25 30 35 40 45 50 55
- $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$
Achievable rate contours in DCM

DCM, $d_{tx}=2\,\text{m}$, half power semiangle $\Phi_{1/2}=60$

Percentage of the area of room supporting the rate for a BER of $10^{-5}$

Percentage (%)

Achievable bpcu

Average SNR (dB)

DCM in VLC

Concluding remarks
VLC with lighting constraints
VLC with dimming support

- Human eye perceives the **average intensity** (when intensity changes faster than 200 Hz)
- Need dimming support in lighting applications
  - dimming target (e.g., 75%, 50%, 25%)
- Two approaches
  - **time-domain (TD) approach**
    - adds compensation symbols of two levels (ON/OFF) within a max. flickering time period (MFTP) to match dimming target
    - **Adv:** easy to implement; **Disadv:** rate loss
  - **intensity-domain (ID) approach**
    - changes the intensity levels; also includes bias scaling (alters DC bias level), intensity distribution adaptation
    - **Adv:** high rate; suited for multi-level modulation like PAM
    - an optimization problem formulation
      - maximize rate w.r.t intensity level distribution
• Data modulation (e.g., using OFDM) with dimming control (e.g., using PWM)


Examples of dimming support

- TD approach: (b) intra-pulse insertion; (c) inter-pulse padding (IEEE 802.15.7 OOK mode uses this)
- ID approach: (d) bias-scaling; (e) distribution adaptation

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VLC with dimming support

- **PPM to support dimming control**

- **other PPM variants** (MPPM, OPPM, VPPM)

Outdoor VLC, VLC attocells
Outdoor VLC

- **Vehicular communication** (intelligent transportation systems)
  - a challenging and challenging outdoor VLC application
  - vehicle-to-vehicle (V2V), infrastructure-to-vehicle (I2V), vehicle-to-infrastructure (V2I)
  - Outdoor VLC elements: traffic lights, street lights, head/tail lights, etc.
- **Motivation**: *road-safety*; reduce road accidents
- **Typical requirements**
  - Indoor applications:
    - High data rates (Mbps-Gbps)
    - Short range (1-2 m)
  - Vehicle (outdoor) applications:
    - Relatively low data rates (Kbps)
    - Longer range (80-100 m)
    - Robustness to numerous sources of parasitic light (vehicular VLC channel is extremely noisy)

Outdoor VLC

- **IEEE 802.11p (DSRC: Dedicated Short Range Communication)**
  - standard for RF wireless access in vehicular environments
  - based on IEEE 802.11a
  - 75 MHz allotted in 5.9 GHz
  - rates: 3-27 Mbps; MAC: CSMA/CA; range: up to 1 Km

- **Issues in DSRC**
  - high traffic densities (numerous packet collisions, delay)

- **Vehicular VLC can play a complementary role to DSRC**

- **IEEE 802.15.7 VLC standard - PHY I**
  - intended for outdoor, long-range, low data rate applications such as I2V and V2V communication

- **VLC is still an early stage technology for usage in ITS**
Optical attocells

- **Spatial reuse**
  - an efficient approach to improve spectral efficiency

- **Multiple light fixtures (luminaires)** installed in large indoor environments (e.g., offices, airports, hospitals)
  - provide an opportunity to set up VLC systems with dense spatial reuse

- **Optical attocell network**
  - use each luminaire as a small base station (BS) or access point (AP)
  - smaller cell sizes compared to RF femtocells
  - uplink connection to achieve full-duplexing
  - handovers to allow users to roam within the room or an entire building
  - co-channel interference (CCI) is a key issue
An example optical attocell network

- Room size: 24m × 23m × 3m
- No. of cells: 27; Cell radius: 3.3 m

Source: Ref. [1]

• **Channel response at different receiver locations**

(c) Receivers near walls have more variation (3 dB) than receivers far off from walls (1.5 dB)

(d) This is because of the strong 1st order reflections by walls

• Adaptive bit loading in OFDM can compensate for this variation
- **CCI mitigation in optical attocell networks**
  - resource partitioning
  - use of different wavelengths in adjacent cells
  - interference coordination based on busy-burst signaling
  - fractional frequency reuse
    - offers good balance between average spectral efficiency, cell edge performance, system complexity

- **Fractional frequency reuse (FFR)**
  - strict FFR
    - one common sub-band (for cell center users)
    - multiple protected sub-bands (for cell edge users)
  - soft frequency reuse (SFR)
    - different sub-band for cell edge users in each adjacent cell
    - allows center users to take edge users’ sub-bands in adjacent cells
- FR pattern in two-layer optical attocell network model
  - pattern in edge regions: reuse factor 3

- Shown to be a good model to use to estimate interference statistics and user performance in attocells

Source: Ref. [1]
Visible light wireless communication
  - an emerging and promising complementary technology to RF communication technology

Several hard-to-resist advantages
  - with matching challenges

A fast growing area with great potential

MIMO and OFDM techniques for VLC are promising

QCM and DCM: simple and novel signaling for VLC

Open areas for research and innovation
  - New VLC signaling schemes
  - Outdoor VLC issues (robustness, range, rate)
  - VLC networking issues (MAC, coverage, mobility, handovers in attocells)

Bright future for VLC!
Thank you