Visible Light Wireless Communications

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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
- 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

Source: *Wikipedia*
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**
LEDs and photo diodes
• Efficient lighting using white LEDs
Why LEDs?

- Efficient lighting using white LEDs
- **Lumen**: SI unit of luminous flux (luminous power)
  - measure of the quantity of visible light emitted by a source
  - example LED specs: 5 lumens, 90 lumens, 160 lumens
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- Target for 2020: 200 lm/W
  - claimed to have been breached! 208 lm/W LED (prototype)
• **Lighting arrangement in** Golden Jubilee Seminar Hall, ECE

  ![Diagram of lighting arrangement]

• **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*)
- **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: Luminous Intensity Definition](Wikipedia)

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

- **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; $\theta = 55^\circ$
    $\Rightarrow \text{Luminous flux} = 41.8$ lm
  - Luminous intensity $= 11200$ mcd (11.2 cd); $\theta = 45^\circ$
    $\Rightarrow \text{Luminous flux} = 5.35$ lm
• Luminous intensity (LI):
  
  • Two LEDs with same luminous flux of 0.2 lumens
  • Left LED’s solid angle is $15^\circ$. $\Rightarrow$ $LI = 3.7$ cd
  • Right LED’s solid angle is $30^\circ$. $\Rightarrow$ $LI = 0.9$ cd
  
  • Left LED produces a smaller, brighter spot
**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)

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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)

- **Half-power semi-angle, $\Phi_{1/2}:$**
Generalized Lambertian radiation pattern of LED

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

- 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., $85^\circ$)
    • only the rays coming within FOV create response
VLC characteristics
• **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
- VLC Tx-Rx

- Source bits → Intensity modulation → LED → IM/DD channel
- LED → PD → Direct Detection
- Sink bits
- **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., $X \sim \mathcal{P}(\Lambda + \lambda_0)$

![Diagram](image)

- 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 $\mathcal{N}(\lambda, \lambda)$

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• VLC Tx-Rx

Source bits → Intensity modulation → IM/DD channel → LED → PD → Direct Detection → Sink bits

• Baseband communication (no passband involved)

• Signaling: positive, real-valued tx. signals

- 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

---

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

![Diagram of 4x4 MIMO VLC system]

**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

- 8 x 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 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)


• **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
  - $\eta_{gssk} = \lfloor \log_2 \left( \frac{N_t}{N_a} \right) \rfloor$ bpcu

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

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MIMO VLC system model

- Each active LED emits an $M$-ary intensity modulation symbol $l_m \in \mathcal{M}$
  - $\mathcal{M}$: set of all possible intensity levels given by
    \[
    l_m = \frac{2l_p m}{M + 1}, \quad m = 1, 2, \ldots, M, \quad M = |\mathcal{M}|
    \]
- $\mathbf{x}$: $N_t \times 1$ transmit signal vector; $x_i \in \{\mathcal{M} \cup 0\}$
- $\mathbf{n}$: $N_r \times 1$ 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
  \[
  \mathbf{y} = a\mathbf{Hx} + \mathbf{n}
  \]
- $a$: responsivity of the PD (amp/Watt)
- Average received SNR
  \[
  \overline{\gamma} = \frac{a^2 P_r^2}{\sigma^2}, \quad P_r^2 = \frac{1}{N_r} \sum_{i=1}^{N_r} \mathbb{E}[|h_i x|^2]
  \]
- $h_i$: $i$th row of $\mathbf{H}$
GSM-MIMO transmitter for VLC system with $N_t = 4$, $N_a = 2$, $M = 2$

<table>
<thead>
<tr>
<th>1st pair of bits</th>
<th>LED activation pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>(1,2)</td>
</tr>
<tr>
<td>01</td>
<td>(1,3)</td>
</tr>
<tr>
<td>10</td>
<td>(2,4)</td>
</tr>
<tr>
<td>11</td>
<td>(3,4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>Intensity Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>$(I_1, I_1)$</td>
</tr>
<tr>
<td>01</td>
<td>$(I_1, I_2)$</td>
</tr>
<tr>
<td>10</td>
<td>$(I_2, I_1)$</td>
</tr>
<tr>
<td>11</td>
<td>$(I_2, I_2)$</td>
</tr>
</tbody>
</table>
• Intensity levels are $I_1 = \frac{2}{3}$ and $I_2 = \frac{4}{3}$

• 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:

$$S_{N_t,M}^{N_a} = S_{4,2}^2 = \begin{bmatrix}
\frac{2}{3} & \frac{2}{3} & \frac{4}{3} & \frac{4}{3} & \frac{2}{3} & \frac{2}{3} & \frac{4}{3} & \frac{4}{3} \\
0 & 0 & \frac{2}{3} & \frac{4}{3} & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{2}{3} & \frac{4}{3} & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{2}{3} & \frac{4}{3} & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{2}{3} & \frac{4}{3} & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{2}{3} & \frac{4}{3} & 0 & 0 & 0 & 0
\end{bmatrix}$$
Upper bound on BER

Maximum likelihood (ML) detection rule is

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

Pairwise error probability (PEP) is

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

Define $L \triangleq |\mathbb{R}_{N_t, M}^{N_a}|$. 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
(× denotes an LED and ● denotes a PD)

(a) Tx, N_t = 4   (b) Rx, N_r = 4   (c) Tx, N_t = 16
Placement of LEDs and PDs
<table>
<thead>
<tr>
<th>System parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Room</strong></td>
</tr>
<tr>
<td>Length ((X))</td>
</tr>
<tr>
<td>Width ((Y))</td>
</tr>
<tr>
<td>Height ((Z))</td>
</tr>
<tr>
<td><strong>Transmitter</strong></td>
</tr>
<tr>
<td>Height from the floor</td>
</tr>
<tr>
<td>Elevation</td>
</tr>
<tr>
<td>Azimuth</td>
</tr>
<tr>
<td>(\Phi_{1/2})</td>
</tr>
<tr>
<td>Mode number, (n)</td>
</tr>
<tr>
<td>(d_{tx})</td>
</tr>
<tr>
<td><strong>Receiver</strong></td>
</tr>
<tr>
<td>Height from the floor</td>
</tr>
<tr>
<td>Elevation</td>
</tr>
<tr>
<td>Azimuth</td>
</tr>
<tr>
<td>Responsivity, (a)</td>
</tr>
<tr>
<td>FOV</td>
</tr>
<tr>
<td>(d_{rx})</td>
</tr>
</tbody>
</table>
- LED placements in a $4 \times 4$ square grid
- Different GSM configurations for $\eta = 8 \text{ bpcu}$, $5 \text{ bpcu}$

\[
\begin{array}{c|c|c|c}
\hline 
\times & \circ & \times & \\
\circ & \times & \circ & \\
\times & \circ & \times & \\
\hline 
\end{array} \quad \quad \quad \quad \\
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array}
\]

(d) GSM, $8 \text{ bpcu}$  
$N_t = 4, N_a = 2, M = 8$

\[
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array} \quad \quad \quad \quad \\
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array}
\]

(e) GSM, $5 \text{ bpcu}$  
$N_t = 6, N_a = 2, M = 2$

\[
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array} \quad \quad \quad \quad \\
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array}
\]

(f) GSM, $8 \text{ bpcu}$  
$N_t = 7, N_a = 2, M = 4$

\[
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array} \quad \quad \quad \quad \\
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array}
\]

(g) GSM, $8 \text{ bpcu}$  
$N_t = 7, N_a = 3, M = 2$

\[
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array} \quad \quad \quad \quad \\
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array}
\]

(h) GSM, $8 \text{ bpcu}$  
$N_t = 12, N_a = 2, M = 2$

\[
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array} \quad \quad \quad \quad \\
\begin{array}{c|c|c|c}
\hline 
\times & \times & \times & \\
\times & \times & \times & \\
\times & \times & \times & \\
\hline 
\end{array}
\]

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

![Graph showing GSM performance with different parameters.]

**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 $\eta = 8$ bpcu

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

- The minimum Euclidean distance between any two GSM signal vectors $x_1$ and $x_2$ transmitted through $H$ is given by
  \[
  d_{H,\text{min}} \triangleq \min_{x_1, x_2 \in S_{N_t, M}^{N_a}} \|H(x_2 - x_1)\|^2
  \]

- Similarly, the average Euclidean distance between any two GSM signal vectors $x_1$ and $x_2$ transmitted through $H$ is
  \[
  d_{H,\text{avg}} = \frac{1}{\binom{|S_{N_t, M}^{N_a}|}{2}} \sum_{x_1, x_2 \in S_{N_t, M}^{N_a}} \|H(x_2 - x_1)\|^2
  \]

- 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 for varying $d_{tx}$

- GSM performance as a function of $d_{tx}$ for different SNRs

![GSM performance graph]

**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** $\eta = 8 \text{ bpcu}$
  - **SMP:**
    - $N_t = 4$, $N_a = 4$, $M = 4$
  - **GSSK:**
    - $N_t = 13$, $N_a = 3$, $M = 1$
  - **SM:**
    - $N_t = 16$, $N_a = 1$, $M = 16$
  - **GSM:**
    - $N_t = 7$, $N_a = 2$, $M = 4$
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 $10^{-5} \text{ BER}$) compared to SMP, SSK, GSSK, SM
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)


Figure: A general single-LED OFDM system model in VLC.
OFDM 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)


DCO OFDM

Transmitter

\[ x(n) \rightarrow \text{Adding DC bias and clipping at zero} \rightarrow P/S, D/A \rightarrow \text{LED} \]

\[ \text{Data in} \rightarrow \text{QAM modulation \\& S/P} \rightarrow \text{Hermitian symmetry mapping} \rightarrow \text{N-point IFFT} \rightarrow x(n) \]

\[ \{X_0, X_1, X_2, \ldots, X_{N-1}\} \]

\[ \rightarrow \text{Adding DC bias and clipping at zero} \rightarrow P/S, D/A \rightarrow \text{LED} \]

\[ \text{Receiver} \]

\[ \{Y_0, Y_1, Y_2, \ldots, Y_{N-1}\}^T \]

\[ \text{Data out} \rightarrow \text{QAM demodulation \\& P/S} \rightarrow \text{Demapping} \rightarrow \text{N-point FFT} \rightarrow y(n) \]

\[ \rightarrow \text{Remove DC bias} \rightarrow \text{A/D, S/P} \rightarrow \text{PD} \rightarrow \text{VLC channel} \]

\[ \frac{N}{2} - 1 \text{ QAM symbols are modulated per OFDM symbol} \]

- 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{N}{2} - 1 \cdot \frac{1}{N} \log_2 M \\
\approx \frac{1}{2} \log_2 M \text{ bpcu, for large } N
• $\frac{N}{4}$ 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

$$\eta_{flip} = \frac{N}{2} - \frac{1}{2N} \log_2 M$$

$$\approx \frac{1}{4} \log_2 M \text{ bpcu, for large } N$$
Figure: Comparison of the BER performance of ACO OFDM, flip OFDM, and DCO OFDM with 7dB bias for $\eta = 2$ bpcu, $N_t = N_r = 1$. 

### Bit Error Rate

- **ACO OFDM, M=256**
- **Flip OFDM, M=256**
- **DCO OFDM, M=16**
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.
\[ \eta_{\text{ndc}} = \frac{N - 1}{N} \log_2 M \approx \frac{1}{2} \log_2 M \text{ bpcu, for large } N \]

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

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

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

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 $H, \ i = 1, 2.$
I-NDC OFDM transmitter

\[ [X_0, X_1, X_2, \cdots, X_{N-1}]^T \]

If \( b(n) = 0 \)

If \( b(n) = 1 \)

\( N_P: \text{No. of pairs of LEDs, } N_P = 2 \)

I-NDC OFDM receiver

\[ [Y_0, Y_1, Y_2, \cdots, Y_{N-1}]^T \]

Demapping, demodulation & P/S

N-point FFT

SM detector & S/P

\( \hat{b}(n) \)

\( y_1(n) \)

A/D

PD1

\( y_2(n) \)

A/D

PD2

\( y_3(n) \)

A/D

PD3

\( y_4(n) \)

A/D

PD4
The detector output $y(n)$, $n = 0, 1, 2, \ldots, N - 1$, 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)
NDC OFDM and I-NDC OFDM performance

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

![Graph showing the Bit Error Rate vs. Eb/No for different modulation schemes.]

Figure: Reliability of modulation bits and index bits in I-NDC OFDM for \( \eta = 4 \) bpcu, \( N_r = 4 \)

- Reliability of index bits is poor!
- Use coding for index bits
**CI-NDC OFDM transmitter**

- **Rate-r LDPC/Walsh encoder**
- **QAM modulation, S/P & Hermitian symmetry mapping**
- **N-point IFFT**
- **P/S**
- **Polarity separator**

**CI-NDC OFDM receiver**

- **Demapping, demodulation & P/S**
- **N-point FFT**
- **SM detector & S/P**
- **Rate-r LDPC/Walsh decoder**
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 $s = s_I + j s_Q$ to LEDs activity in QCM

<table>
<thead>
<tr>
<th>Real part</th>
<th>Status of LEDs</th>
<th>Imag. part</th>
<th>Status of LEDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_I$</td>
<td></td>
<td>$s_Q$</td>
<td></td>
</tr>
<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 $\mathbf{x} = [0 \ 3 \ 1 \ 0]^T$

- 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

Data in $\log_2|A|$ bits

\[ s = s_I + js_Q \]

Real part

\[ |s_I| \]

\[ s_I \geq 0 \]

DAC $\rightarrow$ LED 1

\[ s_I < 0 \]

DAC $\rightarrow$ LED 2

Imaginary part

\[ |s_Q| \]

\[ s_Q \geq 0 \]

DAC $\rightarrow$ LED 3

\[ s_Q < 0 \]

DAC $\rightarrow$ LED 4

- QCM receiver

PD 1 $\rightarrow$ ADC $\rightarrow$ $y_1$

PD 2 $\rightarrow$ ADC $\rightarrow$ $y_2$

PD 3 $\rightarrow$ ADC $\rightarrow$ $y_3$

PD 4 $\rightarrow$ ADC $\rightarrow$ $y_4$

QCM detector and demapper

\[ \hat{s} \]

QAM/PSK demapper

Data bits
QCM performance

- Crossover between performance of 4-QAM and 16-QAM
  - due to multiuser detection effect - strong interferer helps
QCM performance

- Effect of varying LED spacing ($d_{tx}$)

- optimum LED spacing
  - due to opposing effects of weak channel gain and weak channel correlation for increasing $d_{tx}$
• Rotation of complex modulation symbols
  • known to improve performance in RF wireless
• Effect of phase rotation in QCM (QCM-PR) in VLC?

- Phase rotation helps. There is optimum rotation.
• Performance of QCM and QCM-PR (with optimum rotation) as a function of $d_{tx}$

![Graph showing the bit error rate as a function of $d_{tx}$ for different modulation schemes.](image)
QCM-OFDM

- 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

\[ \text{Bit error rate} \]

\[ \text{Eb/No in dB} \]
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

![Diagram of QCM, $d_{tx}=2m$, half power semiangle $\Phi_{1/2}=60$]
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 \( \mathbf{x} = [r \ \phi]^T \)
- 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

Eb/No in dB

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
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

VLC with dimming support

- PPM to support dimming control

- Other PPM variants (MPPM, OPPM, VPPM)

Outdoor VLC, VLC attocells
• **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)

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• **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
• 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

• Channel response at different receiver locations

- Receivers near walls have more variation (3 dB) than receivers far off from walls (1.5 dB)
- 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]
Concluding remarks

- 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