Visible Light Wireless Communications

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IISc, Bangalore

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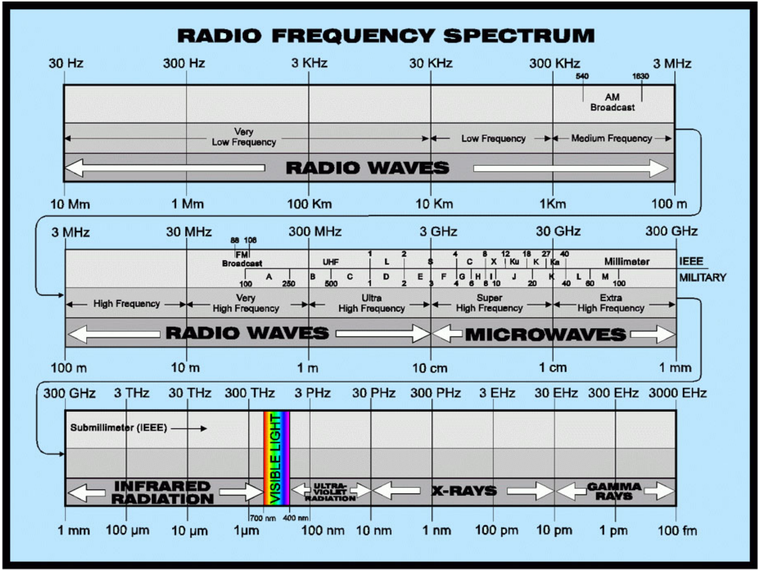
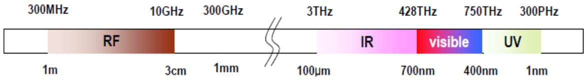
Outline

Wireless spectrum



Source: Internet

- 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)



Source: www.ieee802.org/15

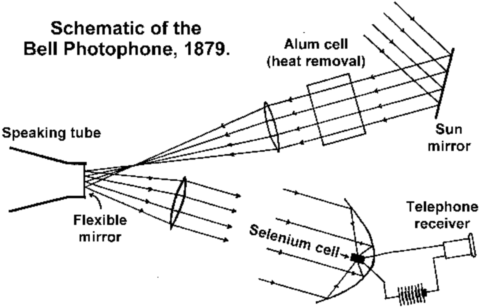
- Visible light communication (VLC)
  - communications using visible light spectrum
  - abundant VLC spectrum ($\sim$ 300 THz bandwidth)
  - multi-gigabit rates over short distances
  - LEDs as transmitters and photo diodes (PD) as receivers

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
  (Patented Dec. 14, 1880. Filing date: Sep. 25, 1880. Patent No. US235496 A. Title: Photophone-Transmitter)
  - Analog voice transceiver
  - Transmitter: a mirror controls the amount of light reflected from a source
  - Receiver: a photocell connected to a speaker

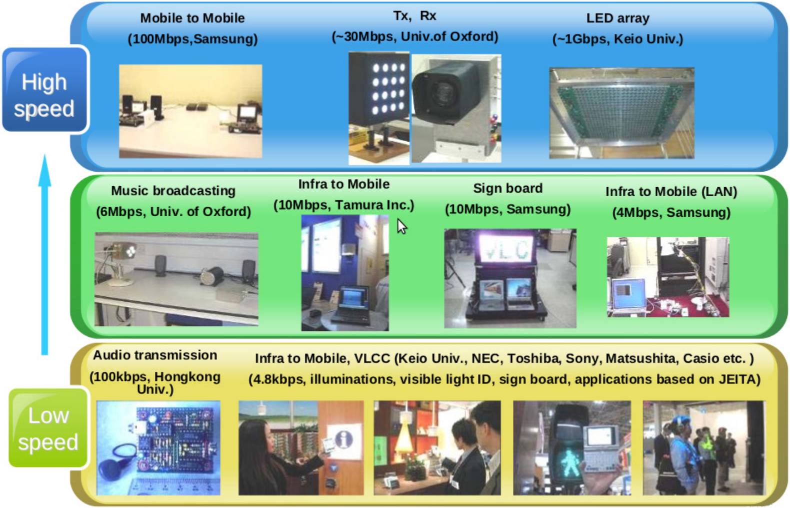


Source: Wikipedia

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

VLC implementations/applications



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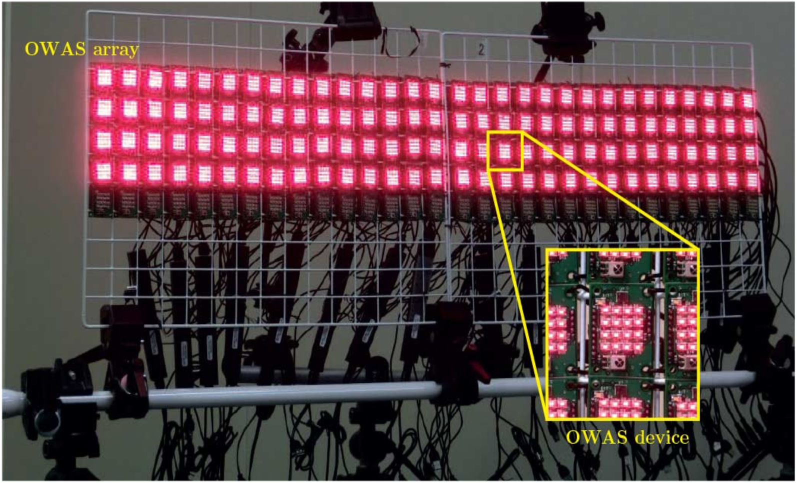

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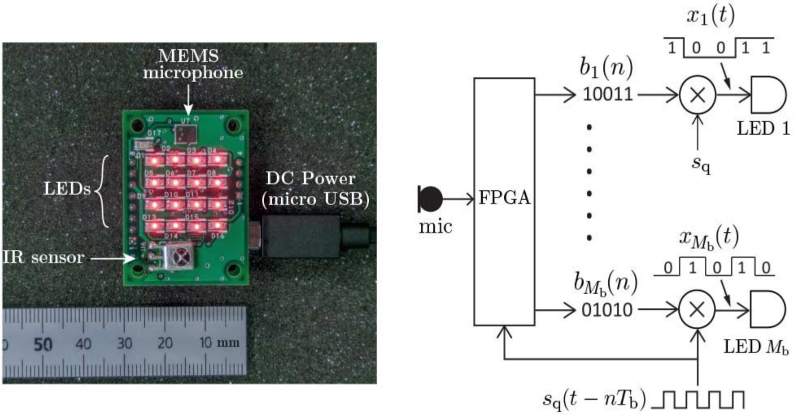

(a) (b)

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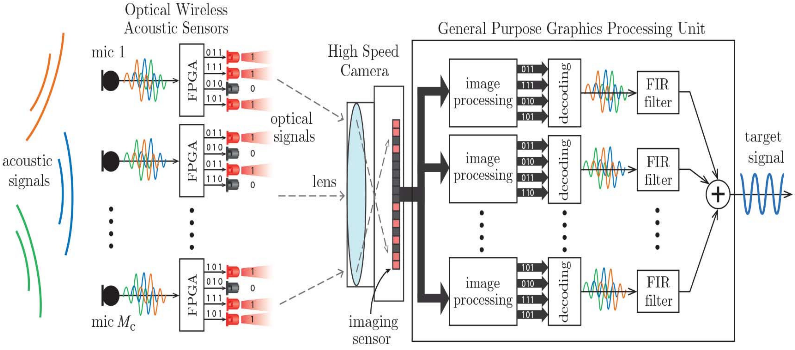

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LEDs and photo diodes

Why LEDs?

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- Efficient lighting using white LEDs

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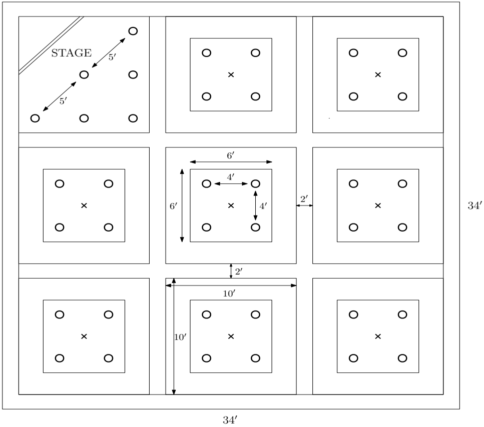
- Target for 2020: 200 lm/W
  - claimed to have been breached! 208 lm/W LED (prototype)

- Lighting arrangement in Golden Jubilee Seminar Hall, ECE



- 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)

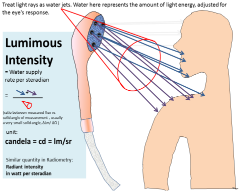


Image source: Wikipedia

  - Solid angle (in steradians) of a cone with apex angle θ (in degrees) $= 2\pi(1 - \cos\frac{\theta^\circ}{2})$, i.e., $\text{cd} = \text{lm}/(2\pi(1 - \cos\frac{\theta^\circ}{2}))$
  - 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; $\theta = 55^\circ$
      $\Rightarrow$ Luminous flux $= 41.8$ lm
    - luminous intensity $= 11200$ mcd (11.2 cd); $\theta = 45^\circ$
      $\Rightarrow$ Luminous flux $= 5.35$ lm

LEDs

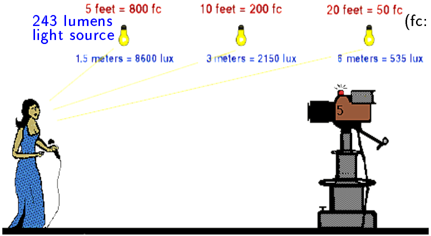
- Luminous intensity (LI):
  - Two LEDs with same luminous flux of 0.2 lumens
  - Left LED's solid angle is 15°. $\Longrightarrow$ LI $= 3.7$ cd
  - Right LED's solid angle is 30°. $\Longrightarrow$ LI $= 0.9$ cd
  - Left LED produces a smaller, brighter spot

(a)

(b)

Image source: Internet

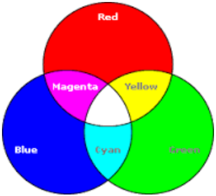
- Illuminance:
  - measure of how much luminous power is incident on a given area
  - brightness: subjective impression of illuminance
  - SI unit of illuminance: Lux (lx)
  - Lux: Lumens per square meter ($\mathrm{lm/m^2}$)
  - illuminance varies inversely with square of the distance from the source in free-space line of sight
    - Luminous flux (lumens) = Illuminance (lx) $\times\ 4\pi r^2$ (r: distance from source in meters)



(fc: foot-candles)

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)

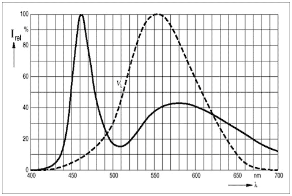
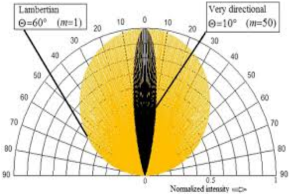


Image source: Internet

- Half-power semi-angle, $\Phi_{\frac{1}{2}}$:



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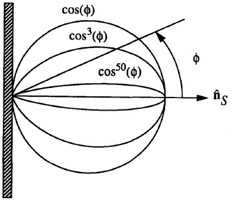


$R(\phi) = \frac{n+1}{2\pi} P_S \cos^n(\phi) \quad \text{for } \phi \in [-\frac{\pi}{2}, \frac{\pi}{2}]$

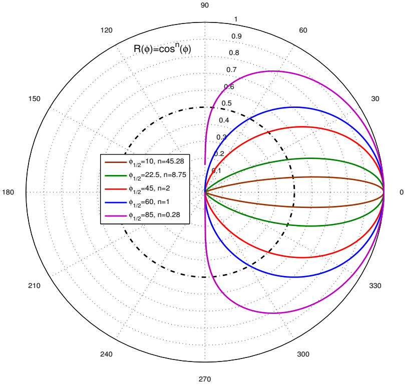
Generalized Lambertian radiation pattern of LED

- n is the mode number of the radiating lobe given by

$$n = \frac{-\ln(2)}{\ln \cos \Phi_{\frac{1}{2}}}, \qquad \Phi_{\frac{1}{2}} \text{ is half-power semi-angle}$$

- 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

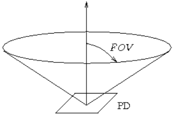


Generalized Lambertian radiation pattern of LED

- 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 diodes

- 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

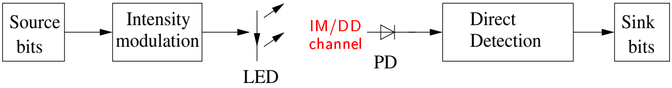


VLC characteristics

RFC vs VLC

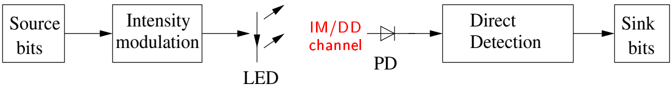
- RF communication
  - Transmitter
    - Tx RF chain (up converter, power amplifier), Tx antenna
  - Receiver
    - Rx antenna, Rx RF chain (low noise amplifier, down converter)
- VLC
  - Transmitter
    - LED
    - Tx data by intensity modulating (IM) the LED
  - Receiver
    - Photo detector
    - Rx data by direct detection (DD)
  - LEDs/PDs with fast switching times
    - rise and fall times typ. tens of nsec

- VLC Tx-Rx


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

IM/DD channel

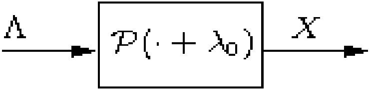
- VLC Tx-Rx



- 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 λ
    - λ 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

IM/DD channel model

- 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., $X \sim \mathcal{P}(\Lambda + \lambda_0)$



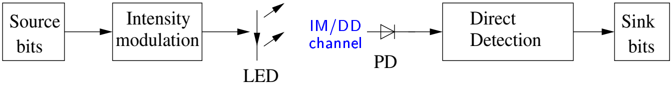
  - Non-negative term λ_0:
    - a constant related to ambient light or thermal noise
  - Conditional output probability of this channel is

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

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

A. Tsiatmas, F. M. J. Willems, and C. P. M. J. Baggen, "Square root approximation to the Poisson channel," *IEEE ISIT'2013.*

- VLC Tx-Rx



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

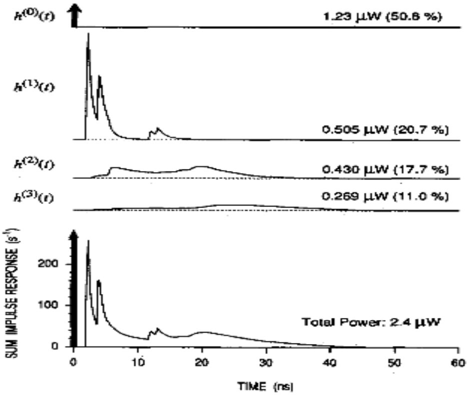
D.C.O'Brien *et al*, "Visible light communications: challenges and possibilities", *IEEE PIMRC'2008.*

VLC channel

- CIR between source $\mathcal{S}$ and receiver $\mathcal{R}$ at time t is given by

$$h(t;\mathcal{S},\mathcal{R}) = \sum_{k=0}^{\infty} h^{(k)}(t;\mathcal{S},\mathcal{R})$$

$h^{(k)}(t)$: response of light undergoing exactly k reflections



LOS

Walls

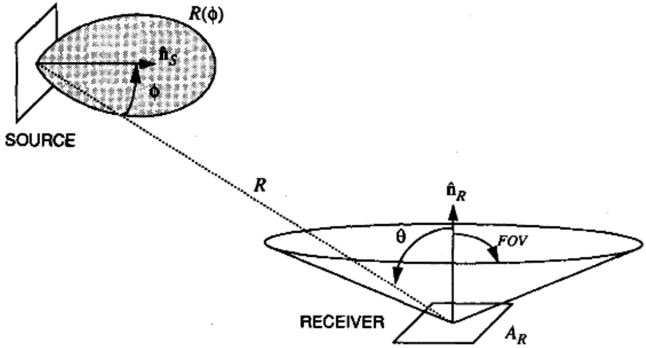
Floor, ceiling

Others

J. Barry *et al*, "Simulation of multipath impulse response for indoor wireless optical channels," *IEEE J. Sel. Areas in Commun.*, vol. 11, no. 3, pp. 367-379, Apr. 1993.

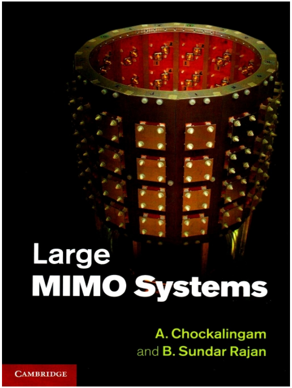
- h_{ij}: LOS channel gain between jth LED and ith PD is

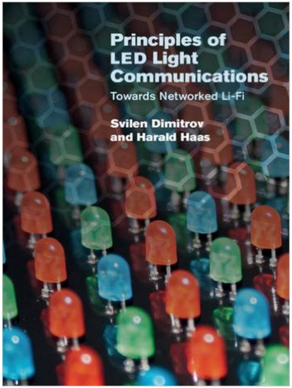
$$h_{ij} = \frac{n+1}{2\pi} \cos^n \phi \, \cos \theta \, \frac{A}{R^2} \mathrm{rect}\left(\frac{\theta}{FOV}\right)$$



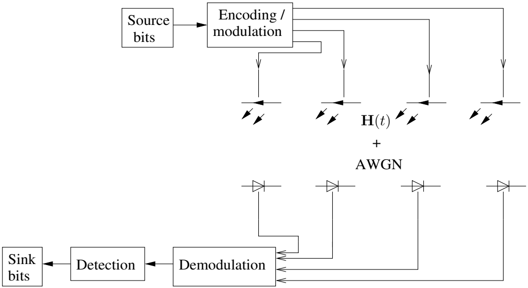
Geometry of LED source and photo detector

MIMO in VLC


Large
MIMO Systems
A. Chockalingam
and B. Sundar Rajan
CAMBRIDGE


Principles of
LED Light
Communications
Towards Networked Li-Fi
Svilen Dimitrov
and Harald Haas

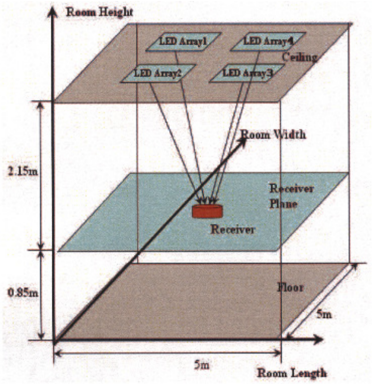
- Multiple LEDs and PDs
- N_t: no. of LEDs at Tx; N_r: no. of PDs at Rx



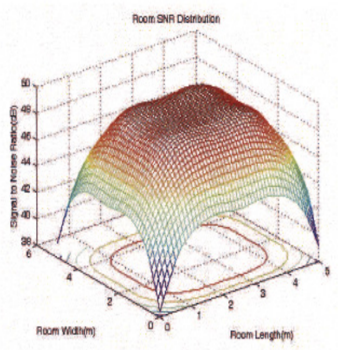
4×4 MIMO VLC

- 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

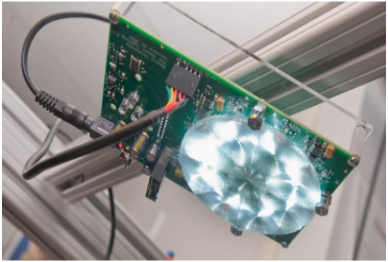


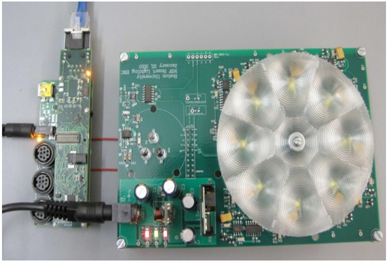
(h) SNR as a function of receiver position

D.C.O'Brien *et al*, "Visible light communications: challenges and possibilities", *IEEE PIMRC'2008*.

MIMO LED arrays

- 8×8 MIMO VLC system





Source: Internet (Boston Univ.)

MIMO LED arrays

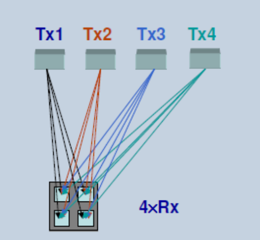
- 48-LED array

Source: Internet

VLC channel

- 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

$$\mathbf{H}_{d_{tx}=1m} = \begin{bmatrix} 0.5600 & 0.5393 & 0.5196 & 0.5393 \\ 0.5393 & 0.5600 & 0.5393 & 0.5196 \\ 0.5196 & 0.5393 & 0.5600 & 0.5393 \\ 0.5393 & 0.5196 & 0.5393 & 0.5600 \end{bmatrix} \times 10^{-5}$$

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

$$\mathbf{H}_{d_{tx}=4m} = \begin{bmatrix} 0.9947 & 0.9337 & 0.8782 & 0.9337 \\ 0.9337 & 0.9947 & 0.9337 & 0.8782 \\ 0.8782 & 0.9337 & 0.9947 & 0.9337 \\ 0.9337 & 0.8782 & 0.9337 & 0.9947 \end{bmatrix} \times 10^{-6}$$

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)

T. Fath and H. Haas, "Performance comparison of MIMO techniques for optical wireless communications in indoor environments," *IEEE Trans. Commun.*, vol. 61, no. 2, pp. 733-742, Feb. 2013.

S. P. Alaka, T. Lakshmi Narasimhan, and A. Chockalingam, "Generalized spatial modulation in indoor wireless visible light communication," *IEEE GLOBECOM'2015*, San Diego, USA, Dec. 2015.

R. Tejaswi, T. Lakshmi Narasimhan, A. Chockalingam, "Quad-LED complex modulation (QCM) for visible light wireless communications" IEEE WCNC'16 Workshop on Opt. Wireless Commun., Apr. 2016.

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
  - $\eta_{sm} = \lfloor \log_2 N_t \rfloor + \log_2 M$ bpcu
- Space shift keying (SSK)
  - Special case of SM
  - Only index of active LED conveys information
  - $\eta_{ssk} = \lfloor \log_2 N_t \rfloor$ bpcu

MIMO VLC schemes

- Generalized space shift keying (GSSK)
  - Generalization of SSK
  - $N_a \leq N_t$ active LEDs
  - $\eta_{gssk} = \left\lfloor \log_2 \binom{N_t}{N_a} \right\rfloor$ bpcu
- Generalized spatial modulation (GSM)
  - Generalization of SM
  - $N_a \leq N_t$ active LEDs
  - $\eta_{gsm} = \left\lfloor \log_2 \binom{N_t}{N_a} \right\rfloor + N_a \lfloor \log_2 M \rfloor$ bpcu

T. Fath and H. Haas, "Performance comparison of MIMO techniques for optical wireless communications in indoor environments," *IEEE Trans. Commun.*, vol. 61, no. 2, pp. 733-742, Feb. 2013.

S. P. Alaka, T. Lakshmi Narasimhan, and A. Chockalingam, "Generalized spatial modulation in indoor wireless visible light communication," *IEEE GLOBECOM'2015*, San Diego, USA, Dec. 2015.

- 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

$$\mathbf{y} = a\mathbf{H}\mathbf{x} + \mathbf{n}$$

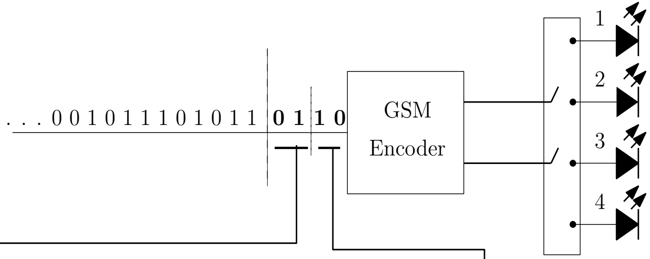
a: responsivity of the PD (amp/Watt)

- Average received SNR

$$\overline{\gamma} = \frac{a^2 P_r^2}{\sigma^2}, \quad P_r^2 = \frac{1}{N_r}\sum_{i=1}^{N_r} \mathbb{E}[|\mathbf{h}_i \mathbf{x}|^2]$$

$\mathbf{h}_i$: ith row of $\mathbf{H}$

GSM-MIMO in VLC



1st pair of bits	LED activation pattern
00	(1,2)
01	**(1,3)**
10	(2,4)
11	(3,4)

2st pair of bits	Intensity Levels
00	(I_1, I_1)
01	(I_1, I_2)
10	**(I_2, I_1)**
11	(I_2, I_2)

GSM-MIMO transmitter for VLC system with $N_t = 4, N_a = 2, M = 2$

- 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:

$$\mathbb{S}_{N_t,M}^{N_a} = \mathbb{S}_{4,2}^{2} = \left\{ \begin{bmatrix} \frac{2}{3} \\ \frac{2}{3} \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \frac{2}{3} \\ \frac{4}{3} \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \frac{4}{3} \\ \frac{2}{3} \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \frac{4}{3} \\ \frac{4}{3} \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \frac{2}{3} \\ 0 \\ \frac{2}{3} \\ 0 \end{bmatrix}, \begin{bmatrix} \frac{2}{3} \\ 0 \\ \frac{4}{3} \\ 0 \end{bmatrix}, \begin{bmatrix} \frac{4}{3} \\ 0 \\ \frac{2}{3} \\ 0 \end{bmatrix}, \begin{bmatrix} \frac{4}{3} \\ 0 \\ \frac{4}{3} \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ \frac{2}{3} \\ 0 \\ \frac{2}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ \frac{2}{3} \\ 0 \\ \frac{4}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ \frac{4}{3} \\ 0 \\ \frac{2}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ \frac{4}{3} \\ 0 \\ \frac{4}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \frac{2}{3} \\ \frac{2}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \frac{2}{3} \\ \frac{4}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \frac{4}{3} \\ \frac{2}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \frac{4}{3} \\ \frac{4}{3} \end{bmatrix} \right\}$$

Maximum likelihood (ML) detection rule is

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

Pairwise error probability (PEP) is

$$PEP_{gsm} = Q\left(\frac{a}{2\sigma}\|\mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1)\|\right)$$

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

$$\begin{aligned} BER_{gsm} &\leq \frac{1}{L}\sum_{i=1}^{L}\sum_{j=1,i\neq j}^{L-1} PEP(\mathbf{x}_i \to \mathbf{x}_j|\mathbf{H})\frac{d_H(\mathbf{x}_i,\mathbf{x}_j)}{\eta_{gsm}} \\ &= \frac{1}{L}\sum_{i=1}^{L}\sum_{j=1,i\neq j}^{L-1} Q\left(\frac{r}{2\sigma}\|\mathbf{H}(\mathbf{x}_j - \mathbf{x}_i)\|\right)\frac{d_H(\mathbf{x}_i,\mathbf{x}_j)}{\eta_{gsm}} \end{aligned}$$

where $d_H(\mathbf{x}_i, \mathbf{x}_j)$ is the Hamming distance between the bit mappings corresponding to the signal vectors $\mathbf{x}_i$ and $\mathbf{x}_j$

Indoor VLC - A typical geometric set-up

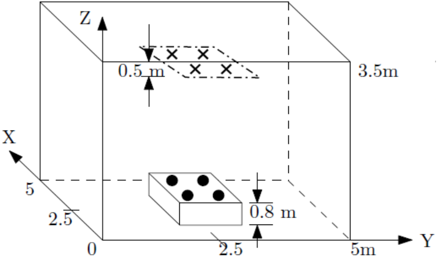
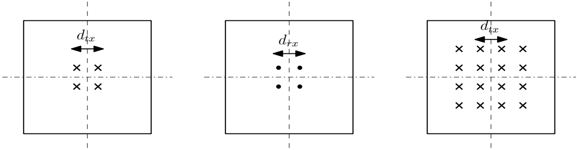


Figure : Geometric set-up of a typical indoor VLC system
(× denotes an LED and ● denotes a PD)



(a) **Tx**, $N_t = 4$ (b) **Rx**, $N_r = 4$ (c) **Tx**, $N_t = 16$

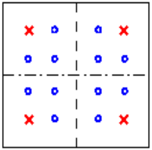
Placement of LEDs and PDs

System parameters

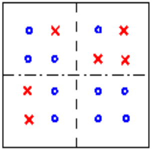
Room	Length (X)	5m
	Width (Y)	5m
	Height (Z)	3.5m
Transmitter	Height from the floor	3m
	Elevation	-90°
	Azimuth	0°
	$\Phi_{1/2}$	60°
	Mode number, n	1
	d_{tx}	0.6m
Receiver	Height from the floor	0.8m
	Elevation	90°
	Azimuth	0°
	Responsivity, a	0.75 Ampere/Watt
	FOV	85°
	d_{rx}	0.1m

GSM performance

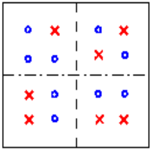
- LED placements in a 4×4 square grid
- Different GSM configurations for $\eta = 8$ bpcu, 5 bpcu



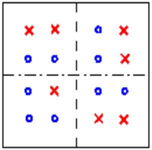
(d) GSM, 8 bpcu
$N_t = 4$, $N_a = 2$, $M = 8$



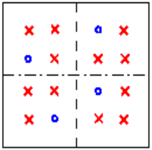
(e) GSM, 5 bpcu
$N_t = 6$, $N_a = 2$, $M = 2$



(f) GSM, 8 bpcu
$N_t = 7$, $N_a = 2$, $M = 4$



(g) GSM, 8 bpcu
$N_t = 7$, $N_a = 3$, $M = 2$



(h) GSM, 8 bpcu
$N_t = 12$, $N_a = 2$, $M = 2$

$\times$ indicates the presence of an LED. $\circ$ indicates the absence of LED.

- Comparison of analytical upper bound and simulated BERs

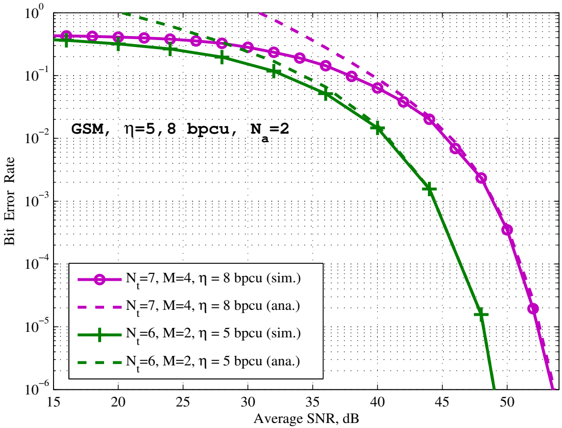


Figure : GSM with $N_t = 6, 7$, $N_a = 2$, $M = 2, 4$, $\eta_{gsm} = 5, 8$ bpcu.

- Performance of different GSM configurations for fixed $\eta = 8$ bpcu

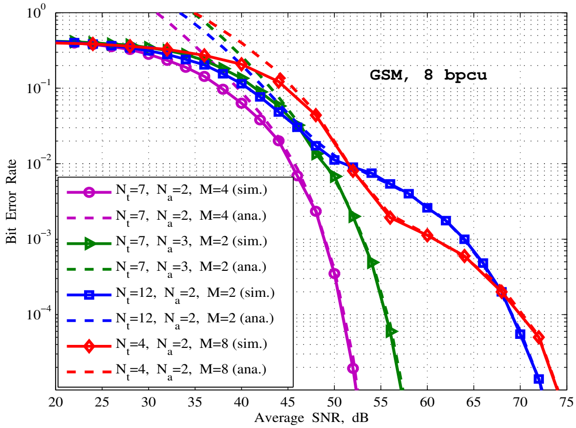


Figure : Comparison of the BER performance of different configurations of GSM with $\eta_{gsm} = 8$ bpcu, $N_r = 4$.

- Optimum placement of LEDs
  - The minimum Euclidean distance between any two GSM signal vectors $\mathbf{x}_1$ and $\mathbf{x}_2$ transmitted through $\mathbf{H}$ is given by

$$d_{\mathbf{H},min} \triangleq \min_{\mathbf{x}_1,\mathbf{x}_2 \in \mathbb{S}_{N_t,M}^{N_a}} \left\|\mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1)\right\|^2$$

  - Similarly, the average Euclidean distance between any two GSM signal vectors $\mathbf{x}_1$ and $\mathbf{x}_2$ transmitted through $\mathbf{H}$ is

$$d_{\mathbf{H},avg} = \frac{1}{\binom{|\mathbb{S}_{N_t,M}^{N_a}|}{2}} \sum_{\mathbf{x}_1,\mathbf{x}_2 \in \mathbb{S}_{N_t,M}^{N_a}} \left\|\mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1)\right\|^2$$

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

System	GSM configuration	$d_{\mathbf{H},min}$	$d_{\mathbf{H},avg}$
1	$N_t = 4, N_a = 2, M = 8$	4.623×10^{-17}	4.520×10^{-11}
2	$N_t = 7, N_a = 2, M = 4$	1.977×10^{-14}	6.601×10^{-11}
3	$N_t = 7, N_a = 3, M = 2$	1.541×10^{-14}	6.003×10^{-11}
4	$N_t = 12, N_a = 2, M = 2$	1.346×10^{-16}	4.842×10^{-11}

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

- Configuration 2 has the largest $d_{\mathbf{H},min}$, $d_{\mathbf{H},avg}$ and hence the best BER performance

GSM performance for varying d_{tx}

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

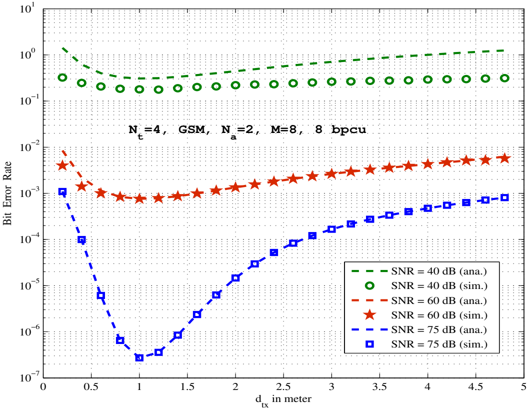
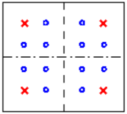


Figure : GSM with $N_t = 4$, $N_a = 2$, $M = 8$, $\eta_{gsm} = 8$ bpcu.

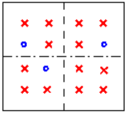
- Opposing effects of channel correlation and channel chains for increasing d_{tx} results in optimum d_{tx}

GSM vs other MIMO techniques

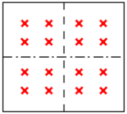
- SMP, GSSK, SM, and GSM with $\eta = 8$ *bpcu*
- SMP:
  - $N_t = 4,\ N_a = 4,\ M = 4$



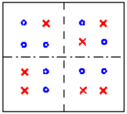
- GSSK:
  - $N_t = 13,\ N_a = 3,\ M = 1$



- SM:
  - $N_t = 16,\ N_a = 1,\ M = 16$

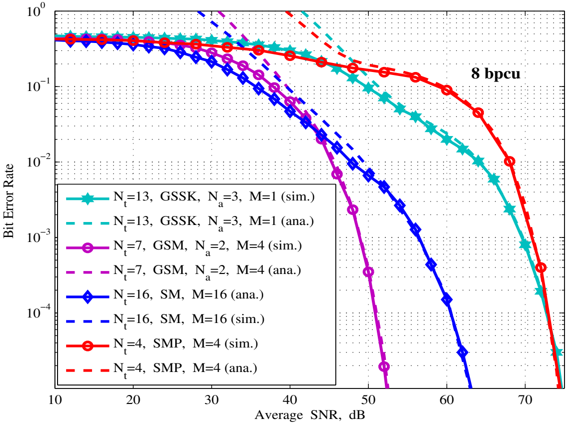


- GSM:
  - $N_t = 7,\ N_a = 2,\ M = 4$



GSM vs other MIMO techniques

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



- For the same $\eta = 8$ bpcu, GSM performs better (by about 9 dB at 10^{-5} 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)

J. Armstrong, "OFDM for optical communications," *J. Lightwave Tech.*, vol. 27, no. 3, pp. 89-204, Feb. 2009.

H. Elgala, R. Mesleh, H. Haas, and B. Pricope, "OFDM visible light wireless communication based on white LEDs," *Proc. IEEE VTC 2007-Spring*, pp. 2185-2189, Apr. 2007.

D. Tsonev *et al*, "A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride μLED," *IEEE Photonics Tech. Lett.*, vol. 26, no. 7, pp. 637-640, Jan. 2014.

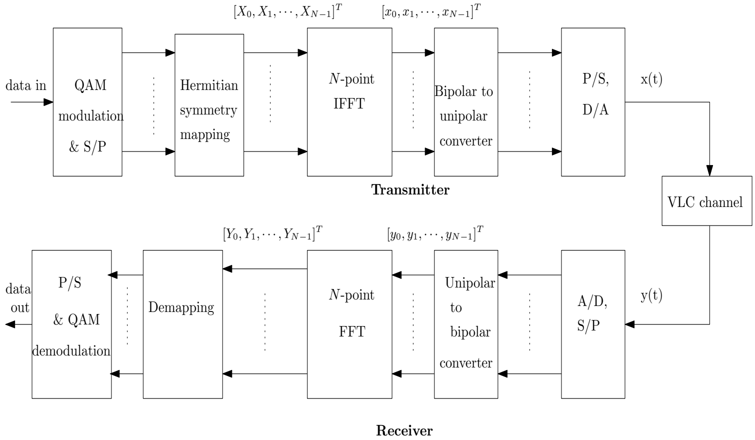


Figure : A general single-LED OFDM system model in VLC.

- 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)

O. Gonzlez *et al*, "OFDM over indoor wireless optical channel," *Proc. IEE Optoelectronics*, vol. 152, no. 4, pp. 199-204, Aug. 2005.

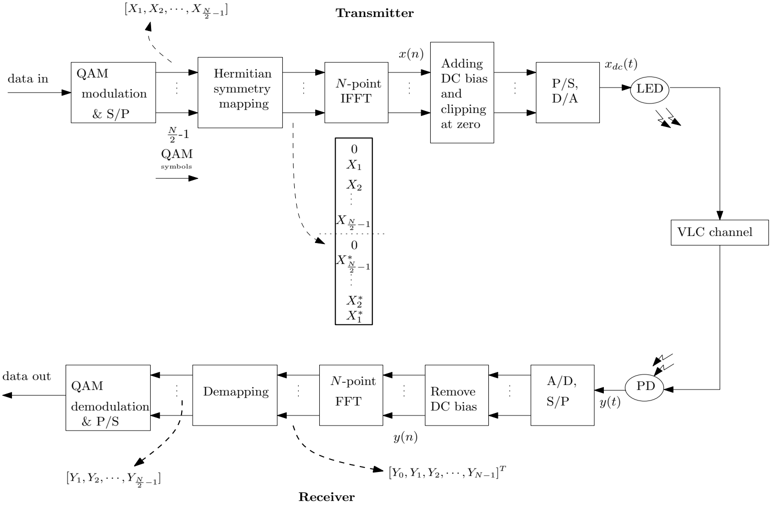
J. Armstrong and B. J. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN," *IEEE Commun. Letters*, vol. 12, no. 5, pp. 343-345, May 2008.

N. Fernando, Y. Hong, and E. Viterbo, "Flip-OFDM for unipolar communication systems," *IEEE Trans. Commun.*, vol. 60, no. 12, pp. 3726-3733, Aug. 2012.

Y. Li, D. Tsonev, and H. Haas, "Non-DC-biased OFDM with optical spatial modulation," IEEE PIMRC 2013, pp. 486-490, Sep. 2013.

S. P. Alaka, T. Lakshmi Narasimhan, and A. Chockalingam, "Coded index modulation for non-DC-biased OFDM in multiple LED visible light communication," IEEE VTC'2016-Spring, May 2016.

DCO OFDM



O. Gonzlez *et al*, "OFDM over indoor wireless optical channel," *Proc. IEE Optoelectronics*, vol. 152, no. 4, pp. 199-204, Aug. 2005.

DCO OFDM

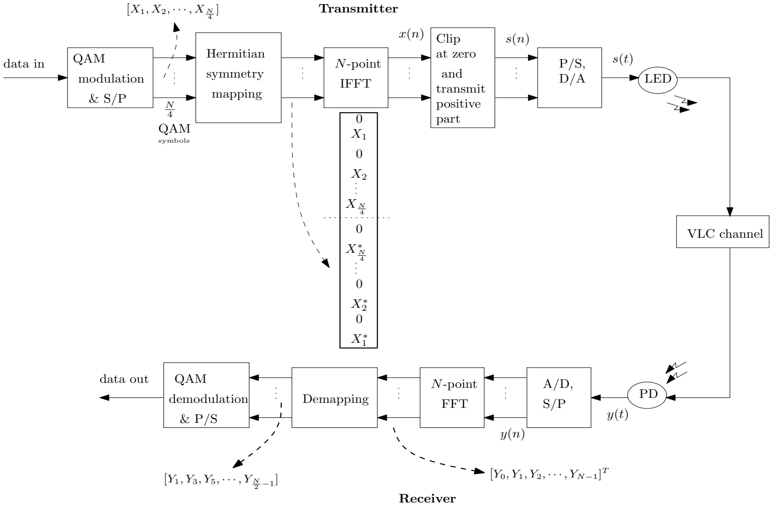
- $\frac{N}{2} - 1$ QAM symbols are modulated per OFDM symbol
- The unipolar OFDM signal $x_{dc}(t)$ is given by

$$x_{dc}(t) = x(t) + B_{dc}$$

  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

$$\begin{aligned} \eta_{dco} &= \frac{\frac{N}{2} - 1}{N} \log_2 M \\ &\approx \frac{1}{2} \log_2 M \text{ bpcu, for large} N \end{aligned}$$

ACO OFDM



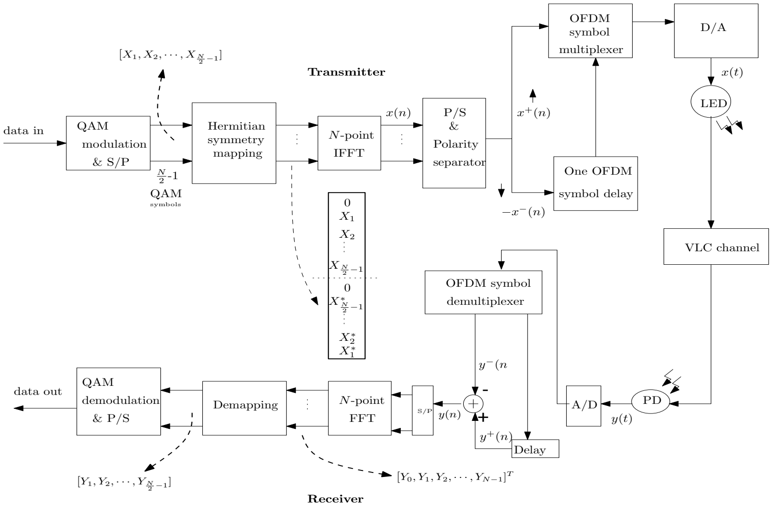
J. Armstrong and B. J. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN," *IEEE Commun. Letters*, vol. 12, no. 5, pp. 343-345, May 2008.

ACO OFDM

- $\frac{N}{4}$ 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

$$\eta_{aco} = \frac{1}{4} \log_2 M \text{ bpcu}$$

Flip OFDM



N. Fernando, Y. Hong, and E. Viterbo, "Flip-OFDM for unipolar communication systems," *IEEE Trans. Commun.*, vol. 60, no. 12, pp. 3726-3733, Aug. 2012.

- $\frac{N}{2} - 1$ 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

$$\begin{aligned} \eta_{flip} &= \frac{\frac{N}{2} - 1}{2N} \log_2 M \\ &\approx \frac{1}{4} \log_2 M \quad \text{bpcu, for large } N \end{aligned}$$

DCO, ACO, flip OFDM performance

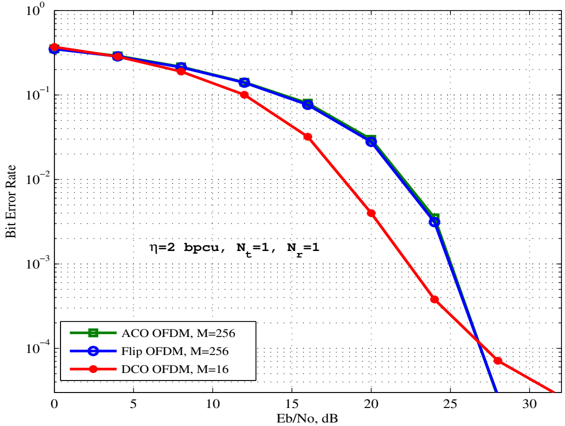


Figure : Comparison of the BER performance of ACO OFDM, flip OFDM, and DCO OFDM with 7dB bias for $\eta = 2$ bpcu, $N_t = N_r = 1$.

DCO OFDM performance for varying DC bias

- Optimum DC bias

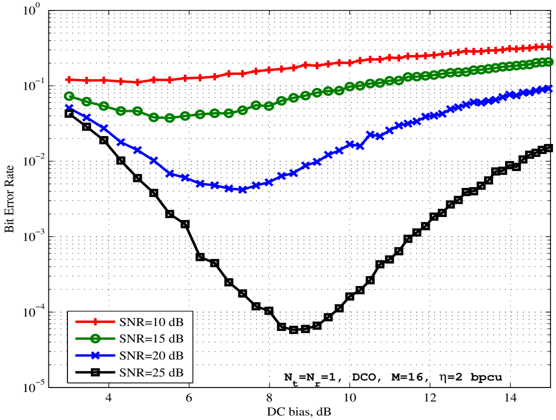
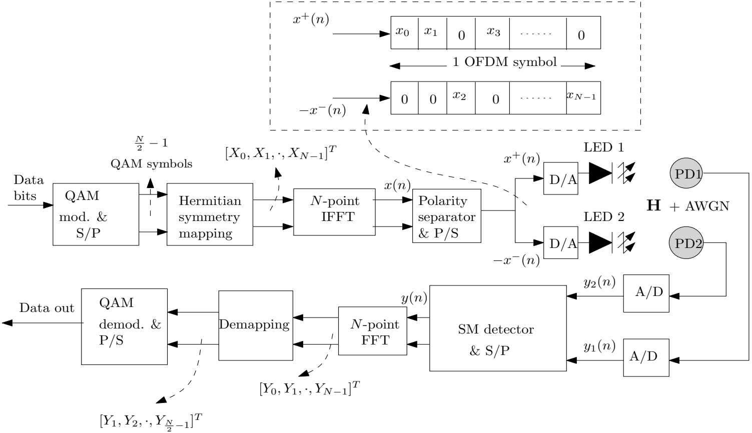


Figure : BER performance of DCO OFDM as a function of DC bias with $\eta = 2$ bpcu, $M = 16$, and $N_t = N_r = 1$, for SNR = 10, 15, 20, 25 dB.

NDC OFDM



- $\eta_{\text{ndc}} = \frac{\frac{N}{2}-1}{N} \log_2 M \approx \frac{1}{2}\log_2 M$ bpcu, for large N

Y. Li, D. Tsonev, and H. Haas, “Non-DC-biased OFDM with optical spatial modulation,” IEEE PIMRC 2013, pp. 486-490, Sep. 2013.

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

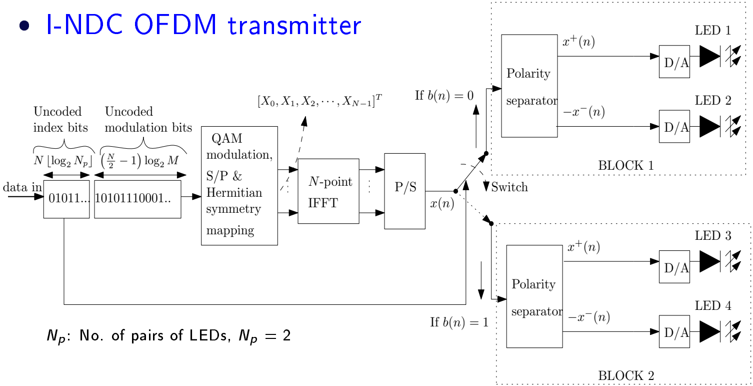
$$
\begin{aligned}
|y(n)| &= \max_{i=1,2} |z_i(n)| \\
\text{sign}\{y(n)\} &= \begin{cases} +\text{ve}, & \text{if } \arg\max_{i=1,2} |z_i(n)| = 1 \\ -\text{ve}, & \text{if } \arg\max_{i=1,2} |z_i(n)| = 2, \end{cases}
\end{aligned}
$$

where

$$
\begin{bmatrix} z_1(n) \\ z_2(n) \end{bmatrix} = \begin{bmatrix} \left(\mathbf{h}_1^T \mathbf{h}_1\right)^{-1} \mathbf{h}_1^T \; \mathbf{y} \\ \left(\mathbf{h}_2^T \mathbf{h}_2\right)^{-1} \mathbf{h}_2^T \; \mathbf{y} \end{bmatrix},
$$

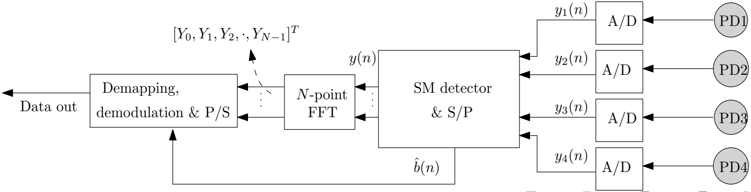
and $\mathbf{h}_i$ is the ith column of channel matrix $\mathbf{H}$, $\; i = 1, 2$.

- I-NDC OFDM transmitter



N_p: No. of pairs of LEDs, $N_p = 2$

- I-NDC OFDM receiver



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

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

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

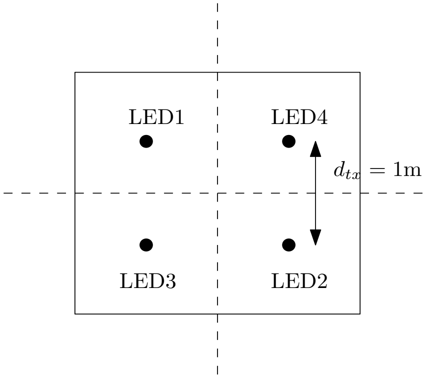
where

$$\begin{bmatrix} z_1(n) \\ z_2(n) \\ z_3(n) \\ z_4(n) \end{bmatrix} = \begin{bmatrix} \left(\mathbf{h}_1^T \mathbf{h}_1\right)^{-1} \mathbf{h}_1^T \ \mathbf{y} \\ \left(\mathbf{h}_2^T \mathbf{h}_2\right)^{-1} \mathbf{h}_2^T \ \mathbf{y} \\ \left(\mathbf{h}_3^T \mathbf{h}_3\right)^{-1} \mathbf{h}_3^T \ \mathbf{y} \\ \left(\mathbf{h}_4^T \mathbf{h}_4\right)^{-1} \mathbf{h}_4^T \ \mathbf{y} \end{bmatrix},$$

and $\mathbf{h}_i$ is the ith column of channel matrix $\mathbf{H}$, $i = 1, 2, 3, 4$.

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

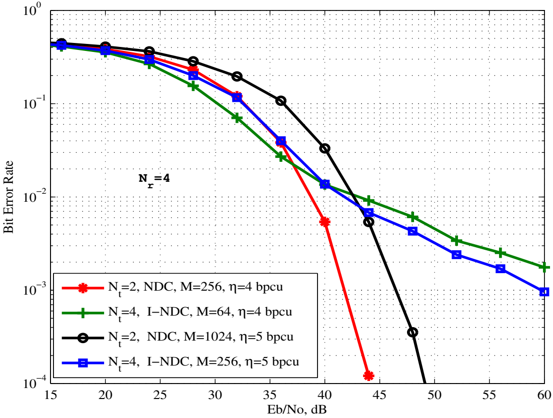


Figure : BER performance of I-NDC OFDM and NDC OFDM for $\eta = 4,\ 5$ bpcu, $N_r = 4$

NDC OFDM and I-NDC OFDM performance

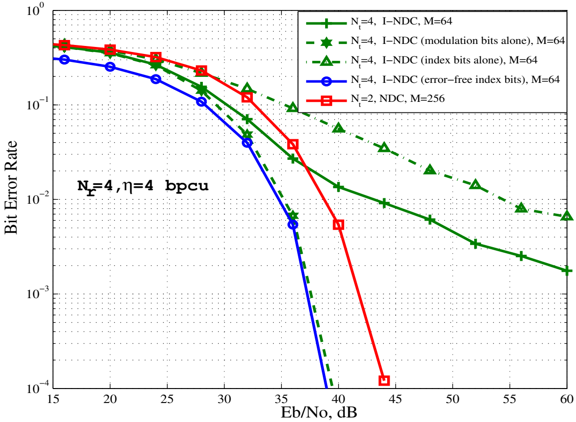
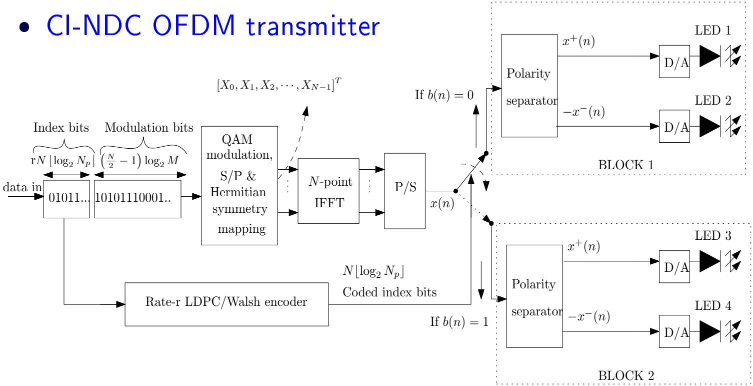


Figure : Reliability of modulation bits and index bits in I-NDC OFDM for $\eta = 4$ bpcu, $N_r = 4$

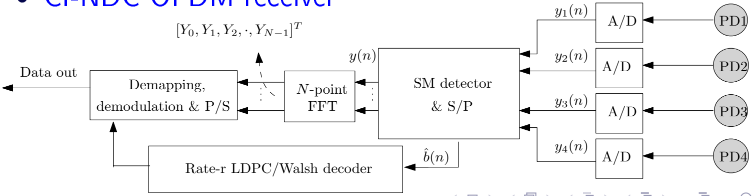
- Reliability of index bits is poor!
- Use coding for index bits

Coded I-NDC OFDM

- CI-NDC OFDM transmitter



- CI-NDC OFDM receiver



CI-NDC OFDM performance

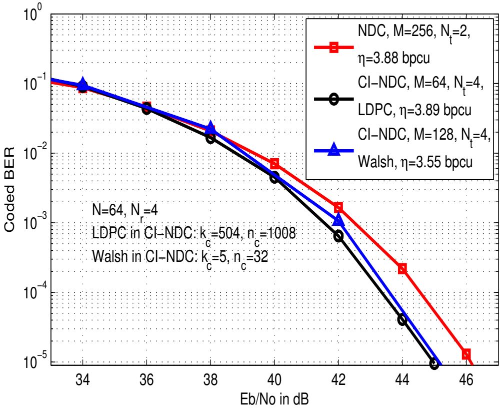


Figure : BER performance of CI-NDC OFDM and NDC OFDM at $\eta = 3.8$ bpcu, $N_r = 4$

- 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

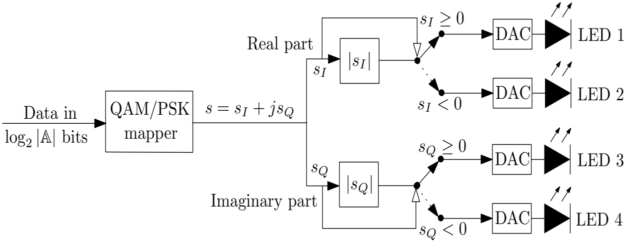
R. Tejaswi, T. Lakshmi Narasimhan, A. Chockalingam, "Quad-LED complex modulation (QCM) for visible light wireless communications" IEEE WCNC'16 Workshop on Optical Wireless Commun., Apr. 2016.

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

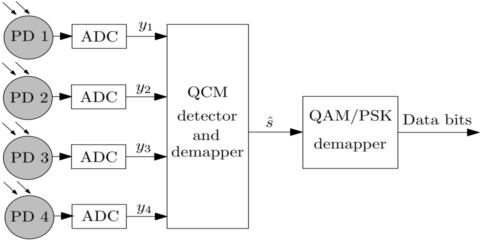
Real part s_I	Status of LEDs	Imag. part s_Q	Status of LEDs
≥ 0	LED1 emits $\lvert s_I \rvert$ LED2 is OFF	≥ 0	LED3 emits $\lvert s_Q \rvert$ LED4 is OFF
< 0	LED1 is OFF LED2 emits $\lvert s_I \rvert$	< 0	LED3 is OFF LED4 emits $\lvert s_Q \rvert$

- Example:
  - If $s = -3 + \text{j}1$, 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

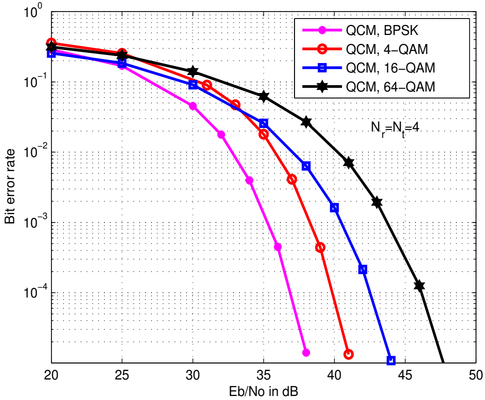
- QCM transmitter



- QCM receiver



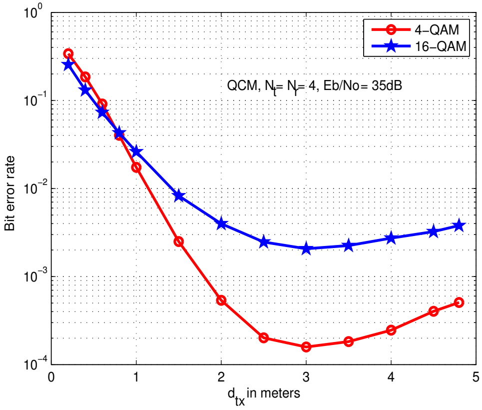
QCM performance



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

QCM performance

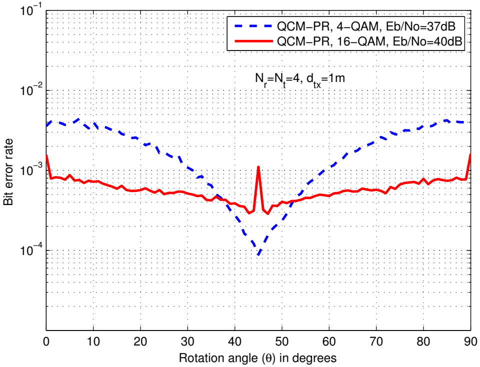
- Effect of varying LED spacing (d_{tx})



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

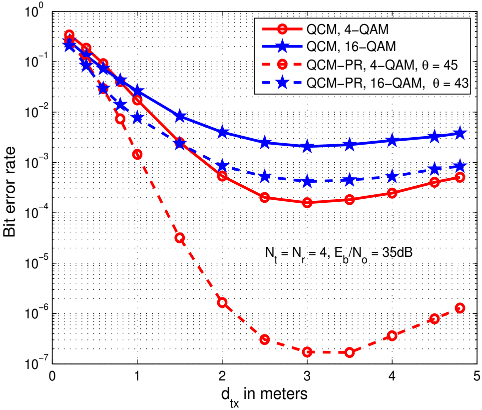
QCM with phase rotation

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

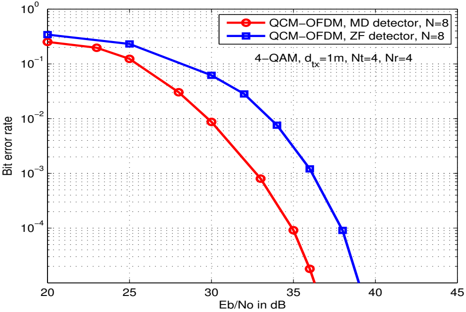


- Phase rotation helps. There is optimum rotation.

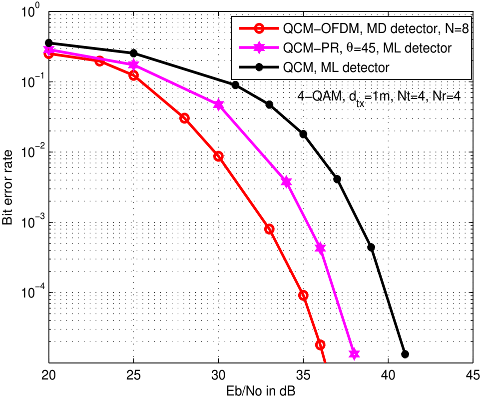
- Performance of QCM and QCM-PR (with optimum rotation) as a function of d_{tx}



- 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

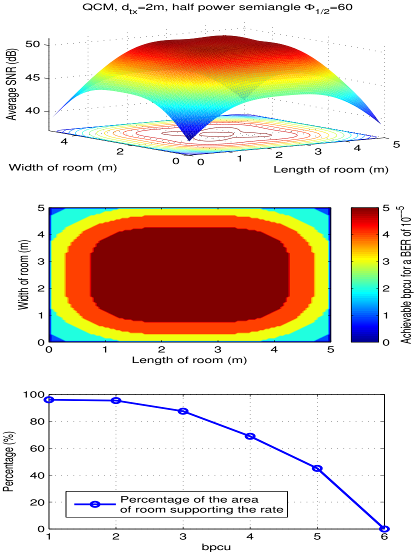


- Performance comparison between QCM, QCM-PR, QCM-OFDM



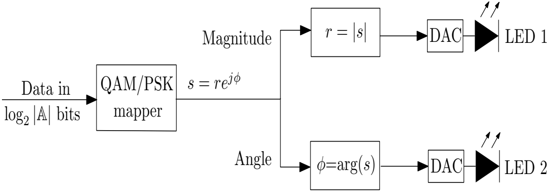
Achievable rate contours in QCM

- 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 $s = re^{j\phi}, \quad r \in \mathbb{R}^+, \quad \phi \in [0, 2\pi)$
  - only two LEDs suffice
  - no sign information to convey
- The 2×1 DCM tx. vector is $\mathbf{x} = [r \ \phi]^T$
- DCM transmitter:



T. Lakshmi Narasimhan, R. Tejaswi, and A. Chockalingam, "Quad-LED and Dual-LED complex modulation for visible light communications" arXiv:1510.08805v2 [cs.IT] 2 May 2016.

- DCM signal detection
  - The $N_r \times 1$ received signal vector is

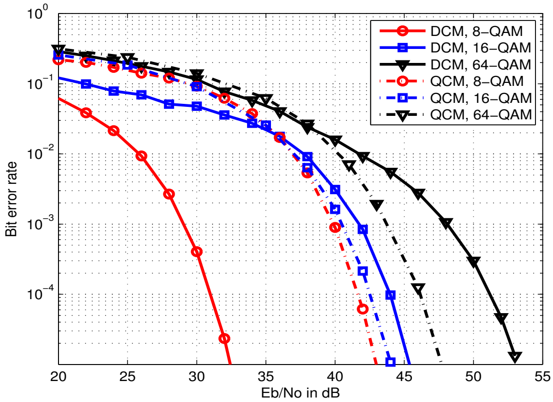
$$\mathbf{y} = r\mathbf{H}\mathbf{x} + \mathbf{n}$$

  - ML estimate of the transmit vector $\mathbf{x}$ is

$$\hat{\mathbf{x}}_{ML} = \underset{\mathbf{x}\in\mathbb{S}_D}{\text{argmin}} \, \|\mathbf{y} - r\mathbf{H}\mathbf{x}\|^2$$

    $\mathbb{S}_D$: DCM signal set (all possible tx. vectors $\mathbf{x}$)
  - $\hat{\mathbf{x}}_{ML}$ 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)

Performance of QCM and DCM



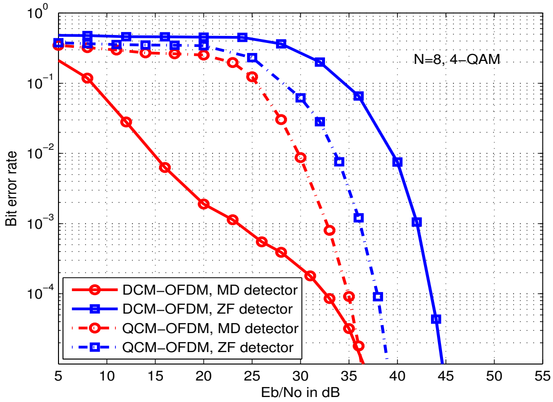
- For small sized QAM (8-QAM), DCM performs better than QCM
- For larger sized QAM (16-QAM, 64-QAM), QCM performs better

Performance of QCM and DCM

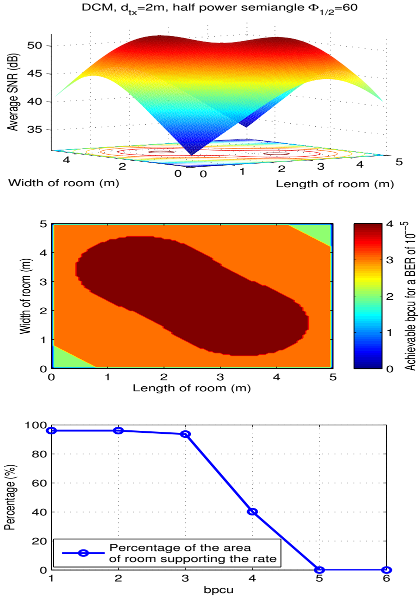
Modulation alphabet	DCM	QCM	QCM-PR
8-QAM	29.2 dB	39.8 dB	39.2 dB
16-QAM	41.8 dB	40.6 dB	38.6 dB
32-QAM	45.5 dB	41.8 dB	40 dB
64-QAM	48.2 dB	43.7 dB	40.2 dB

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



Achievable rate contours in DCM

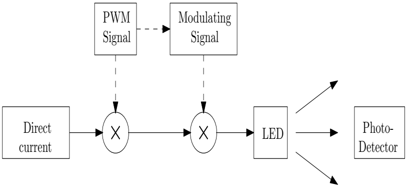


VLC with lighting constraints

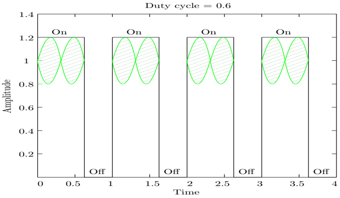
VLC with dimming support

- 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)



(a)

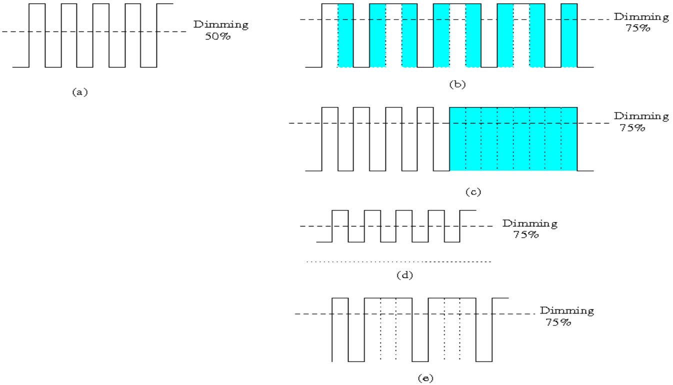


(b)

Z. Wang. W-D. Zhong, C. Yu, J. Chen, C. P. S. Francois, and W. Chen, Performance of dimming control scheme in visible light communication system, Optics Express, vol. 20, no. 17, pp. 18861-18868 (2012).

T. D. C. Little and H. Elgala, Adaptation of OFDM under visible light communications and illumination constraints, Asilomar Conf. Signals, Systems, and Computers, pp. 1739-1744, 2014.

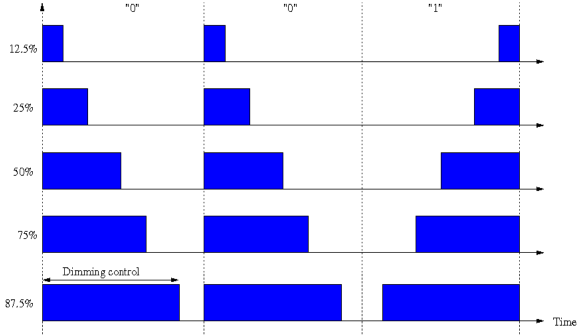
- Examples of dimming support
  - TD approach: (b) intra-pulse insertion; (c) inter-pulse padding (IEEE 802.15.7 OOK mode uses this)
  - ID approach: (d) bias-scaling; (e) distribution adaptation



S. H. Lee, S-Y. Jung, and J. K. Kwon, Modulation and coding for dimmable visible light communication, IEEE Commun. Mag., pp. 136-142, Feb. 2015.

VLC with dimming support

- PPM to support dimming control



- other PPM variants (MPPM, OPPM, VPPM)

S. Arnon, Ed., Visible light communication, Cambridge Univ. Press, 2015.

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)

A-M. Cailean, B. Cagneau, L. Chassagne, V. Popa, and M. Dimian, "A survey on the usage of DSRC and VLC in communication-based vehicle safety applications," Proc. IEEE Symp. on Commun. and Veh. Tech. (SCVT), pp. 69-74, Nov. 2014.

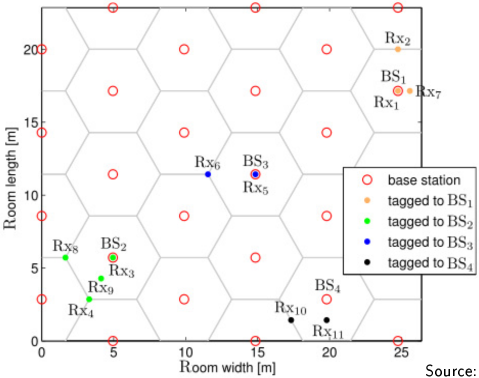
- IEEE 802.11p (DSRC: Dedicated Short Range Communication)
  - standard for RF wireless access in vehicular environments
  - based on IEEE 802.11a
  - 75 MHz allotted in 5.9 GHz
  - rates: 3-27 Mbps; MAC: CSMA/CA; range: up to 1 Km
- Issues in DSRC
  - high traffic densities (numerous packet collisions,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

Optical attocells

- An example optical attocell network
  - Room size: 24m × 23m × 3m
  - No. of cells: 27; Cell radius: 3.3 m

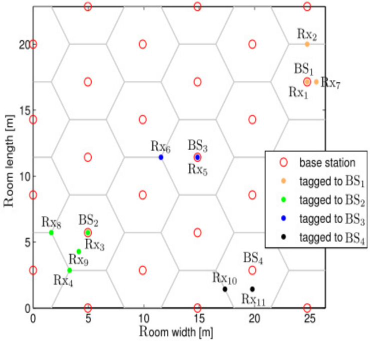


Source: Ref. [1]

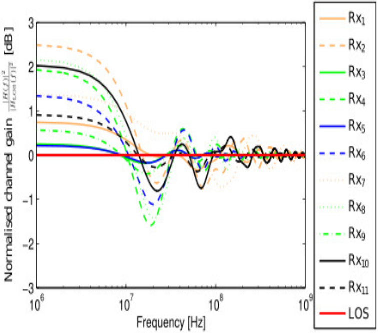
[1] C. Chen, S. Videv, D. Tsonev, and H. Hass, Fractional frequency reuse in DCO-OFDM-based optical attocell networks, Jl. of Lightwave Tech., vol. 33, no. 19, pp. 3989-4000, Oct. 2015.

Optical attocells

- Channel response at different receiver locations



(c)



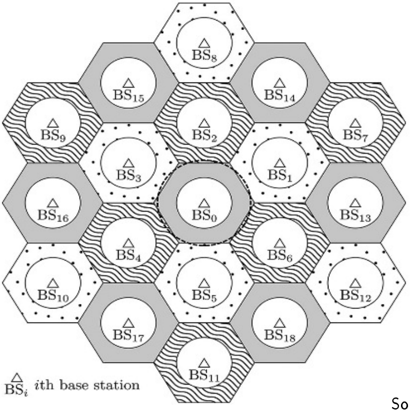
(d)

Source: Ref. [1]

- 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



Source: Ref. [1]

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

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