Part I: LiFi (Visible Light Communication)
LEDs and photo diodes
VLC characteristics
MIMO and OFDM in VLC
QCM and DCM for VLC
Part II: RF Mirrors (Media-Based Modulation)
Concluding Remarks

LiFi, Mirrors, and Wireless Communications

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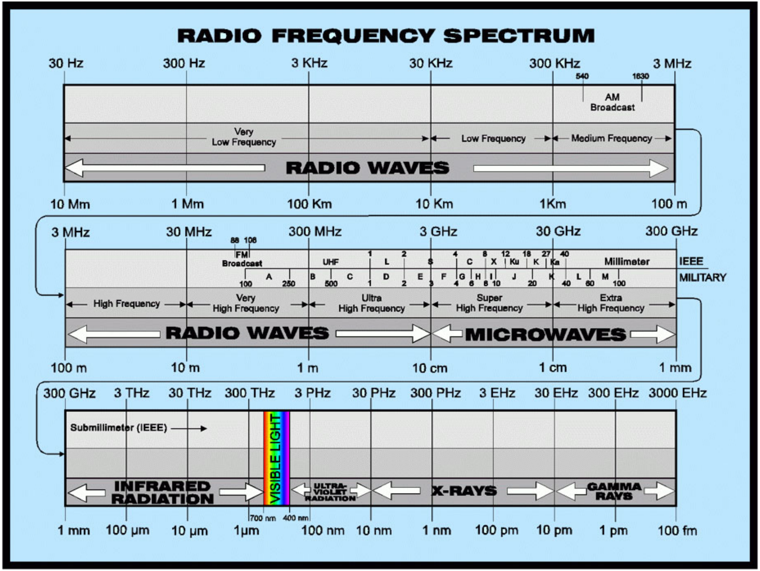
Outline

1. Part I: LiFi (Visible Light Communication)
2. Part II: RF Mirrors (Media-Based Modulation)
3. Concluding Remarks

Wireless spectrum

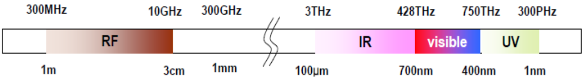


Source: Internet

Part I
LiFi (Visible Light Communication)

Optical wireless

- 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

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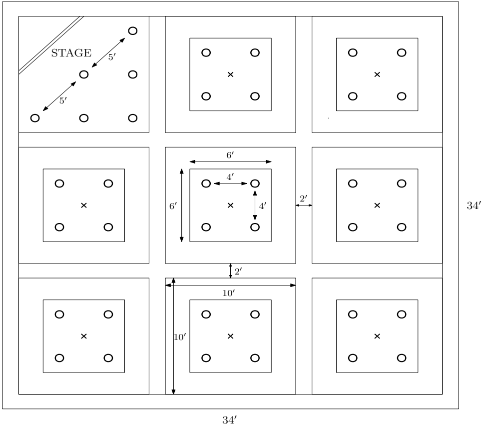
- Target for 2020: 200 lm/W
    - claimed to have been breached! 208 lm/W LED (prototype)

Why LEDs?

- Lighting arrangement in Golden Jubilee Seminar Hall, ECE, IISc



- Off-stage
  - 32 bulbs (20 W bulbs previously; now replaced with 5 W LED bulbs)
- On-stage
  - 6 bulbs (60 W bulbs previously; now replaced with 18 W LED bulbs)

LEDs

- Luminous flux through spectral integration

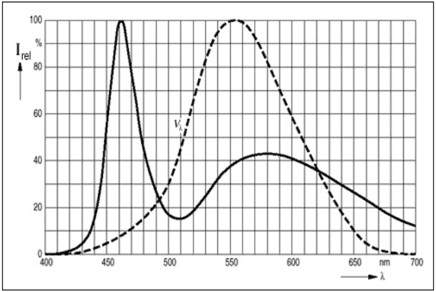


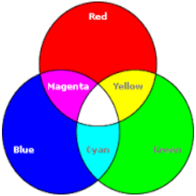
Image source: Internet

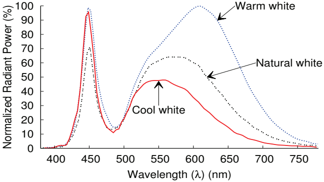
- Spectral power distribution of LED, $S_T(\lambda)$, (watts/nm) (solid curve)
- Spectral sensitivity of human eye (luminosity fn.), $V(\lambda)$ (dashed curve)
- Luminous flux, F_T (lumens):

$$F_T = 683(lumens/watt)\int_{380nm}^{780nm} S_T(\lambda)V(\lambda)d\lambda$$

LEDs

- Color temperature:
  - different shades of white





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

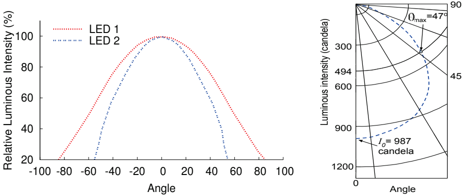
Image source: Internet

LEDs

Image source: Internet

LEDs

- Luminous flux through spatial integration



(a) (b)

Source: Pathak et al., IEEE Comm. Surv. & Tuts., 2015

- Luminous intensity, $g_t(\theta)$
    - Luminous flux per unit solid angle (in a specific direction)
    - Unit of LI: Candela (Lumens/Steradian); cd (lm/sr)
    - Most LEDs have Lambertian beam distribution
        - intensity drops as the cosine of the incident angle; $g_t(\theta) = \cos^n \theta$
    - Axial intensity, I_0: LI in candelas at 0° solid angle
    - Half beam angle, θ_{max}: angle at which LI decreases to $I_0/2$

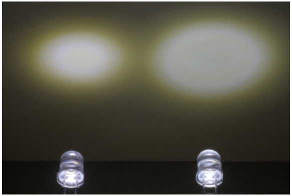
LEDs

- Solid angle (in steradians) of a cone with apex angle θ ($= 2\theta_{max}$ in degrees), $\Omega_{max} = 2\pi(1 - \cos\frac{\theta^\circ}{2})$; i.e., $\text{cd} = \text{lm}/(2\pi(1 - \cos\frac{\theta^\circ}{2}))$
- Luminous flux, F_T:

$$F_T = \int_0^{\Omega_{max}} I_0 g_t(\theta) d\Omega = \int_0^{\theta_{max}} 2\pi I_0 g_t(\theta) \sin\theta d\theta$$

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

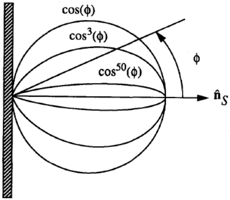
(e)



(f)

Image source: Internet

LEDs



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

Generalized Lambertian radiation pattern of LED

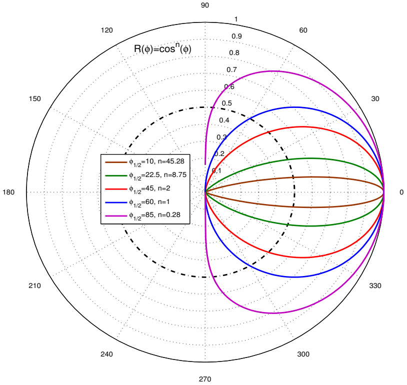
- n is the mode number of the radiating lobe given by

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

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

LEDs

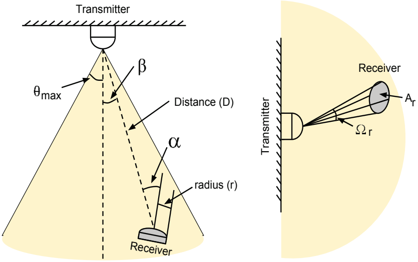
- Generalized Lambertian radiation pattern



Generalized Lambertian radiation pattern of LED

Path loss

- Path loss
  - ratio of luminous flux at the Rx and Tx, $L_L = \frac{F_R}{F_T}$
  - need to specify the relative positions of the Tx and Rx

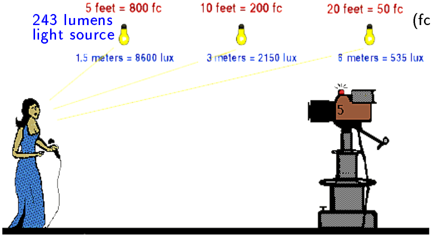


Source: Pathak et al., IEEE Comm. Surv. & Tuts., 2015

- $F_R = I_0 g_t(\beta)\Omega_r; \quad A_r \cos\alpha = D^2\Omega_r$
- $L_L = \frac{F_R}{F_T} = \frac{I_0 g_t(\beta) A_r \cos\alpha / D^2}{\int_0^{\theta_{max}} 2\pi I_0 g_t(\theta)\sin\theta d\theta} = \frac{(n+1)A_r}{2\pi D^2}\cos\alpha\cos^n\beta$

LEDs

- Illuminance:
    - measure of how much luminous power is incident on a given area
    - SI unit of illuminance: Lux (lx)
    - Lux: Lumens per square meter (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) × $4\pi d^2$ (d: distance from source in meters)

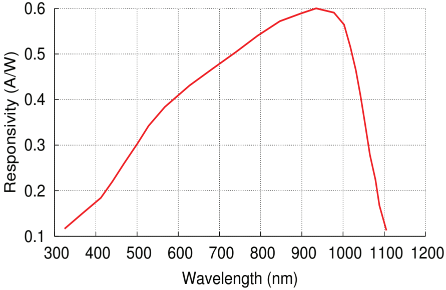


(fc: foot-candles)

Image source: Internet

Photo diodes

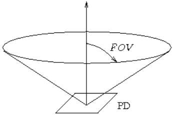
- Photo diode
    - Semiconductor (e.g., Si, Ge) device that converts light into current (may contain optical filters, built-in lenses)
    - Spectral response, $R(\lambda)$: (responsivity, Amperes/Watt)



- LOS optical received power $P_{R_o} = \int_{\lambda_{rL}}^{\lambda_{rH}} S_R(\lambda)R(\lambda)d\lambda$, where $S_R(\lambda) = L_L S_T(\lambda)$

Photo diodes

- Field of view (FOV): angle (e.g., 85°)



  - only the rays coming within FOV create response
  - accounting for FOV, L_L is

    $$L_L = \frac{(n+1)A_r}{2\pi D^2} \cos\alpha \cos^n\beta \, \mathrm{rect}\left(\frac{\alpha}{FOV}\right)$$

- Response/rise time (t_r):
  - determined by resistance and capacitance of the photo diode and external circuitry (typ. tens of nsec)
  - determines f_{bw}, the bandwidth available for signal modulation (and hence for data transmission)

- Modulation signal bandwidth:
  - $f_{bw} = \frac{0.35}{t_r}$; e.g., $t_r = 50$ ns $\Rightarrow f_{bw} = 7$ MHz

LEDs

- Switching speed (rise/fall times):
  - typ. tens of nsec
  - decides modulation signal bandwidth
  - 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

LEDs

- 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

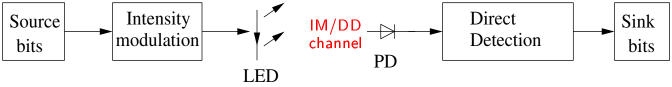
VLC characteristics

RFC vs VLC

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

IM/DD channel

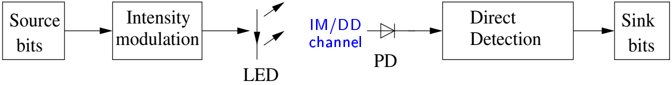
- VLC Tx-Rx



- 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

VLC Tx-Rx

- VLC Tx-Rx



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

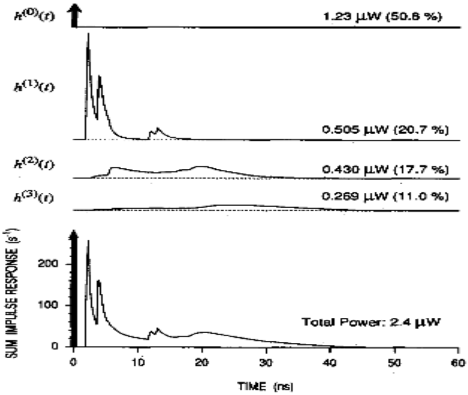
D.C.O'Brien *et al*, "Visible light communications: challenges and possibilities," *IEEE PIMRC'2008.*

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

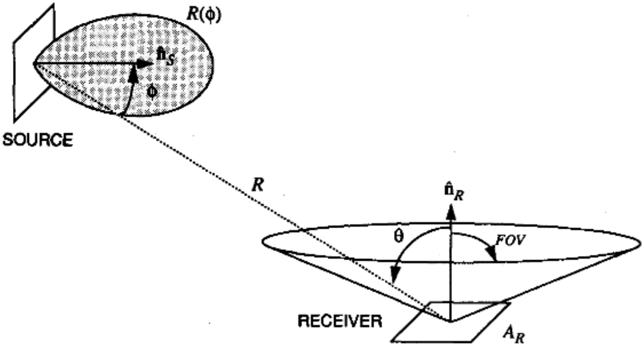
Others

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.

VLC channel

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

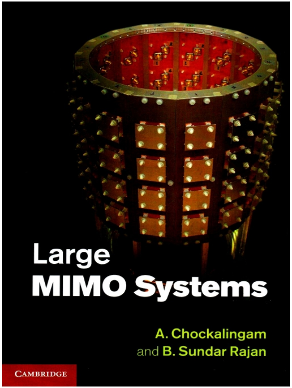
$$h_{ij} = \frac{n+1}{2\pi} \cos^n \phi \, \cos\theta \frac{A}{R^2} \text{rect}\left(\frac{\theta}{FOV}\right)$$

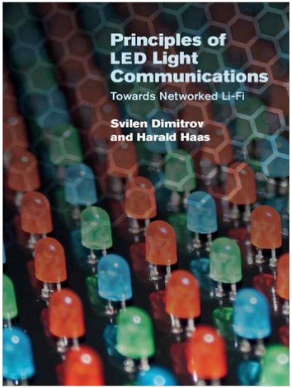


Geometry of LED source and photo detector

MIMO in VLC

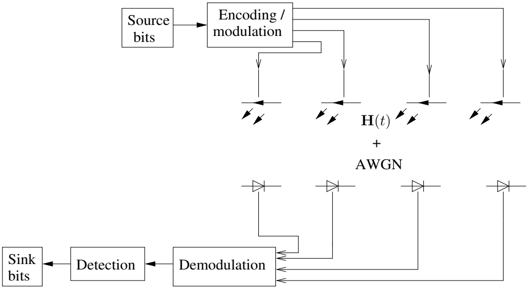
MIMO RFC and MIMO VLC


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


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

MIMO in VLC

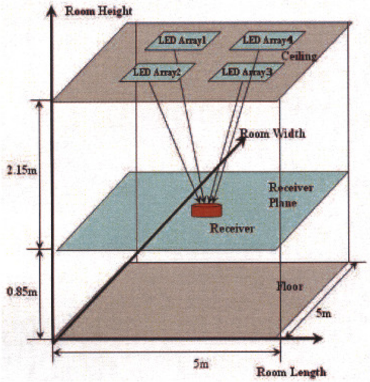
- Multiple LEDs and PDs
- N_t: no. of LEDs at Tx; N_r: no. of PDs at Rx



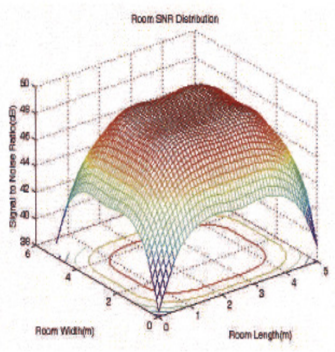
4 × 4 MIMO VLC

- 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



(i) Typical indoor VLC configuration

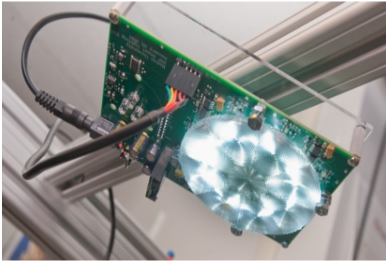


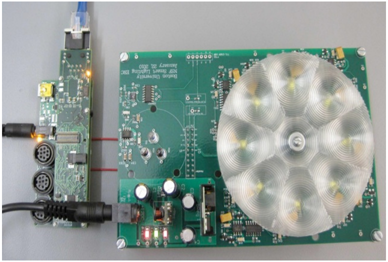
(j) SNR as a function of receiver position

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

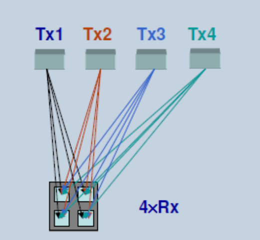
- 48-LED array

Source: Internet

VLC channel

- N_t LEDs (transmitter)
- N_r photo detectors (receiver)
- **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
  - $\eta_{gssk} = \lfloor \log_2 \binom{N_t}{N_a} \rfloor$ bpcu
- Generalized spatial modulation (GSM)
  - Generalization of SM
  - $N_a \leq N_t$ active LEDs
  - $\eta_{gsm} = \lfloor \log_2 \binom{N_t}{N_a} \rfloor + N_a \lfloor \log_2 M \rfloor$ 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.

MIMO VLC system model

- Each active LED emits an M-ary intensity modulation symbol $I_m \in \mathbb{M}$
  - $\mathbb{M}$: set of all possible intensity levels given by

$$I_m = \frac{2I_p m}{M+1}, \quad m = 1, 2, \cdots, M, \quad M = |\mathbb{M}|$$

- $\mathbf{x}$: $N_t \times 1$ transmit signal vector; $x_i \in \{\mathbb{M} \cup 0\}$
- $\mathbf{n}$: $N_r \times 1$ noise vector at the receiver; $n_i \sim \mathcal{N}(0, \sigma^2)$
- $\mathbf{n}$: $N_r \times 1$ received signal vector at the receiver

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

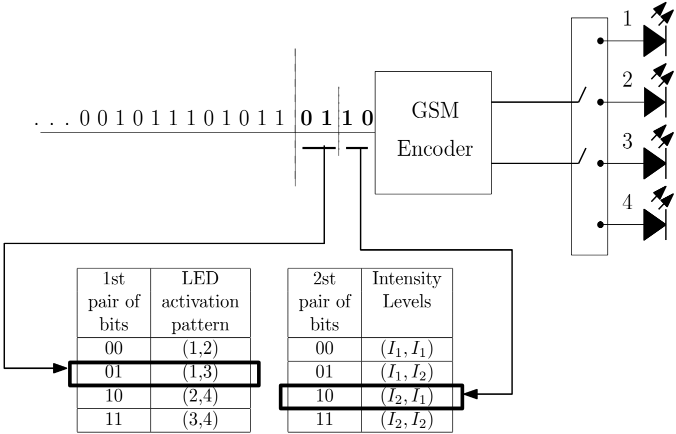
a: responsivity of the PD (Amp/Watt)

- Average received SNR

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

$\mathbf{h}_i$: 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 $N_t = 4, N_a = 2, M = 2$

GSM for VLC system

- 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:

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

$$\left. \begin{bmatrix} 0 \\ \frac{2}{3} \\ 0 \\ \frac{2}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ \frac{2}{3} \\ 0 \\ \frac{4}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ \frac{4}{3} \\ 0 \\ \frac{2}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ \frac{4}{3} \\ 0 \\ \frac{4}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \frac{2}{3} \\ \frac{2}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \frac{2}{3} \\ \frac{4}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \frac{4}{3} \\ \frac{2}{3} \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \frac{4}{3} \\ \frac{4}{3} \end{bmatrix} \right\}$$

Upper bound on BER

Maximum likelihood (ML) detection rule is

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

Pairwise error probability (PEP) is

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

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

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

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

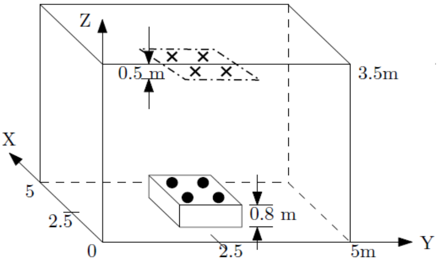
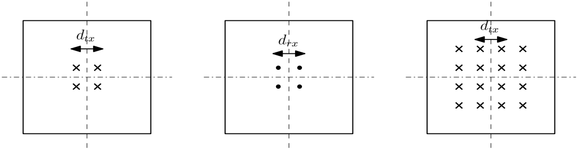


Figure : Geometric set-up of a typical indoor VLC system (× denotes an LED and ● denotes a PD)



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

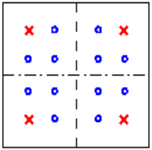
Placement of LEDs and PDs

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 Amp/Watt
	FOV	85°
	d_{rx}	0.1m

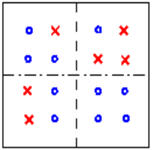
GSM performance

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



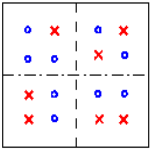
(d) GSM, 8 bpcu

$N_t = 4,\ N_a = 2,\ M = 8$



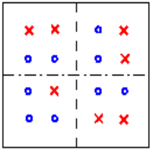
(e) GSM, 5 bpcu

$N_t = 6,\ N_a = 2,\ M = 2$



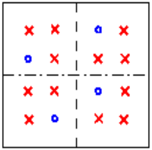
(f) GSM, 8 bpcu

$N_t = 7,\ N_a = 2,\ M = 4$



(g) GSM, 8 bpcu

$N_t = 7,\ N_a = 3,\ M = 2$



(h) GSM, 8 bpcu

$N_t = 12,\ N_a = 2,\ M = 2$

× indicates the presence of an LED. ○ indicates the absence of LED.

GSM performance

- Comparison of analytical upper bound and simulated BERs

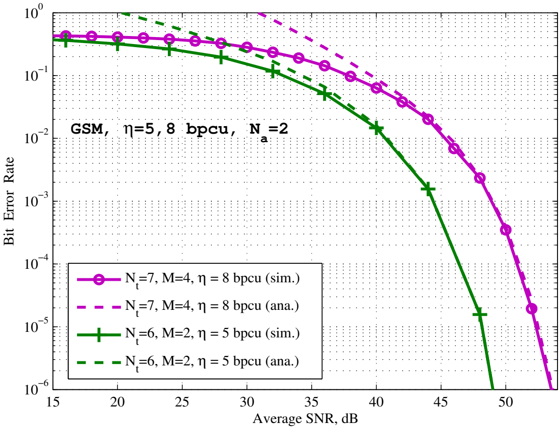


Figure : GSM with $N_t = 6, 7,\ N_a = 2,\ M = 2, 4,\ \eta_{gsm} = 5, 8$ bpcu.

GSM performance

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

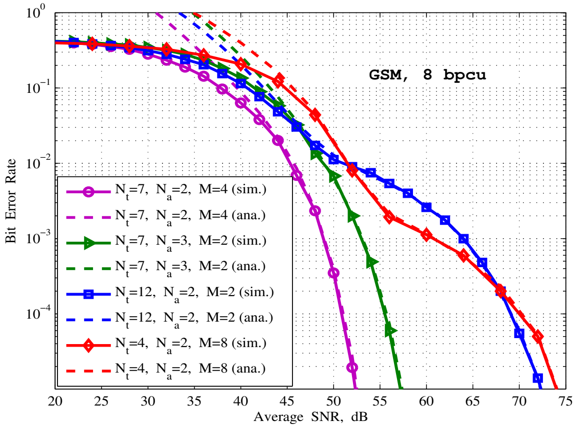


Figure : Comparison of the BER performance of different configurations of GSM with $\eta_{gsm} = 8$ bpcu, $N_r = 4$.

GSM performance for varying d_{tx}

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

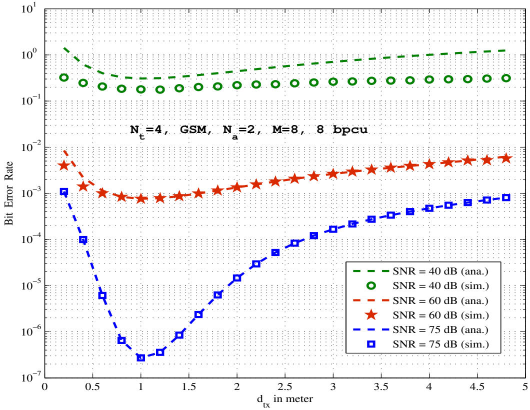
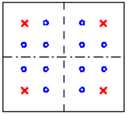


Figure : GSM with $N_t = 4$, $N_a = 2$, $M = 8$, $\eta_{gsm} = 8$ bpcu.

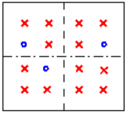
- Opposing effects of channel correlation and channel chains for increasing d_{tx} results in optimum d_{tx}

GSM vs other MIMO techniques

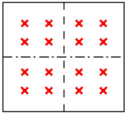
- SMP, GSSK, SM, and GSM with $\eta = 8\ bpcu$
- SMP:
  - $N_t = 4,\ N_a = 4,\ M = 4$



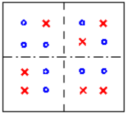
- GSSK:
  - $N_t = 13,\ N_a = 3,\ M = 1$



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

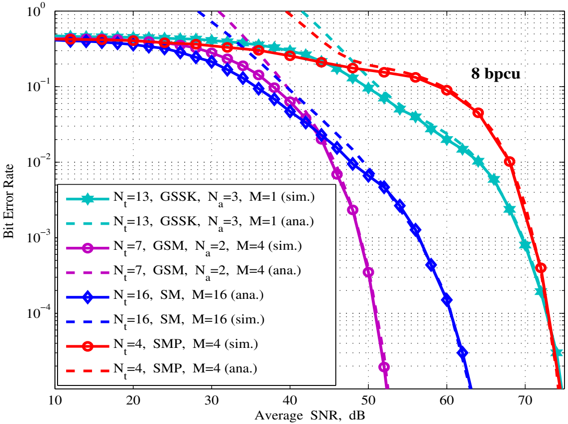


- GSM:
  - $N_t = 7,\ N_a = 2,\ M = 4$



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 in VLC

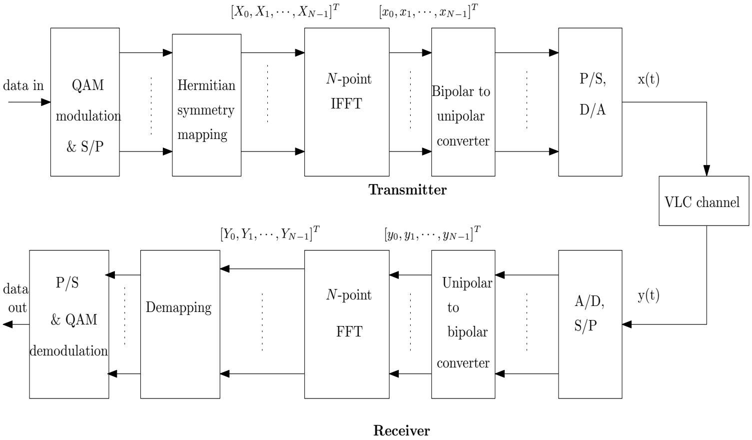
- OFDM
  - Popular in wired and wireless RF communications
  - Attractive in VLC as well
- OFDM in RF communications
  - OFDM signals are in the complex domain
  - Signals can be bipolar
- OFDM in VLC
  - VLC transmit signal must be real and positive
  - Use Hermitian symmetry on information symbols 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.

OFDM in VLC



$[X_0, X_1, \cdots, X_{N-1}]^T$ $[x_0, x_1, \cdots, x_{N-1}]^T$

data in

QAM modulation & S/P

Hermitian symmetry mapping

N-point IFFT

Bipolar to unipolar converter

P/S, D/A

x(t)

Transmitter

VLC channel

$[Y_0, Y_1, \cdots, Y_{N-1}]^T$ $[y_0, y_1, \cdots, y_{N-1}]^T$

data out

P/S & QAM demodulation

Demapping

N-point FFT

Unipolar to bipolar converter

A/D, S/P

y(t)

Receiver

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)

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

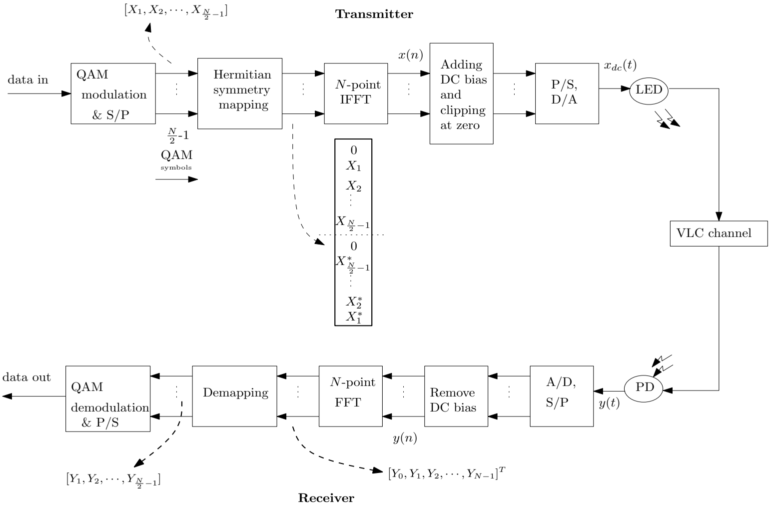
J. Armstrong and B. J. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN," *IEEE Commun. Letters*, vol. 12, no. 5, pp. 343-345, May 2008.

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

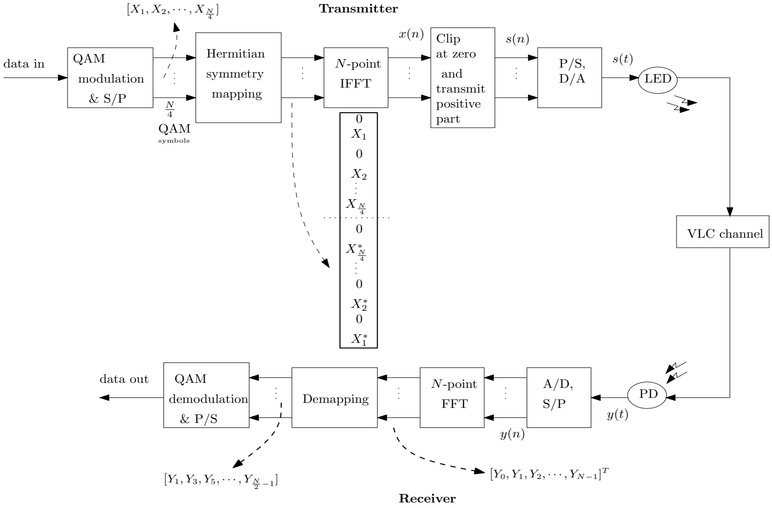
- $\frac{N}{2} - 1$ QAM symbols are modulated per OFDM symbol
- The unipolar OFDM signal $x_{dc}(t)$ is given by

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

  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



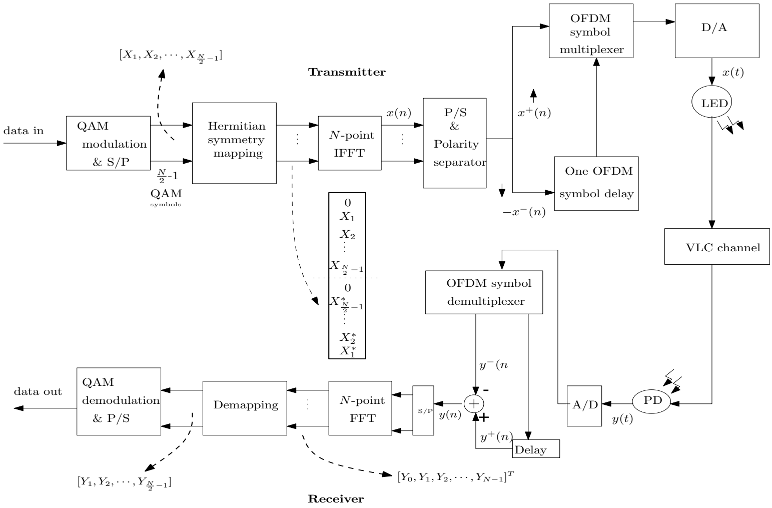
J. Armstrong and B. J. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN," *IEEE Commun. Letters*, vol. 12, no. 5, pp. 343-345, May 2008.

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

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

DCO, ACO, flip OFDM performance

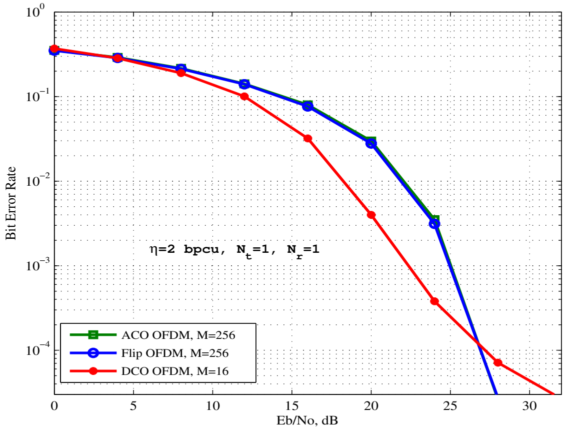


Figure : Comparison of the BER performance of ACO OFDM, flip OFDM, and DCO OFDM with 7dB bias for $\eta = 2$ bpcu, $N_t = N_r = 1$.

DCO OFDM performance for varying DC bias

- Optimum DC bias

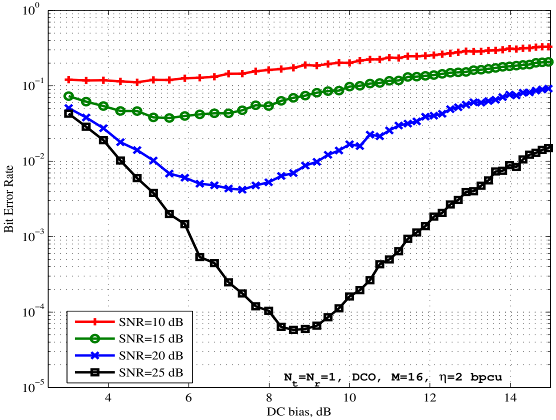
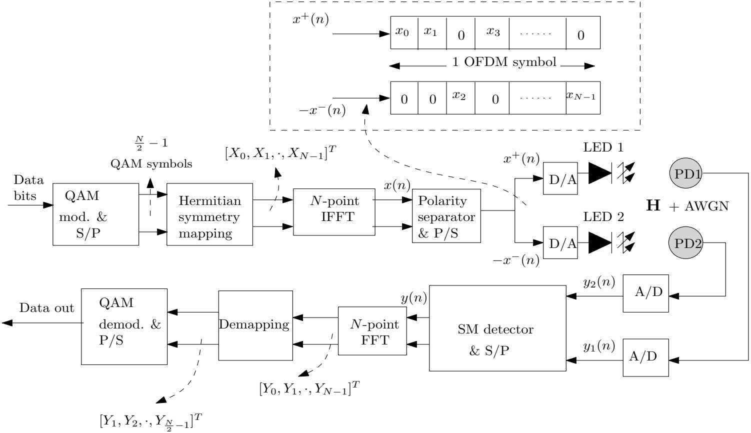


Figure : BER performance of DCO OFDM as a function of DC bias with $\eta = 2$ bpcu, $M = 16$, and $N_t = N_r = 1$, for SNR $= 10, 15, 20, 25$ dB.

NDC OFDM

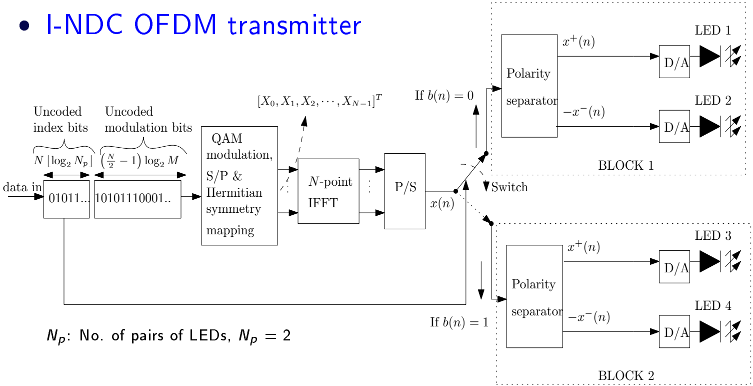


- $\eta_{\mathrm{ndc}} = \frac{\frac{N}{2}-1}{N} \log_2 M \approx \frac{1}{2} \log_2 M$ bpcu, for large N

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

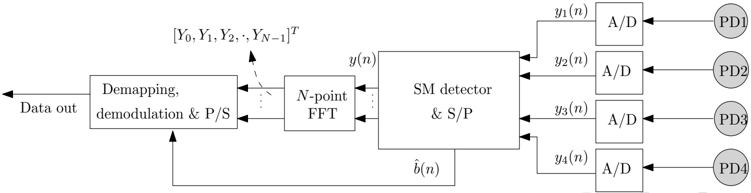
Indexed-NDC OFDM

- I-NDC OFDM transmitter



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

- I-NDC OFDM receiver



NDC OFDM and I-NDC OFDM performance

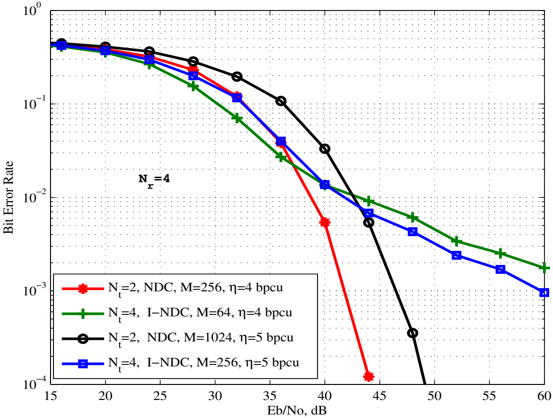


Figure : BER performance of I-NDC OFDM and NDC OFDM for $\eta = 4,\ 5$ bpcu, $N_r = 4$

NDC OFDM and I-NDC OFDM performance

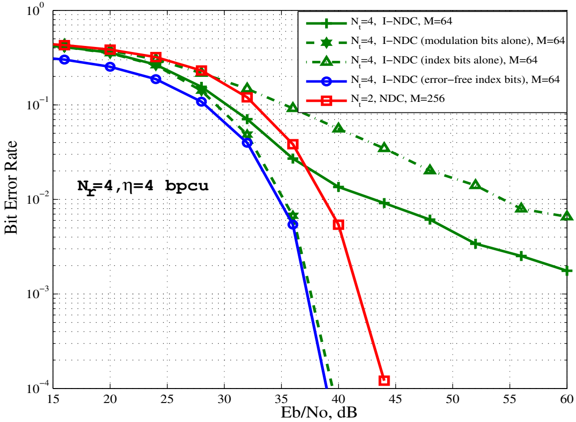
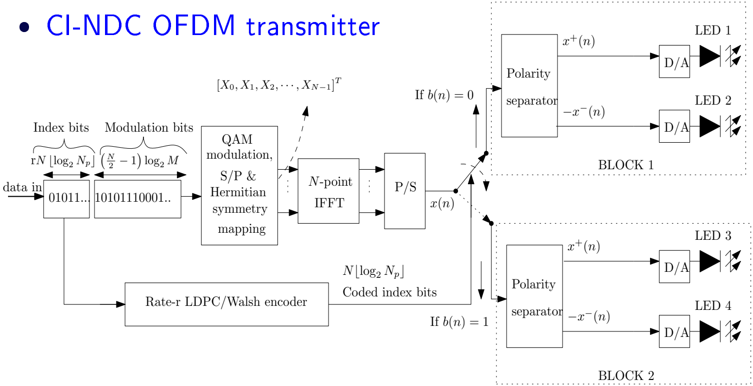


Figure : Reliability of modulation bits and index bits in I-NDC OFDM for $\eta = 4$ bpcu, $N_r = 4$

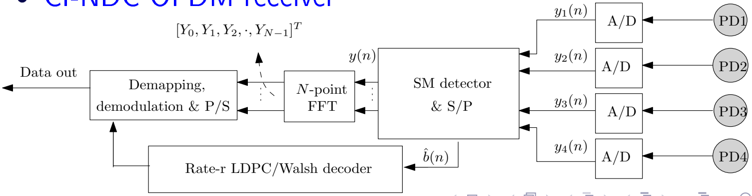
- Reliability of index bits is poor!
- Use coding for index bits

Coded I-NDC OFDM

- CI-NDC OFDM transmitter



- CI-NDC OFDM receiver



CI-NDC OFDM performance

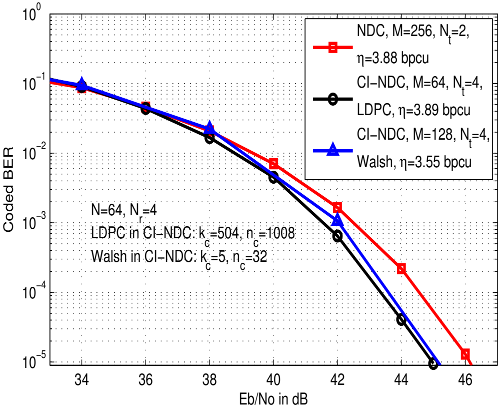


Figure : BER performance of CI-NDC OFDM and NDC OFDM at $\eta = 3.8$ bpcu, $N_r = 4$

- 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.

QCM for VLC

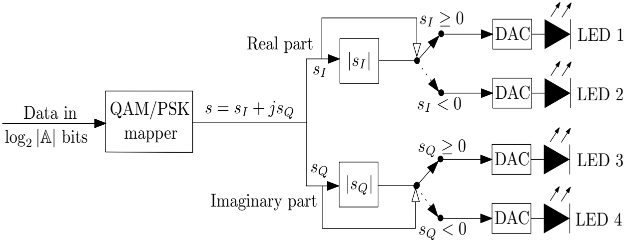
- Mapping of complex symbol $s = s_I + js_Q$ to LEDs activity in QCM

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 $\lvert s_Q \rvert$

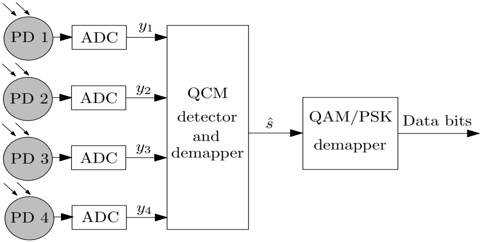
- Example:
  - If $s = -3 + \text{j}1$, then
    LED1: OFF; LED2: emits 3;
    LED3: emits 1; LED4: OFF
    Corresponding QCM tx. vector is $\mathbf{x} = [0\ 3\ 1\ 0]^T$
- Note:
  - Two LEDs (one among LED1 and LED2, and another one among LED3 and LED4) will be ON simultaneously. Other two LEDs will be OFF

QCM for VLC

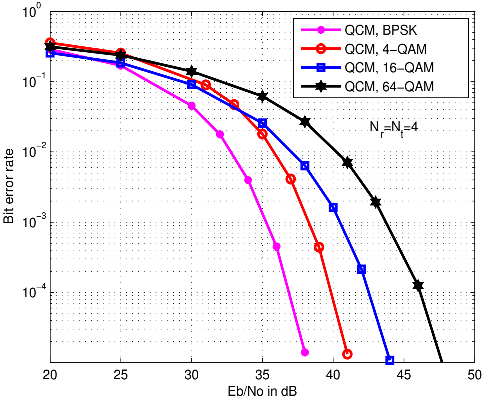
- QCM transmitter



- QCM receiver



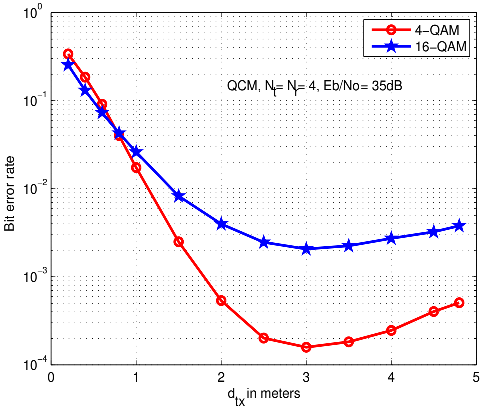
QCM performance



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

QCM performance

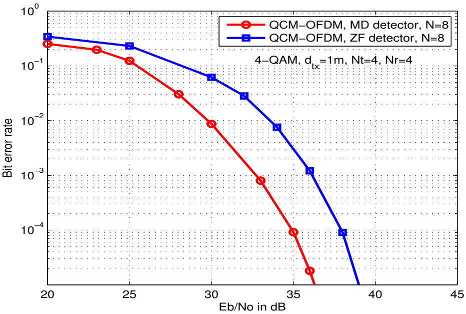
- Effect of varying LED spacing (d_{tx})



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

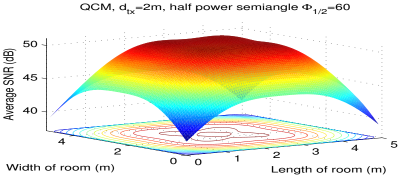
QCM-OFDM

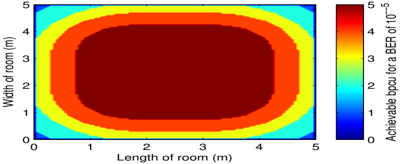
- OFDM signaling along with QCM (QCM-OFDM)
    - N complex symbols drive N-point IFFT
    - IFFT output vector (OFDM symbol) drives QCM transmitter block in N channel uses
    - QCM-OFDM signal detection
        - Zero-forcing (ZF), minimum distance (MD) detectors
    - Performance of QCM-OFDM

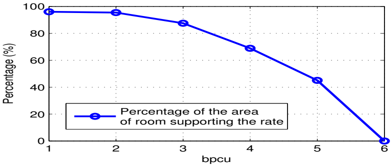


Achievable rate contours in QCM

- 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

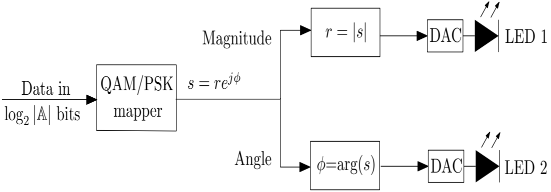






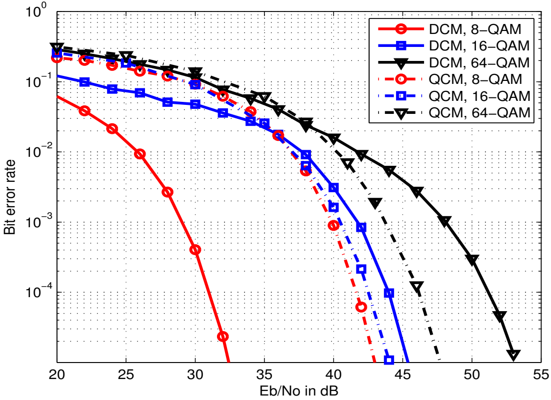
Dual-LED complex modulation (DCM)

- 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:



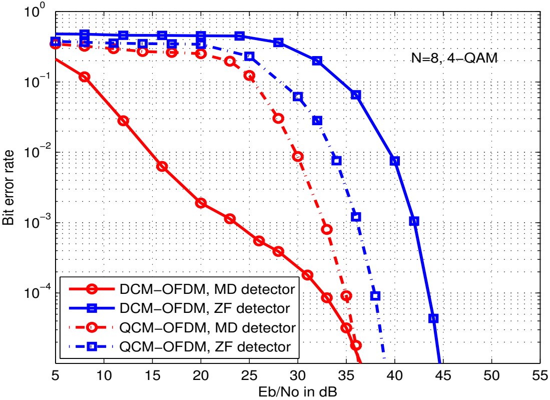
T. Lakshmi Narasimhan, R. Tejaswi, and A. Chockalingam, "Quad-LED and Dual-LED complex modulation for visible light communications" arXiv:1510.08805v2 [cs.IT] 2 May 2016.

Performance of QCM and DCM

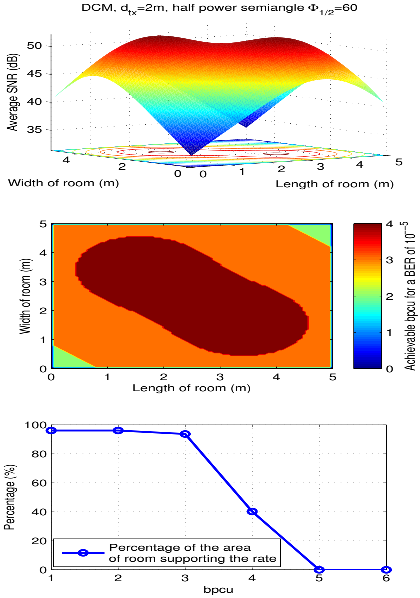


- For small sized QAM (8-QAM), DCM performs better than QCM
- For larger sized QAM (16-QAM, 64-QAM), QCM performs better

Performance of QCM-OFDM and DCM-OFDM



Achievable rate contours in DCM

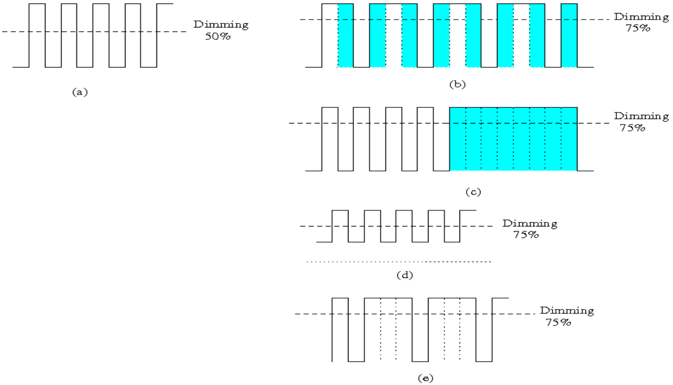


VLC with dimming support

- 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

VLC with dimming support

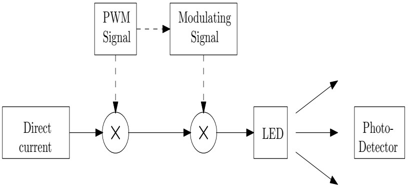
- Examples of dimming support
  - TD approach: (b) intra-pulse insertion; (c) inter-pulse padding (IEEE 802.15.7 OOK mode uses this)
  - ID approach: (d) bias-scaling; (e) distribution adaptation



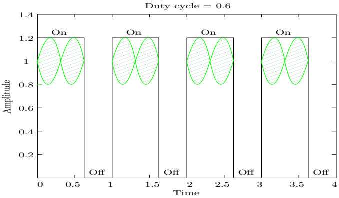
S. H. Lee, S-Y. Jung, and J. K. Kwon, Modulation and coding for dimmable visible light communication, IEEE Commun. Mag., pp. 136-142, Feb. 2015.

VLC with dimming support

- 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.

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.

Outdoor VLC

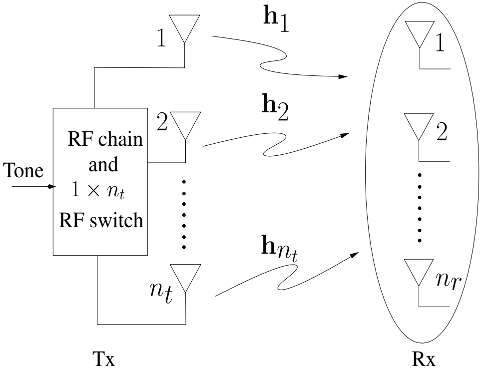
- IEEE 802.11p (DSRC: Dedicated Short Range Communication)
    - standard for RF wireless access in vehicular environments
    - based on IEEE 802.11a
    - 75 MHz allotted in 5.9 GHz
    - rates: 3-27 Mbps; MAC: CSMA/CA; range: up to 1 Km
- Issues in DSRC
    - high traffic densities (numerous packet collisions, delay)
- Vehicular VLC can play a complementary role to DSRC
- IEEE 802.15.7 VLC standard - PHY I
    - intended for outdoor, long-range, low data rate applications such as I2V and V2V communication
- VLC is still an early stage technology for usage in ITS

Part II
RF Mirrors (Media-Based Modulation)

Modulation approaches

- Conventional view
  - Symbols from complex modulation alphabet (e.g., QAM/PSK) convey information bits
  - Channel fades viewed as causing amplitude/phase distortion to transmitted symbols
- Alternate view
  - View complex channel fade coefficients themselves to constitute a modulation alphabet
  - Example:
    - Space shift keying (SSK)

Space shift keying



- # tx. antennas, $n_t > 1$; # tx. RF chains, $n_{rf} = 1$
- Constellation: $\mathbb{H}_{\text{ssk}} = \{\mathbf{h}_1, \mathbf{h}_2, \cdots, \mathbf{h}_{n_t}\}$

Y. A. Chau and S.-H. Yu, "Space modulation on wireless fading channels," in *Proc. IEEE 54th VTC'2001 (Fall)*, vol. 3, Oct. 2001, pp. 1668-1671.

J. Jeganathan, A. Ghrayeb, L. Szczecinski, and A. Ceron, "Space shift keying modulation for MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3692-3703, Jul. 2009.

Parasitic elements

- Parasitic elements
    - capacitors, varactors or switched capacitors that can adjust the resonance frequency
- Use of parasitic elements external to antennas
    - Applications
        - beamforming, DoA estimation
        - selection/switched diversity
        - reconfigurable antennas
- Indexing using parasitic elements
    - *aerial modulation:* index orthogonal antenna patterns realized using parasitic elements
    - *media-based modulation:* index channel fades realized using RF mirrors

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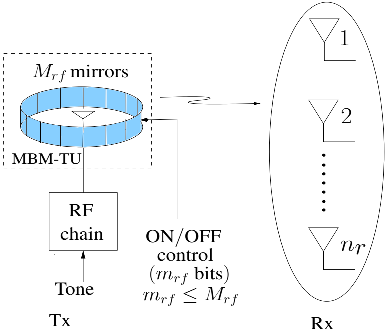
O. N. Alrabadi, A. Kalis, C. B. Papadias, R. Prasad, “Aerial modulation for high order PSK transmission schemes,” in *Wireless VITAE 2009*, May 2009, pp. 823-826.
A. K. Khandani, “Media-based modulation: A new approach to wireless transmission,” in *Proc. IEEE ISIT'2013*, Jul. 2013, pp. 3050-3054.

Media-based modulation



- # tx. antennas, $n_t = 1$; # tx. RF chains, $n_{rf} = 1$
- # RF mirrors available, M_{rf}; # RF mirrors used, m_{rf}
- ON/OFF status of mirrors create independent fade realizations
- Constellation: $\mathbb{H}_{\text{mbm}} = \{\mathbf{h}_1, \mathbf{h}_2, \cdots, \mathbf{h}_{2^{m_{rf}}}\}$

[A] A. K. Khandani, "Media-based modulation: A new approach to wireless transmission," in *Proc. IEEE ISIT'2013*, Jul. 2013, pp. 3050-3054.

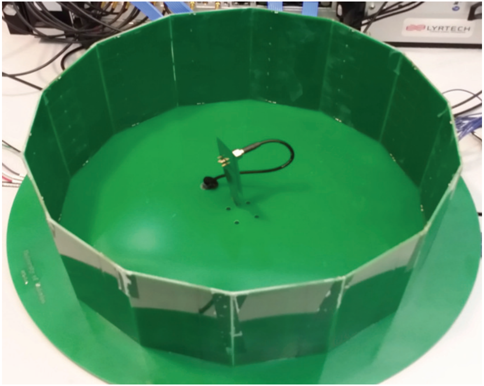
[B] A. K. Khandani, "Media-based modulation: Converting static Rayleigh fading to AWGN," in *Proc. IEEE ISIT'2014*, Jun-Jul. 2014, pp. 1549-1553.

[C] E. Seifi, M. Atamanesh, and A. K. Khandani, "Media-based modulation: A new frontier in wireless communications," online: arXiv:1507.07516v3 [cs.IT] 7 Oct 2015.

MBM

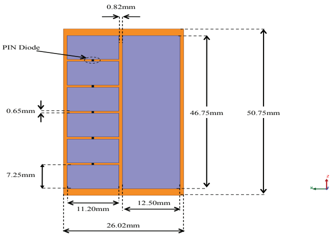
- MBM
  - Multiple RF mirrors create channel fade alphabet $\mathbb{H}_{\mathsf{mbm}}$
  - Advantage
    - $|\mathbb{H}_{\mathsf{mbm}}| = 2^{m_{rf}}$; $\eta_{\mathsf{mbm}} = m_{rf}$ bpcu
    - bpcu increases linearly with m_{rf}
    - better performance compared to conventional modulation
  - Issue
    - need to estimate $|\mathbb{H}_{\mathsf{mbm}}| = 2^{m_{rf}}$ constellation points at the rx. through pilot transmission

MBM implementation

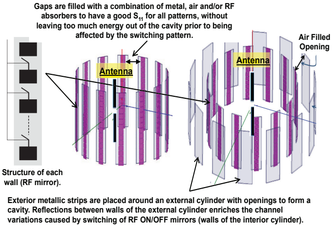


Source: E. Seifi, M. Atamanesh, and A. K. Khandani, "Media-based Modulation: Improving Spectral Efficiency Beyond Conventional MIMO," E&CE Department, University of Waterloo.

MBM implementation



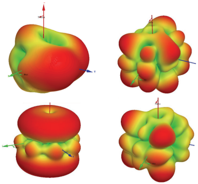
(c) RF mirror


Gaps are filled with a combination of metal, air and/or RF absorbers to have a good S_{11} for all patterns, without leaving too much energy out of the cavity prior to being affected by the switching pattern.

Structure of each wall (RF mirror).

Exterior metallic strips are placed around an external cylinder with openings to form a cavity. Reflections between walls of the external cylinder enriches the channel variations caused by switching of RF ON/OFF mirrors (walls of the interior cylinder).

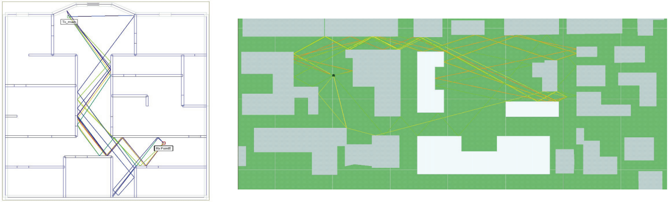
(d) Cylindrical structure with RF mirrors



(e) Antenna patterns

Source: Refs. [A], [B], [C].

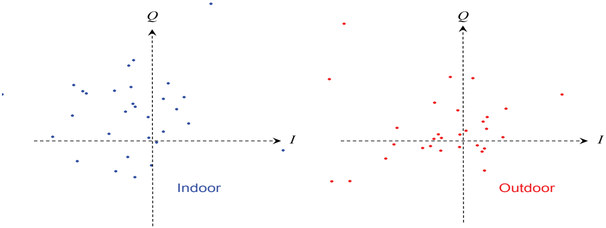
MBM in indoor/outdoor environments



Indoor (residential building with dry-walls)

Outdoor Model (down-town Ottawa)

(f) Indoor/outdoor propagation environments



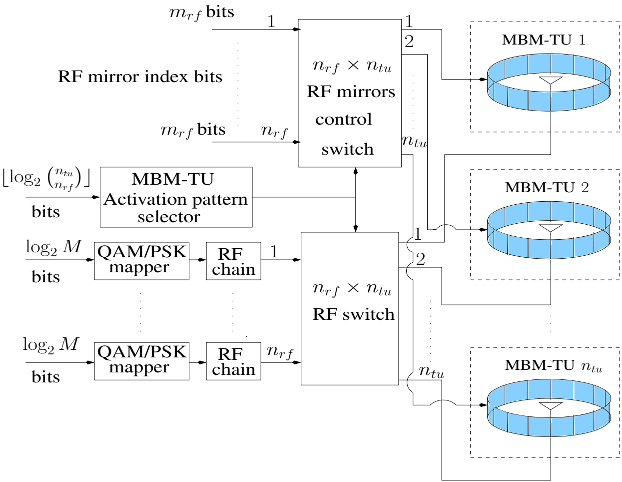
(g) MBM constellation points

Source: Refs. [A], [B], [C].

MBM: An instance of index modulation

- Index modulation
  - bits are conveyed through indices of transmit entities
- Examples
  - Indexing in spatial domain in multiantenna systems
    - SSK, SM, GSM
  - Indexing in frequency domain in multicarrier systems
    - subcarrier index modulation in OFDM
  - Indexing in space and frequency
    - GSFIM (generalized space-frequency index modulation)
  - Indexing in space and time
    - STIM (space-time index modulation)
  - Indexing precoders
    - PIM (precoder index modulation)
  - Indexing RF mirrors
    - MBM (media-based modulation)

GSM-MBM transmitter



Y. Naresh and A. Chockalingam, “On media-based modulation using RF mirrors,” in Proc. ITA’2016, San Diego, Feb. 2016. Also in IEEE Trans. Veh. Tech., Oct. 2016. IEEE Xplore: DOI: 10.1109/TVT.2016.2620989.

GSM-MBM

- Information bits are conveyed through
    - MBM-TU indexing
        - n_{rf} out of n_{tu} MBM-TUs selected using $\lfloor \log_2 \binom{n_{tu}}{n_{rf}} \rfloor$ bits
    - M-ary modulation (QAM/PSK) symbols
        - n_{rf} M-ary symbols (formed using $n_{rf} \log_2 M$ bits) are sent on the selected MBM-TUs
    - RF mirror indexing
        - ON/OFF status of m_{rf} mirrors (mirror activation pattern) conveys m_{rf} bits per MBM-TU
- Achieved rate in GSM-MBM

$$\eta = \underbrace{\left\lfloor \log_2 \binom{n_{tu}}{n_{rf}} \right\rfloor}_{\text{MBM-TU index bits}} + \underbrace{n_{rf}\, m_{rf}}_{\text{mirror index bits}} + \underbrace{n_{rf} \log_2 M}_{\text{QAM/PSK symbol bits}} \quad \text{bpcu}$$

MBM performance

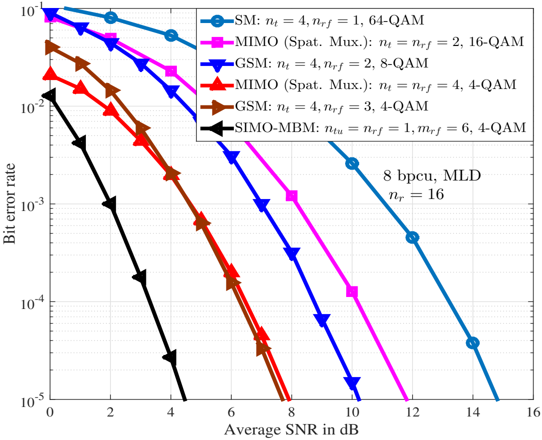


Figure : Comparison between SIMO-MBM with RF mirrors and other multi-antenna schemes without RF mirrors (MIMO, SM, GSM). 8 bpcu, $n_r = 16$, MLD.

GSM-MBM performance

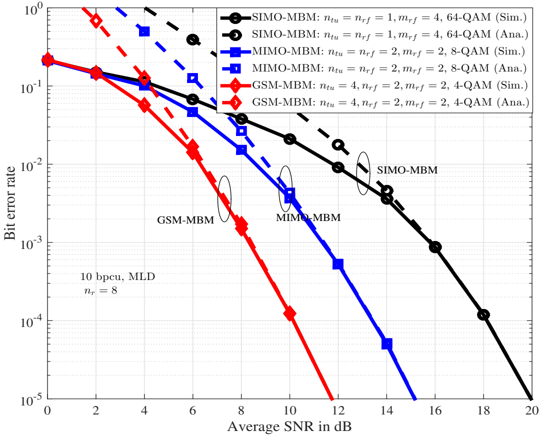


Figure : Performance of SIMO-MBM, MIMO-MBM, and GSM-MBM with $n_r = 8$, and 10 bpcu.

Concluding remarks

- Visible light communication
  - emerging complementary technology to RF communication
  - LEDs act as transmitters. PDs act as receivers
  - several hard-to-resist advantages (with matching challenges)
- Media-based modulation
  - a promising approach for next generation wireless
  - convey information by indexing antennas, subcarriers, time slots, precoders, RF mirrors
  - rate, performance, hardware, and cost advantages
- Both are fast growing areas with great potential
  - several open areas for research and innovation
  - they add interesting dimensions to the state-of-the-art in wireless

Thank you