Visible Light Communication: An Emerging Area in Wireless

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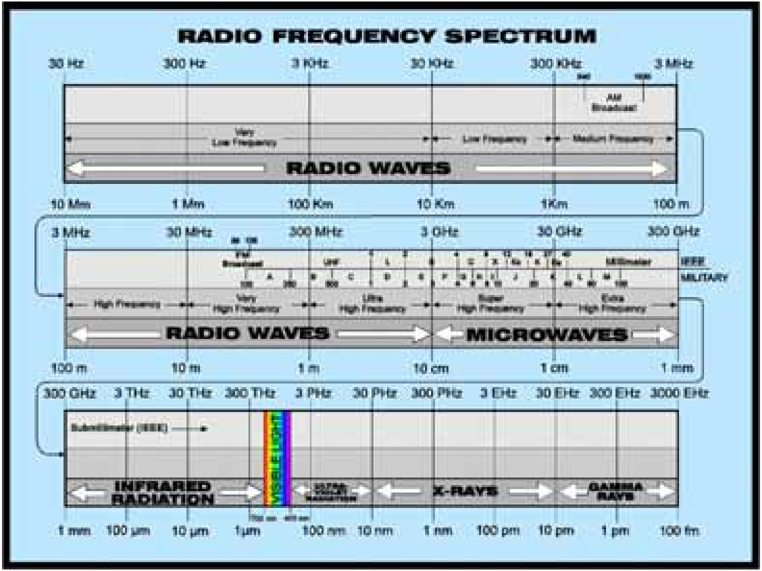
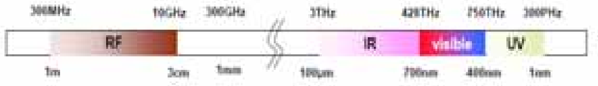
Outline



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)



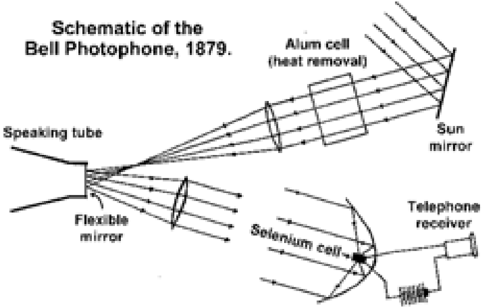
Source: www.ieee802.org/15

- Visible light communication (VLC)
  - communications using visible light spectrum
  - abundant VLC spectrum ($\sim$ 300 THz bandwidth)
  - multi-gigabit rates over short distances

- 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
    - Light emitting diode (LED)
    - Tx data by intensity modulating (IM) the LED
    - LEDs with fast switching times
  - Receiver
    - Photo detector (PD)
    - Direct detection (DD)

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

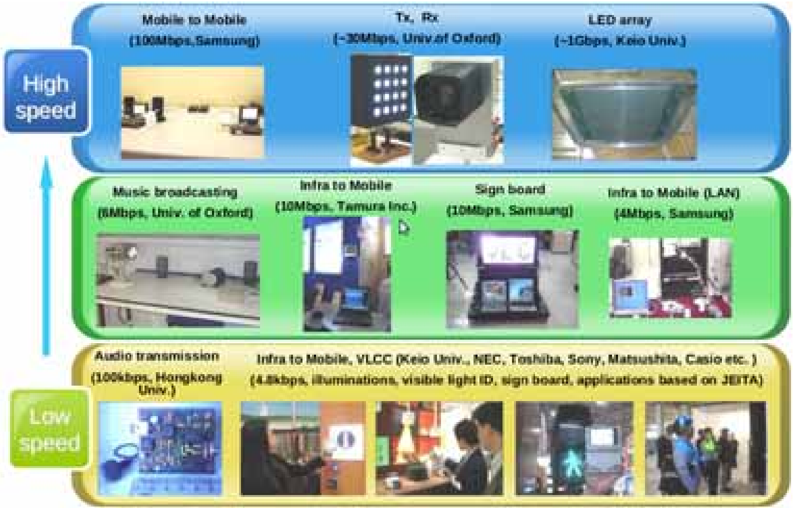


Source: Wikipedia

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

VLC implementations/applications



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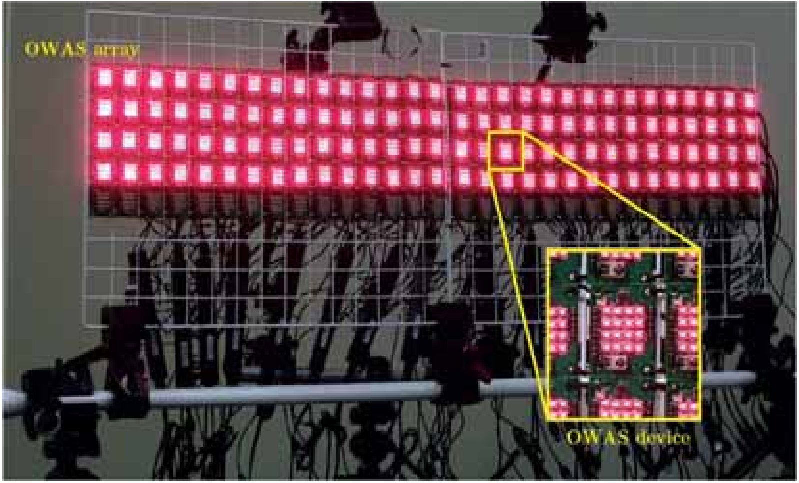

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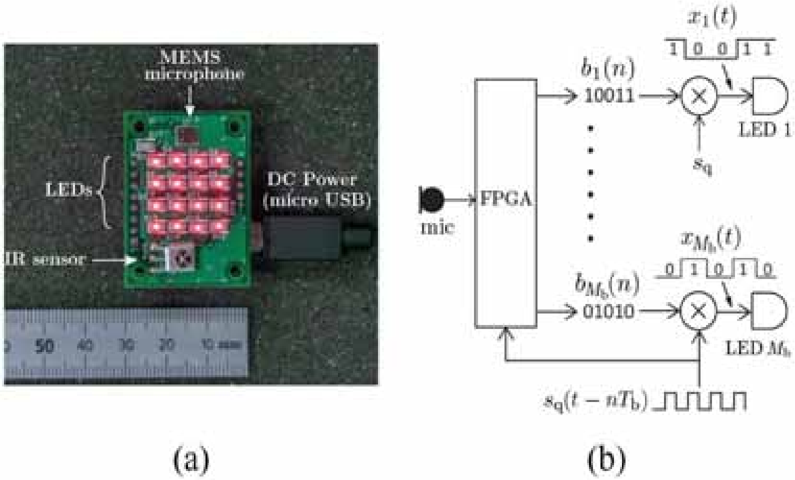

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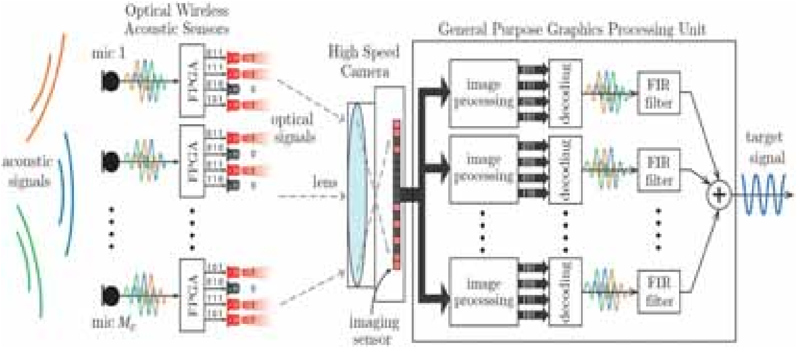

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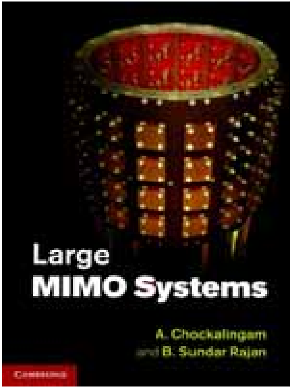
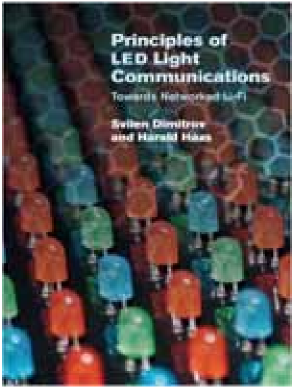
VLC characteristics

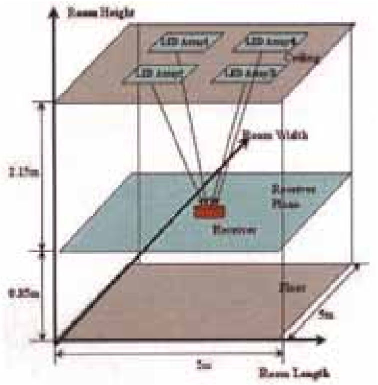
- Baseband communication (no passband involved)
- Signaling: positive, real-valued tx. signals
- Advantages
  - low power, low cost devices (LEDs, PDs)
  - no spectrum cost
  - no RF radiation issues
  - inherent security in closed-room applications
  - simultaneous data transmission and lighting
  - MIMO and OFDM techniques
    - improve spectral efficiency and performance
- Issues
  - channel itself!
  - ambient light noise/interference
  - alignment between Tx and Rx (but diffused light helps)
  - scattering and multipath dispersion (ISI)

The MIMO connection

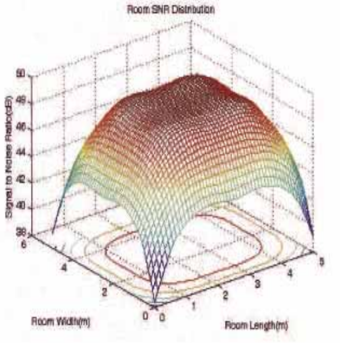




A typical indoor VLC configuration



(c) Typical indoor VLC configuration



(d) SNR as a function of receiver position

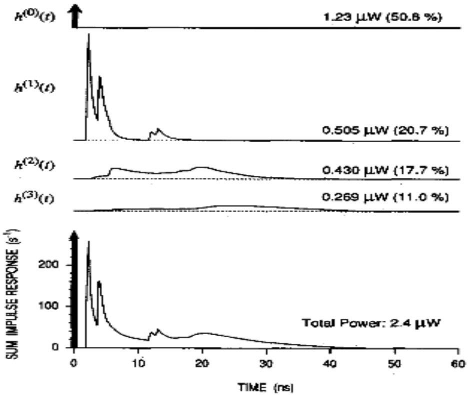
D.C.O'Brien *et al*, "Visible light communications: challenges and possibilities", *IEEE PIMRC'2008*.

Introduction
VLC characteristics
MIMO and OFDM in VLC
QCM for VLC
Concluding remarks

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

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

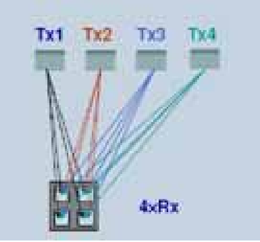
$h^{(k)}(t)$: response of light undergoing exactly k reflections



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.

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

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

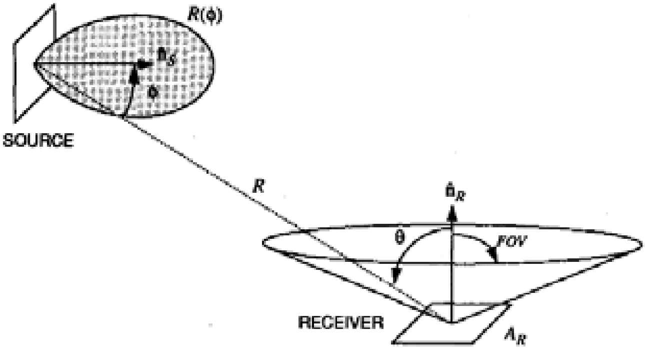


MIMO channel between LEDs and PDs

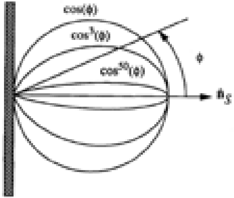
MIMO VLC channel

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

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



Geometry of LED source and photo detector



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

Generalized Lambertian radiation pattern of LED

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

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

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

Example VLC channel matrices

- 4×4 VLC MIMO channel matrix
- Channel matrix for $d_{tx} = 1\text{m}$ (d_{tx}: separation between LEDs)
  - 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 (recently proposed by us)

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. Online arXiv:1503.03308 [cs.IT] 11 Mar 2015.

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

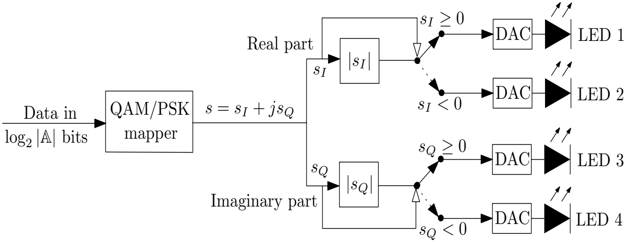
R. Tejaswi, T. Lakshmi Narasimhan, and A. Chockalingam, "Quad-LED complex modulation (QCM) for visible light wireless communications" arXiv:1510.08805 [cs.IT] 29 Oct 2015.

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

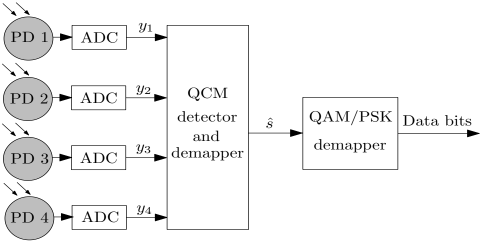
Real part s_I	Status of LEDs	Imag. part s_Q	Status of LEDs
≥ 0	LED1 emits $\lvert s_I \rvert$ LED2 is OFF	≥ 0	LED3 emits $\lvert s_Q \rvert$ LED4 is OFF
< 0	LED1 is OFF LED2 emits $\lvert s_I \rvert$	< 0	LED3 is OFF LED4 emits $\lvert s_Q \rvert$

- Example:
  - If $s = -3 + j1$, then
    LED1: OFF ; LED2: emits 3 ;
    LED3: emits 1 ; LED4: OFF
    Corresponding QCM tx. vector is $\mathbf{x} = [0\ 3\ 1\ 0]^T$
- Note:
  - Two LEDS (one among LED1 and LED2, and another one among LED3 and LED4) will be ON simultaneously. Other two LEDs will be OFF

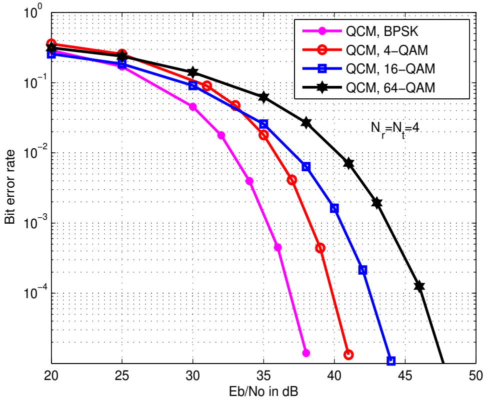
- QCM transmitter



- QCM receiver

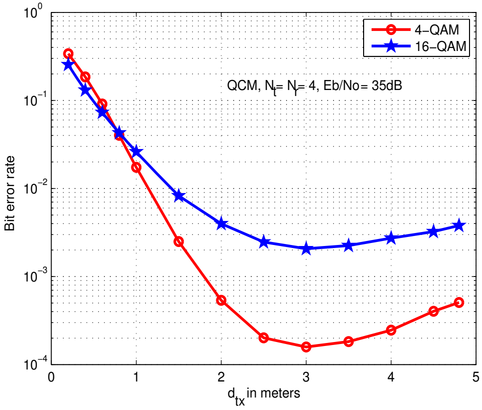


QCM performance



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}

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 for VLC - our recent contribution (promising)
- Bright future for VLC

Thank you