Visible Light Communication: An Emerging Area in Wireless

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81st Annual Meeting
IISER, Pune
7 November 2015
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Introduction
VLC characteristics
MIMO and OFDM in VLC
QCM for VLC
Concluding remarks

Source: Internet
**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)

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

*Source: www.ieee802.org/15*
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
  - Analog voice transceiver
  - Transmitter: a mirror controls the amount of light reflected from a source
  - Receiver: a photocell connected to a speaker

OWC and VLC in recent days

- 1980
  - infrared remote controls (analog)

- 1993
  - infrared data transfer in mobiles, laptops, etc.
  - standards body: IrDA (9.6-128 kbps).

- IEEE 802.15c
  - low power, high data rate systems in satellites, portable devices, etc.

- VLCC: Visible Light Communication Consortium

- VLC for home networks
  - hOME Gigabit Access (OMEGA) project

- IEEE 802.15.7
  - VLC PHY, up to 96 Mbps
VLC implementations/applications

VLC implementations/applications

Introduction

VLC characteristics

MIMO and OFDM in VLC

QCM for VLC

Concluding remarks

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

• CIR between source $S$ and receiver $R$ at time $t$ is given by

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

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

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

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

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

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

Geometry of LED source and photo detector
$R(\phi) = \frac{n+1}{2\pi} P_S \cos^n(\phi)$ for $\phi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$

**Generalized Lambertian radiation pattern of LED**

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

- 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

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

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

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

- Transmit signals in VLC must be
  - positive real-valued for intensity modulation of LEDs
- Approaches
  - OOK
  - M-PAM with positive signal points
  - M-QAM/M-PSK with Hermitian symmetry
  - SSK and spatial modulation using multiple LEDs
  - QCM (recently proposed by us)


Quad-LED Complex Modulation (QCM)

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

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

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

Example:

- If $s = -3 + j1$, then
  - LED1: OFF
  - LED2: emits 3
  - LED3: emits 1
  - LED4: OFF

Corresponding QCM tx. vector is $x = [0 3 1 0]^T$

Note:

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

Data in \( \log_2 |A| \) bits is mapped to QAM/PSK. The signal is given by \( s = s_I + js_Q \). The real part is \( |s_I| \) and the imaginary part is \( |s_Q| \). Based on these, the DAC sends the signal to the LED.

- **QCM receiver**

The PDs (PD 1 to PD 4) convert the optical signal into an electrical signal, which is then amplified by ADCs (ADC 1 to ADC 4). The QCM detector and demapper processes the signals to recover the data bits.
QCM performance

- QCM, BPSK
- QCM, 4-QAM
- QCM, 16-QAM
- QCM, 64-QAM

Eb/No in dB

Bit error rate

$N_r = N_t = 4$
• **Effect of varying LED spacing** \((d_{tx})\)

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