Recent Progress in Image Sensor Communication

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http://owc.ustc.edu.cn/
Key Research Units at USTC

Optical Wireless Communication & Network Center

Team: 7 faculty (1-1000plan, 2-young 1000plan),
2 engineers, 2 staff, graduate students (>40)
Space: 1300 sq. meters
Competitive grants: central government, local
government, industry, CAS, university

http://owc.ustc.edu.cn/

Key Lab of Wireless-Optical Communications, CAS

Team: 38 faculty from 4 colleges (2-1000plan, 2-Changjiang
2-Distinguished Young Scholars, etc)
Deliverables in recent 5 years:
357 papers, 194 patents, 138 projects (4-973, 13-863, 32-Key Projects)
Research Topics

Optical Wireless Communication & Network Center

http://owc.ustc.edu.cn/

Analytical/Experimental study

Localization
PAT & Sensing

Optical Wireless
Commun/Networking

Wireless Big
Data & AI

AoA/DoA/TDoA
Device
Channel
Comm
Net

terminal environment
biological

Data mining
Feature mapping
Data-driven
system design

LD lighting, LED reception, array design
LOS/NLOS in/outdoor/underwater channel
Signaling, AMC, dynamic sig detection, IC
S/T/F/C/A/P modulation & diversity techniques
Synchronization, beam/power control
MA/routing/scheduling, resource allocation
Hybrid OWC/RF/wired networks
Books/Chapters, Journal and Conference Publications

<table>
<thead>
<tr>
<th>Book</th>
<th>Authors/Editors</th>
<th>Year</th>
<th>Publisher</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Short Range Optical Wireless: Theory and Applications</td>
<td>Authors: M. Kavehrad, M.I. Chowdhury, and Z. Zhou</td>
<td>2016</td>
<td>Wiley</td>
</tr>
<tr>
<td>4 Principles of LED Light Communications: Towards Networked Li-Fi</td>
<td>Authors: S. Dimitrov and H. Hass</td>
<td>2015</td>
<td>Cambridge University</td>
</tr>
<tr>
<td>5 Wireless Optical Communication Systems</td>
<td>Authors: S. Hranilovic</td>
<td>2005</td>
<td>Springer</td>
</tr>
<tr>
<td>7 Optical Wireless Communications: An Emerging Technology</td>
<td>Editors: M. Uysal, C. Capsoni, Z. Ghassemlooy, A. Boucouvalas, and E. Udvary</td>
<td>2016</td>
<td>Springer</td>
</tr>
<tr>
<td>8 Visible Light Communication</td>
<td>Editor: S. Arnon</td>
<td>2015</td>
<td>Cambridge University</td>
</tr>
</tbody>
</table>

IEEE/OSA Journals and Conferences

- IEEE Transactions on Signal Processing
- IEEE Journal of Selected Areas in Communications
- IEEE Transactions on Wireless Communications
- IEEE Transactions on Communications
- IEEE/OSA Journal of Lightwave Technology
- IEEE/OSA Journal of Optical Communications and Networking
- IEEE Wireless Communications
- IEEE Photonics Journal
- IEEE Communications Letters
- OSA Optics Letters
- OSA Optics Express
- OSA Journal of the Optical Society of America A
- OSA Photonics Research
- Conferences (IEEE ICC, IEEE GC, OSA CLEO, ECOC)

Patents

Journal Editor/Conference Chair (IEEE JSAC’14,’17, GC OWC Workshop’10-12, ONS’16, IPC’17)
Achievements

IEEE Series on Digital & Mobile Communication
Testbeds
Image Sensors and Characteristics

Image Sensor Communication (ISC)
- Background and current status
- LED and sensor based ISC noise characteristics and models
- Color-intensity modulation in MIMO ISC
- LED and phone-camera based cloud ISC
- LCD-display and phone-camera based ISC
- LED and camera based NLOS scattering ISC

Source Detection and Tracking

Conclusion
CCD vs. CMOS Image Sensors

- **Charge-coupled device (CCD)**
  - High-quality, low-noise, high uniformity and sensitivity
  - High-pixel resolution, but high power and cost
  - Special need for reconnaissance satellites, spectrometers
  - Biomedical photography, industrial applications

- **Complementary metal–oxide–semiconductor (CMOS)**
  - Low-power, silicon production line, high
    integration, inexpensive, but noisy
  - Wide applications in smart phones, digital camera
    automotive lidar and consumer areas

- **CMOS manufacturers**
  - Sony, Samsung, Canon, OmniVision, Panasonic, Onsemi,
    STMicroelectronics and SK Hynix
Image Sensor Commun (ISC)

Transmitter
- LED Array
- LCD/LED/OLED Display

Channel

Receiver
- Phone Camera
- Industrial Camera
- Image Sensor
- Webcam
- SLR Camera

Transmitter
- Imaging Optics
- Micro-lens Array Filter and Image Sensor
- Data Recovery
A similar example: Quick Response (QR) code
- Visible and machine-friendly
- Limited information
- Limited distance

Covert Display-Phone Communication
- Good viewing experience (user-friendly)
- Improved information-carrying capability
- Longer distance
- Enhanced video advertisement

The price of this Samsung smartphone is...
You can purchase from the following website: http://...
### Comparison between VLC and ISC

<table>
<thead>
<tr>
<th></th>
<th>VLC</th>
<th>ISC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver</td>
<td>Photodetector (PD)</td>
<td>Image sensor /camera</td>
</tr>
<tr>
<td>Interference</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>SNR</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>MIMO multiplexing</td>
<td>Difficult to implement</td>
<td>Easy to implement</td>
</tr>
<tr>
<td>Decoding</td>
<td>Low complexity</td>
<td>High complexity</td>
</tr>
</tbody>
</table>

### Bluetooth vs. WiFi vs. VLC vs. ISC

<table>
<thead>
<tr>
<th></th>
<th>Bluetooth</th>
<th>WiFi</th>
<th>VLC</th>
<th>ISC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Security</td>
<td>High</td>
<td>High</td>
<td>Highest (LOS)</td>
<td>Highest (LOS)</td>
</tr>
<tr>
<td>Link setup</td>
<td>Scan-and-link</td>
<td>Scan-and-link</td>
<td>LOS</td>
<td>Look-and-link</td>
</tr>
<tr>
<td>Protocol</td>
<td>IEEE 802.15.1</td>
<td>IEEE 802.11a/b</td>
<td>IEEE 802.15.7</td>
<td>IEEE 802.15.7m</td>
</tr>
<tr>
<td>Frequency band</td>
<td>2.4 GHz</td>
<td>2.4/3.6/5 GHz</td>
<td>400THz-800THz</td>
<td>IR, VL, UV</td>
</tr>
<tr>
<td>Data rate</td>
<td>800 kpbs</td>
<td>11 Mbps</td>
<td>11kpbs-96Mpbs</td>
<td>Lower than VLC</td>
</tr>
<tr>
<td>Coverage</td>
<td>30m</td>
<td>46-100m</td>
<td>1m-100m</td>
<td>1m-3km</td>
</tr>
</tbody>
</table>
Advantages

- Pervasiveness: integrated in most consumer electronics
- Massive MIMO receiver: Optical lens+ pixel based receiver
- Multi-color receiver: Bayer/Foveon-X3 pattern color filters
- Anti-interference receiver: Optical subsystem+ image processing

Challenges

- Unstable frame rate and sampling error
- Nonlinearity: O-E conversion of color CMOS sensor
- Channel crosstalk: spectrum overlap between LED R/G/B colors and mismatch with the Bayer-pattern filters
- Rolling shutter: readout mechanism of CMOS image sensor
<table>
<thead>
<tr>
<th>System</th>
<th>Affiliation</th>
<th>Year</th>
<th>Transmitter/Receiver</th>
<th>System Performs</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] PixNet</td>
<td>MIT</td>
<td>2010</td>
<td>LCD Display, Standalone Camera</td>
<td>7-15Mbps, &gt; 10m</td>
<td>2D OFDM</td>
</tr>
<tr>
<td>[2] COBRA</td>
<td>Michigan State U</td>
<td>2012</td>
<td>Phone Display, Phone Camera</td>
<td>90-120kbps, 20-30cm</td>
<td>2D Color code</td>
</tr>
<tr>
<td>[5] NLOS-OCC</td>
<td>Feng Chia U</td>
<td>2017</td>
<td>LED, Phone Camera</td>
<td>5.76kbps, 20cm</td>
<td>Rolling shutter</td>
</tr>
<tr>
<td>[7] CeilingTalk</td>
<td>Nanyang Tech U</td>
<td>2017</td>
<td>LED luminaries, Phone Camera</td>
<td>1kbps, 5m</td>
<td>Raptor coding</td>
</tr>
<tr>
<td>[8] Visual MIMO</td>
<td>Rutgers U</td>
<td>2012</td>
<td>LCD Display, Phone Camera</td>
<td>6kbps, BER 0.054</td>
<td>Gray images / Pyramid decomposition</td>
</tr>
<tr>
<td>[9] HiLight</td>
<td>Dartmouth College</td>
<td>2014-2015</td>
<td>Phone Display (60Hz), Phone Camera</td>
<td>1.1kbps, BER 0.1</td>
<td>Color videos / Transparency / BFSK</td>
</tr>
<tr>
<td>[10] InFrame++</td>
<td>Beihang U</td>
<td>2014-2015</td>
<td>LCD Display (120Hz), Phone Camera</td>
<td>150-240kbps, BER 0.1-0.4</td>
<td>Color videos / STCF / CDMA-like modulation</td>
</tr>
<tr>
<td>[11] Spatially Adaptive Embedding</td>
<td>Rutgers U/WINLAB</td>
<td>2016</td>
<td>LCD Display (120Hz), Phone Camera</td>
<td>22kbps, BER 0.1</td>
<td>Color videos / Block-superpixel hybrid encoding</td>
</tr>
<tr>
<td>[12] IS-based VLC</td>
<td>Nagoya U</td>
<td>2016</td>
<td>LCD Display, Image Sensor</td>
<td>1.2kbps, BER&lt; 0.1</td>
<td>Color images / Blue color difference modulation</td>
</tr>
<tr>
<td>[14] Covert CSC</td>
<td>USTC</td>
<td>2017</td>
<td>LCD Display (60Hz) Phone Camera</td>
<td>16.67kbps, BER 0.1</td>
<td>Color videos / Gaussian-based block design / Synchronization Anchors</td>
</tr>
</tbody>
</table>
Research Status


LED and Sensor based ISC

The $M$-CIM-MIMO ISC system diagram

Spatial frame format and packet format for each LED

Noise


CIM-MIMO Modulation and Channel

- Considering $L$-intensity levels and three colors, totally $M=L^3$ CIM symbols
  \[
  S = \{s_1, s_2, \ldots, s_M\} \quad s_m = [i_r^m \quad i_g^m \quad i_b^m]
  \]

- Channel matrix for $N \times N$ Tx-Rx pairs
  \[
  H \triangleq \begin{bmatrix}
  H_{1,1} & H_{1,2} & \cdots & H_{1,N} \\
  H_{2,1} & H_{2,2} & \cdots & H_{2,N} \\
  \vdots & \vdots & \ddots & \vdots \\
  H_{N,1} & H_{N,2} & \cdots & H_{N,N}
  \end{bmatrix}
  \]
  \[
  H_{i,j} \triangleq \begin{bmatrix}
  h_{r,r}^{i,j} & h_{r,g}^{i,j} & h_{r,b}^{i,j} \\
  h_{g,r}^{i,j} & h_{g,g}^{i,j} & h_{g,b}^{i,j} \\
  h_{b,r}^{i,j} & h_{b,g}^{i,j} & h_{b,b}^{i,j}
  \end{bmatrix}
  \]
  \[
  h_{p,q}^{i,j} \triangleq \xi_{i,j} \int S_q^j(\lambda)F_{p}^i(\lambda) d\lambda, \quad p, q \in \{r, g, b\}
  \]

- Path loss
- Power spectral density
- Spectral response of filter

- Channel input-output relation
  \[
  Y_n = H_{n,n}X_n + \sum_{k \neq n} H_{n,k}X_k + Z_n,
  \]
  \[
  Z_n = Z_0 + \sqrt{X_n}Z_1 + X_nZ_2
  \]

Mixed signal-dependent Gaussian noise:
- photo response non-uniformity (PRNU)
- fixed-pattern noise (FPN)
- random telegraph noise (RTN)
- ...

\[
SNR = \frac{E\{X_n^2\}}{\sigma^2E\{1 + \zeta_1^2X_n + \zeta_2^2X_n^2\}}
\]
### Parameter Settings

#### Simulation parameters

<table>
<thead>
<tr>
<th>Manufacture process</th>
<th>CMOS</th>
<th>PRNU factor</th>
<th>0.6%~1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>$3.75 \mu m \times 3.75 \mu m$</td>
<td>Dark current FPN factor</td>
<td>1%</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>1080×720</td>
<td>Column offset FPN factor</td>
<td>0.1%</td>
</tr>
<tr>
<td>Wavelength ( \lambda )</td>
<td>550nm</td>
<td>Dark current figure of merit</td>
<td>1.00 nA/cm$^2$</td>
</tr>
<tr>
<td>Fill factor</td>
<td>55%</td>
<td>Sense node gain</td>
<td>5.00 ( \mu V/e^- )</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>65%</td>
<td>Read noise</td>
<td>30 ( e^- )</td>
</tr>
<tr>
<td>Full well</td>
<td>60000 ( e^- )</td>
<td>ADC bit</td>
<td>12 bit</td>
</tr>
</tbody>
</table>

#### Experimental parameters

<table>
<thead>
<tr>
<th>Process</th>
<th>CMOS</th>
<th>Model</th>
<th>OV4688</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>$2 \mu m \times 2 \mu m$</td>
<td>Resolution</td>
<td>672×380</td>
</tr>
<tr>
<td>Data format</td>
<td>10bit RAW</td>
<td>Frame rate</td>
<td>330 fps</td>
</tr>
<tr>
<td>Binning</td>
<td>4×4</td>
<td>Dark current</td>
<td>4mV/sec</td>
</tr>
</tbody>
</table>
CIM-MIMO Testbed

Programmable 196-element RGB-LED array

maximum resolution 2688*1520
FPGA of OCC receiver
Rate 330fps

256CIM+196-MIMO
Real-time 126kbps,
1.5m, raw BER<1.0e-4,
up to 20m with lens

demodulation

Noise Distribution

- The ISC noise is white Gaussian noise
- Output noise variance is signal-dependent, linear function of received intensity, and is linear function of transmitted signal

The noise distribution characteristic

\[ 0.1539 \times \text{exp}\left(-\frac{(x-0.0020)^2}{3.67^2}\right) \]

\[ 0.1524 \times \text{exp}\left(-\frac{(x+0.018)^2}{3.69^2}\right) \]
SNR Performance

- SNR improves as pixel size, photocurrent, integral time and diversity order
- ISC supports high SNR
- Multiplexing/diversity gain tradeoff

SNR performance with different parameters

- Readout noise + dark current dominate
- Shot noise dominates
- PRNU dominates

Incident Photons (1/cm²) vs. SNR (dB)

Photocurrent $I_{ph}$ (A) vs. SNR (dB)

SNR (dB) vs. $t_{int}$ (ms)

Incident Photons (1/cm²) vs. SNR (dB) for different pixel sizes

SNR (dB) vs. $I_{ph}$ (A) for different pixel sizes

SNR (dB) vs. $I_{ph}$ (A) for different $t_{int}$ (ms)
LED & Phone-camera based Cloud ISC

Display

Cloud

- Inserting frame synchronization
- Inserting Training Sequence
- CIM Modulation
- LED
- Channel
- Image Sensor Of Smartphone
- Frame Synchronization
- Perspective Correction
- Hough Circle Detection
- Coordinate Recovery
- Training Sequence Detection
- CIM Demodulation
- Smartphone

Experimental parameters and platform

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array size</td>
<td>$16 \times 16$</td>
</tr>
<tr>
<td>LED pixel pitch</td>
<td>1 cm</td>
</tr>
<tr>
<td>Array refresh rate</td>
<td>30 fps / 60 fps</td>
</tr>
<tr>
<td>Smartphone</td>
<td>Samsung note3</td>
</tr>
<tr>
<td>Frame rate</td>
<td>60 fps / 120 fps</td>
</tr>
<tr>
<td>Resolution</td>
<td>$4128 \times 3096$</td>
</tr>
<tr>
<td>Pixel size</td>
<td>2 um x 2 um</td>
</tr>
<tr>
<td>Distance</td>
<td>(60-100) cm</td>
</tr>
</tbody>
</table>

Data rate 57.6kbps at 1m and BER < $10^{-3}$, viewing angle is up to 40°.
K-means clustering to optimize constellation from 64-CIM to 32-CIM, increasing the Euclidean distance.

BER with different size of ROI

BER with different distances
Transceiver diagram

Transmitter

Video Sequences

Transmitter

Copy / Decompose

Packets

Packets

{ S_i } ← Encoding

{ e_j } ← Visual Modulation

Packeting + Synchronous anchor

{ S_{2i} } ← Multiplex

Extractor

Decoding

Demodulation

Synchronization

Extract frame + Frame rectification

Receiver

{ S_2i-1 } ← Display

Output bits

{ S_2i } ← { e_j }

{ D_j } ← { R_k }

{ C_k } ←

Intensity modulation

1 → 10, 0 → 01

 temporal embedding by Manchester encoding

Spatial embedding by $3 \times 3$ Gaussian-based block design

Packet and frame synchronization (anchors)

\[ \alpha = \frac{\gamma}{2\pi\sigma^2} e^{-\frac{(i-c_i)^2+(j-c_j)^2}{2\sigma^2}} \]

Intensity modulation

Pixel value of $\alpha$

10 15 20 25 30

10 15 20 25 30

0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05 0.055

Packet

Frame Anchors

Packet Anchor

N Frames

LCD-display & Phone-camera based ISC
LCD-display & Phone-camera based ISC

- Perspective correction
  - Harris corners detection
  - Feature matching between two sequential Frames \((a_1, a_2)\)
  - Frame alignment \(a_2\) to \(a_1\)
  - RANSAC
  - Edges detection
  - Hough line detection
  - Perspective Correction
  - ROI extraction
  - Four borders recognition

- Synchronization and demodulation
  - Determine location of packets by packet anchor
  - Demodulate frame anchors
  - Obtain the estimate of two originally transmitted frames
  - Demodulate information bits block by block

\[
M_i = \begin{cases} 
\frac{1}{2} (frame_1^{(1)} + frame_2^{(1)}) & w_{i,1} = w_{i,2} = 1 \\
frame_1^{(1)} & w_{i,1} = 1 \text{ and } w_{i,2} = 0 \\
frame_2^{(1)} & w_{i,1} = 0 \text{ and } w_{i,2} = 1 
\end{cases}
\]

- Original Video: 30fps
- Embedded Video: 60fps
- Captured Video: 120fps

1st-group: \(M_1\)
2nd-group: \(M_2\)
Experimental Setup

<table>
<thead>
<tr>
<th>Transmit</th>
<th>27” LCD monitor (AOC G2770PQU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness</td>
<td>90%</td>
</tr>
<tr>
<td>Refresh rate</td>
<td>60Hz</td>
</tr>
<tr>
<td>Resolution</td>
<td>1080 × 1920</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receiver</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Smartphone</td>
<td>Samsung Galaxy S5</td>
</tr>
<tr>
<td>Frame rate</td>
<td>120fps</td>
</tr>
<tr>
<td>Resolution</td>
<td>720 × 1080</td>
</tr>
</tbody>
</table>

Distance | 90 cm (Camera was fixed)

#### Quality assessment

- **21 volunteers**: 16 males + 5 females
- **8 test videos**: the original video + the embedded video
- **Assessment**: score two videos twice separately

If score **exceeds 8**, we assume that the quality of the embedded video is **good enough** for human eyes.

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–2</td>
<td>So badly and can not stand</td>
</tr>
<tr>
<td>3–4</td>
<td>Strong flicker or artifact</td>
</tr>
<tr>
<td>5–6</td>
<td>Evident flicker and unacceptable</td>
</tr>
<tr>
<td>7–8</td>
<td>Slight flicker and almost unnoticeable</td>
</tr>
<tr>
<td>9–10</td>
<td>No difference and viewing good</td>
</tr>
</tbody>
</table>
Experimental Performance

Video Quality Scores

- Near-zero flicker perception for all the tested videos.
- The video quality with chrominance modulation is **better** than intensity modulation, especially when video content is dark (*Little Prince*) or bright (*Sheep*).

Communication Performance

\[\text{Rate} = 16.67\text{~to~}30.61\text{kbps}\]
\[\text{Distance} = 90\text{cm}\]

- The average BER with chrominance modulation is **lower** than intensity modulation for all the test videos.
- The average BER of chrominance modulation - iPhone 8Plus is within 0.1.

LED & Camera based NLOS Scattering ISC

- Non-line of sight (NLOS) ISC
  - Light source is blocked by vehicle/bldg./tree, etc
  - Applications in advertising, navigation, communication link recovery
  - Challenges in link quality and distance

- Camera noise modeling and measurement
  - HAMAMATSU CMOS C11440-52U

\[ y = Hx + xZ_2 + \sqrt{x}Z_1 + Z_0 \]

Pixels 2048×2048
Rate 30~25655 fps
A/D 16bit
Digital binning 2×2, 4×4
Global exposure 1ms
Noise 2.3 electrons
**System Performance**

- **Predicted BER vs. range under practical noise**

  ![Graph showing the relationship between error probability and distance](image)

  PDFs of measured signal and noise at 130m

  PDFs of measured signal and noise at 300m

  - Signal variance increases with mean value
  - Maximum distance over 300m at 100bps with error free

Source Detection and Tracking

Detection

1. Live Scene
2. Image Acquisition
3. Differentiate
4. Image Processing
5. Identification
6. Coordinate of light source

Adaptive region of interest

Tracking

1. FPGA
2. PMC Controller
3. Servo Driver
4. Servo Motor
5. Rotating Platform
6. APD & Camera
Source Detection and Tracking

<table>
<thead>
<tr>
<th>Camera frame rate</th>
<th>200 fps</th>
<th>flag signal freq</th>
<th>100Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>1024 × 512</td>
<td>Max rotation speed</td>
<td>100° /s</td>
</tr>
</tbody>
</table>

Light source moving fast ~50° /s
ISC is a potentially widespread technology in consumer electronics, and valuable for (covert) information transfer, PAT, positioning, control and AI.

Display-camera ISC achieved high speed, NLOS ISC achieved long distance.

Challenges still exist in mobility & instability handling, synchronization, interference mitigation, capacity increase, computing capability, etc.
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