Visible Light Communication (VLC) for Cars

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Visible Light Communication (VLC) for Cars

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Visible light communications for Cars

- Brief history of LED and invention of blue LED
- Visible light communications (VLC), Image sensor communications (ISC)
- VLC using high-speed camera
- High-speed image processing for automotive applications
  - Vehicle to infrastructure visible light communication system
  - Range estimation using POC
  - ISC using rolling-shutter image sensor
Blue LED (innovation history)
"Incandescent light bulbs lit the 20th century; the 21st century will be lit by LED lamps."
1961 Robert Biard and Gary Pittman (TI) invented an infra-red LED.

1962 Nick Holonyak, Jr. (GE) invented a visible red light LED.

1970s Scientists succeeded in making LEDs that emit a cyan (pale green) light.

1980s Ultra-bright magenda (orange-red), orange, green, and yellow LEDs were produced.
1961 Robert Biard and Gary Pittman (TI) invented an infra-red LED.

1962 Nick Holonyak, Jr. (GE) invented a visible red light LED.

But scientists realized that the emission of blue light was considerably difficult.

LEDs that emit a cyan (pale green) light.

1980s Ultra-bright magenda (orange-red), orange, green, and yellow LEDs were produced.
Gallium nitride (GaN)

- Gallium nitride was the material of choice.
- Material was considered appropriate, but practical difficulties had proved enormous.
- No one could grow gallium nitride crystals of high enough quality.

https://en.wikipedia.org/wiki/Gallium_nitride
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
</table>
| 1952 | Graduated from the School of Science, Kyoto University  
     | Began working at Kobe Kogyo Corporation |
| 1959 | Research Associate, School of Engineering, Nagoya University |
| 1964 | Lecturer, School of Engineering, Nagoya University |
| 1964 | Received Doctorate of Engineering, School of Engineering, Nagoya University |
| 1981 | Professor, School of Engineering, Nagoya University |
| 1992 | Retirement from Nagoya University  
     | Professor, Meijo University  
     | Professor Emeritus, Nagoya |
| 2004 | University Professor at Nagoya University |

1960 | Born in the city of Hamamatsu, Shizuoka Prefecture |
| 1979 | Graduated from Shizuoka Prefectural Hamamatsu Nishi Senior School |
| 1983 | Graduated from the School of Engineering, Nagoya University |
| 1985 | Completed Master's Course of the Graduate School of Engineering, Nagoya University |
| 1988 | Completed All But Dissertation (ABD) for a PhD degree of the Graduate School of Engineering, Nagoya University |
| 1988 | Research Associate, School of Engineering, Nagoya University |
| 1989 | Acquired the Doctor of Engineering, Nagoya University |
| 1992 | Assistant Professor, Faculty of Science and Technology, Meijo University |
| 1998 | Associate Professor, Faculty of Science and Technology, Meijo University |
| 2002 | Professor, Faculty of Science and Technology, Meijo University |
| 2010 | Professor, Graduate School of Engineering, Nagoya University |

Dr. Isamu Akasaki

Dr. Hiroshi Amano
1986 Profs. Akasaki and Amano were the first to create a high-quality GaN crystal.

End of 1980s, they made a breakthrough in creating a p-type layer.

1992 Profs. Akasaki and Amano were able to present their first diode emitting a bright blue light.
Without a blue LED, there is no white light

White light source implementation

BlueLED

Yellow phosphor

white

BlueLED GreenLED RedLED

White
Energy-efficient LED lights up the world brighter than ever.
Visible Light Communication (VLC)
1999  Proposed by Prof. Masao Nakagawa, Keio University

2001  Visible Light Communication Consortium  
      (Chair: Prof. Shinichiro Haruyama, Keio University)

2014  Visible Light Communications Association

2023  JPC Optical Wireless Group (Chair: Prof. Yamazato)

http://www.vlcc.net/modules/xpage1/?ml_lang=en (2021/9/3)  
http://www.sdm.keio.ac.jp/en/faculty/haruyama_s.html (2021/9/3)
Electromagnetic spectrum

<table>
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<tr>
<th>Class</th>
<th>Wavelength ( \lambda )</th>
<th>Frequency ( f )</th>
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<tr>
<td>Gamma rays</td>
<td>1 pm</td>
<td>300 EHz</td>
</tr>
<tr>
<td>HX</td>
<td>10 pm</td>
<td>30 EHz</td>
</tr>
<tr>
<td>SX</td>
<td>100 pm</td>
<td>3 EHz</td>
</tr>
<tr>
<td>EUV</td>
<td>1 nm</td>
<td>30 Pre</td>
</tr>
<tr>
<td>NUV</td>
<td>100 nm</td>
<td>3 Pre</td>
</tr>
<tr>
<td>SR</td>
<td>10 pm</td>
<td>30 THz</td>
</tr>
<tr>
<td>MR</td>
<td>100 pm</td>
<td>3 THz</td>
</tr>
<tr>
<td>FIR</td>
<td>1 mm</td>
<td>300 GHz</td>
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<tr>
<td>EHF</td>
<td>1 cm</td>
<td>3 GHz</td>
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<tr>
<td>SHF</td>
<td>1 m</td>
<td>300 MHz</td>
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<tr>
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<td>VLF</td>
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<td>300 kHz</td>
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<tr>
<td>ULF</td>
<td>1000 km</td>
<td>300 Hz</td>
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<tr>
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<tr>
<td>ELF</td>
<td>100000 km</td>
<td>3 Hz</td>
</tr>
<tr>
<td>ELF</td>
<td>100000 km</td>
<td>3 Hz</td>
</tr>
</tbody>
</table>

Visible Spectrum

750 nm to 380 nm

790 THz to 400 THz

Radio wave

Audible Sounds

Radio & TV

Microwave

Infrared

Infrared

Ultra violet

X-rays
VLC Transmitter
In most cases, VLC uses LEDs for a transmitter.

- VLC signal modulation
- On-off keying (OOK)
- Pulse-width modulation (PWM)
- Intensity modulation (IM)
- Optical orthogonal frequency division multiplexing (optical OFDM)
On-off keying (OOK)
The simplest form of modulation

Data rate is $R_b = 1/T_b$
Pulse-width modulation (PWM)
The simplest form of modulation
VLC Transmitter
In most cases, VLC uses LEDs for a transmitter.

Intensity modulation and direct detection (IM/DD) systems
Image sensor communications (ISC)
• Proposed by Mr. Iizuka of Casio Co.
• Basically the same as optical camera communication (OCC) standardized in IEEE 802.15.7.
• It has spatial separation characteristics:
  • Spatial separation characteristics enable spatial parallel transmission using LED arrays.
  • Easy tracking of the transmission source
  • Simultaneous communication and ranging (position estimation)
CMOS (complementary metal oxide semiconductor)

Electron-to-voltage conversion

Photon-to-electron conversion

Row Access

Row Drivers

Column MUX

A/D

To frame buffer

Bottle neck:
- 1 Mega pixels → 1 Mbps
- 10 bits resolution for each pixel → 10 Mbps
- 30 fps → 300 Mbps

CMOS sensors read out the voltage using row and column decoders, like a digital memory.

Photo sensitive area is reduced by additional circuitry (low fill factor)
High-Speed Image Sensor as a Reception Device of VLC Signals

Spatial separation of sources
- Ability to process multiple sources
- Easy integration of both positioning and reception data

Noise sources (the sun, town lights.....)

LED array transmitter and Image sensor receiver

- Spatial separation

Image sensor receiver can receive and process multiple transmitting sources.
Transmitter (3x3 LEDs aligned in a grid (LED array))

Receiver (Image sensor with 6x6 pixels, each image is sampled with the rate $2R_b$)
VLC using high-speed camera
How fast can we achieve? — Ideal case —

1920 × 1080 × 240 fps × 12 bit × 3 colors

Considering Nyquist sampling (1/2)

960 × 540 × 120 fps × 6 bit × 3 colors

Spatial  Temporal  Dynamic range

1,119,744,000 bps (1.1 Gbps)

1920 × 1080 × 920 fps × 12 bit × 3 colors

Considering Nyquist sampling (1/2)

960 × 540 × 460 fps × 6 bit × 3 colors

4,292,352,000 bps (4.3 Gbps)
LED array: 500 Hz

High-speed camera: 1000 fps
High-speed Image Sensor

160 km/h

High-speed image processing for automotive applications
LED traffic light to vehicles (I2V-VLC)

LED tail lights to vehicle (V2V-VLC)

LED pavement marker to vehicle (I2V-VLC)

V2X Visible Light Communication
Fast recognition of LED arrays

Two consecutive images → two consecutive image differences → Binarization

Nth image → 2ms → N+1th image
Gray-scale movie obtained by the high speed camera

LED array tracking

LED array transmitting audio data
(Data rate: 32 kbps)

High speed camera

<table>
<thead>
<tr>
<th>Frame rate</th>
<th>1,000 fps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal of lens</td>
<td>35mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>1024x512 pixel</td>
</tr>
</tbody>
</table>

Speed of vehicle 30 km/h

OCI-based Optical-OFDM

- New automotive VLC system
- 55 Mbps VLC signal transmission
- Faster than DSRC

Transmitter

1010...

FEC Coding → Interleaving → S/P & QAM Mapping → Subcarrier Assignment → IFFT → Add CP & P/S → D/A & LPF → Bipolar to Unipolar → LED

Receiver

1010...

FEC Decoding → Deinterleaving → QAM Demapping & P/S → Equalization → FFT → S/P & Remove CP → LPF & A/D

LED Array

Optical Communication Image Sensor (OCI)

How we estimate distance using only one camera

\[ L = \frac{1}{2} S \frac{P}{W} \tan^{-1}\left(\frac{\theta}{2}\right) \]

We can estimate distance by using parameter \( W \)
Phase-only correlation (POC) result and Sinc function approximation

\[ G_{12}(W_m, W_n) = \xi < 1 \]

\[ G_{12}(W_m + \delta_m, W_n + \delta_n) = 1 \]

\[ G_{k,k+1}(m, n) \approx \text{sinc}(m + \Delta_m) \text{sinc}(n + \Delta_n) \] (2)

Estimate the displacement in sub-pixel order
The range estimation error plots along with numerically obtained error curves assuming sub-pixel error. The curves labeled 2-pixel and 1-pixel are the case without POC while the curves labeled 0.5-pixel and 0.1-pixels are the case with POC. The black solid curve is the approximate curve of the range estimation (plots).
ISC using Rolling-shutter image sensor
Rolling-shutter image sensor

Optical signal

On-chip lens

Color filter

Electrical signal

Photo detector

Rolling-shutter scheme
Sequential readout of voltages line by line

Timing chart of rolling-shutter scheme

Read out time $T_R$

Exposure time $T_e$
Achieving Successful VLC Signal Reception Using a Rolling Shutter Image Sensor While Driving at 40 km/h

Conclusion

- Brief history of LED and invention of blue LED
- Visible light communications (VLC)
  - Image sensor communications (ISC)
- VLC using high-speed camera
  - High-speed image processing (eyes of robot)
- High-speed image processing for automotive applications
  - Vehicle to infrastructure visible light communication system
    - Successful audio signal transmission at driving speed of 30 km/h
    - 55Mbps VLC signal transmission (faster than DSRC)
  - Range estimation using POC
    - Estimation error of less than 0.5 m from a 30-60 m range
  - ISC using Rolling-shutter image sensor
    - Successful VLC signal reception using a rolling shutter image sensor while driving at 40 km/h

Thank you and your questions or comments are welcome!
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Optical wireless communication (OWC) systems over terrestrial, space or underwater links are gaining much attention as cost-effective, sustainable and energy efficient candidates to meet the ever-increasing demand for capacity and quality for 5G/6G networks. Besides the compelling advantages of the high-power solid-state laser diodes for medium to long range applications, remarkable advances have been achieved in semiconductor sources such as light emitting diodes (LEDs) in visible light and ultraviolet wavelengths, multi-array light sources and detectors, tracking and steering. These advances provide huge potential for short/medium range wireless communication applications at low power and cost.

Despite the conspicuous advantages of OWC-based systems, their design and implementation are still facing several challenges due to the properties of the optical beam propagation through the atmosphere. In fact, different distortions may be experienced due to susceptibility to weather conditions, channel impairments, and compatibility and integration with existing radio frequency networks. In order to circumvent these challenges, further research on the OWC channel and the different system components, and innovative and more efficient techniques are still required to further facilitate the wide-scale implementation of OWC systems.