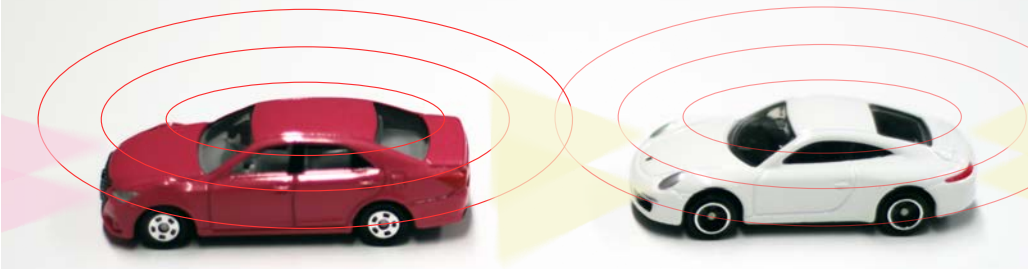
可視光通信　Visible Light Communications: VLC



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yamazato@nagoya-u.jp

以下の発表資料をベースにしています。
信学技報 IEICE Technical Report
WBS2022-43,ITS2022-19,RCC2022-43(2022-12)

可視光通信 Visible Light Communications (VLC)

1. 可視光通信（Visible light communications: VLC）
   - イメージセンサ通信（Image sensor communications: ISC）
2. 高速度カメラを用いた ISC
3. ローリングシャッタ方式のイメージセンサを用いた ISC
4. イベントカメラを用いた ISC

1999　慶應義塾大学中川正雄教授により提唱

2001　可視光通信コンソーシアム
(会長：慶應義塾大学春山真一郎教授)

2014 可視光通信協会

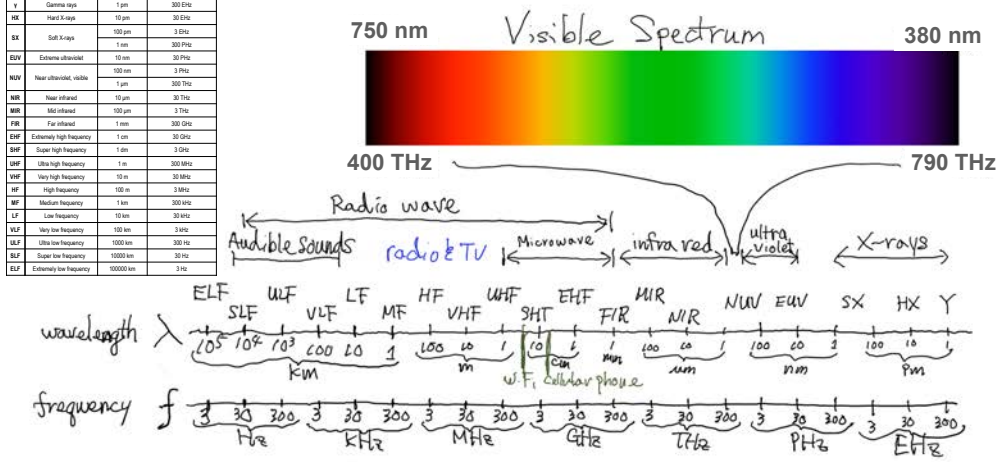
2018 日本フォトニクス協議会・可視光通信分科会

2023 日本フォトニクス協議会・光無線分科会（会長：山里）

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

	Class	Wavelength λ	Frequency f
γ	Gamma rays	1 pm	300 EHz
HX	Hard X-rays	10 pm	30 EHz
SX	Soft X-rays	100 pm	3 EHz
		1 nm	300 PHz
EUV	Extreme ultraviolet	10 nm	30 PHz
NUV	Near ultraviolet, visible	100 nm	3 PHz
		1 μm	300 THz
NIR	Near infrared	10 μm	30 THz
MIR	Mid infrared	100 μm	3 THz
FIR	Far infrared	1 mm	300 GHz
EHF	Extremely high frequency	1 cm	30 GHz
SHF	Super high frequency	1 dm	3 GHz
UHF	Ultra high frequency	1 m	300 MHz
VHF	Very high frequency	10 m	30 MHz
HF	High frequency	100 m	3 MHz
MF	Medium frequency	1 km	300 kHz
LF	Low frequency	10 km	30 kHz
VLF	Very low frequency	100 km	3 kHz
ULF	Ultra low frequency	1000 km	300 Hz
SLF	Super low frequency	10000 km	30 Hz
ELF	Extremely low frequency	100000 km	3 Hz



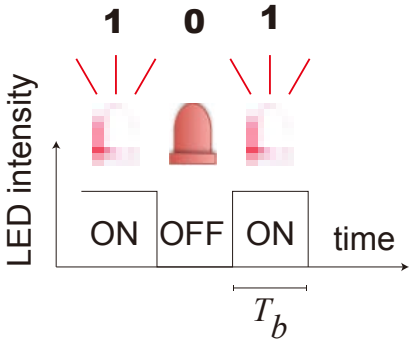
VLC Transmitter

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)

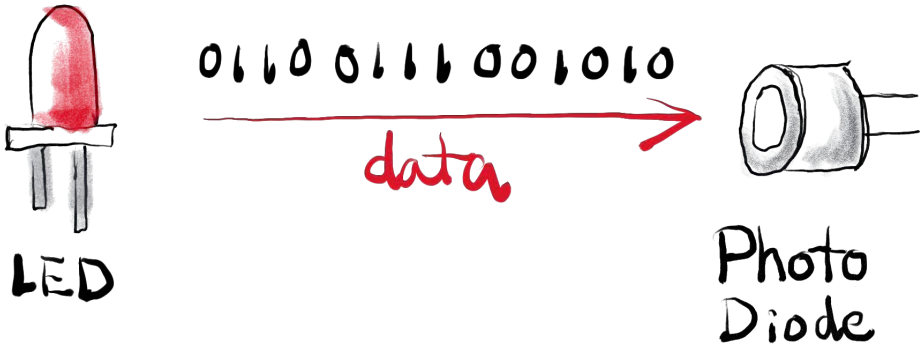
The simplest form of modulation



Data rate is $R_b = 1/T_b$

VLC Transmitter

In most cases, VLC uses LEDs for a transmitter.



Intensity modulation and direct detection (IM/DD) systems

イメージセンサ通信
Image Sensor Communications: ISC

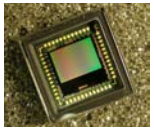
イメージセンサ通信（ISC）

カシオ・飯塚宣男アドバイザリーエンジニア

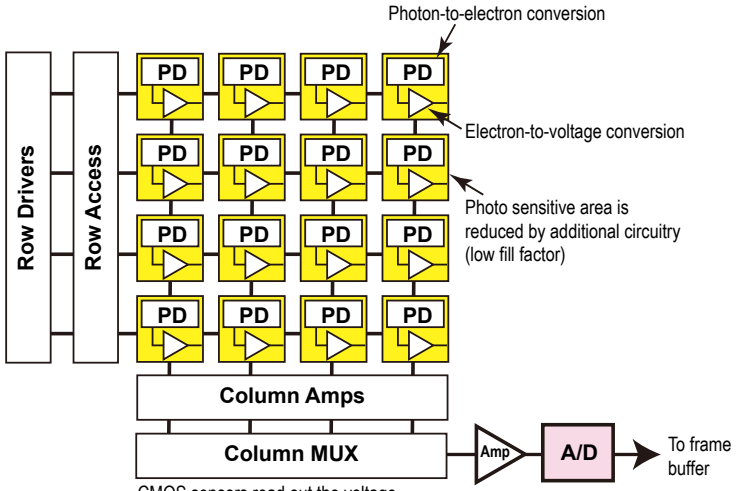
カシオ計算機「ピカリコ」 LED×カメラの可視光通信、“第3の測位技術”注目
https://news.aperza.jp/カシオ計算機「ピカリコ」-ledxカメラの可視光通信/ （閲覧：2022/12/12）

- カシオ・飯塚氏により提唱される
- IEEE 802.15.7 で 標準化された光カメラ通信 (Optical camera communication: OCC)と基本的には同じ
- 特徴：
  - 空間分離特性を持ち，LED アレイを用いた空間並列伝送ができる
  - 送信源のトラッキングが容易
  - 通信と測距(位置推定)が同時にできる

CMOS (complementary metal oxide semiconductor)

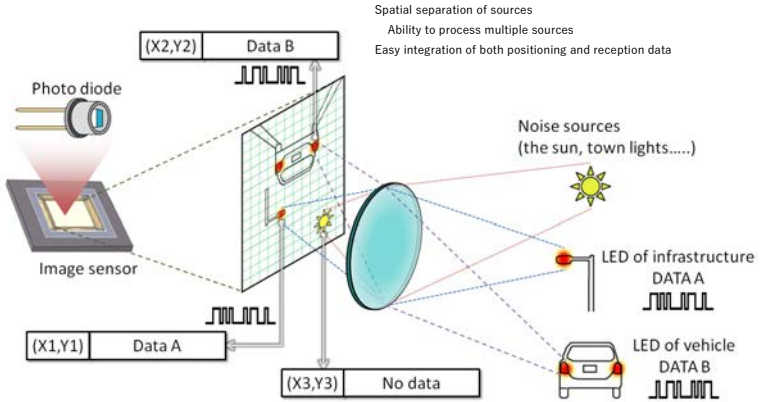


https://en.wikipedia.org/wiki/Active-pixel_sensor

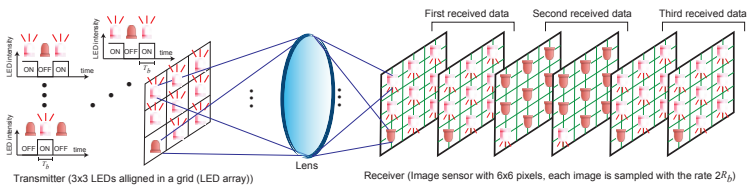


CMOS sensors read out the voltage using row and column decoders, like a digital memory.

High-Speed Image Sensor as a Reception Device of VLC Signals



T. Yamazato, et al. "Vehicle Motion and Pixel Illumination Modeling for Image Sensor Based Visible Light Communication," IEEE JSAC, 2015.



Question

If the source data rate is 120Hz, what is the minimum sampling rate to reconstruct original data?

高速度カメラを用いた ISC

How fast can we achieve? — Ideal case —

iPhone
1080p 240 fps

$$1920 \times 1080 \times 240\ fps \times 12\ bit \times 3\ colors$$

Considering Nyquist sampling (1/2)

$$960 \times 540 \times 120\ fps \times 6\ bit \times 3\ colors$$

Spatial | Temporal | Dynamic range

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

Xperia
1080p 920 fps

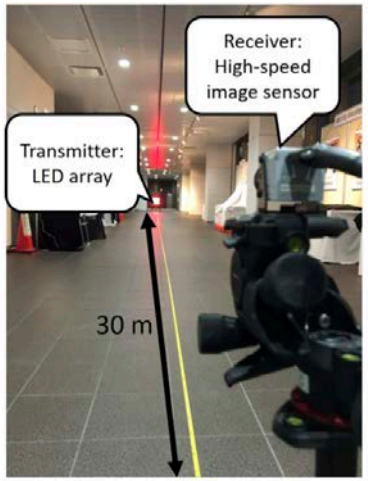
$$1920 \times 1080 \times 920\ fps \times 12\ bit \times 3\ colors$$

Considering Nyquist sampling (1/2)

$$960 \times 540 \times 460\ fps \times 6\ bit \times 3\ colors$$

4,292,352,000 bps (**4.3 Gbps**)

How fast can we achieve? — Our case —



Photoron IDP-Express

$$512 \times 96 \times 10{,}000\ fps \times 8bit$$

Considering Nyquist sampling (1/2)

$$256 \times 48 \times 5{,}000\ fps \times 4bit$$

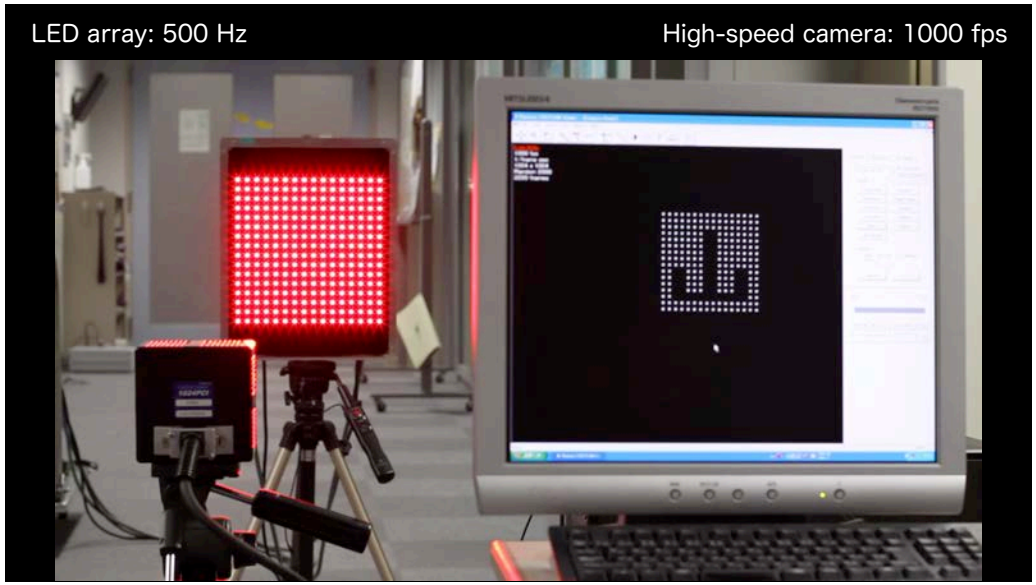
245,760,000 bps (**245 Mbps**)

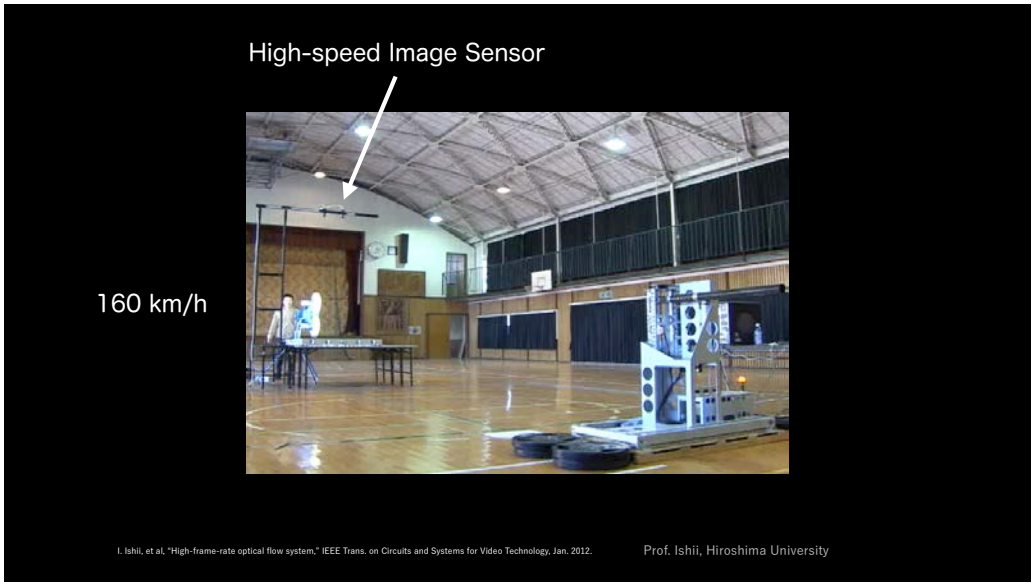
Actual Experiment

$$4 \times 4 \times 5{,}000\ fps \times 4bit$$

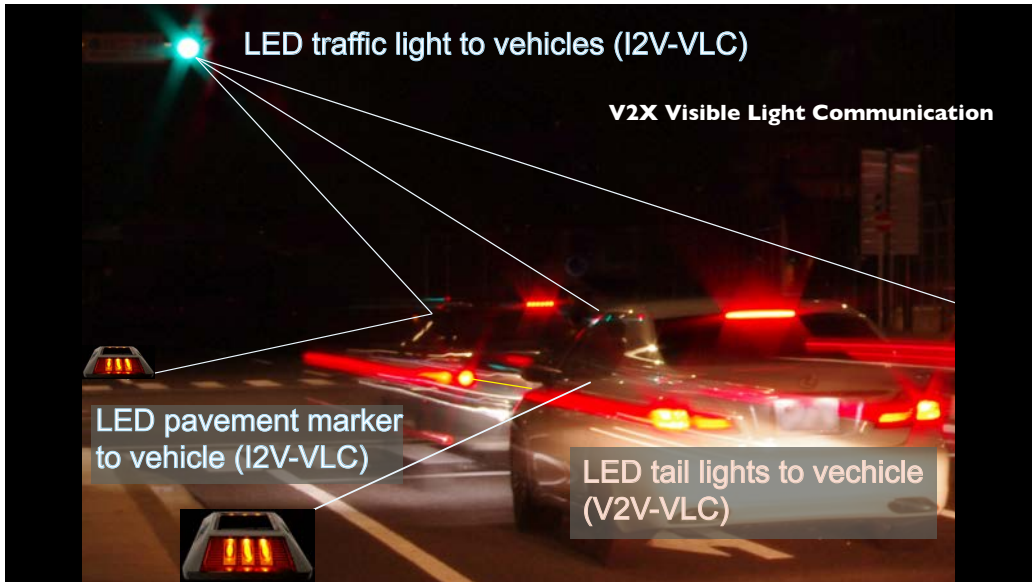
Size of LED array

320,000 bps (**320 kbps**)

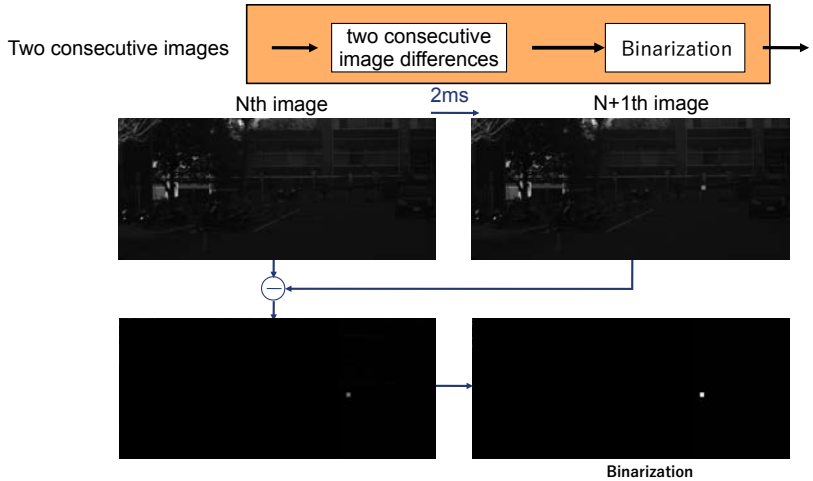


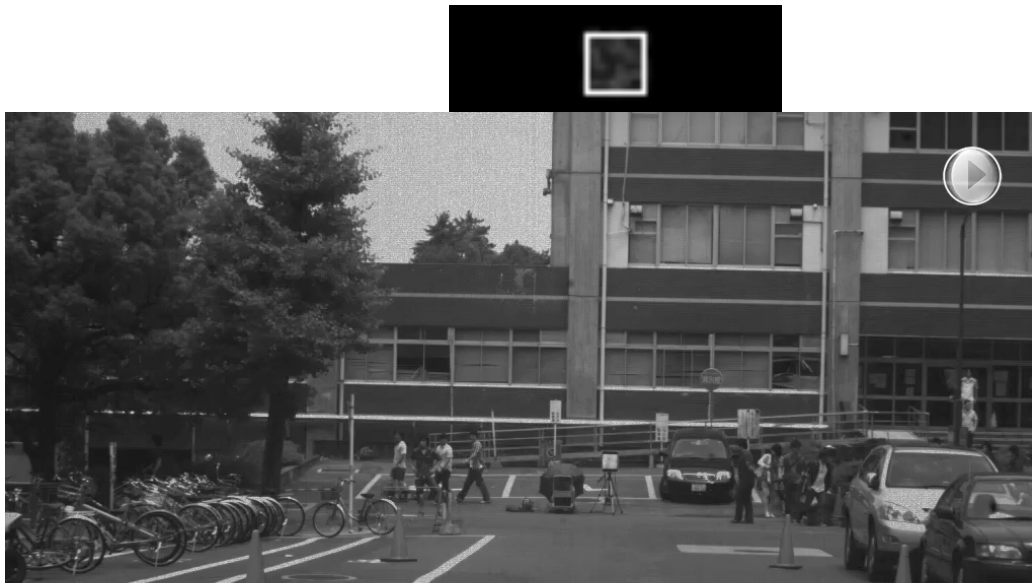


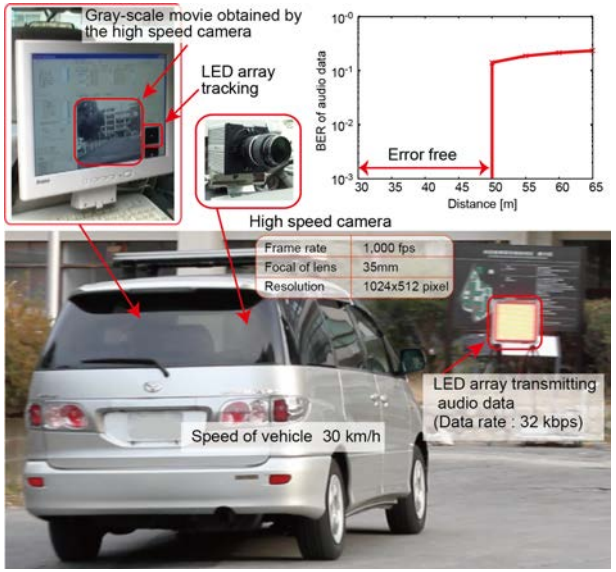
High-speed image processing for automotive applications



Fast recognition of LED arrays





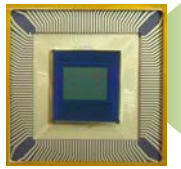


T. Yamazato, et al. "Image Sensor Based Visible Light Communication for Automotive Applications," IEEE Communication Magazine, Jul., 2014.

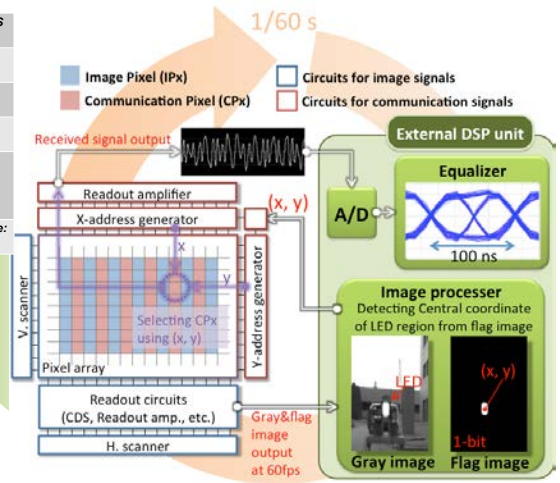
An optical communication image sensor (OCI)

Chip specifications

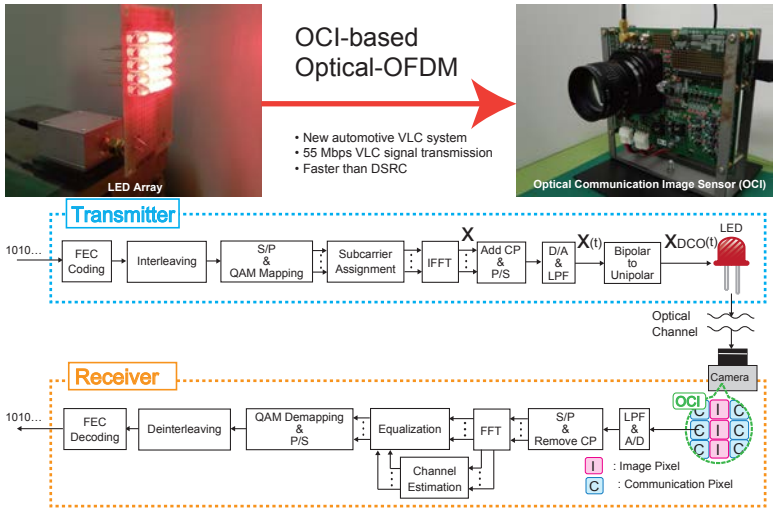
Technology	*0.18 μm 1P4M CMOS process*
Chip size	*7.5 mm x 8.0 mm*
Imaging area size	*1/3 inch*
Pixel size	*7.5 μm x 7.5 μm*
Number of pixels	*Total of 640 x 480 (VGA)* *- CPx: 320 x 480* *- IPx: 320 x 480*
Frame rate	*Gray and Flag image: 60 fps*



OCI chip photograph

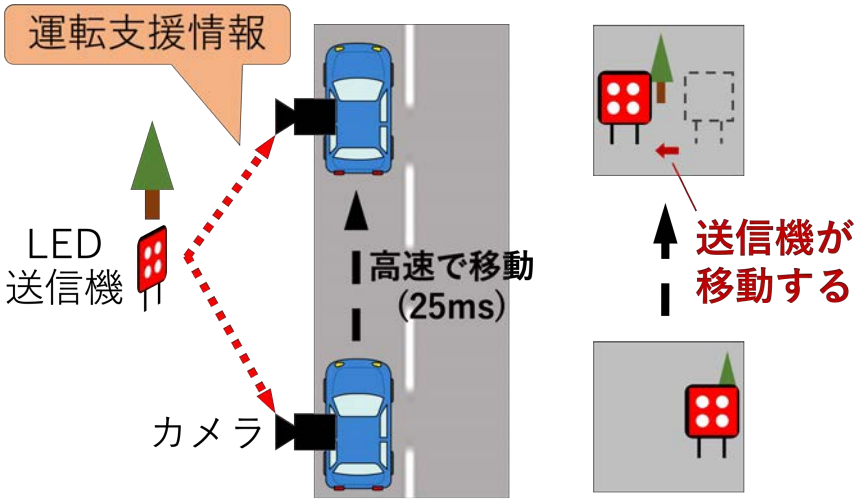


T. Yamazato, et al. "Image Sensor Based Visible Light Communication for Automotive Applications," IEEE Communication Magazine, Jul., 2014.
I. Takai, et al. "LED and CMOS image sensor based optical wireless communication system for automotive applications," IEEE Photonics Journal, Oct. 2013.

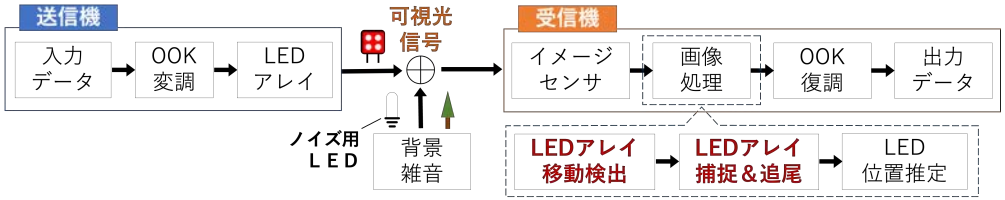


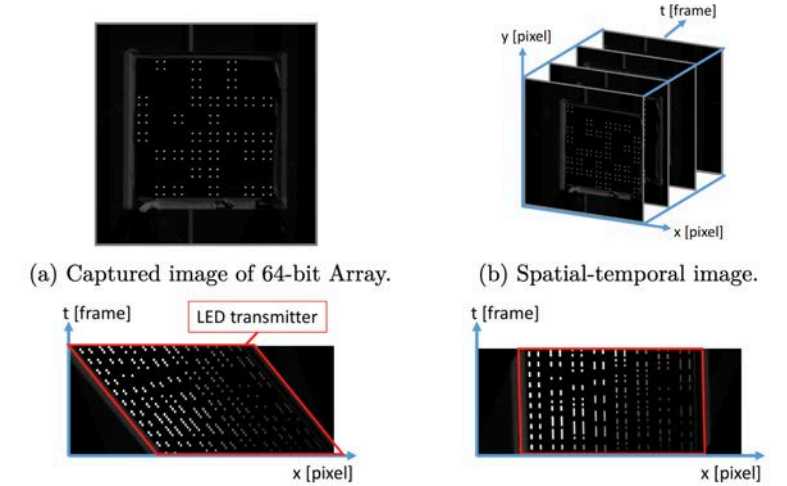
Y. Goto et al. "A New Automotive VLC System Using Optical Communication Image Sensor," IEEE Photonics Journal, Vol. 8, No. 3, June 2016.

LEDアレイを横切る



システムモデル





(a) Captured image of 64-bit Array.
(b) Spatial-temporal image.
(c) Spatial-temporal cross-sectional image.
(d) Spatial-temporal cross-sectional image when LED position corrected.

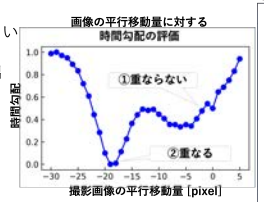
時間勾配を用いたLEDアレイ移動検出

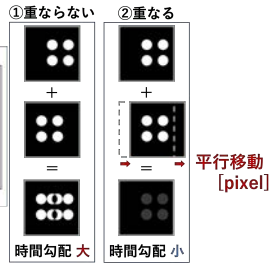
撮影画像内のLEDアレイの位置が移動
⇒時間勾配 (時間軸輝度値変化) が大きい

画像を平行移動させ，時間勾配を算出

LEDアレイが重なる⇒時間勾配が最小

移動量検出後，時空間勾配を
複数画像で重ね合わせ，
LEDアレイを検出[1]

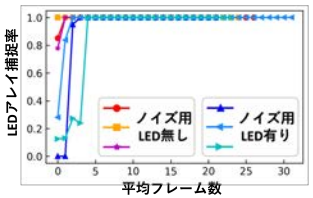




[1] K. Nakamura, et al., "Roadside LED Array Acquisition For Road-to-Vehicle Visible Light Communication Using Spatial-Temporal Gradient Values," IEICE Communications Express, Aug 2022.

走行環境におけるノイズ低減の評価

平均フレーム数に対するLEDアレイ捕捉率とノイズ低減の評価



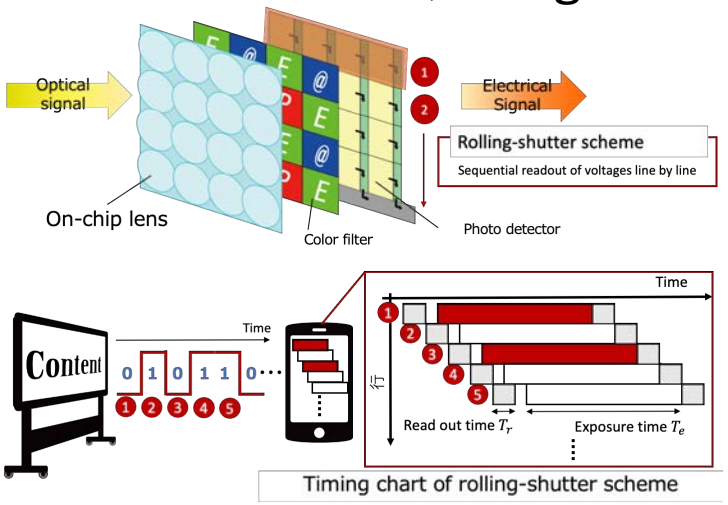
ノイズ用LEDが…
無い場合⇒**2枚以上**
有る場合⇒**5枚以上**
複数の画像で平均すると
LEDアレイ捕捉率が100%

補足したLEDアレイから
25msの撮影で6400bit を
エラーフリーで復調

実験風景

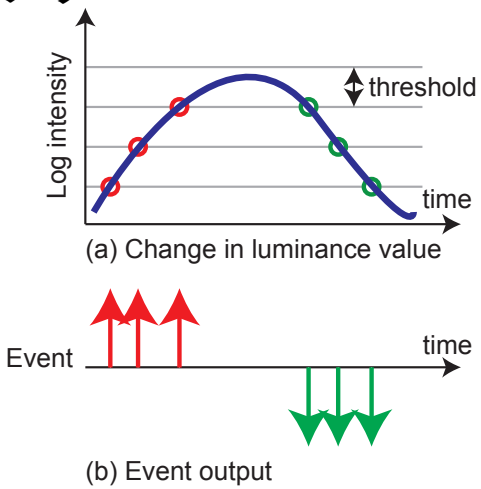
ローリングシャッタ方式の
イメージセンサを用いた ISC

ローリングシャッタ方式（Rolling-shutter）

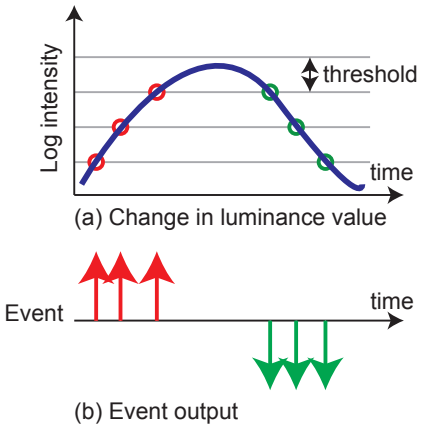


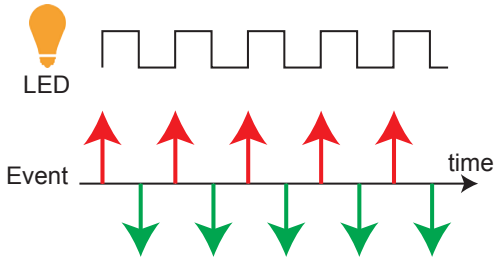
イベントカメラを用いた ISC

イベントカメラ

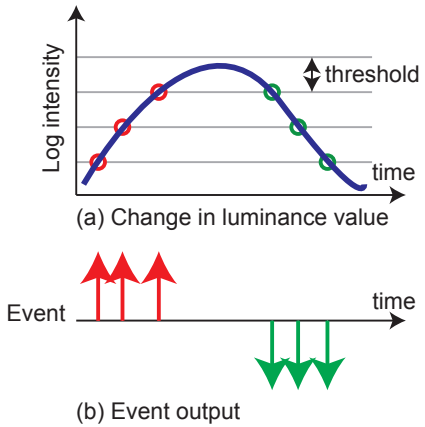


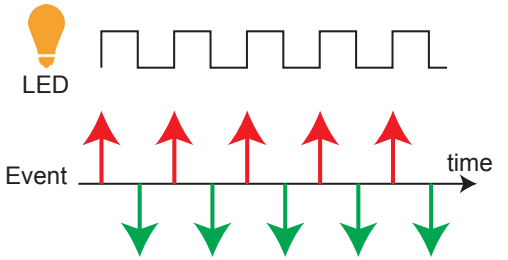
イベントカメラ





イベントカメラ





シーケンシ Sequency

$w_0 =$	+1	+1	+1	+1	+1	+1	+1	+1	(0)
$w_1 =$	+1	+1	+1	+1	−1	−1	−1	−1	(1)
$w_2 =$	+1	+1	−1	−1	−1	−1	+1	+1	(2)
$w_3 =$	+1	+1	−1	−1	+1	+1	−1	−1	(3)
$w_4 =$	+1	−1	−1	+1	+1	−1	−1	+1	(4)
$w_5 =$	+1	−1	−1	+1	−1	+1	+1	−1	(5)
$w_6 =$	+1	−1	+1	−1	−1	+1	−1	+1	(6)
$w_7 =$	+1	−1	+1	−1	+1	−1	+1	−1	(7)

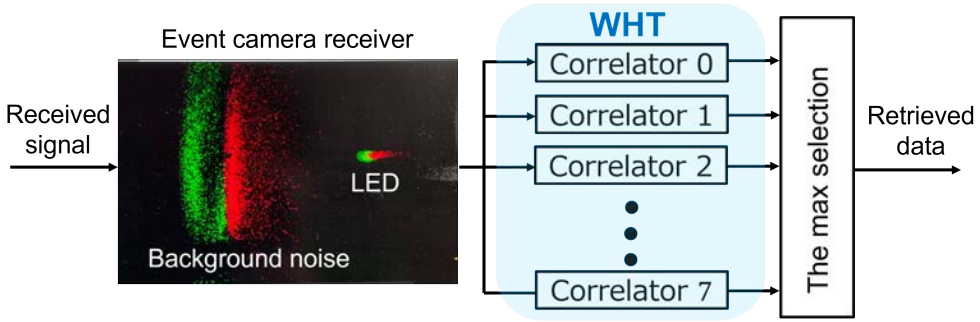
Walsh-Hadmard code assignment

		seq
$a_0 = (0\,0\,0)$	$\rightarrow w_0 = (+1+1+1+1+1+1+1+1)$	0
$a_1 = (0\,0\,1)$	$\rightarrow w_1 = (+1+1+1+1-1-1-1-1)$	250
$a_2 = (0\,1\,0)$	$\rightarrow w_2 = (+1+1-1-1-1-1+1+1)$	500
$a_3 = (0\,1\,1)$	$\rightarrow w_3 = (+1+1-1-1+1+1-1-1)$	750
$a_4 = (1\,0\,0)$	$\rightarrow w_4 = (+1-1-1+1+1+1-1-1+1)$	1000
$a_5 = (1\,0\,1)$	$\rightarrow w_5 = (+1-1-1+1-1+1+1+1-1)$	1250
$a_6 = (1\,1\,0)$	$\rightarrow w_6 = (+1-1+1-1-1+1-1+1)$	1500
$a_7 = (1\,1\,1)$	$\rightarrow w_7 = (+1-1+1-1+1-1+1-1)$	1750

Transmitted data

LED array transmitter

Event camera receiver



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4. イベントカメラを用いた ISC

Thank you and your questions or comments are welcome!
yamazato@nagoya-u.jp