Receiver Technologies for Optical Wireless Communications

Cuiwei He

JAIST

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About Japan Advanced Institute of Science and Technology (JAIST)

- Located in Ishikawa, Japan
- One of the three graduate universities in Japan (The other two are NAIST and OIST)
- Students are from more than 20 countries

About me

Experience

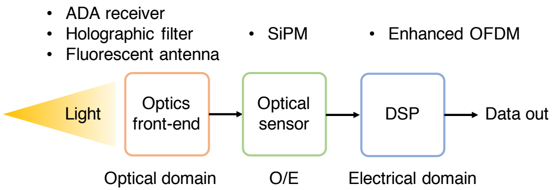
- Japan Advanced Institute of Science and Technology, Japan
  Assistant Professor, 2021 - Now
- University of Oxford, UK
  Postdoctoral Research Assistant, 2020 - 2021
  Supervisor: Prof. Steve Collins
- Monash University, Australia
  Research Fellow, 2017 - 2020
- Monash University, Australia
  PhD Student, 2014 - 2017
  Supervisor: Prof. Jean Armstrong

Research interests

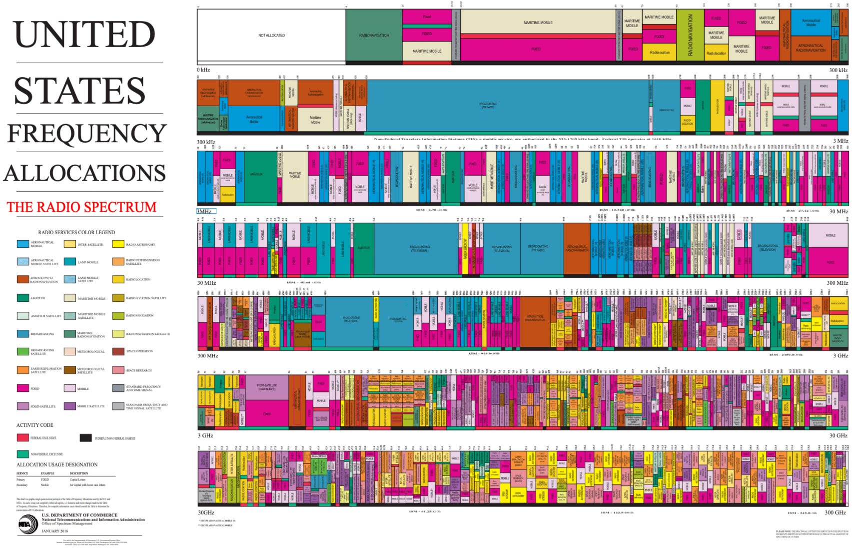
- Visible Light Communications (VLC), Visible Light Positioning (VLP)
- Optical MIMO and optical OFDM
- Single-Photon Avalanche Diode (SPAD) based optical receiver
- Holographic Filter
- Fluorescent materials in OWC
- Artificial Neural Network Algorithms

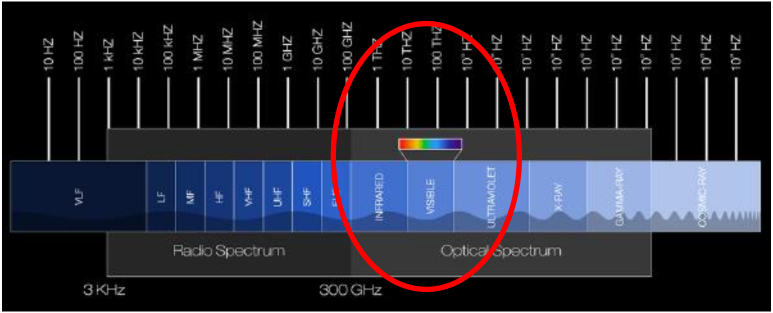
Outline

1. Background
2. Angular Diversity Aperture (ADA) Receivers
   - Applications in optical MIMO
   - Applications in VLP
3. Holographic filter in VLC
   - For simultaneously optical filtering, angular selective and light concentration
4. Fluorescent optical antenna in VLC
   - For simultaneously optical filtering and light concentration and a large FOV
5. Silicon photomultiplier (SiPM) in optical wireless
   - SiPM nonlinearity and solutions using neural network
6. Enhanced optical OFDM
   - Clipping noise for DCO-OFDM
   - Diversity combining for ACO-OFDM
   - Layered ACO-OFDM



Background - the crowded RF spectrum

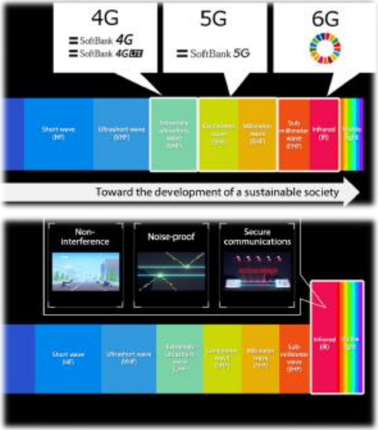




Picture source: NASA website

Why not unlock the optical spectrum for wireless communication?

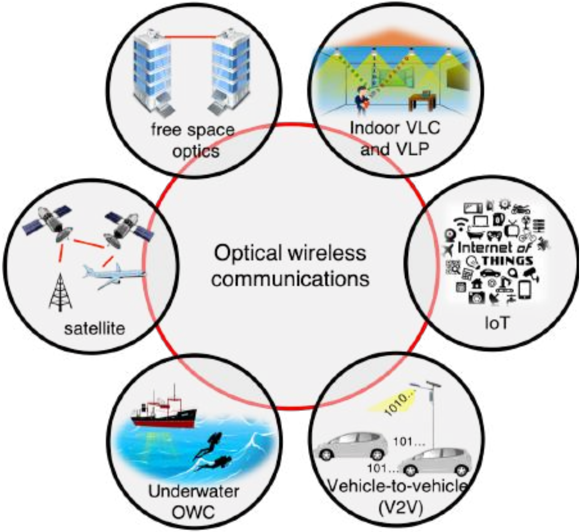
The vision of the wireless industry



Each generation of wireless network always needs to unlock more spectrum resources.

Source Link: https://www.softbank.jp/en/sbnews/entry/20210420_01

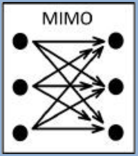
Applications of optical wireless communications



Optical MIMO receiver - ADA

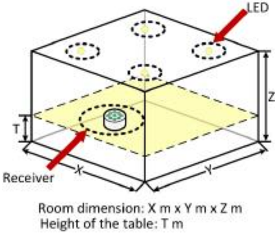
Optical Multiple-input Multiple-output (MIMO)

Transmitters

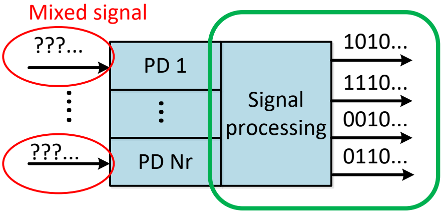


Detectors

What is MIMO?



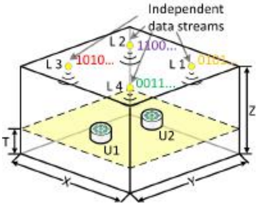
Indoor optical MIMO communication system

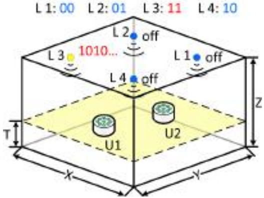


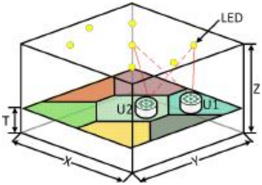
- Each PD receives multiple signals at the same time
- MIMO receiver must be able to decouple the transmitted signals

- Transmitter: multiple lighting LEDs
- Receiver: multiple photo-detectors (PDs)

Different optical MIMO configurations







Optical spatial multiplexing (SMP): Multiple LEDs transmit independent data, and multiple photodetectors are used to detect the signals and further decode the transmitted data.

Optical spatial modulation (OSM): Only one LED luminaire is active during a short time slot. The information is conveyed by both the data symbols modulated on the light intensity and index of the active LED.

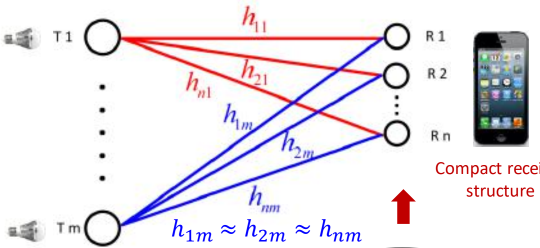
Optical cellular system : The receiver only received the desired signal from the nearest LED and received signals from other LEDs are interfering signals.

All systems need to separate signals transmitted from different LEDs!

Problems in optical MIMO: Singular channel matrix

VLC scenario with multiple LEDs and multiple PDs

$h_{11} \approx h_{21} \approx h_{n1}$



$h_{1m} \approx h_{2m} \approx h_{nm}$

Compact receiver structure

Multiple PDs are needed in MIMO systems

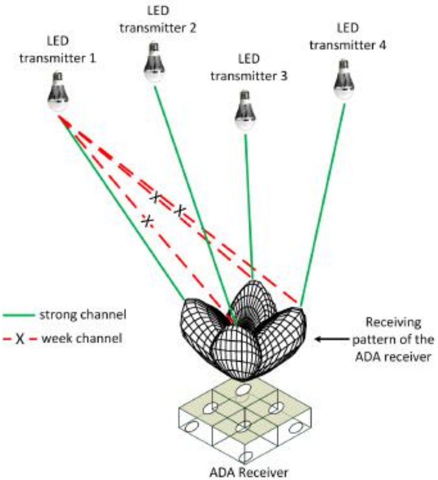
We can NOT solve this:

$$\begin{cases} x + 2y = 1 \\ x + 2y = 1 \end{cases}$$

$$\mathbf{H} = \begin{bmatrix} h_{11} & \cdots & h_{1m} \\ h_{21} & \cdots & h_{2m} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nm} \end{bmatrix}$$

An **ill-conditioned** Channel matrix which has elements in each column with similar values

Solution: Directional optical MIMO receiver



$$\mathbf{H} \approx \begin{bmatrix} h_{11} & 0 & 0 & 0 \\ 0 & h_{22} & 0 & 0 \\ 0 & 0 & h_{33} & 0 \\ 0 & 0 & 0 & h_{44} \end{bmatrix}$$

1.Good channel condition-

diagonal channel matrix

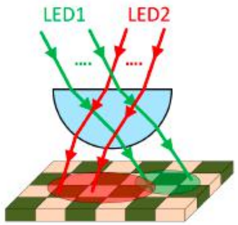
2. Parallel data transmission-

reduced Multi-stream interference (MSI)

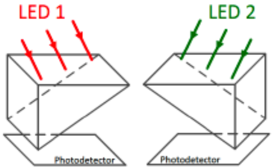
We can EASILY solve this:

$$\begin{cases} x + 0 \times y = 1 \\ 0 \times x + y = 2 \end{cases}$$

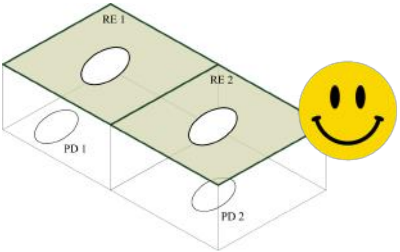
A range of proposed optical MIMO receiver



Hemispherical lens based receiver

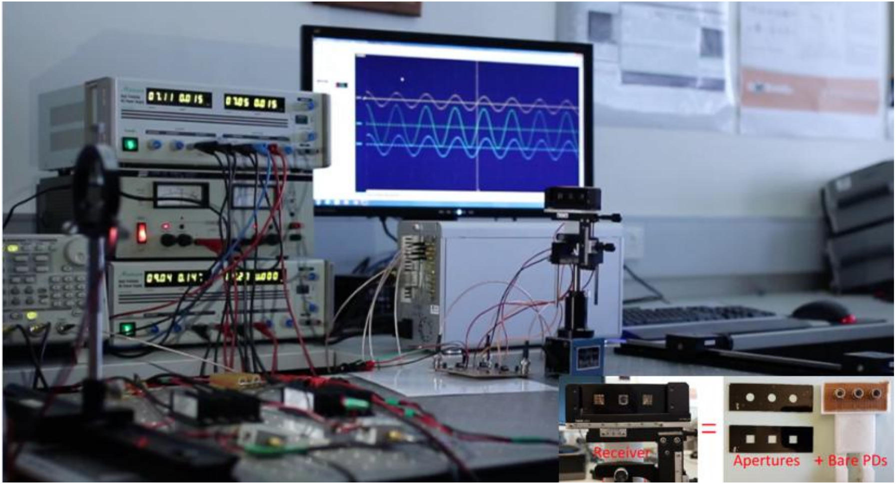


Prism based receiver

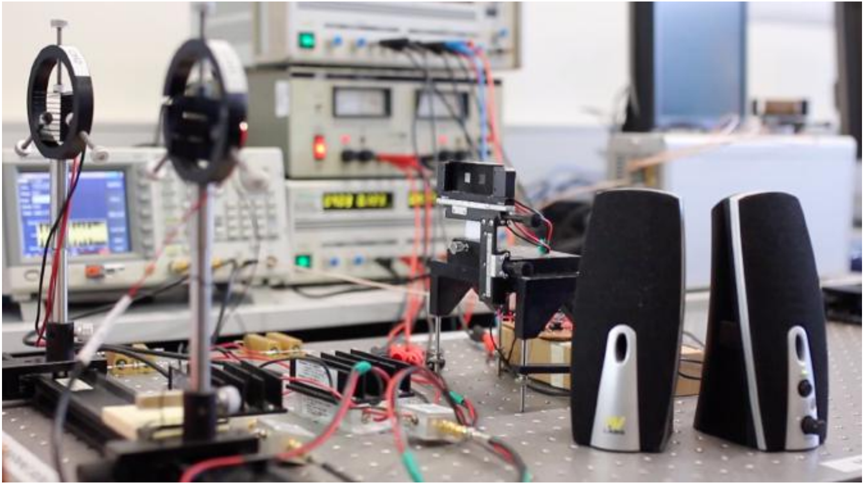


Angular diversity aperture (ADA) based receiver

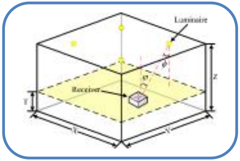
Video of angular diversity validation

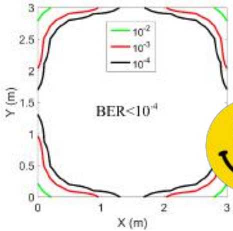


Video of ADA receiver – Music transmission



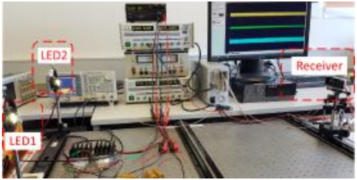
Simulation results

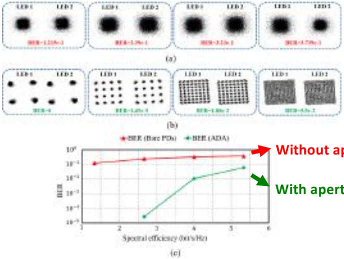




BER as a function of receiver's position

Experimental results





Without apertures

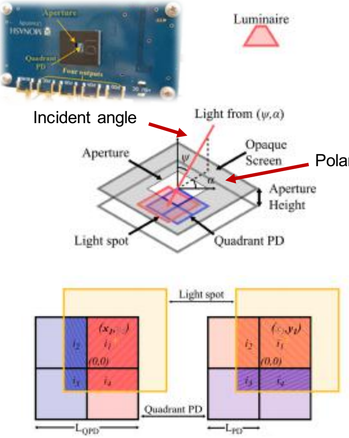
With apertures

A 3 X 2 VLC MIMO experiment

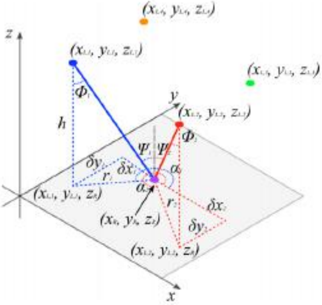
Visible light positioning receiver - QADA

Visible light positioning

Source: Philips Lighting



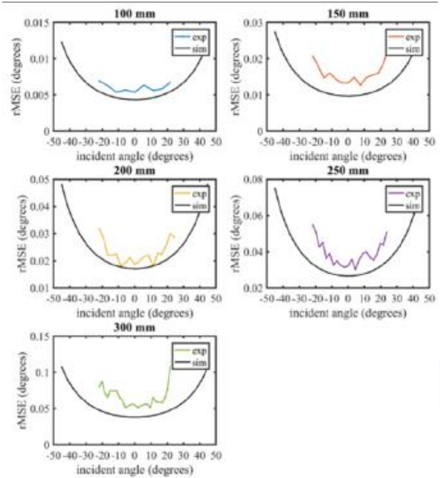
QADA receiver

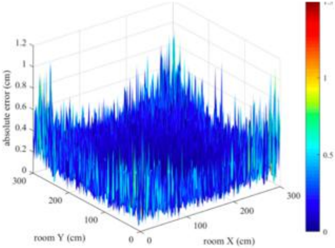


Triangulation

- The QADA receiver front-end consists of an aperture and a quadrant photodiode.
- Based on the received signals by the four quadrants, it can estimate the direction of the light.

QADA performance

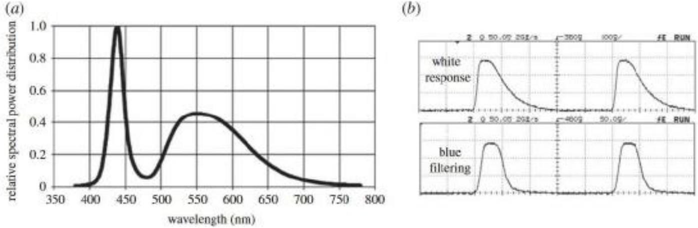




The QADA receiver can achieve cm level positioning accuracy.

Holographic optical filter

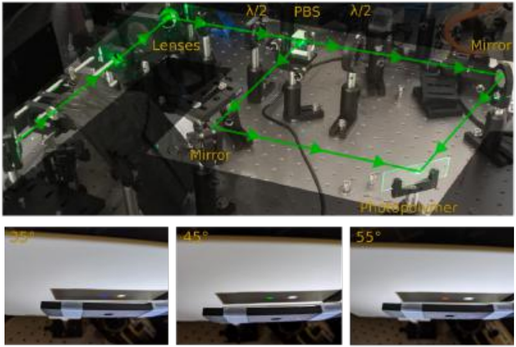
The importance of optical filtering in VLC

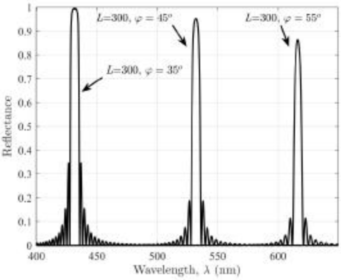


The modulation bandwidth of the emitter is typically 10–20 MHz, whereas the white LED might have a bandwidth of few MHz, due to this slow phosphor response.

Picture source: Dominic O'Brien, Sujan Rajbhandari and Hyunchae Chun,"Transmitter and receiver technologies for optical wireless" *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Volume 378, Issue 2169, 2020.

Holographic filter - both wavelength and angular selective





Measurement

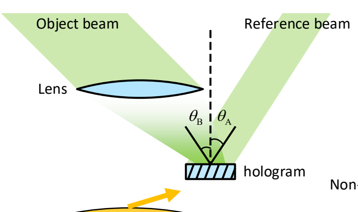
Simulation

Wavelength and light incident angle

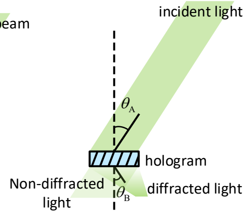
Bragg's law:

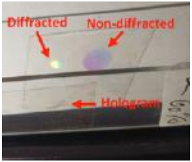
$$\Lambda \sin(\phi) = m\lambda$$

The wavelength of the diffracted light depends on the incident angle.



Phase information
of the object beam
is recorded

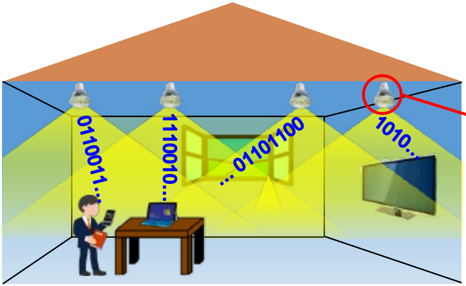


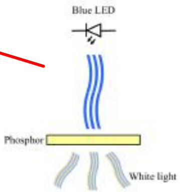


Light concentration

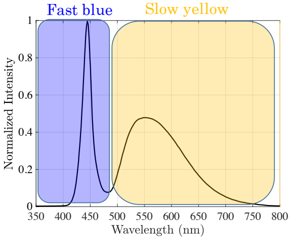
This design can be used to improve the optical power detected by the photodiode.

Fluorescent antenna in VLC





Yellow phosphor excited state lifetime: several micro seconds

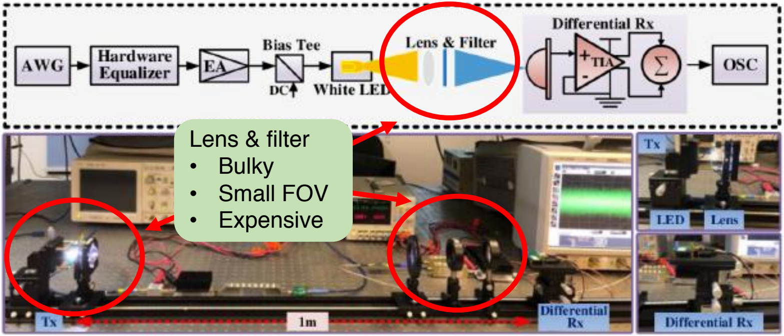


GaN LED emission lifetime: several tens/hundreds of nano seconds

Bandwidth

- The white LED only have a bandwidth of few MHz, due to this slow phosphor response.
- The modulation bandwidth can be significantly improved using blue filtering.

A popular VLC experiment setup

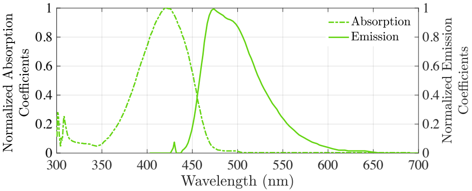


Typical ways for enhancing VLC performance

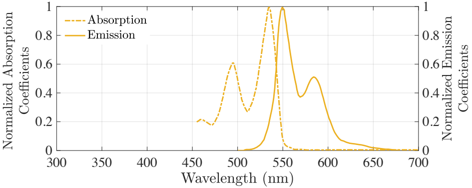
- Optical filters are used to extract the blue light for improving bandwidth
- Optical lenses are used for increasing the light intensity

Picture source: Yingjun Zhou, Yiran Wei, Fangchen Hu, Jian Hu, Yiheng Zhao, Jianli Zhang, Fengyi Jiang, and Nan Chi, "Comparison of nonlinear equalizers for high-speed visible light communication utilizing silicon substrate phosphorescent white LED," *Opt. Express* 28, 2302-2316 (2020)

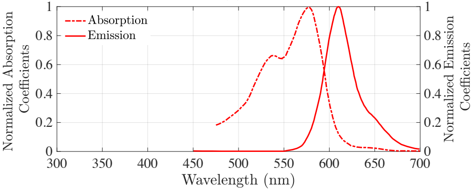
How fluorescent materials can help - optical filtering



(a)



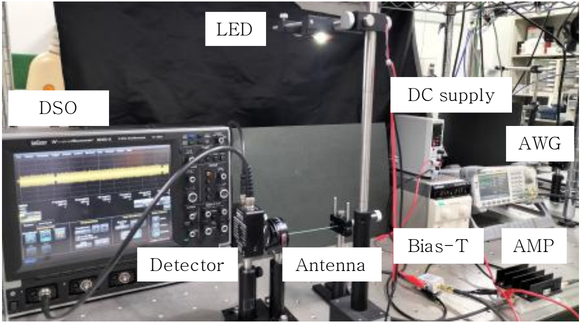
(b)



Optical properties

- Absorb shorter wavelengths and emit longer wavelengths.
- The fluorescent lifetime is only few nanoseconds.

Experimental setup - with fluorescent fiber antenna

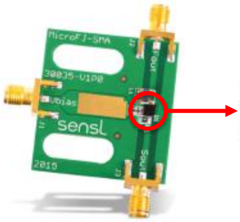


Advantages

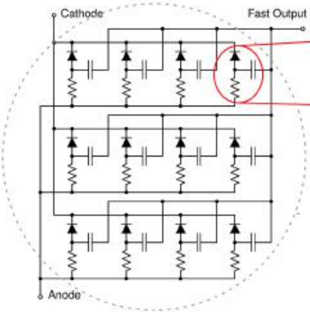
- Optical concentrator (high gains) and optical filter together
- Large field-of-view (FOV)
- Flexible in receiver design
- Not expensive
- Short fluorescent lifetime (several ns)

Photon counting based signal detection

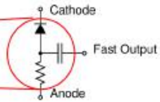
What is silicon photomultipliers (SiPM)?



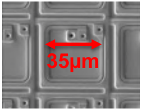
SiPM 30035
on a evaluation PCB board
(manufactured by Sensl/On Semiconductor)



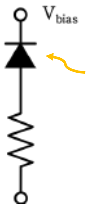
An array of microcells
(5676 microcells in 30035)



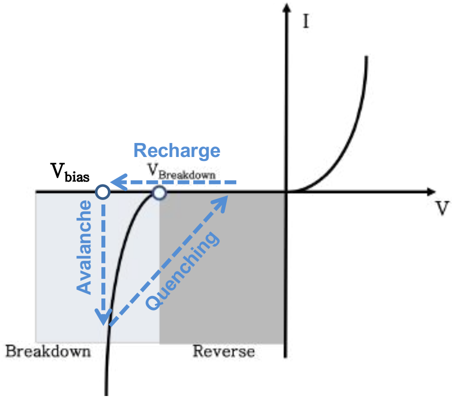
A single microcell



Photon detection & Recovery period (or dead time)

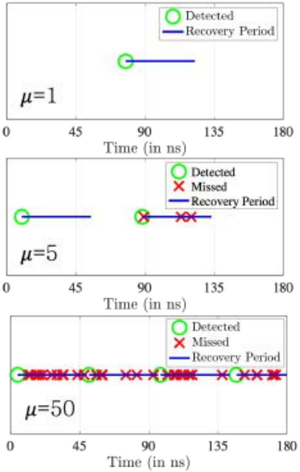


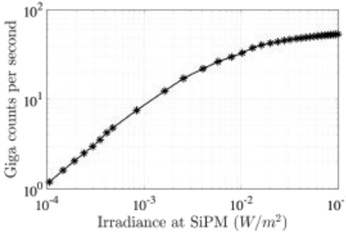
A single microcell



- The avalanche-and-quenching process creates an electrical pulse so that a photon can be counted.
- The avalanche-and-quenching process usually takes several nanoseconds which is known as the **recovery period**. Any photons arriving within this period on the associated microcell cannot be detected.

SiPM nonlinearity

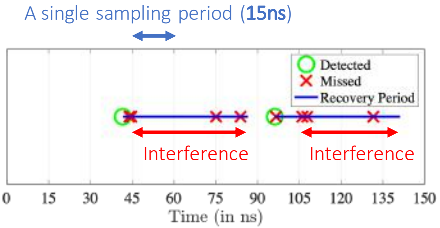


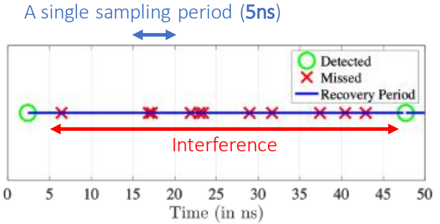


Recovery period causes a nonlinearity response

Missing photons due to the Recovery period/dead time.

A unique form of Inter-symbol interference (ISI) in time domain

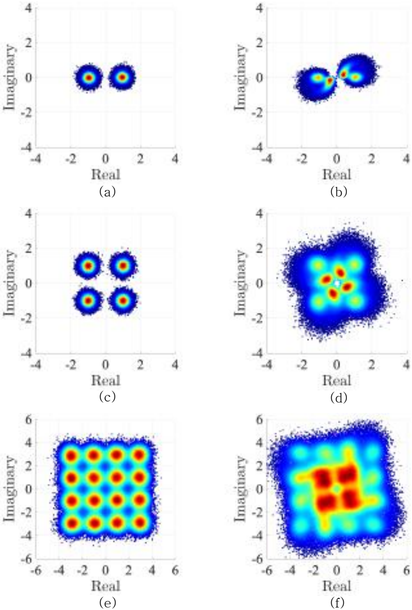




ISI

The recovery period causes interference between signal samples and the interference is related to the transmission data rate.

Signal distortion



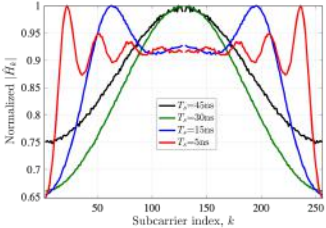


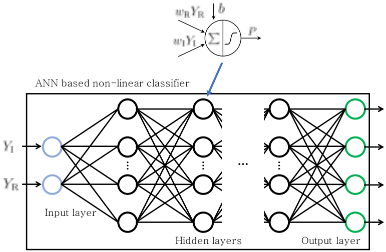
Figure: The frequency response caused by the SiPM recovery period.

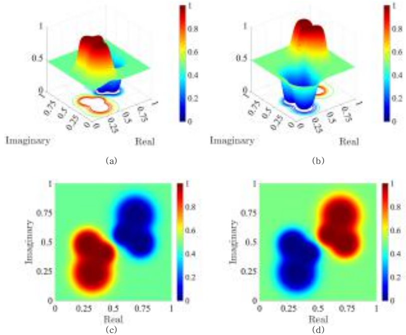
The problem

The SiPM nonlinearity causes complex non-linear signal distortion when the irradiance level is high.

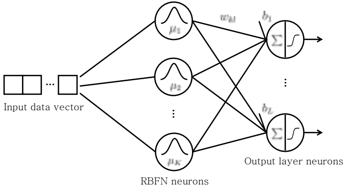
AI-aided signal demodulation

Approach 1: Artificial neural network (ANN)





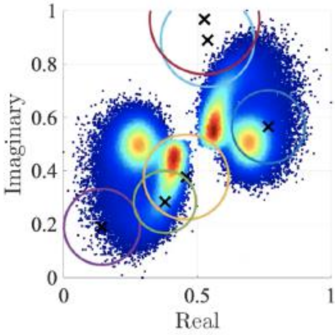
Approach 2: Radial basis function neural network (RBFNN)



The goal

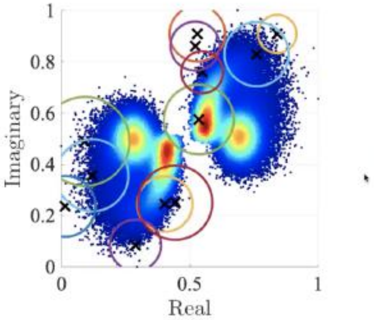
The goal is to obtain non-linear classification boundaries in the Euclidean space to perform more accurate decision making.

Video - updating process of the RFBNN neuron positions and widths



The updating process of the RBFNN using k-means clustering ($K/L=3$) - BPSK

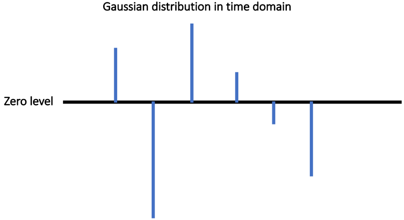
Video - updating process of the RFBNN neuron positions and widths

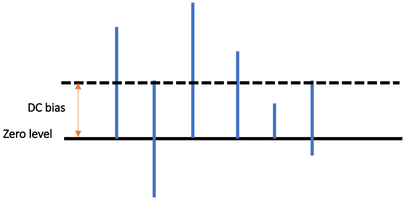


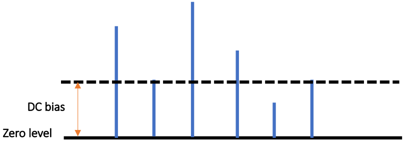
The updating process of the RBFNN using k-means clustering ($K/L=6$) - BPSK

Enhanced Optical OFDM modulation

DC biased optical OFDM (DCO-OFDM)



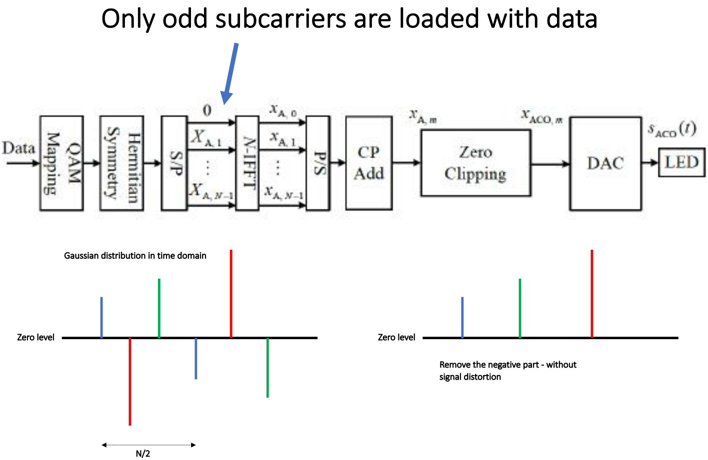




Clipped the negative part

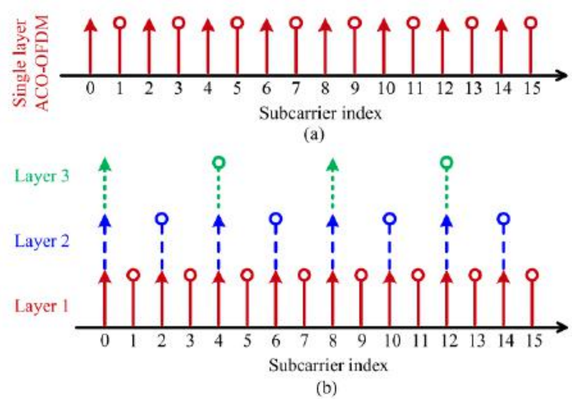
O A DC bias can avoid clipping distortion.
X A huge DC bias is not power efficient.

Asymmetrically clipped optical OFDM (ACO-OFDM)



O Clipping noise only on the even subcarriers.
X When only odd subcarriers are used for data carrying, it is not spectrally efficient.

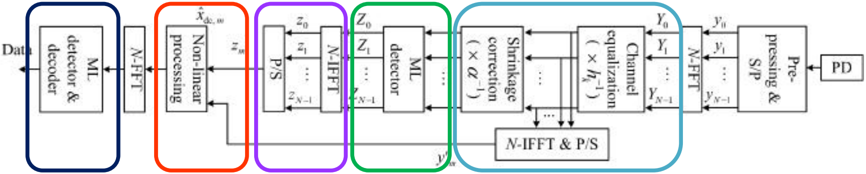
Layered ACO-OFDM



- Even subcarriers are occupied by multiple layers of ACO-OFDM signals
- Increase the spectrum efficiency of ACO-OFDM and avoid clipping noise
- The demodulation step is a SIC process

Step 5: Final detection

Step 3: Convert back to time domain (Note that the clipped parts will be regenerated)

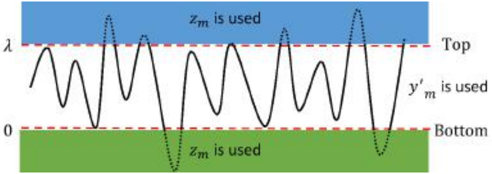


Step 4: Signal reconstruction Step 2: ML detection Step 1: signal equalization

$$r_m = \begin{cases} y'_m, & y'_m > 0 \\ z_m, & y'_m \leq 0 \end{cases}$$

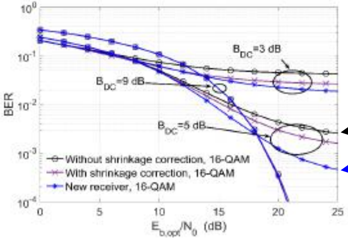
y'_m: Original received signal

z_m: signal after ML detection



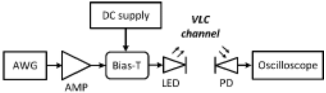
Clipping noise mitigation for DCO-OFDM - results

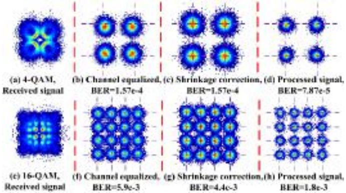
Simulation results



New receiver significantly outperforms conventional receiver !

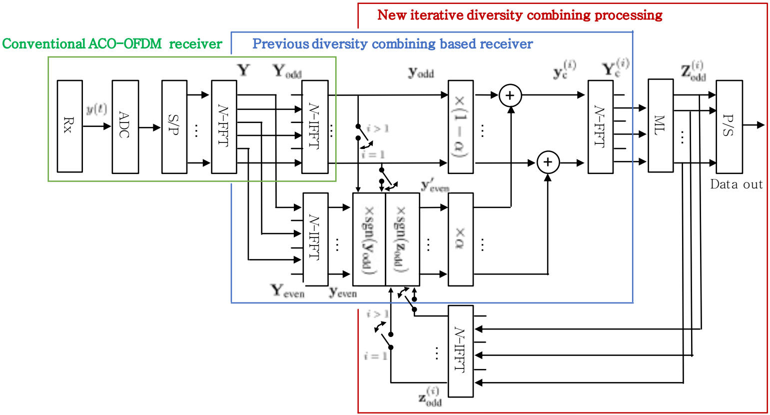
Experimental results





Work very well in practice!

Iterative diversity combining ACO-OFDM receiver

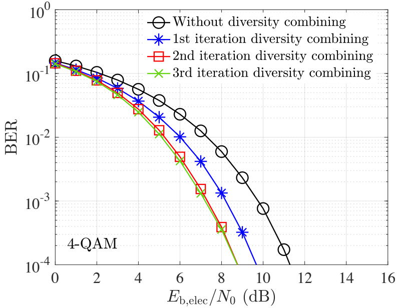


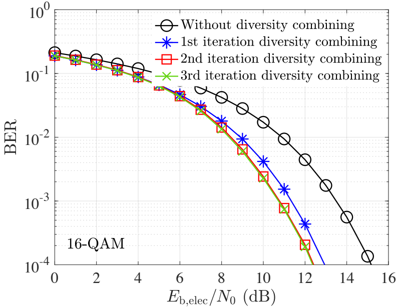
New iterative diversity combining receiver

The sign information can be more accurately recovered after ML decisions. ML detection: $Z_{\text{odd},k} = \text{argmin}_{X \in \mathbb{Z}_{M-\text{QAM}}} ||Y_{\text{c},k} - X||$

Updated diversity combining step: $y'_{\text{even},m} = \text{sgn}\left(z_{\text{odd},m}\right) \times y_{\text{even},m}$

Iterative diversity combining ACO-OFDM receiver - results



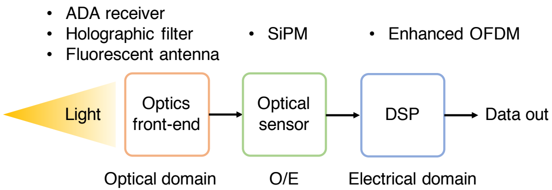


Performance

- The BER can be further reduced using iterative processing.
- The improvement between the 2nd iteration and the 3rd iteration becomes negligible.

Summary

1. Optics front-end
   - Angular Diversity Aperture (ADA) Receivers
   - Holographic filter
   - Fluorescent optical antenna
2. SiPM sensor
   - SiPM nonlinearity and solutions using neural network
3. Enhanced optical OFDM
   - Clipping noise for DCO-OFDM
   - Diversity combining for ACO-OFDM



Thank you!