Indoor SVD-Based MIMO-OFDM Optical Wireless Communication Systems

Presented by

Jariya Panta

Advisor: Prof.Dr. Anh T. Pham (Japan)

Advisor: Assoc.Prof.Dr. Poompat Saengudomlert (Thailand)

Co-advisor: Dr. Karel L. Sterckx (Thailand)

May 2019 – July 2019 Visiting Researcher,
Computer Communications Lab, The University of Aizu, Japan

August 2016 – Present Doctoral Program in Electrical and Computer Engineering,
School of Engineering, Bangkok University, Thailand

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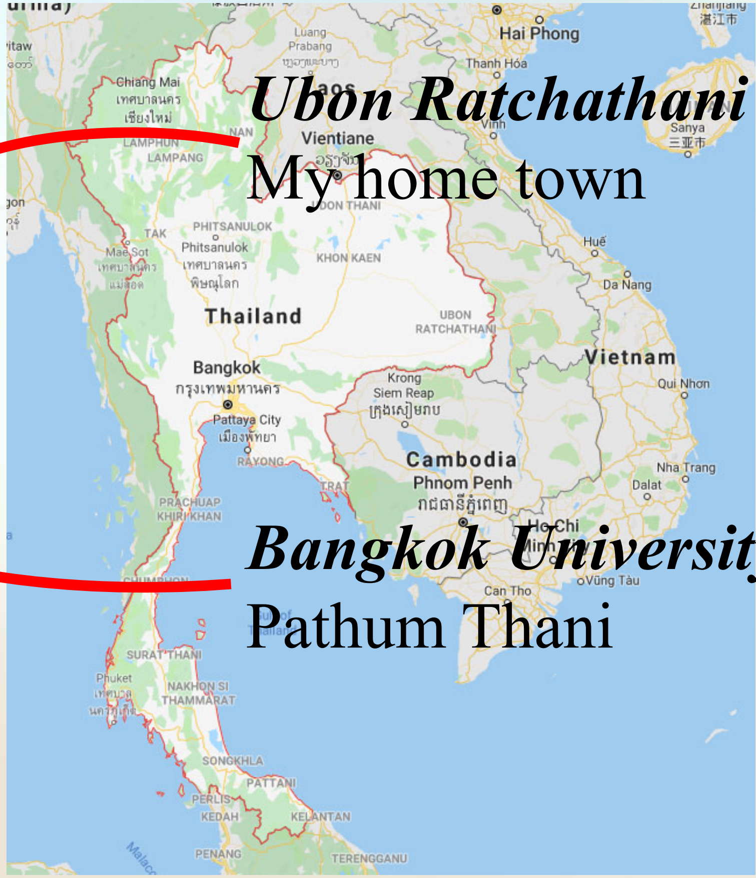
Where do I come form?

THE UNIVERSITY OF AIZU
To Advance Knowledge for Humanity 1993



Ubon Ratchathani

My home town

Bangkok University (Rangsit Campus)

Pathum Thani

Bangkok University

Bangkok University is a leading, creative, and quality institution

Rangsit Campus (Main)

- Bachelor's Degree
- Master and Doctoral in Engineering
- Master and Doctoral in Communication Arts

City Campus

- Bachelor's, Master and Doctoral in Business Administration and Marketing
- International College

Bangkok University

Bangkok University is a leading, creative, and quality institution

Diamond Building: Convention Hall, Admissions and Information Center, Lecture Room

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Bangkok University

BU Theater and Studio : Biggest Studio Systems in Education Areas in Thailand

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School of Engineering

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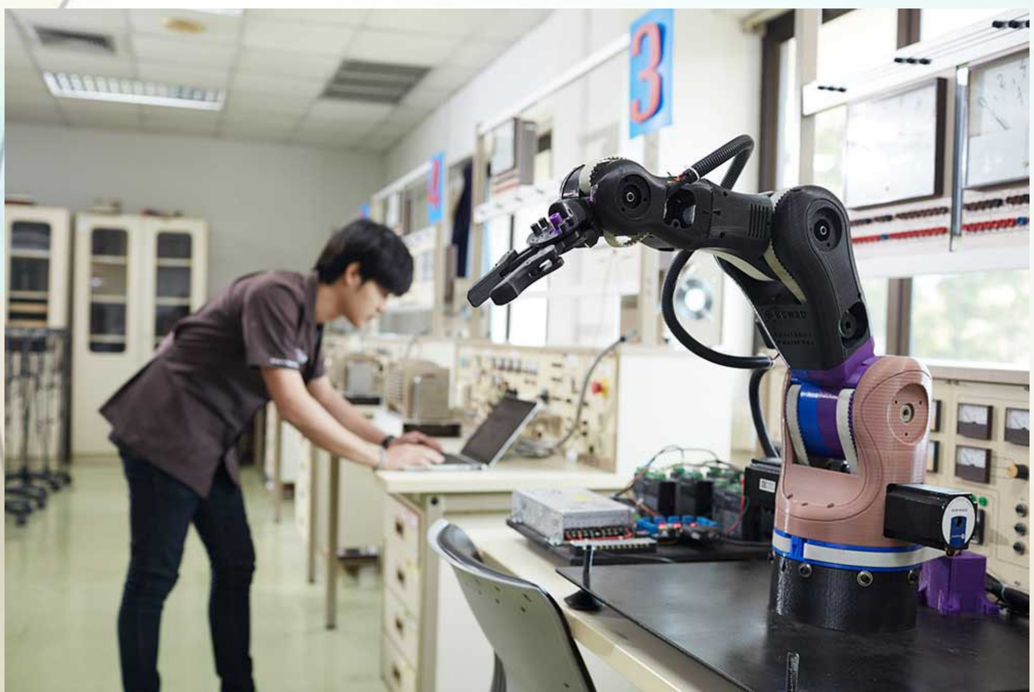
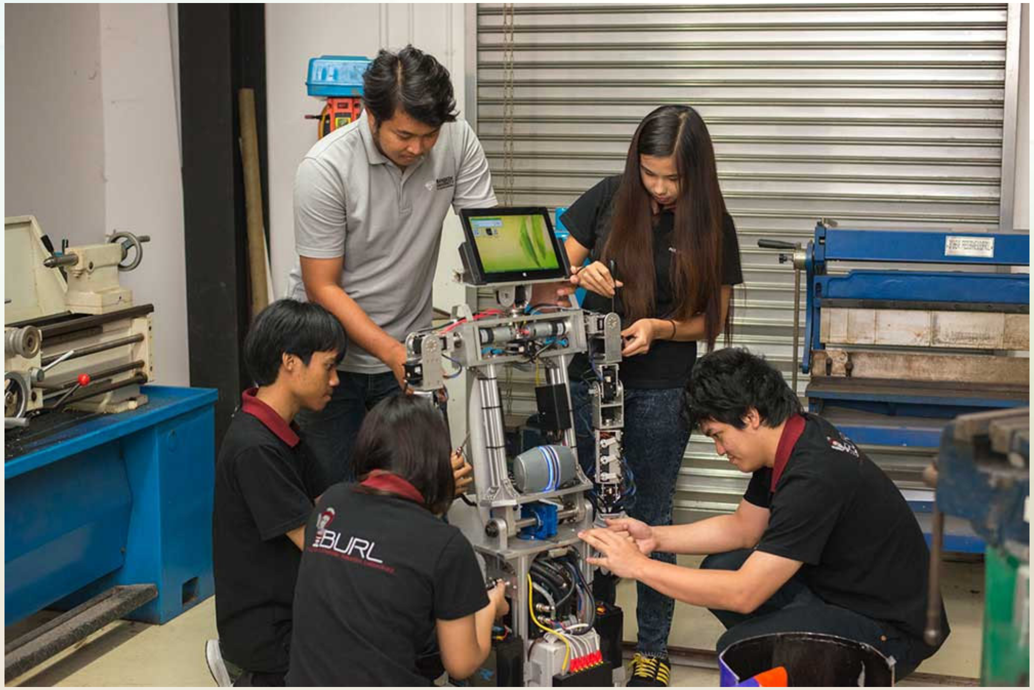
School of Engineering





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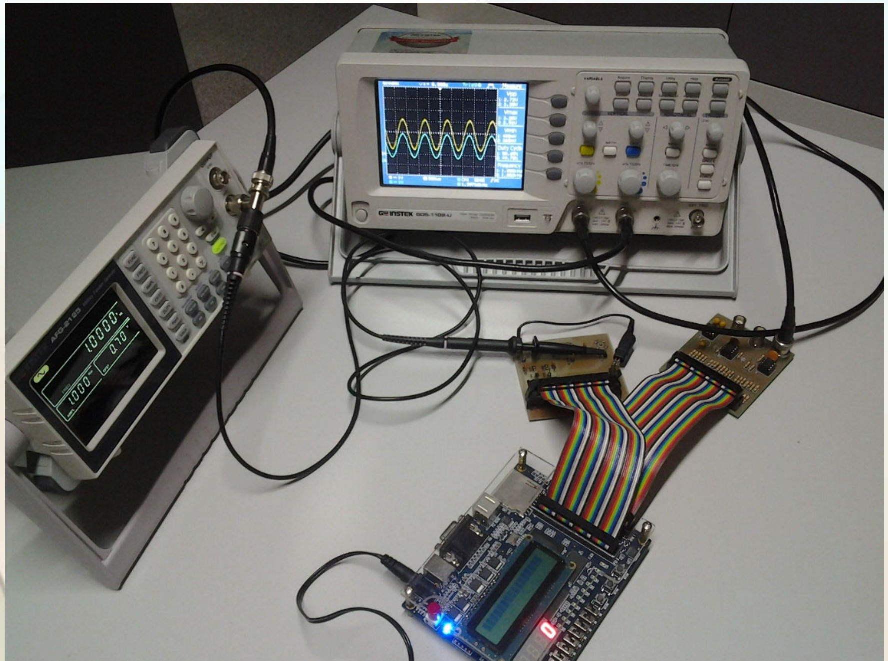

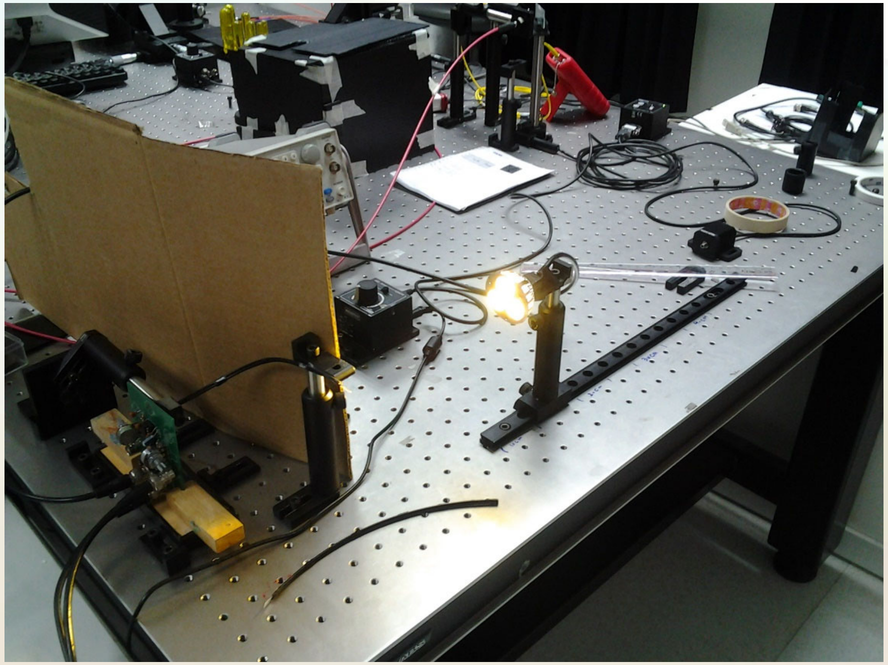

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07-30-2019

Ubon Ratchathani

Most beautiful temple in Ubon Ratchathani

Phu Prao Temple

Phra That Nong Bua Temple

Ubon Ratchathani

Place to visit

Pha Taem National Park

Three Thousand Waving Rocks Beneath Mekong
Grand Canyon of Thailand

07-30-2019

Places Not to Miss in Thailand!!!

Phuket

Phang Nga (James Bond Island)

Places Not to Miss in Thailand!!!

Chiang Mai: Doi Inthanon

The Roof of Thailand

Chiang Rai

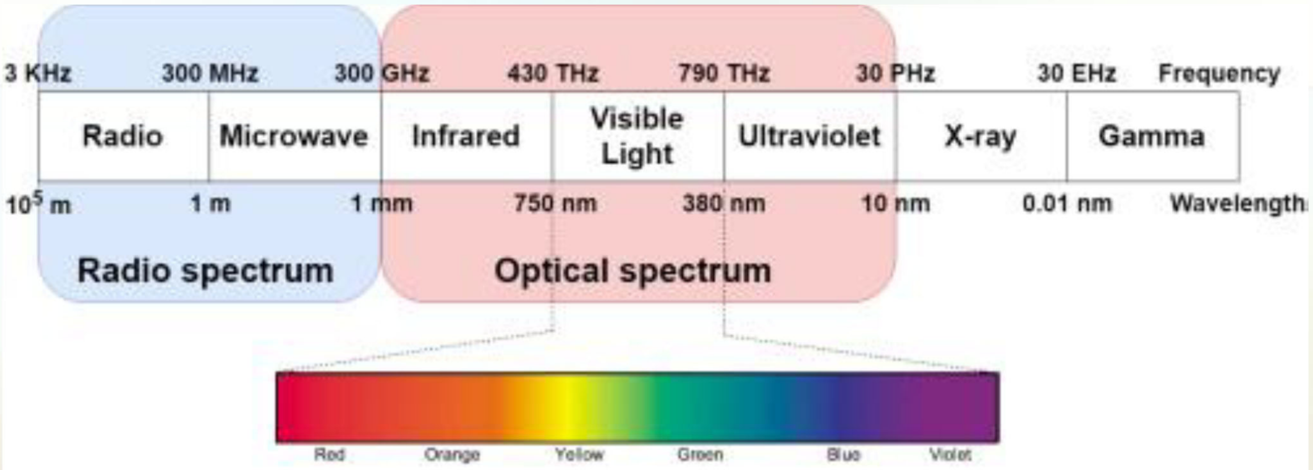
Outline

Introduction

- Overview of Optical Wireless Communications (OWC)
- Overview of Orthogonal Frequency Division Multiplexing (OFDM)
- Overview of OFDM techniques for OWC
- Overview of Multiple Input Multiple Output (MIMO)
- Overview of Singular Value Decomposition (SVD)
    - Bit loading technique

Overview of OWC

- optical carriers: visible, infrared (IR), and ultraviolet (UV) [1]



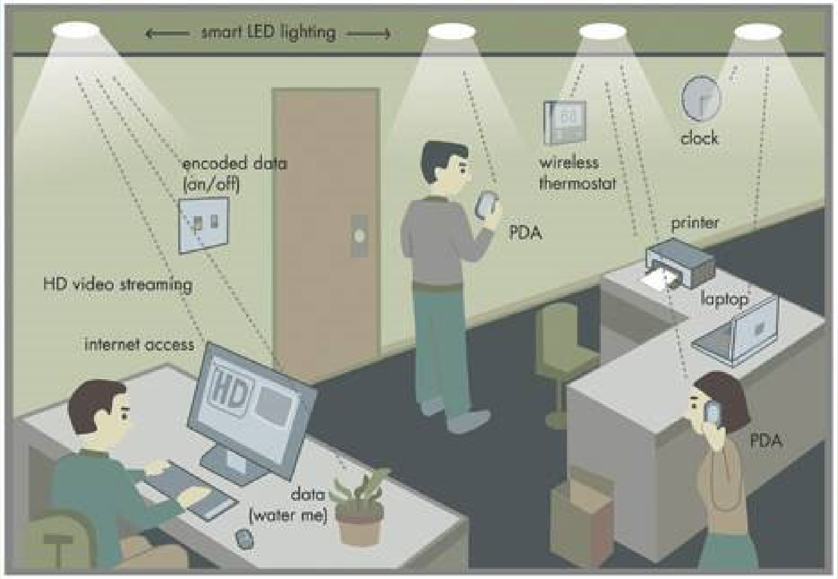
Optical Spectrum [1]

Advantages of OWC over radio frequency (RF) [1] – [3]

- wide bandwidth, license-free frequency band
- higher security, low cost, health-friendly

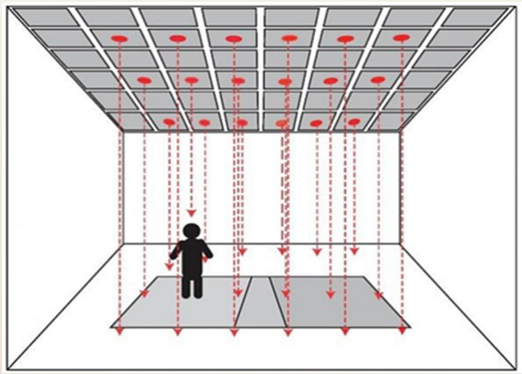
Overview of OWC

- white light emitting diodes (LEDs)
  - **visible light communications (VLC)**
  - **illuminate and communicate** at the same time
  - **limited modulation bandwidth** [1]
- OWC standards [1] – [3]
  - 2003: JEITA standards
  - 2018: IEEE 802.15.13-Standard on OWC (Multi-Gbps OWC)



Light Fidelity (LiFi) [4]

Intelligent Transport System [5]



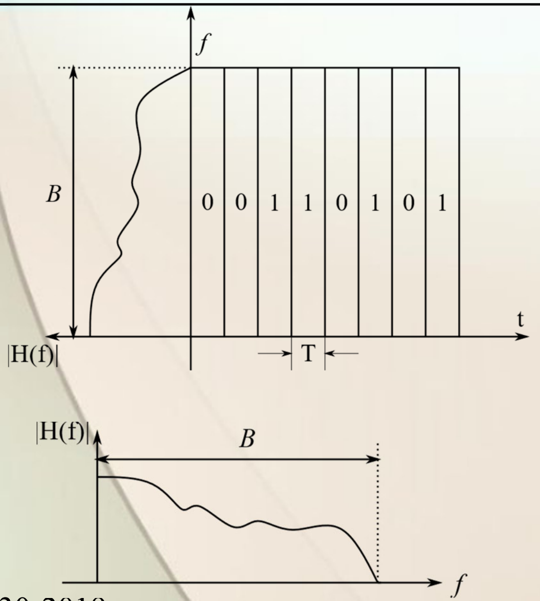
Localization [6]

Underwater VLC [7]

Overview of OFDM

- multi-carrier modulation (MCM)
- robust to intersymbol interference (ISI) and intercarrier interference (ICI)
- higher optical power efficiency than on-off-keying (OOK) and pulse position modulation (PPM)
- standards based on OFDM: Wi-Fi, WiMAX, 3G, LTE, etc.

<table>
<tr><th>Single-carrier</th><th>Multi-carrier</th><th>Spectra of (a) FDM carriers and (b) OFDM subcarriers</th></tr>
<tr>
<td>



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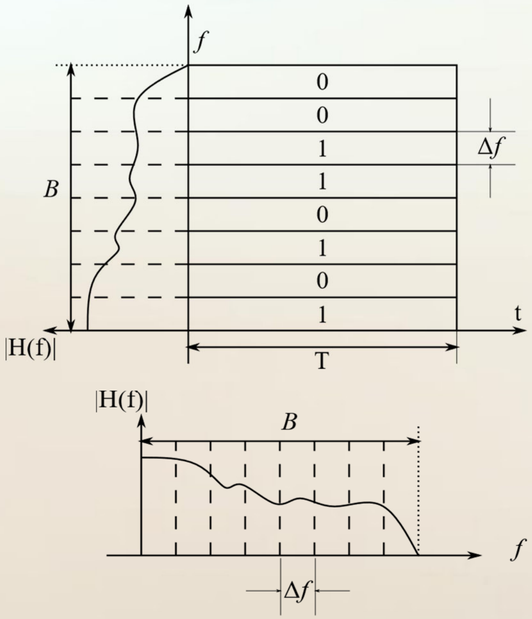

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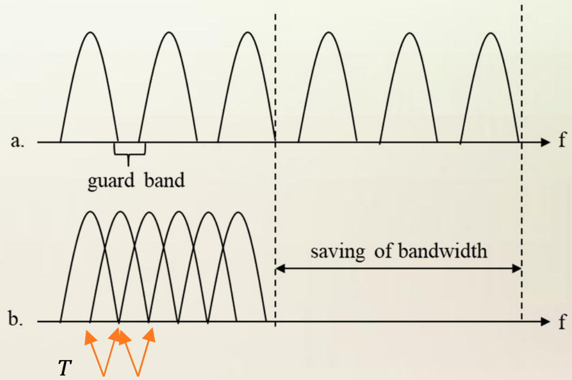

$$\int_0^T s_n(t)s_k^*(t)dt = 0, \qquad n \neq k$$

- $s_n(t)$ presents the transmit signal on subcarrier n,
- $s_k(t)$ presents the transmit signal on subcarrier k.

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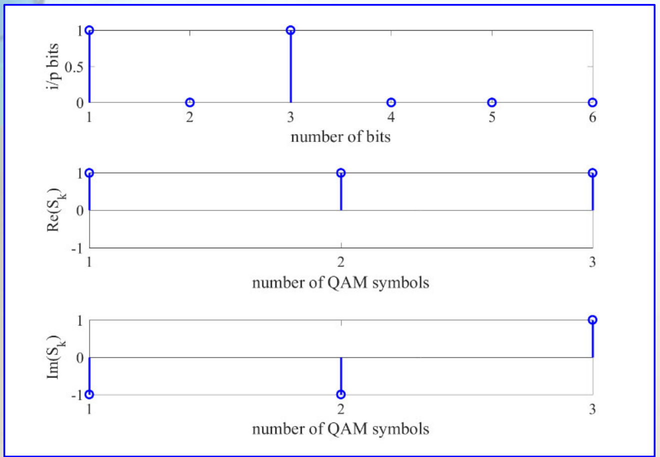
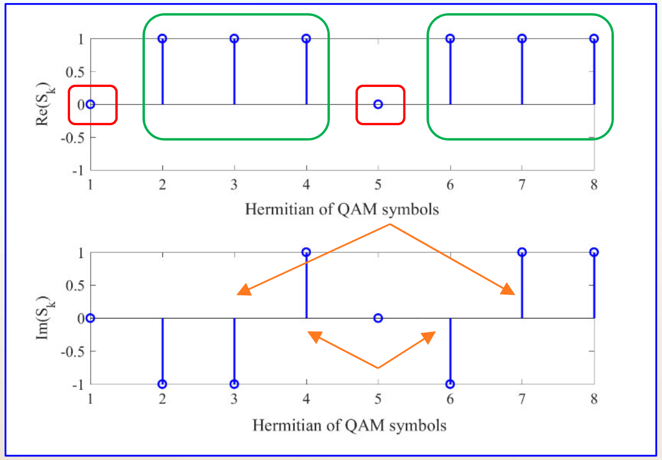
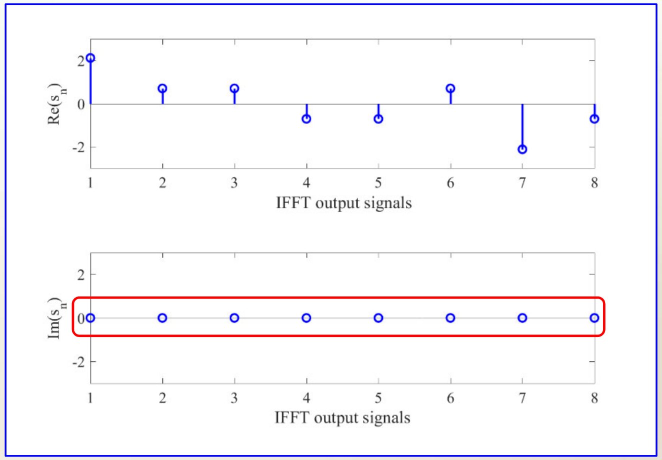
OFDM Techniques for OWC

- Intensity modulation and direct detection (IM/DD) [6]-[12]
  - the transmit signal has to be **real-valued** and **non-negative**.
    - **Hermitian symmetry** is used together with IFFT to create real signals.







bits = [1 0 1 0 0 0],
$S_k = [1 - i,\ 1 - i,\ 1 + i]$

$$S_0 = S_{N/2} = 0$$
$$S_{N-k} = S_k^*,\ k \in \{1, \ldots, N/2 - 1\}$$

$$s_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{i2\pi kn/N},\ n \in \{0, \ldots, N-1\}$$

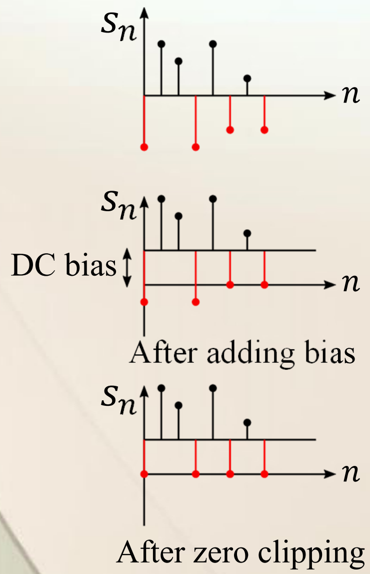
$$S_k = [0,\ S_1,\ S_2,\ S_3, \ldots,\ S_{N/2-1},\ 0,\ S_{N/2-1}^*, \ldots,\ S_3^*,\ S_2^*,\ S_1^*]^T$$

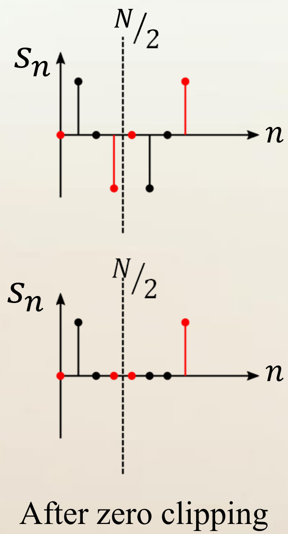
OFDM Techniques for OWC

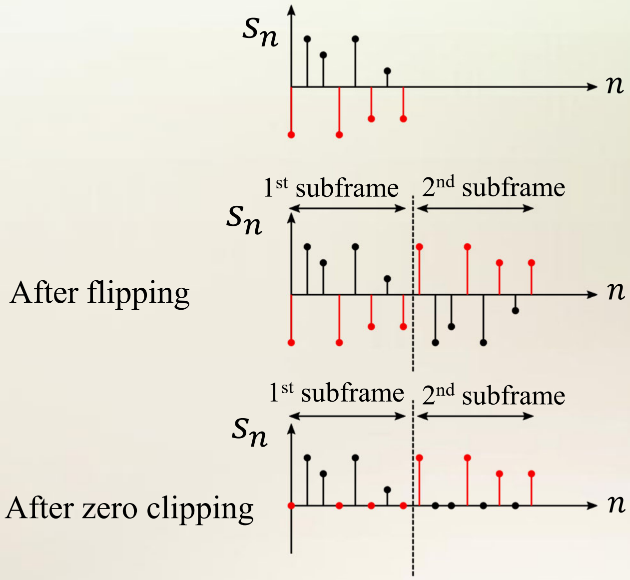
There are 3 well known techniques to make the non-negative signals:

- **DCO-OFDM:** addition of a bias to get non-negative values (odd- and even- numbered subcarriers).
- **ACO-OFDM:** the negative parts of the transmit signal are clipped (odd-numbered subcarriers)
- **Flip-OFDM:** the positive parts are transmitted, to be followed by the negative flipped parts (odd- and even- numbered subcarriers).

DC biased optical OFDM (DCO-OFDM) [6]-[9]	Asymmetrically Clipped Optical OFDM (ACO-OFDM) [6]-[12]	Flip-OFDM [11][12]
(see figure below)	(see figure below)	(see figure below)



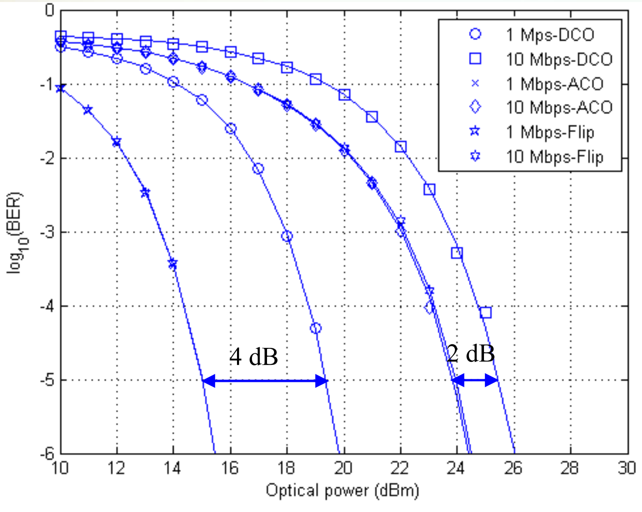




OFDM Techniques for OWC

DCO-OFDM vs. ACO-OFDM vs. Flip-OFDM [6]-[12]

- DCO requires DC-bias,
  - large DC-bias resulting in optical power inefficient.
  - lower DC-bias resulting in clipping of negative parts of time-domain signal.
- ACO-OFDM and flip-OFDM provide more power efficient than DCO-OFDM.
- Flip-OFDM provides the same power efficiency and spectral efficiency as ACO-OFDM, and requires less computation.



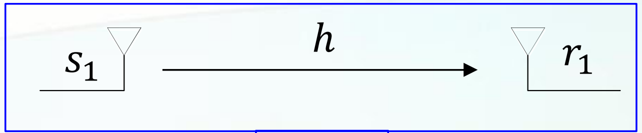
(ACO-OFDM) [6]-[12]	Flip-OFDM [11][12]
• $\left(\frac{N}{4}\right)$ QAM symbol/OFDM symbol	• $\left(\frac{N}{2}-1\right)$ QAM symbol/OFDM symbol
• $\left(\frac{N}{4}\right) \times 2\log_2 M$ bit/OFDM symbol	• $\left(\frac{N}{2}-1\right) \times 2\log_2 M$ bit/OFDM symbol
• $T_s = (N + N_{\text{CP}})\text{T}$	• $T_s = 2(N + N_{\text{CP}})T$

Note:

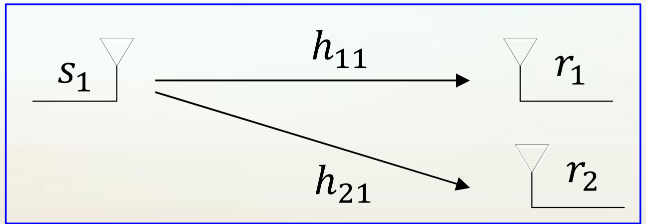
- N = No. of OFDM subcarriers,
- N_{CP} = the number of CP,
- M = QAM constellation size,
- T = transmit pulse period,
- T_s = OFDM symbol pulse period

Overview of MIMO

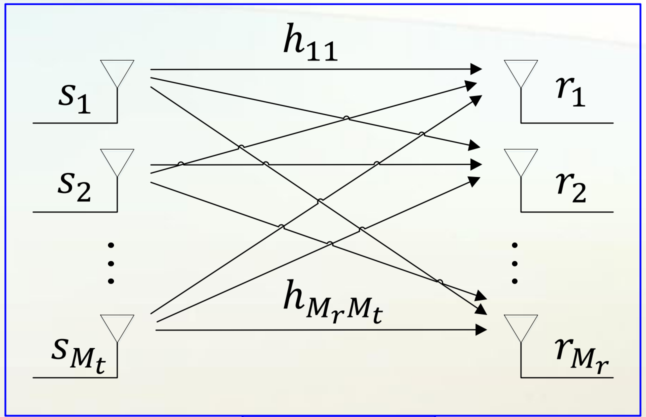
- MIMO exploits the **space dimension** to improve wireless systems capacity, range and reliability
- standards based on MIMO: Wi-Fi, WiMAX, 3G, LTE, etc. [14]-[17]



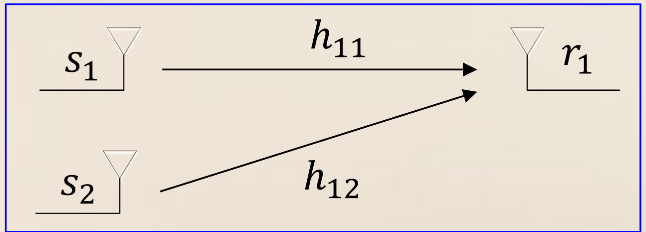
SISO



SIMO: Receiver diversity



MIMO



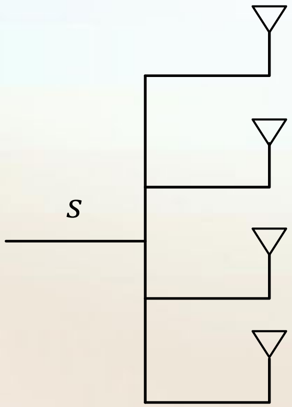
MISO: Transmitter diversity

Note:

- SISO = Single Input Single Output
- SIMO = Single Input Multiple Output
- MISO = Multiple Input Single Output

Overview of MIMO

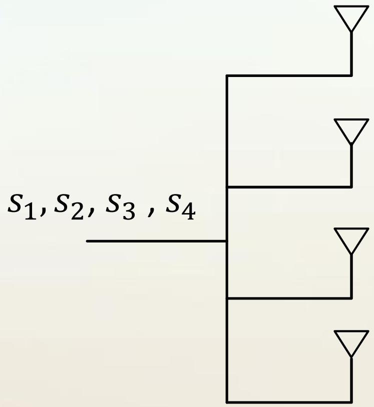
- **Spatial diversity** [13] – [16]
  - same symbol is transmitted from each transmitter to a receiver.
  - **Goal:** improving the reliability



$$x_1 = a_1 s$$
$$x_2 = a_2 s$$
$$x_3 = a_3 s$$
$$x_4 = a_4 s$$

- s represents transmit symbol
- a_i represents weight factor

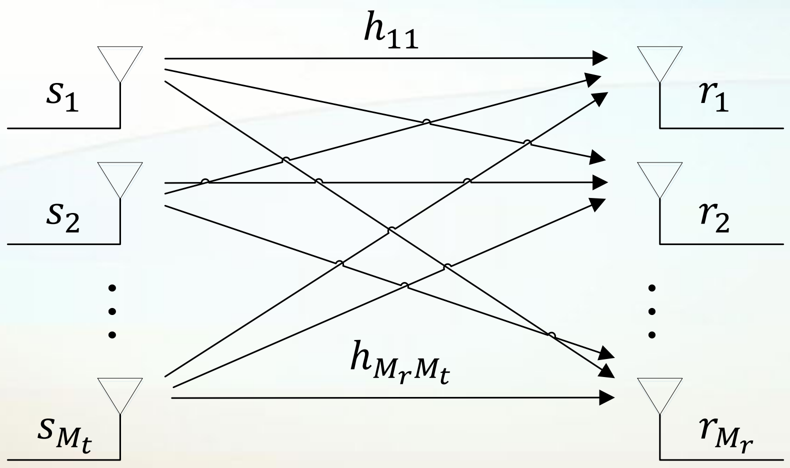
- **Spatial multiplexing (SMP)** [15]-[17]
  - different symbols are transmitted from each transmitter to a receiver.
  - **Goal:** increased data rates



$$x_1 = a_{11}s_1 + a_{12}s_2 + a_{13}s_3 + a_{14}s_4$$
$$x_2 = a_{21}s_1 + a_{22}s_2 + a_{23}s_3 + a_{24}s_4$$
$$x_3 = a_{31}s_1 + a_{32}s_2 + a_{33}s_3 + a_{34}s_4$$
$$x_4 = a_{41}s_1 + a_{42}s_2 + a_{43}s_3 + a_{44}s_4$$

- s_i represents transmit symbol
- a_{ij} represents coefficient of linear combinations for transmit antennas

Overview of MIMO



$$\begin{bmatrix} r_1 \\ \vdots \\ r_{M_r} \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1M_t} \\ \vdots & \ddots & \vdots \\ h_{M_r1} & \cdots & h_{M_rM_t} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_{M_t} \end{bmatrix}$$

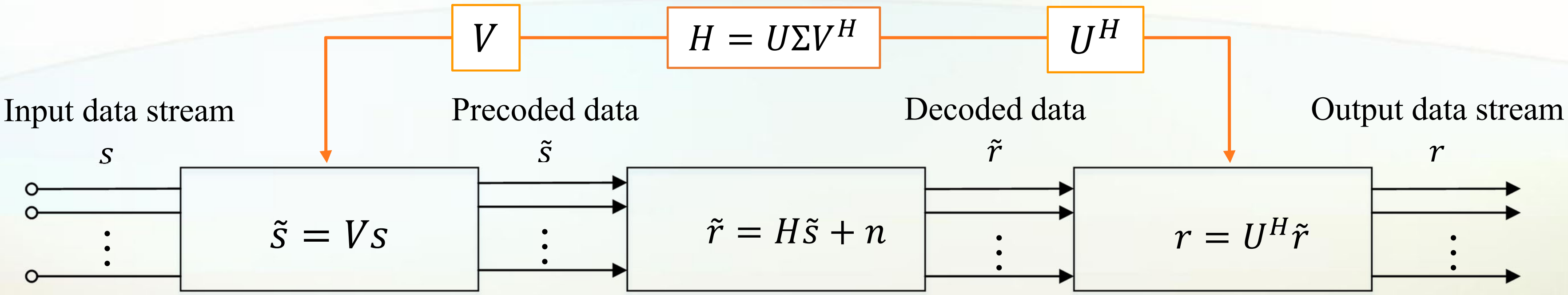
- s_j represents the M_t-dimensional transmitted symbol.
- r_i represents the M_r-dimensional received symbol.
- h_{ij} is the gain from transmit antenna j to receive antenna i

$$r_1 = h_{11}s_1 + h_{12}s_2 + h_{13}s_3 + \ldots + h_{1M_t}s_{M_t}$$

How to recover the data from a signal affected by multi-stream interference ?

Overview of SVD

- Decompose the MIMO channel into a number of unequally weighted independent subchannels [13]
- The channel state information (CSI) is available at both transmitter and receiver
- Transmit precoding and receiver decoding:



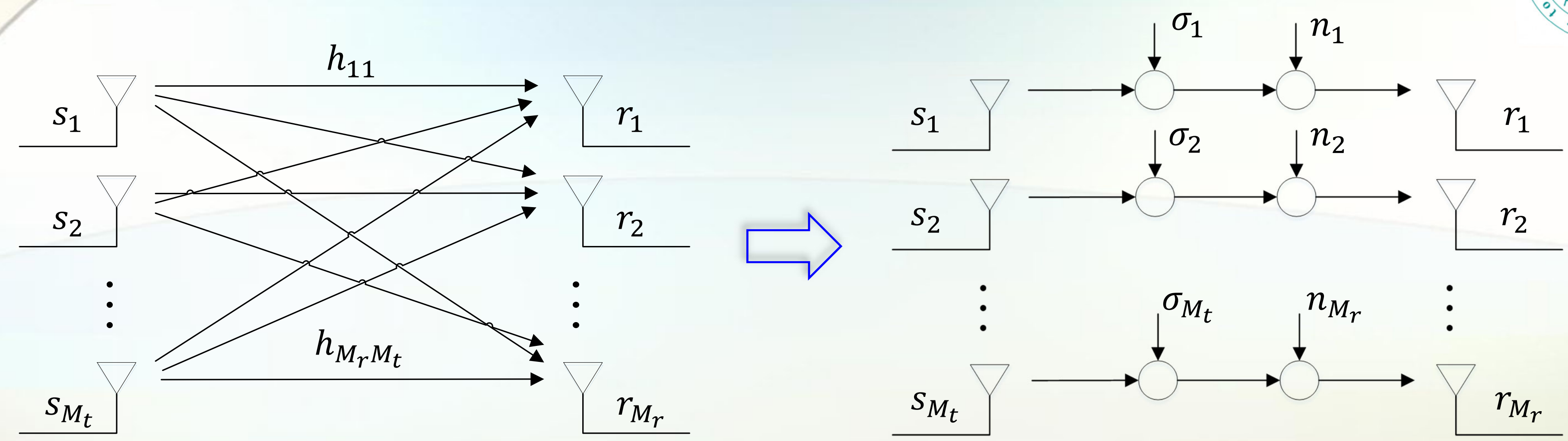
$$\begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_{M_r} \end{bmatrix} = \begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \sigma_{M_t} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_{M_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{M_r} \end{bmatrix}$$

$\Rightarrow$

$$r_1 = \sigma_1 s_1 + n_1$$
$$\vdots$$
$$r_{M_r} = \sigma_{M_t} s_{M_t} + n_{M_r}$$

Note:
- $U_{M_r \times M_r}$ and $V_{M_t \times M_t}$ are unitary matrices, where $U^H U = UU^H = I_{M_r}$ and $VV^H = V^H V = I_{M_t}$,
- $\Sigma_{M_r \times M_t}$ is diagonal matrix of singular value σ_i (channel gain or weighting factor).

Overview of SVD



- Condition numbers of MIMO channel matrices

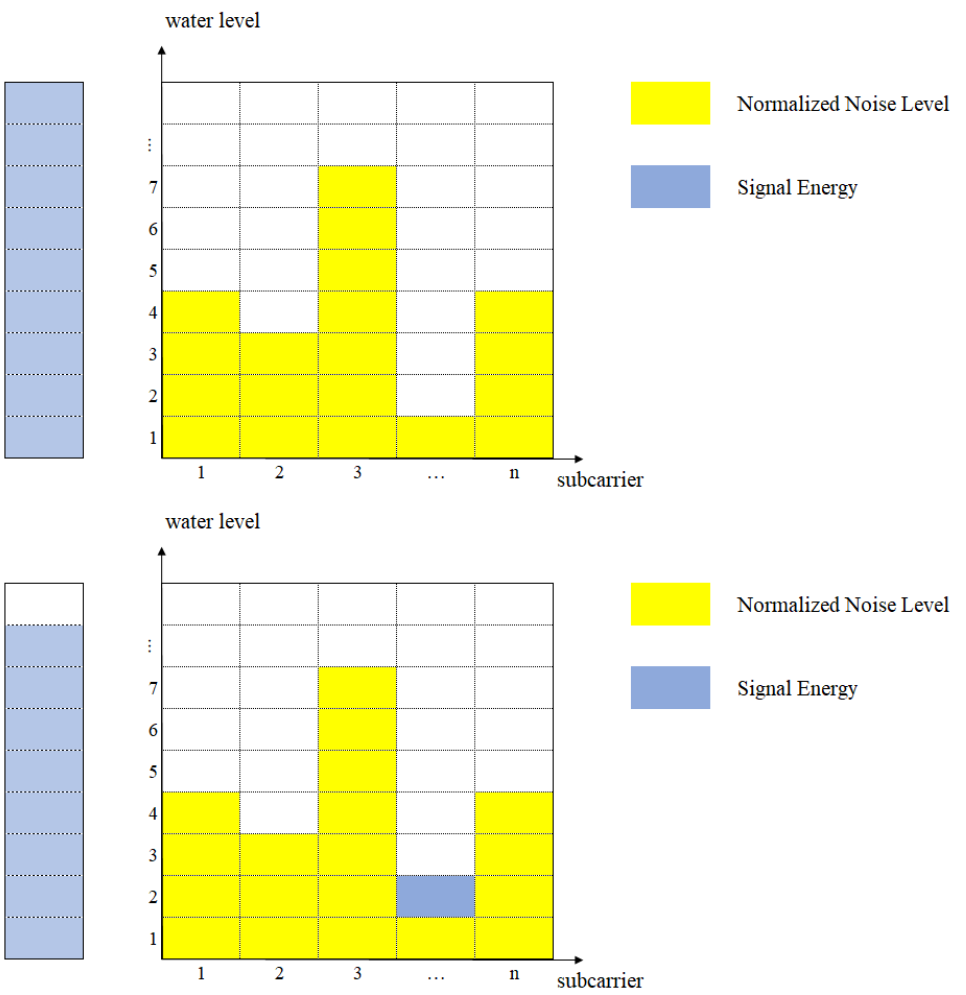
$$\frac{\sigma_{\max}}{\sigma_{\min}} \geq 1$$

Note:
- σ_{max} is the largest singular value in matrix **H**
- σ_{min} the smallest singular value in matrix **H**

- Small values for the condition number imply a well-conditioned channel matrix
- Large values indicate an ill-conditioned channel matrix

Bit Loading technique

- Bit loading is based on the water filling technique [28][29]



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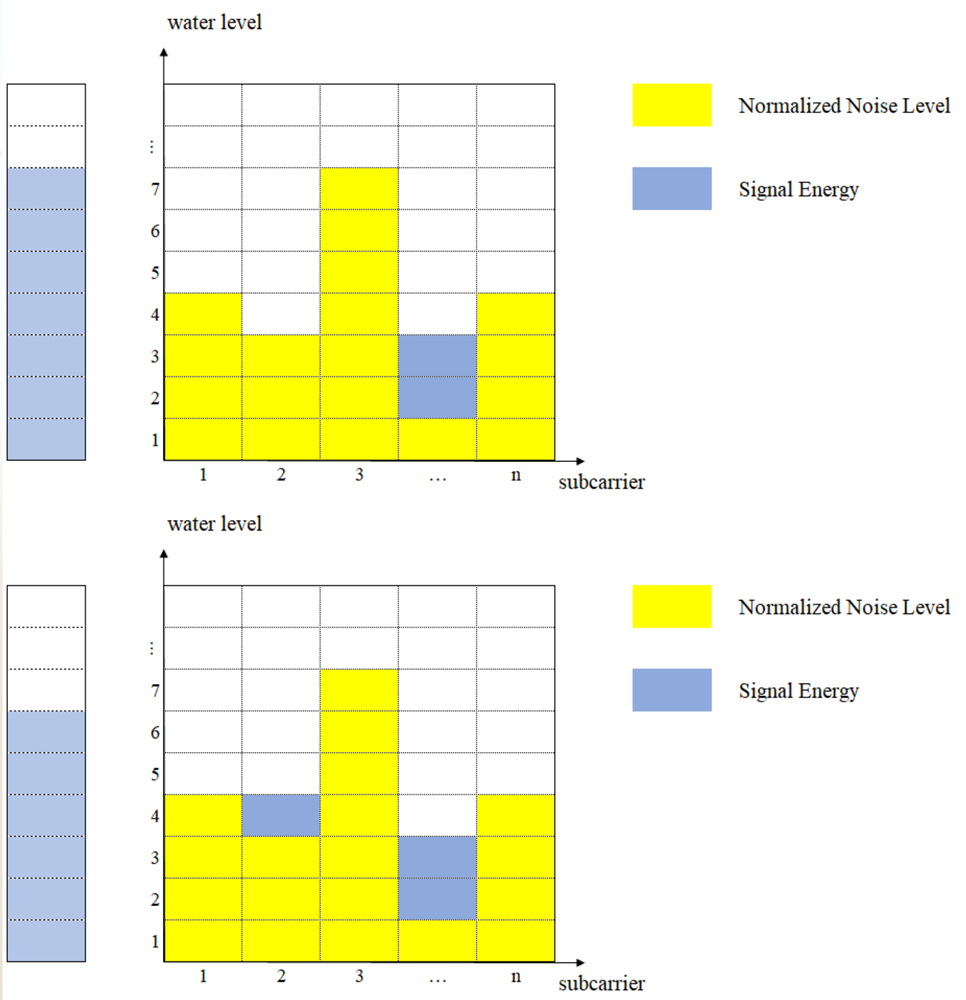

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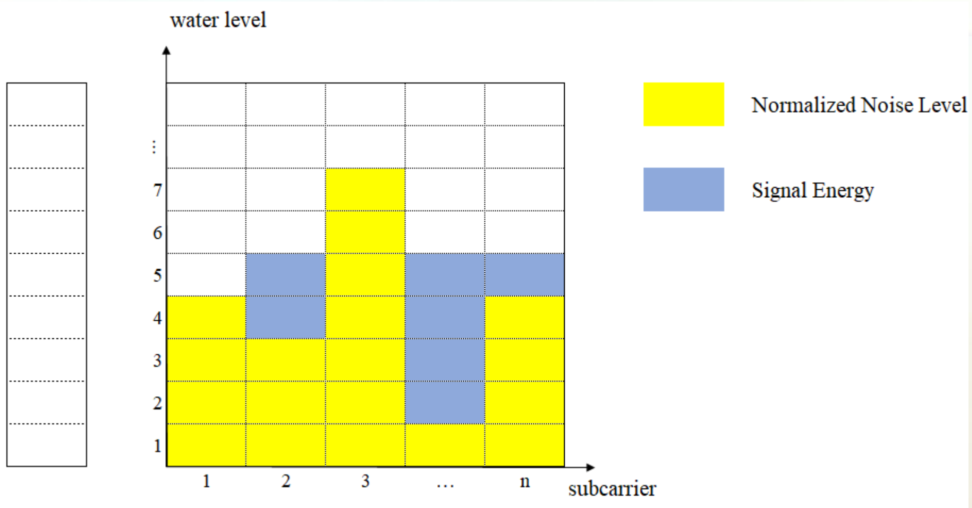
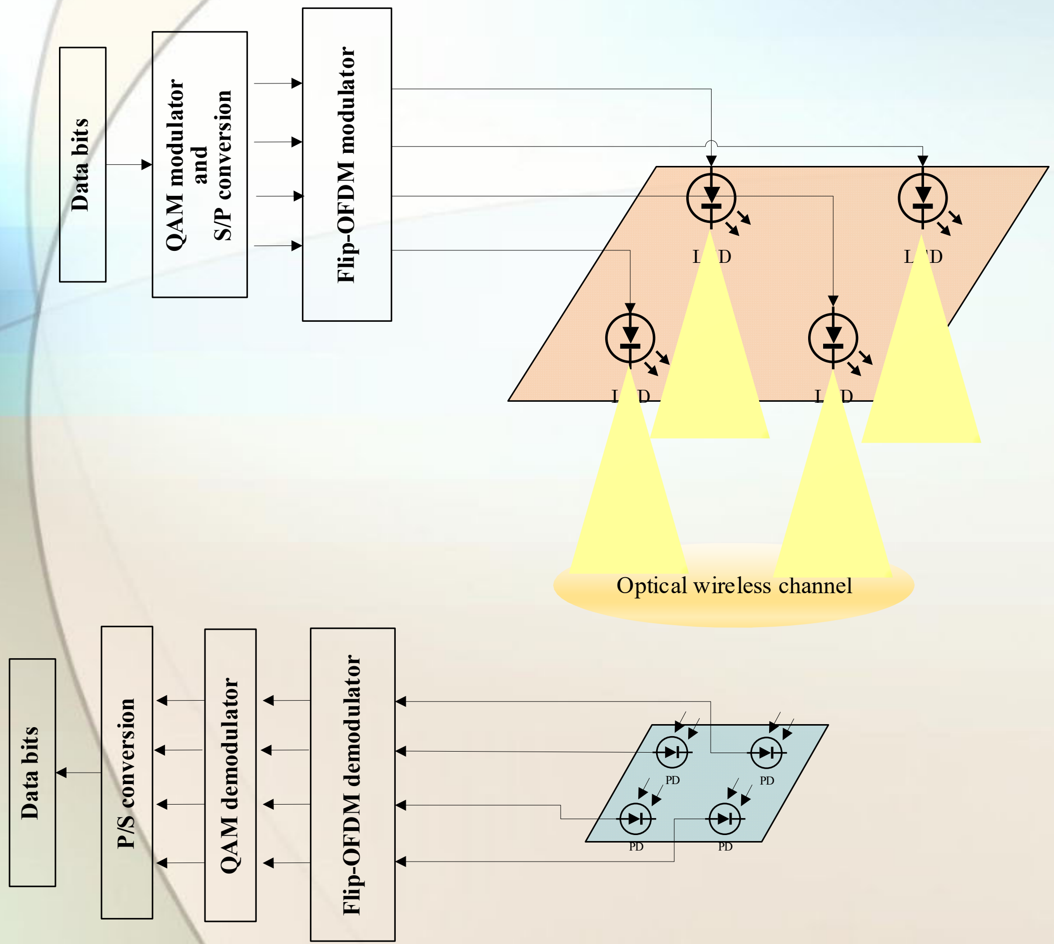


Challenging Issue

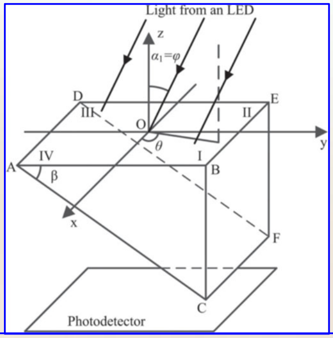
Key challenge: MIMO OWC



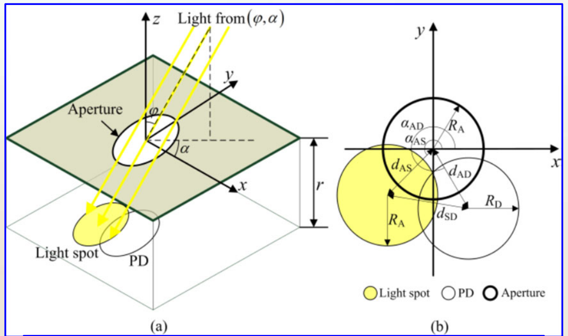
- Strong LOS component in OWC
    - Lack of diversity in MIMO OWC
        - Low multiplexing gain in MIMO OWC
            - Spatial multiplexing is not effective in increasing the throughput.

Possible Solutions

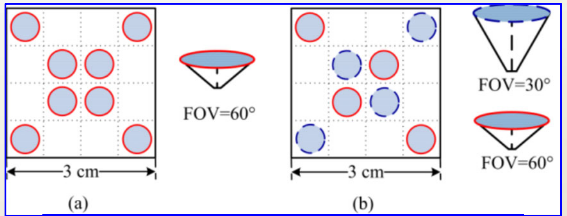
SL	Author	MIMO technique		OFDM technique			Demultiplexing Technique	Receiver front-end	Noted	Ref.
		SMP.	SD.	DCO.	ACO.	Flip.				
1.	T. Q. Wang, R. J. Green and J. Armstrong, 2015	✓			✓		ZF, MMSE	Prism-based Rx.	Studied on new Rx. structure	[18]
2.	C. He, T. Q. Wang and J. Armstrong, 2015	✓			✓		ZF, MMSE	PD	Studied on PD. with diff. FOV	[19]
3.	T. Q. Wang, C. He and J. Armstrong, 2015	✓			✓		ZF	Aperture-based Rx.	Studied on new Rx. structure	[20]
4.	C. He, T. Q. Wang and J. Armstrong, 2016	✓			✓		ZF	Prism-based Rx. and Aperture-based Rx.	Compared Per. of SMP vs. SM.	[21]
5.	T. Q. Wang, C. He and J. Armstrong, 2017	✓			✓		ZF, MMSE	Aperture-based Rx.	Studied on analysis of Rx. structure	[22]



Prism-based array receiver



Aperture-based array receiver



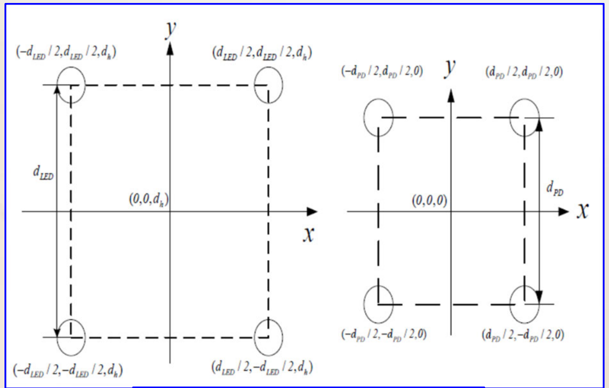
PD. with diff. FOV

Note:

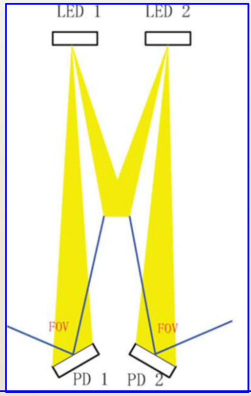
- ZF and MMSE, a channel matrix with full rank is desirable, as matrix inversion is performed.
- Prism-based Rx. and aperture-based Rx. affect power loss and expensive device front-end.

Possible Solutions

SL	Author	MIMO technique		OFDM technique				Demultiplexing Technique	Receiver front-end	Noted	Ref.
		SMP.	SD.	DCO.	ACO.	Flip.	et al.				
6.	Zhen Zhan et al., 2015	✓		✓				ZF	PD	Compared Per. of diff. LED arrangements	[23]
7.	Y. Hong, T. Wu and L. Chen, 2016	✓		✓				SVD	PD	Tilled angle of the PDs.	[24]
8.	Qing-Feng Liu, et al., 2014	✓					OOK	SVD vs. ZF	PD	Compared SVD & ZF with 2x2- & 4x4- MIMO	[25]
9.	Y. Hong, J. Chen, Z. Wang and C. Yu, 2013	✓					OOK	SVD	PD	Studied on MU-MIMO with diff. FOV	[26]



diff. LED arrangements



Angle adjustment

Note:
- ZF and MMSE, a channel matrix with full rank is desirable, as matrix inversion is performed.
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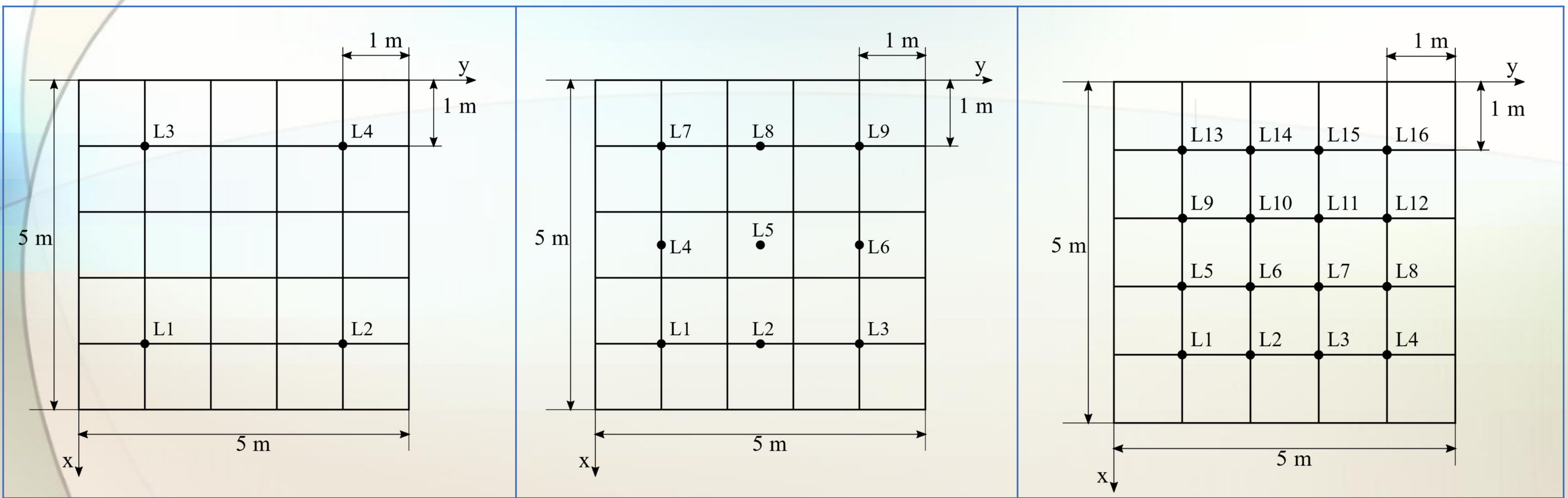
Proposed Research

MIMO transmitter configurations

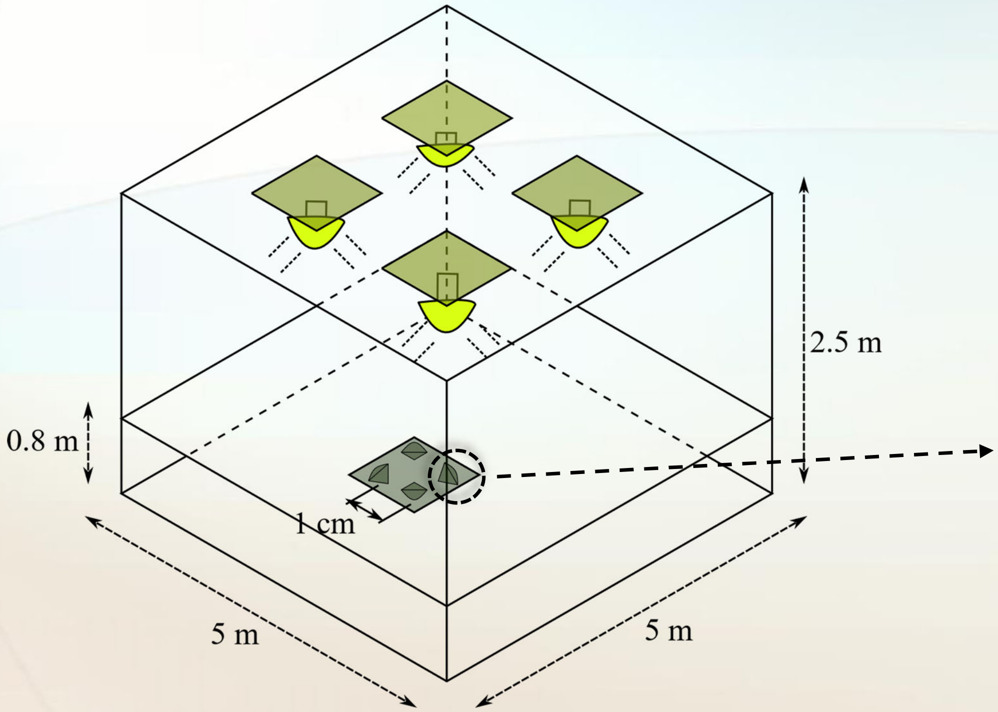


4x4-MIMO flip-OFDM	9x4-MIMO flip-OFDM	16x4-MIMO flip-OFDM

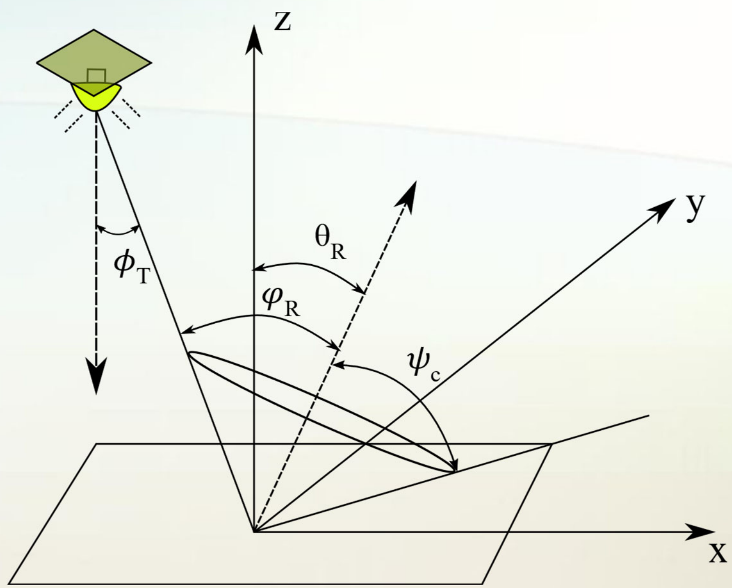
- LED1: (1,1)
- LED2: (1,4)
- LED3: (4,1)
- LED4: (4,4)

- There are 2 considered receiver positions
  - R1: (2.5,2.5) (at the center of the room)
  - R2: (1,1) (near a corner)

Polar angle tilting of PDs



Configuration of the indoor MIMO OWC system

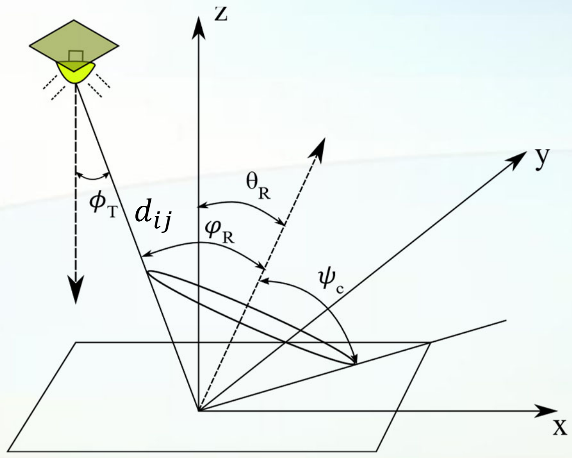


Note:

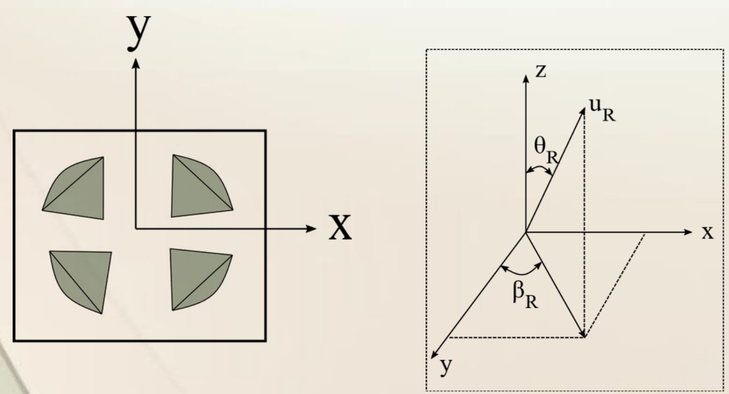
- θ_R = the tilled angles of the PD**,**
- $\emptyset_T$ **=** the emission angle at transmit antenna,
- φ_R = the incident angle at receive antenna,
- Ψ_c = the FOV of the PD.

Methodology

System Model
Configuration of Indoor MIMO OWC system



The configuration of the proposed receiver orientation model



The coordinate of the proposed receiver orientation model

$$h_{ij} = \begin{cases} \frac{(m+1)A}{2\pi d_{ij}^2} \cos^m(\emptyset_T)\cos(\varphi_R), & 0 \le \varphi_R \le \Psi_c \\ 0, & \varphi_R \ge \Psi_c \end{cases} \quad [30]$$

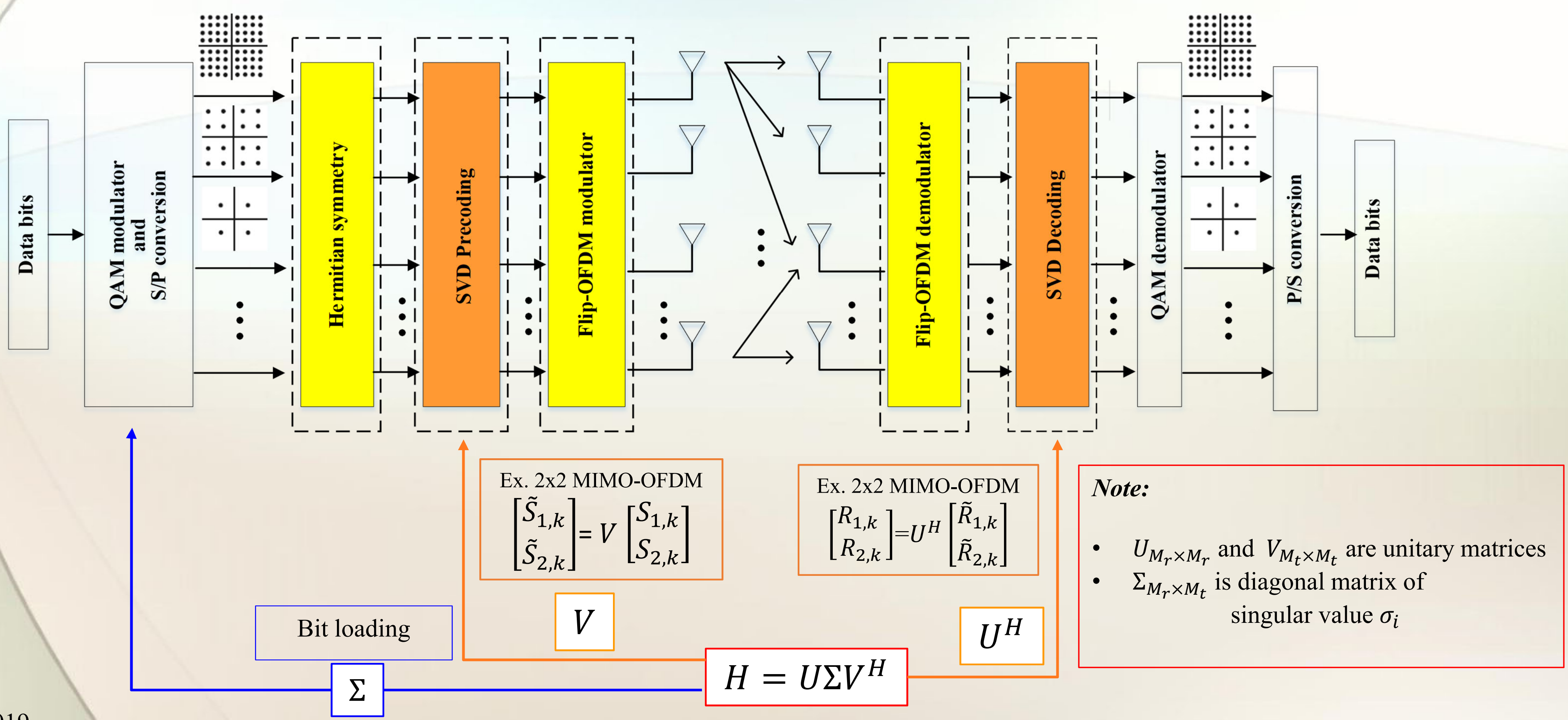
Note:

- h_{ij} = the gain from transmit antenna j (j^{th} LED) to receive antenna i (i^{th} PD),
- A = the receiver collection area,
- m = the Lambertian order,
- d_{ij} = the distance between transmit antenna j to receive antenna i,
- $\emptyset_T$ = the emission angle at the transmit antenna,
- φ_R = the incident angle at the receive antenna.

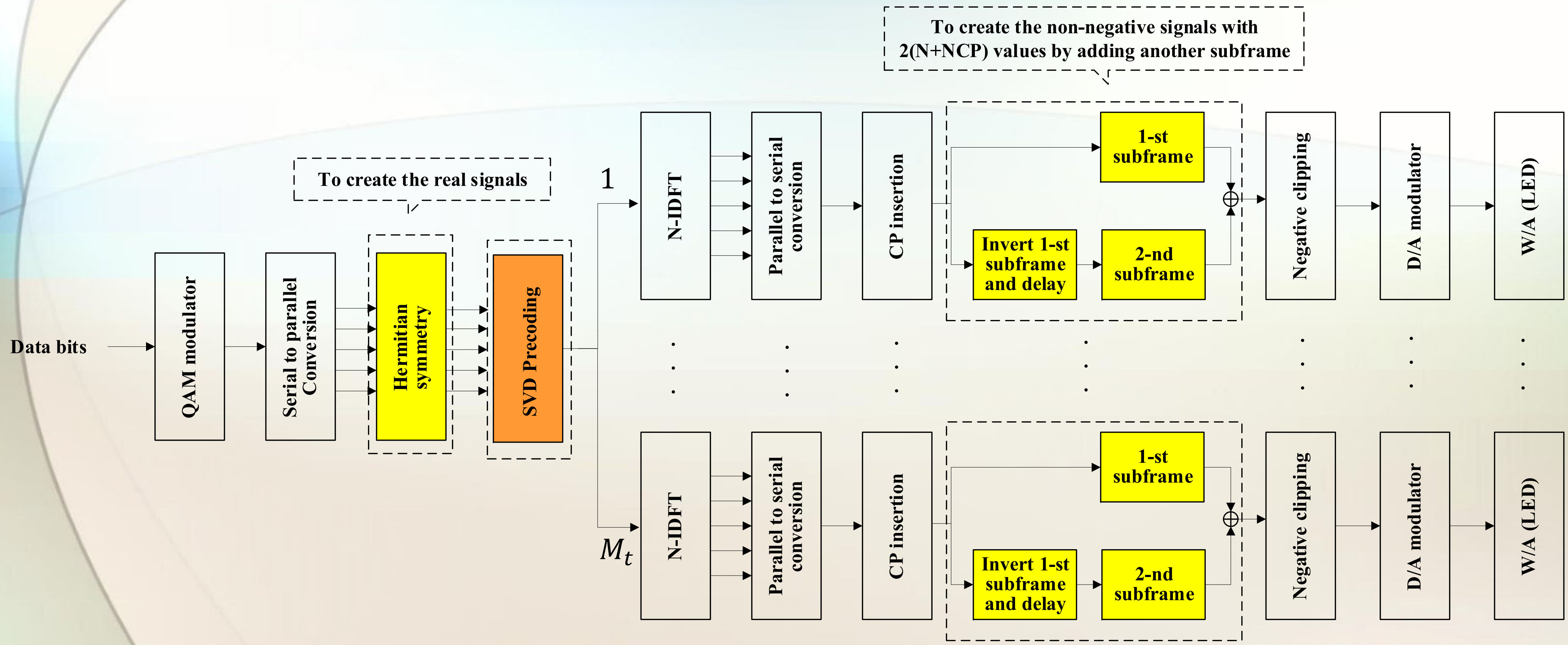
Note:

- θ_T, θ_R = the tilled angles of the LED and PD,
- β_T, β_R = the azimuthal angle values of the four LEDs and the four PDs i.e., $\beta_R = 45^\circ, 135^\circ, 225^\circ$, and 315°

System Model of Bit Loading on MIMO flip-OFDM using SVD

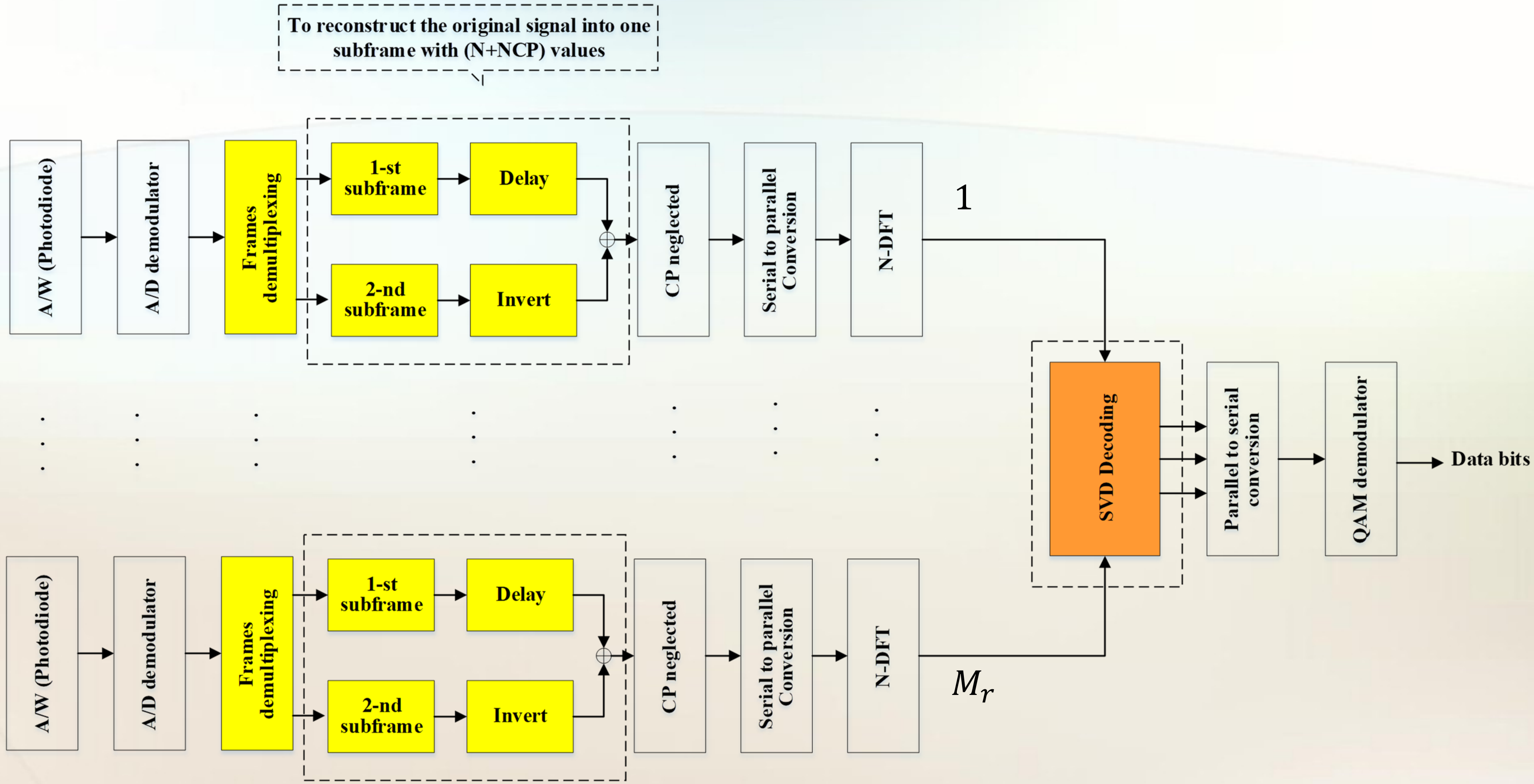


System Model
MIMO Flip-OFDM using SVD



MIMO flip-OFDM Transmitter using SVD

System Model
MIMO Flip-OFDM using SVD



MIMO flip-OFDM Receiver using SVD

Numerical Results

Numerical Results of Mathematical Analysis

BER performance analysis for MIMO flip-OFDM using SVD with bit loading

$$\mathrm{BER} \approx \frac{4}{b_{\mathrm{total}}} \sum_{g=1}^{R_k} \sum_{k=1}^{N/2-1} \frac{(M_{g,k}-1)}{M_{g,k}} \times Q\left(\sqrt{\frac{3\pi b_{\mathrm{total}}}{2N_0(1+N_{\mathrm{CP}}/N)R}} \times \frac{\alpha_{\mathrm{A/W}}\sigma_{g,k}P_{\mathrm{total}}}{\sum_{i=1}^{M_t}\sqrt{\sum_{g=1}^{R_k}\sum_{k=1}^{N/2-1}|a_{jg,k}|^2({M_{g,k}}^2-1)}}\right)$$

$$P_{\mathrm{total}} = \frac{\alpha_{\mathrm{W/A}}d}{\sqrt{6\pi NT}}\left(\sum_{i=1}^{M_t}\sqrt{\sum_{g=1}^{R_k}\sum_{k=1}^{N/2-1}|a_{jg,k}|^2({M_{g,k}}^2-1)}\right)$$

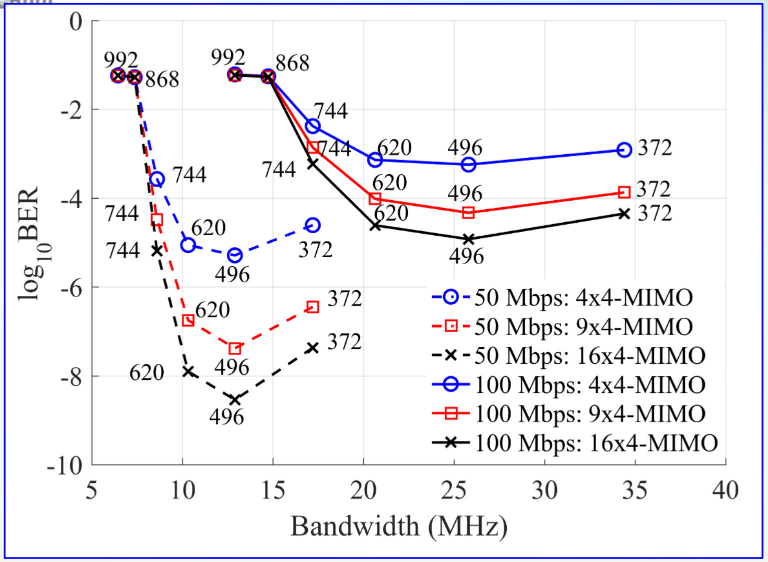
Note:

- BER = bit error rate,
- b_{total} = No. of bits transmitted on all spatial channels and subcarriers,
- P_{total} = total transmit optical power of all transmit antenna,
- R = bit rate,
- M_t= No. of transmit antenna,
- $M_{g,k}$ = QAM constellation on subcarrier k on spatial channel g,
- d = the minimum distance of QAM symbols,
- T = transmit pulse period,
- N = No. of OFDM subcarriers,
- N_{CP} = the number of CP,
- N_0 = PSD of AWGN,
- $\alpha_{\mathrm{A/W}}$ = receiver responsivity,
- $\alpha_{\mathrm{W/A}}$ = source conversion factor
- $\sigma_{g,k}$ = the diagonal elements of $\Sigma_{M_r\times M_t}$,
- $a_{jg,k}$= the elements of precoding matrix (unitary matrix), $V_{M_t\times M_t}$.

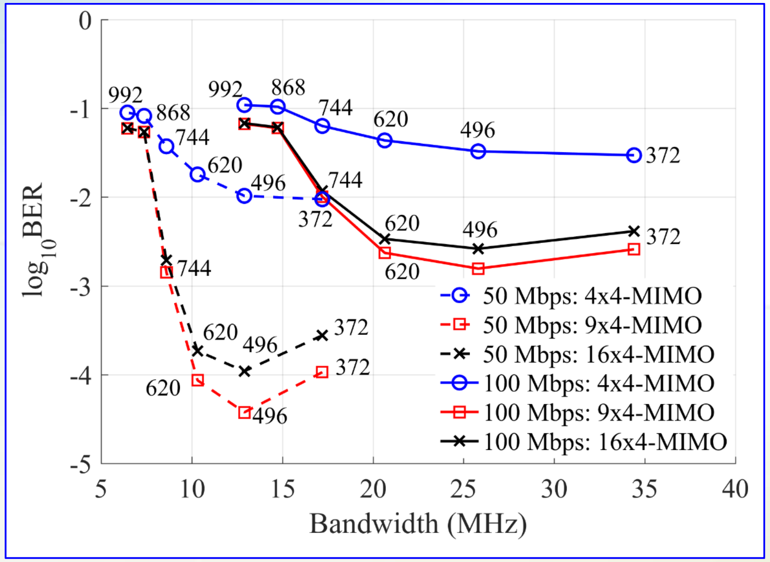
Simulation Parameters

Parameter	Notation	Value
Data Rates	R	50, 100 Mbps
Total transmit optical power	P_T^{total}	0-45 dBm
Number of OFDM subcarriers	N	64 [6][10]
Number of transmitted OFDM symbol	-	10^2
Maximum $M \times M$-QAM constellation size	M	16
Lambertian order	m	1
LED semiangle	$\Phi_{1/2}$	60°
Modulation index	m_l	1
PD responsivity	$\alpha_{\text{A/W}}$	0.53 A/W [16]
PD field of view	Ψ_c	70°
PD effective detection area	A	1 cm^2
Target BER in bit loading algorithm	BER	10^{-5}

Optimization of OFDM symbol



a. R1: (2.5, 2.5)



b. R2: (1, 1)

Note:

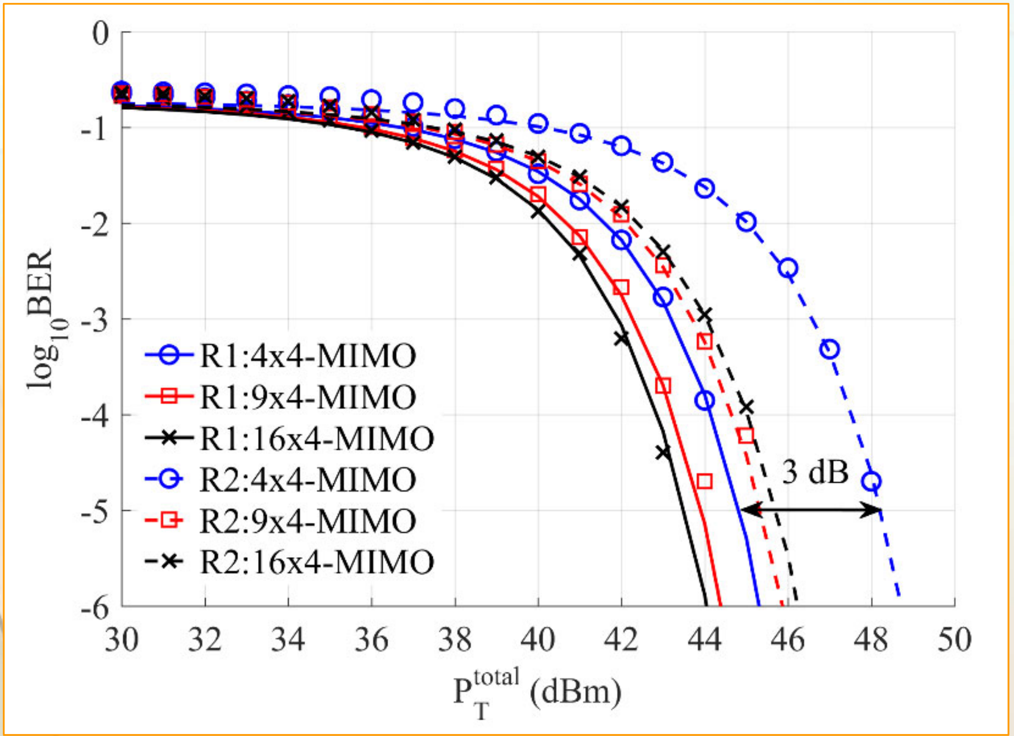
- $P_T^{\text{total}} = 45\ dBm\ (31.6\ W)$
- $BW = \frac{2RN}{b_{\text{OFDM}}}$

$b_{\text{OFDM}} = 496$ bits/OFDM

- BW = 12.9 MHz, $R = 50\ Mbps$,
- BW = 25.8 MHz, $R = 100\ Mbps$

The values b_{OFDM} = 372; 496; 620; 744; 868; 992 correspond to having on average 3, 4, 5, 6, 7, 8 bits per each of the 4 subchannels on each subcarrier, respectively.

MIMO Transmitter Configurations

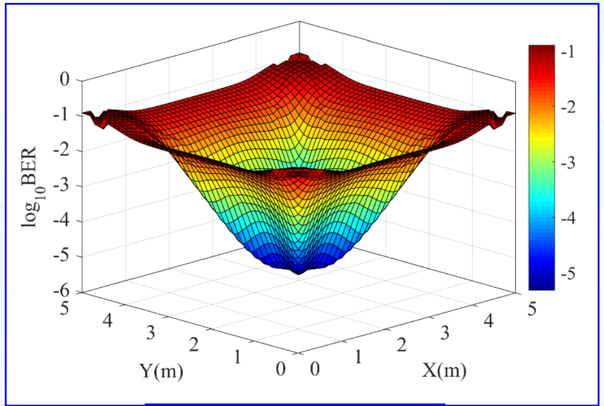


Note:

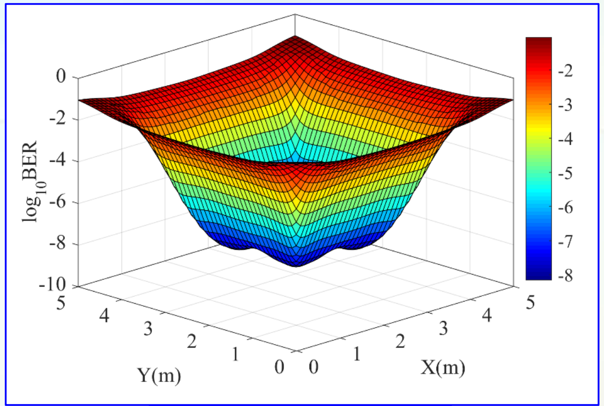
- b_{OFDM} = 496 bits/OFDM
- R = 50 Mbps

- More LEDs improve the system BER,
- Receiver position has a significant impact on the BER
- The power gain is more significant at R2

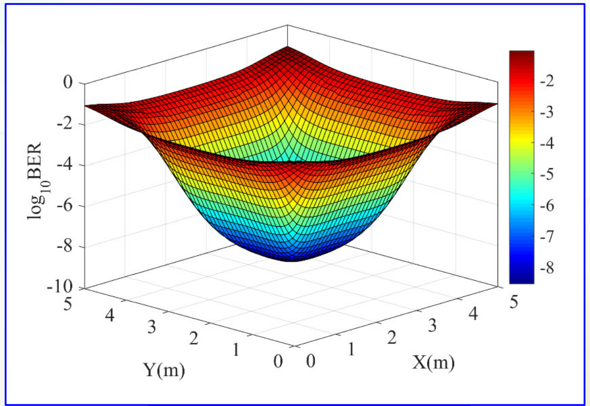
MIMO Transmitter Configurations



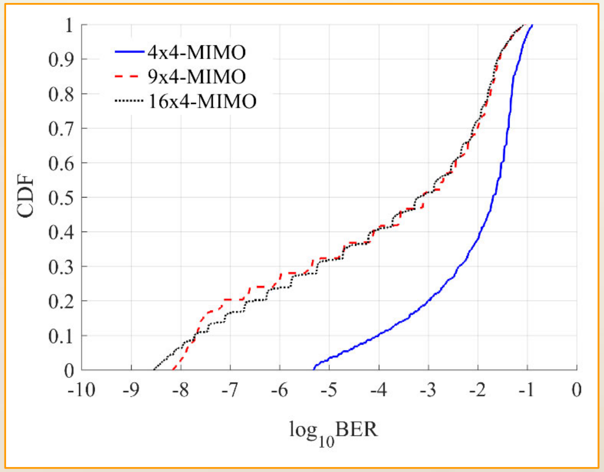
a. 4×4 −MIMO



b. 9×4 −MIMO



c. 16×4 −MIMO

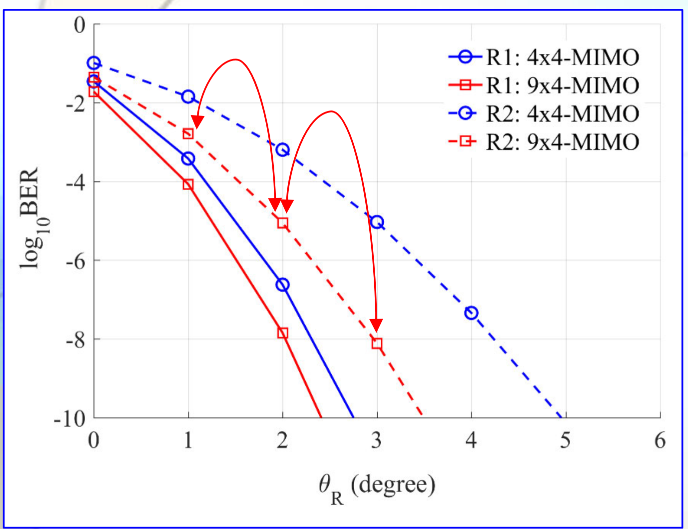


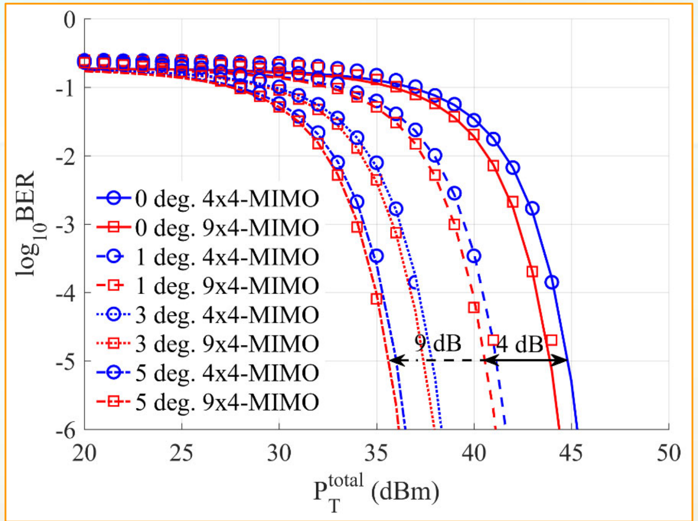
Note: $P_T^{\text{total}} = 45\ dBm\ (31.6\ W)$

9×4 − MIMO system is optimal

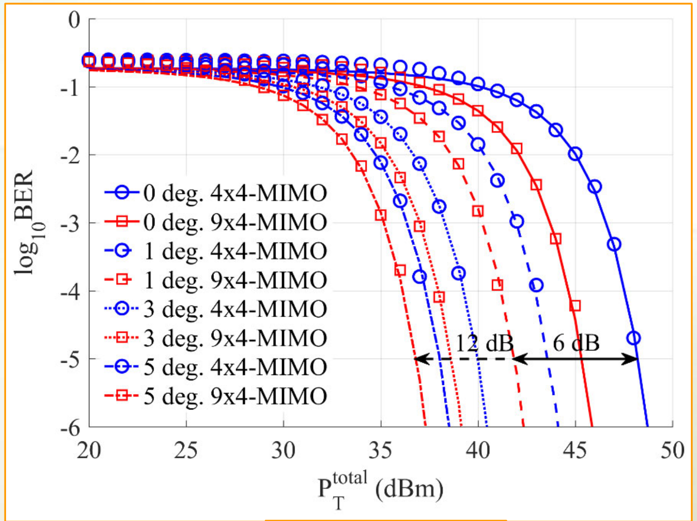
- Large coverage of low BER regions
- Low computational complexity

Polar Angle Tilting of PDs





a. R1: (2.5, 2.5)



b. R2: (1, 1)

Note: $P_T^{\text{total}} = 40\ dBm\ (10\ W)$

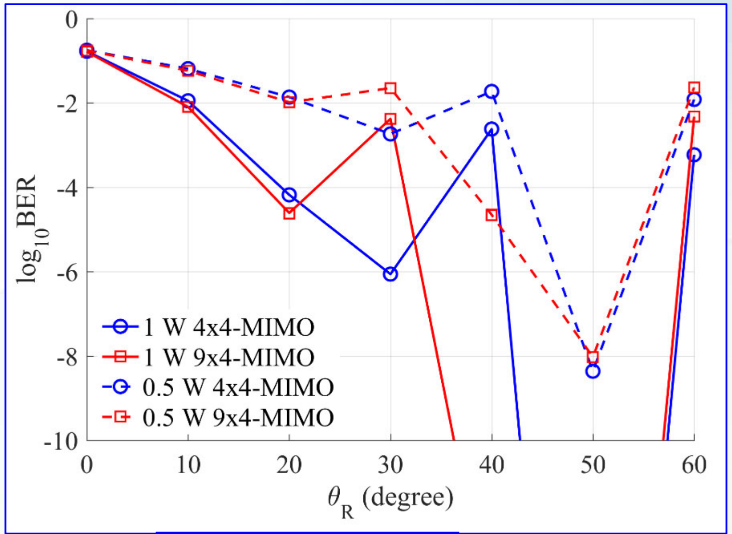
R2:
- BER decreases from 10^{-5} to 10^{-8} with the increase of $\theta_R = 2^{\circ}$ to $\theta_R = 3^{\circ}$

- 9×4 – MIMO system with tilting PD requires lower total power than baseline 4×4 – MIMO without tilting PD
- Large tilting polar angle, low amount of total power is required

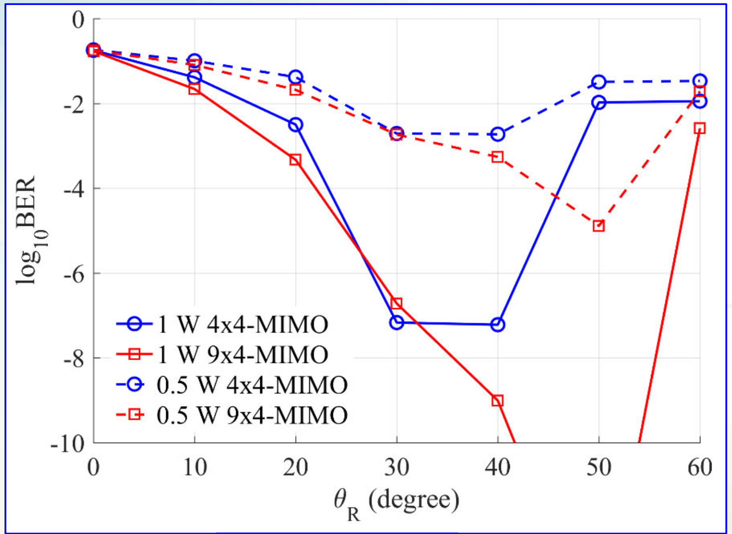
Is it possible to use polar angle tilting in case of light dimming control ?

Dimming Control

Note: R = 50 Mbps



a. R1: (2.5, 2.5)



b. R2: (1, 1)

Condition numbers of MIMO channel matrices

Receiver position	$M_t \times M_r$-MIMO	0°	1°	3°	5°	10°	30°	50°
R1: (2.5,2.5)	4 × 4-MIMO	2.1401×10^4	7.7286×10^3	3.3907×10^3	2.1688×10^3	1.1339×10^3	7.1349	98.9977
	9 × 4-MIMO	5.1300×10^4	1.8525×10^4	8.1266×10^3	5.1976×10^3	2.7168×10^3	19.1206	212.1289
	16 × 4-MIMO	4.5398×10^4	1.8072×10^4	8.1757×10^3	5.2742×10^3	2.7770×10^3	27.9164	20.4013
R2: (1,1)	4 × 4-MIMO	4.4752×10^5	9.4171×10^4	3.6811×10^4	2.2859×10^4	1.1663×10^4	2.3550×10^4	22.1358
	9 × 4-MIMO	9.8249×10^4	3.5396×10^4	1.5625×10^4	1.0019×10^4	5.2514×10^3	45.2626	19.7535
	16 × 4-MIMO	9.4038×10^4	3.6313×10^4	1.6300×10^4	1.0494×10^4	5.5184×10^3	46.2788	16.0005

Low condition number means a good-conditioned matrix (more diversity, high multiplexing gain)

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Conclusion

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- Proposed adjusting orientation of receivers on MIMO flip-OFDM using SVD
  - ✓ Quantified the performances of the system through bit loading for different PD orientations as well as different receiver locations
- Proposed the LED distributions on flip-OFDM using SVD
  - ✓ Investigated the performances of the system through bit loading for different number of LED distributions

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Performance Optimisation of Indoor SVD-Based MIMO-OFDM Optical Wireless Communication Systems

Jariya Panta[1], Poompat Saengudomlert[1], Karel L. Sterckx[1], Anh T. Pham[2]*

[1] School of Engineering, Bangkok University, 9/1 Moo 5, Phaholyothin Road, Klong Luang district, Pathumthani, Thailand
[2] Computer Communications Lab., The University of Aizu, Aizuwakamatsu 965-8580, Japan
** E-mail: jariya.panta@gmail.com*

Future work

- Extend to Multi-user MIMO (Multi-user MIMO OFDM for Indoor OWC)
  - ➢ Multi-user interference (MUI)
    - Precoding design:
      - ✓ block diagonalization (BD)
      - ✓ SVD
      - ✓ ZF
      - ✓ MMSE

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Thank you

Question & Answer