SVD Based MIMO Unipolar OFDM for Indoor Optical Wireless Communications

Advisor: Assoc.Prof.Dr. Poompat Saengudomlert
Co-advisor: Dr. Karel L. Sterckx

Presented by

Jariya Panta

Doctoral Program in Electrical and Computer Engineering,

School of Engineering, Bangkok University, Thailand

Outline

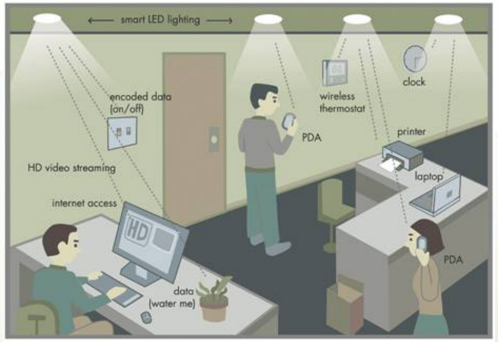
- Introduction
- Problem Statement
- Existing work
- Objective
- Scope and Limitation
- System Model
- Preliminary Results
- Conclusion and Future Work

Introduction
Overview of OWC

- OWC = Optical Wireless Communications
  - optical carriers: visible, infrared (IR), and ultraviolet (UV)
    - white light emitting diodes (LEDs)
    - **illuminate and communicate** at the same time
    - **modulation BW ~ 20MHz** [1]

- Advantages of OWC over radio frequency (RF) [1] – [3]
  - wide bandwidth, license-free frequency band
  - higher security, low cost, health-friendly

- OWC standards [1] – [3]
    - 2003: JEITA standards
    - 2009: IEEE 802.15.7-Standard on VLC

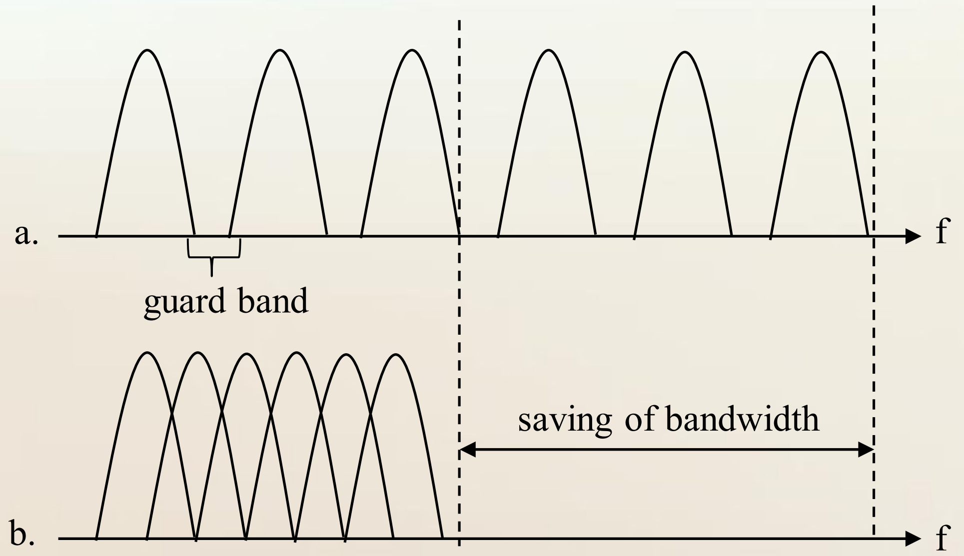


Light Fidelity (LiFi) [4]

Intelligent Transport System [5]

Introduction
Overview of OFDM

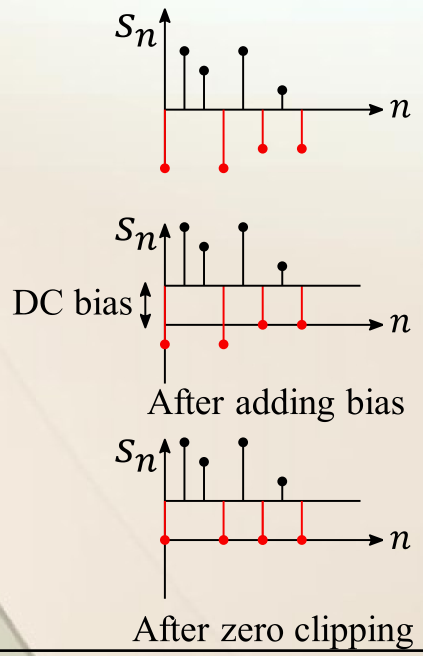
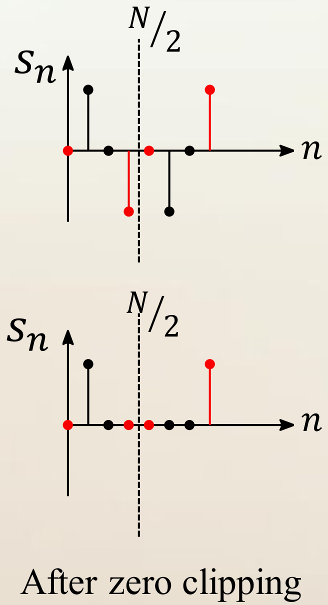
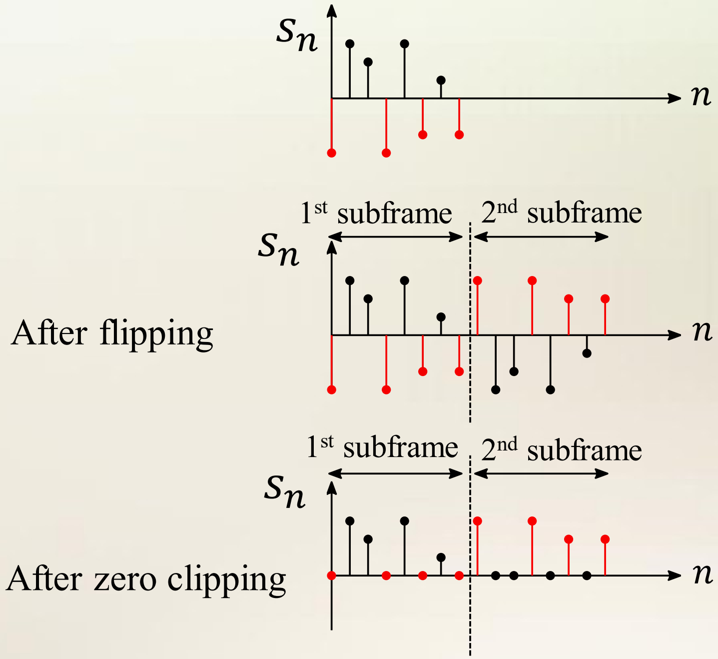
- OFDM = Orthogonal Frequency Division Multiplexing [6][7]
  - multi-carrier modulation (MCM)
  - robust to intersymbol interference (ISI) and intercarrier interference (ICI)
  - higher optical power efficiency than on-off-keying (OOK) and pulse position modulation (PPM)
  - standards based on OFDM: Wi-Fi, WiMAX, 3G, LTE, etc.
  - ○ high peak to average power ratio (PAPR)



Spectra of (a) FDM carriers and (b) OFDM subcarriers

Introduction
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 to create real signals.
- 3 techniques to make the non-negative signals:

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

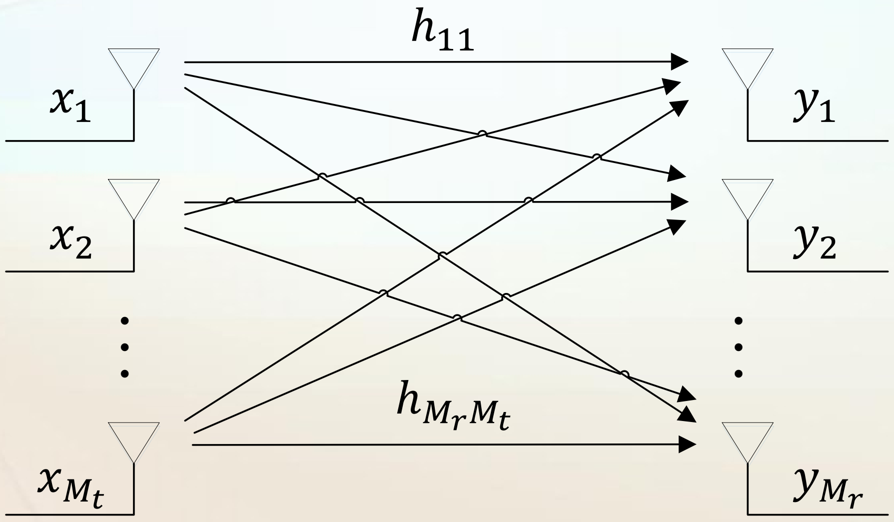
Introduction
OFDM Techniques for OWC

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 in the electrical domain as ACO-OFDM, and requires less computation.
- This research focuses on flip-OFDM.

Introduction
Overview of MIMO

- MIMO = Multiple Input Multiple Output



MIMO Systems [13]

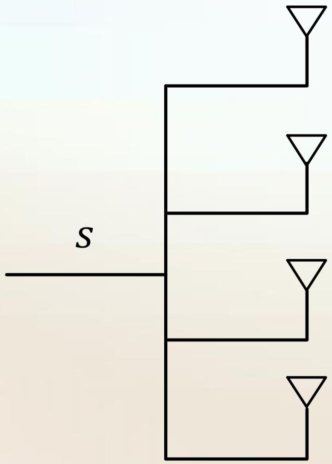
$$\begin{bmatrix} y_1 \\ \vdots \\ y_{M_r} \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1M_t} \\ \vdots & \ddots & \vdots \\ h_{M_r 1} & \cdots & h_{M_r M_t} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{M_t} \end{bmatrix}$$

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

- standards based on MIMO: Wi-Fi, WiMAX, 3G, LTE, etc. [14]-[17]

Introduction
Overview of MIMO

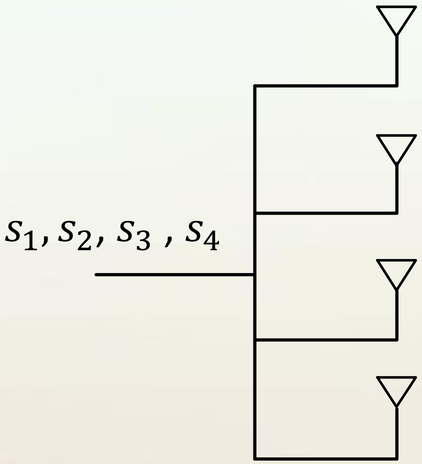
- **Spatial diversity** [13] – [16]
  - same symbol is transmitted from each transmitter to a receiver.
  - **Goal:** improving the reliability



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

- 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

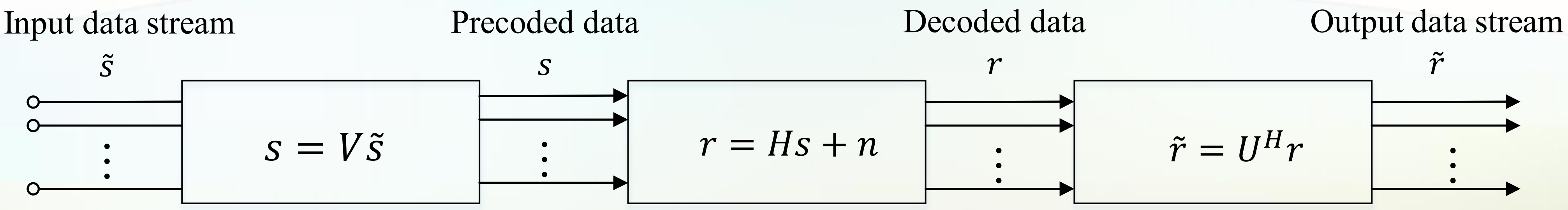


$$x_1 = a_{11}s_1 + a_{12}s_2 + a_{13}s_3 + a_{14}s_4$$
$$x_2 = a_{21}s_1 + a_{22}s_2 + a_{23}s_3 + a_{24}s_4$$
$$x_3 = a_{31}s_1 + a_{32}s_2 + a_{33}s_3 + a_{34}s_4$$
$$x_4 = a_{41}s_1 + a_{42}s_2 + a_{43}s_3 + a_{44}s_4$$

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

Introduction
SVD

- SVD = Singular Value Decomposition [13]
  - Decompose the MIMO channel into a number of unequally weighted independent subchannels.



Transmit precoding and receiver decoding [13]

$$H = U\Sigma V^H$$

$$\begin{bmatrix} \tilde{r}_1 \\ \tilde{r}_2 \\ \vdots \\ \tilde{r}_{M_r} \end{bmatrix} = \begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \sigma_{M_t} \end{bmatrix} \begin{bmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \vdots \\ \tilde{s}_{M_t} \end{bmatrix} + \begin{bmatrix} \tilde{n}_1 \\ \tilde{n}_2 \\ \vdots \\ \tilde{n}_{M_r} \end{bmatrix}$$

$$\tilde{r}_1 = \sigma_1 \tilde{s}_1 + \tilde{n}_1$$
$$\vdots$$
$$\tilde{r}_{M_r} = \sigma_{M_t} \tilde{s}_{M_t} + \tilde{n}_{M_r}$$

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.

Problem Statement

Key challenge on MIMO OWC

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

Existing work
MIMO OFDM for OWC

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]
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]

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.

Existing work
MIMO OFDM for OWC

SL	Author	MIMO technique		OFDM technique				Demultiplexing Technique	Receiver front-end	Noted	Ref .
		SMP.	SD.	DCO.	ACO.	Flip.	et al.				
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]
10.	O. Narmanlioglu, et al., 2017		✓	✓				Maximum Likelihood (ML)	PD	Studied on the effects of diff. MIMO configurations: Tx. & Rx. alignment.	[27]
* **	J.Panta, et al., 2019	✓				✓		SVD	PD	1. Distribute the no. of LEDs 2. LOS	
* **	J.Panta, et al., 2019	✓				✓		SVD, ZF, MMSE	PD	1. Tilled angle of the LEDs & PDs. 2. Consider illumination constraint.	

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.

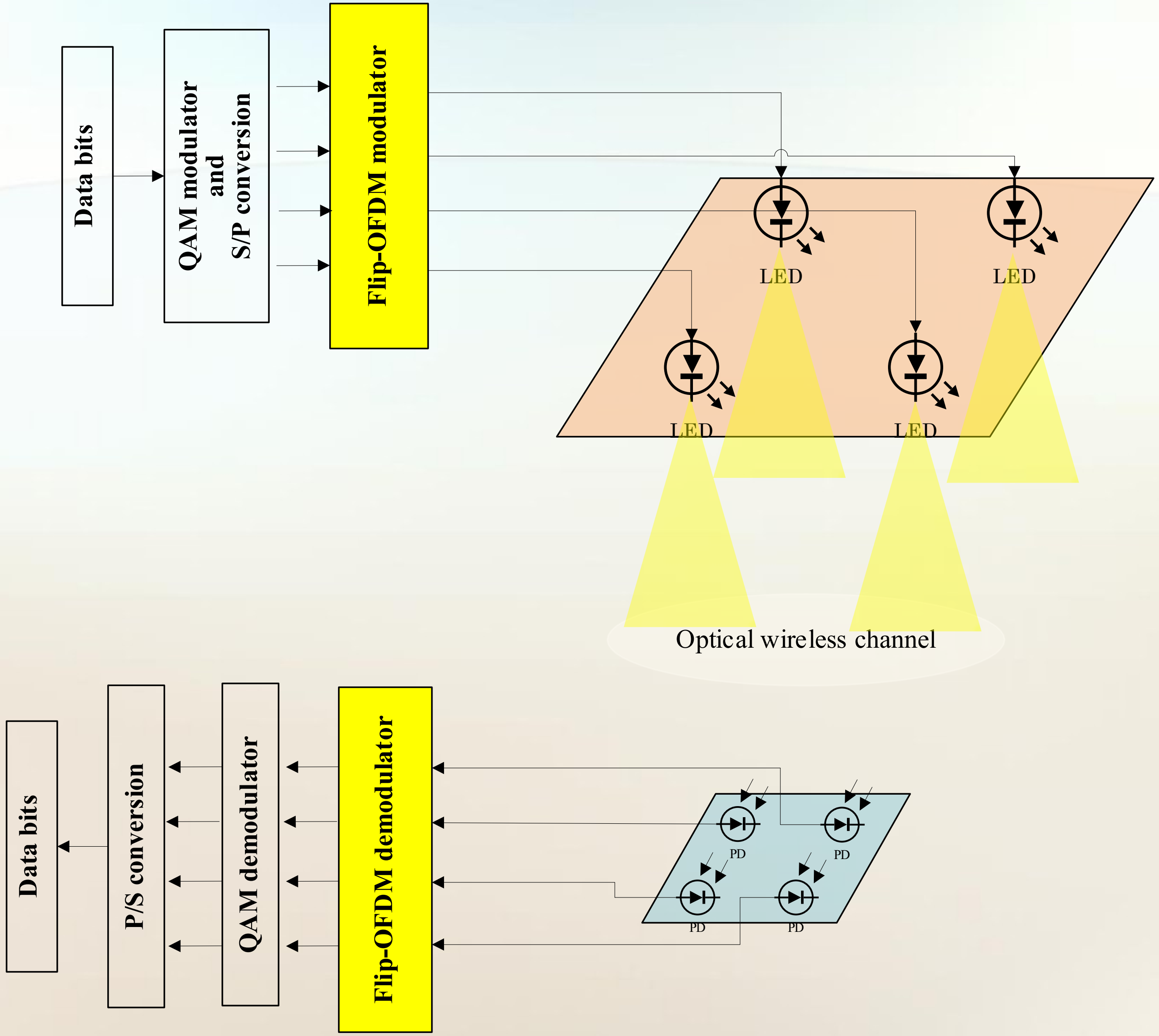
Objectives

- To evaluate the performances of SVD based MIMO flip-OFDM with bit loading for different LED and PD orientations as well as different receiver locations.
- To investigate the performances of MIMO flip-OFDM using SVD through bit loading for different number of LED distributions.
- To compare the performances of SVD, ZF and MMSE on MIMO flip-OFDM.

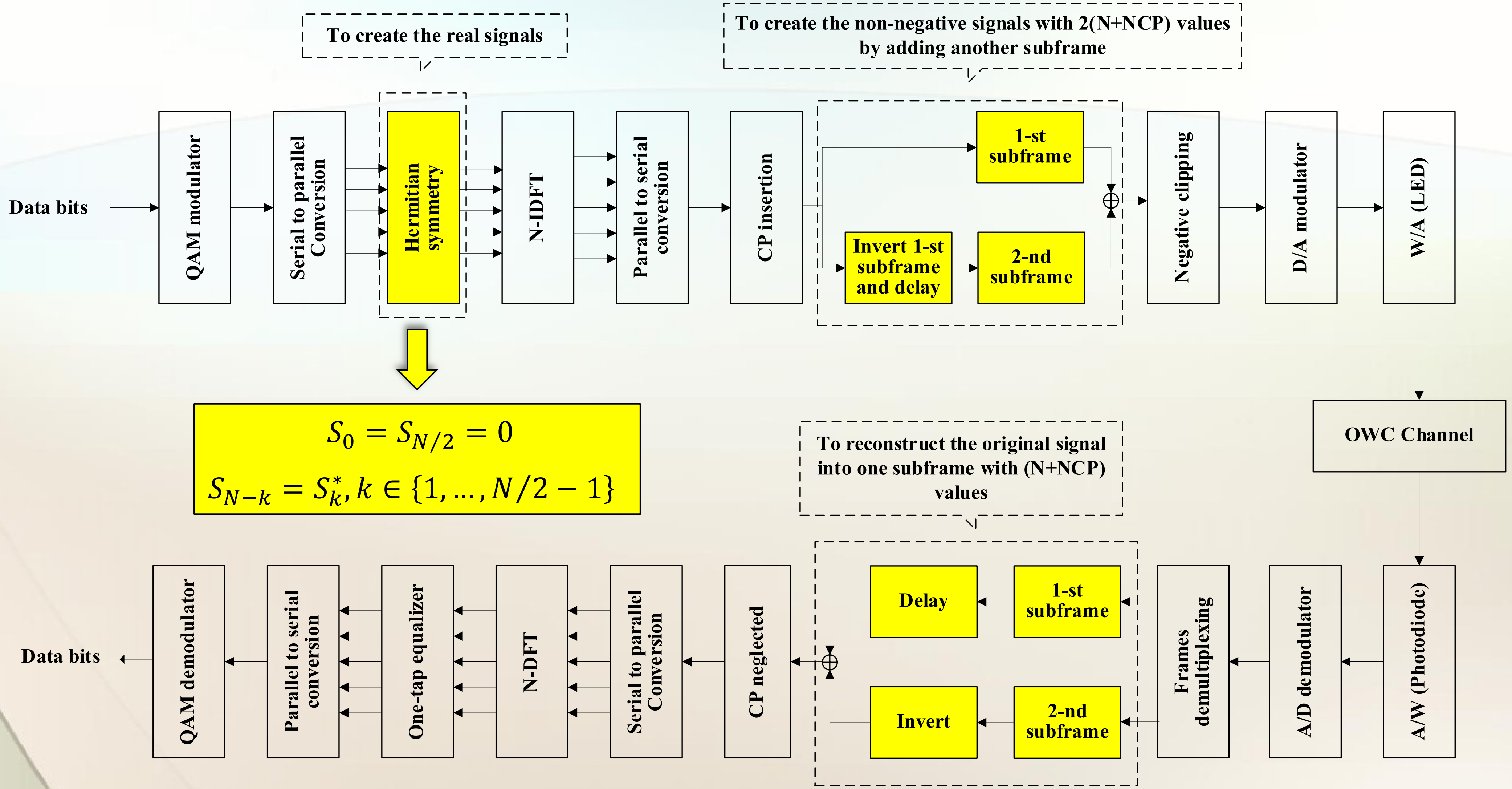
Scope and Limitation

- The modulation method is based on flip-OFDM.
- The system performance evaluation is based on 4x4-MIMO flip-OFDM for transceiver orientation scenario.
- The system performance evaluation is based on 4x4- , 9x4- and 16x4-MIMO flip-OFDM for LED distribution scenario.
- The results are based on theoretical analysis and simulation.
- The optical channel is considered as LOS with Lambertian LED [17][30].

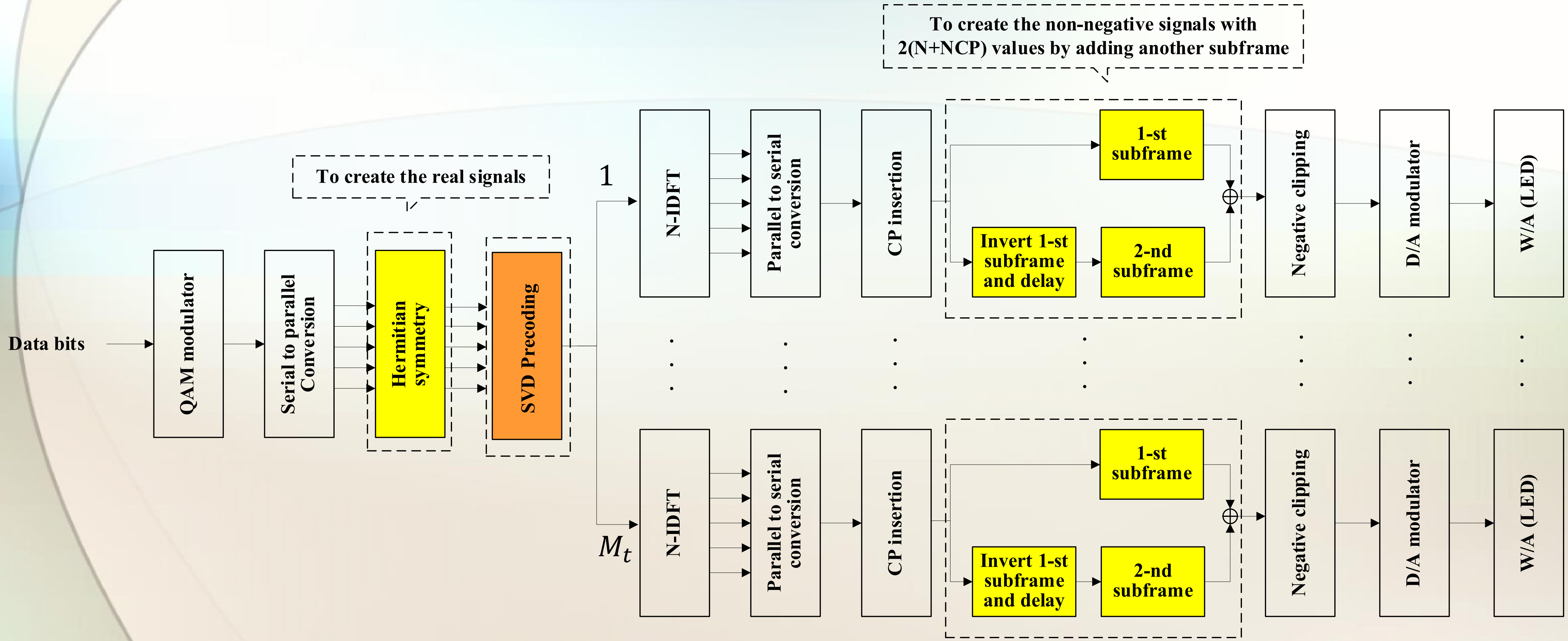
System Model
MIMO Flip-OFDM Transmission System



System Model
Flip-OFDM Transmission System

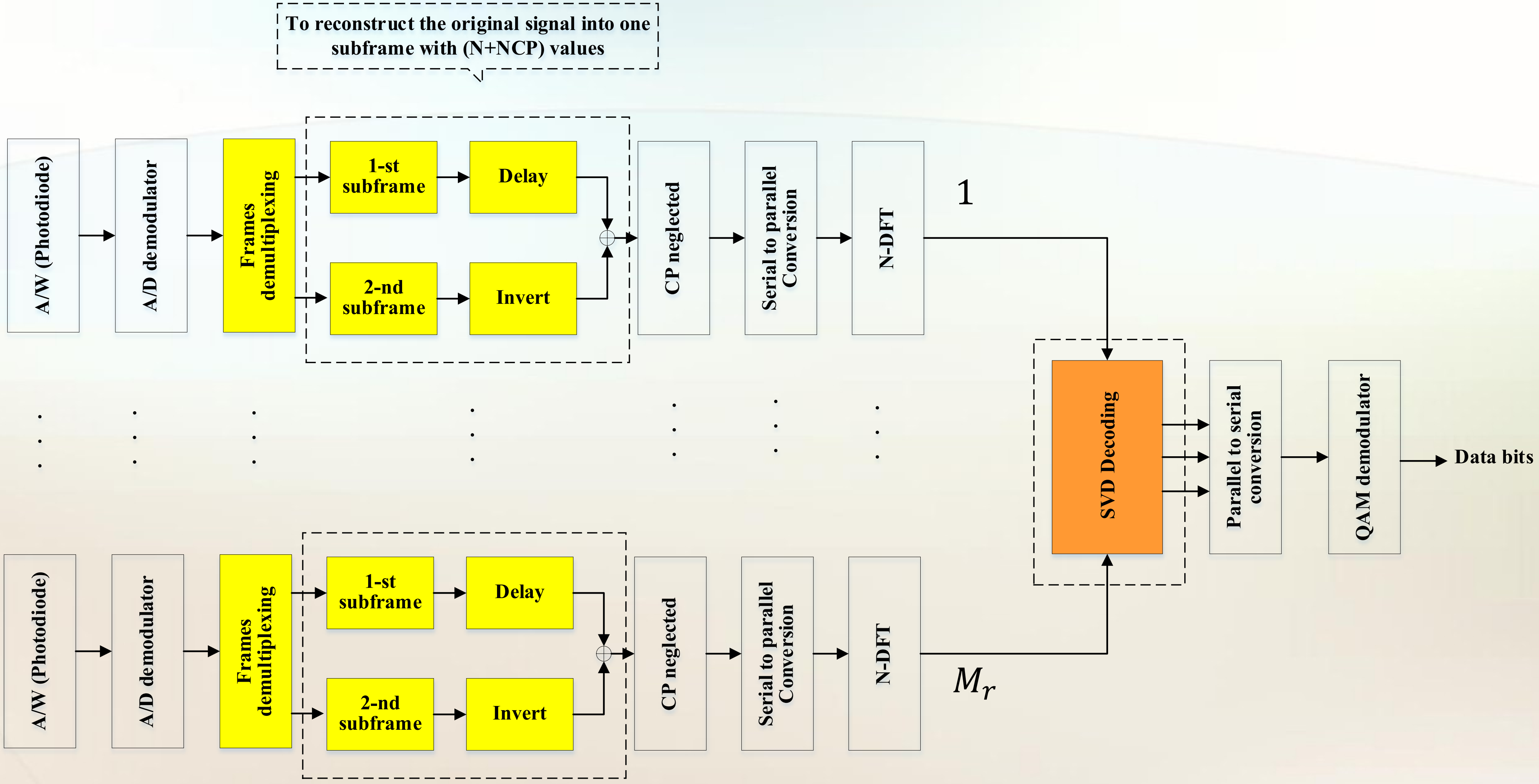


System Model
MIMO Flip-OFDM using SVD



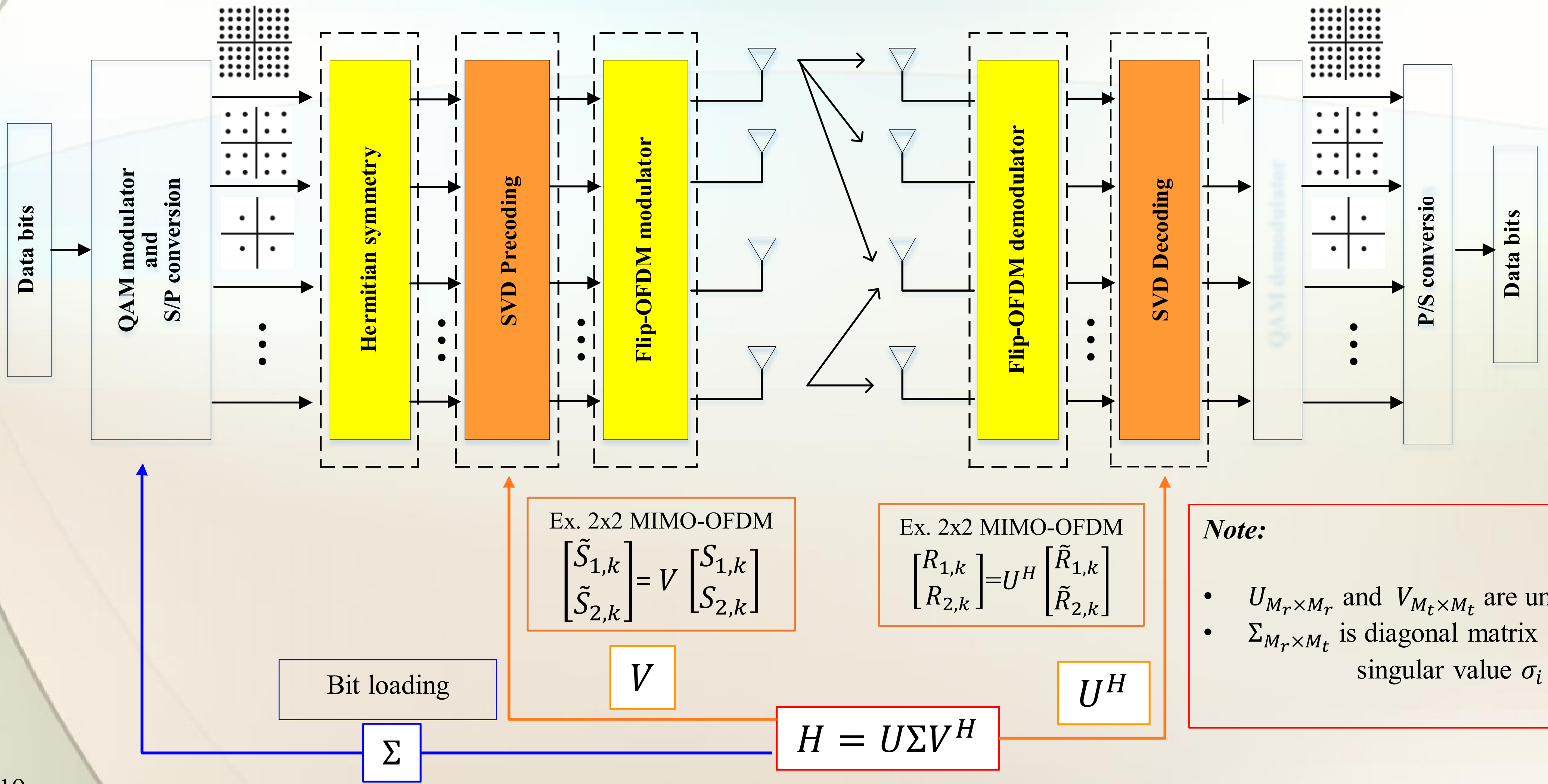
MIMO flip-OFDM Transmitter using SVD

System Model
MIMO Flip-OFDM using SVD



MIMO flip-OFDM Receiver using SVD

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

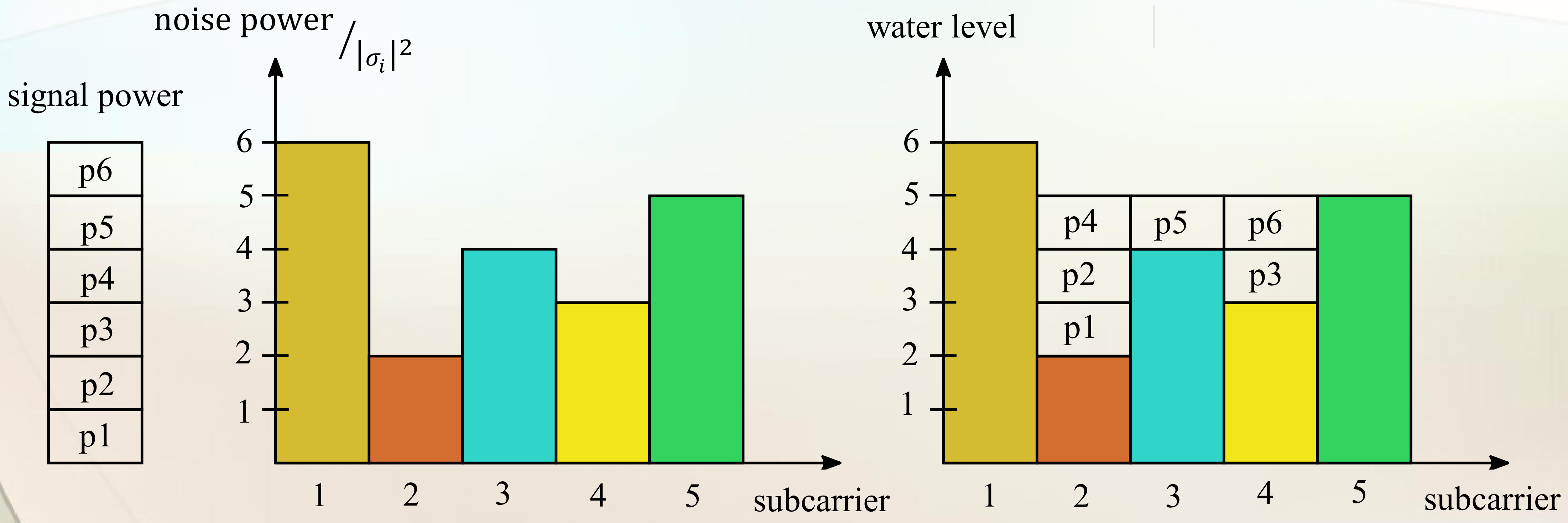


Note:

- $U_{M_r \times M_r}$ and $V_{M_t \times M_t}$ are unitary matrices
- $\Sigma_{M_r \times M_t}$ is diagonal matrix of singular value σ_i

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

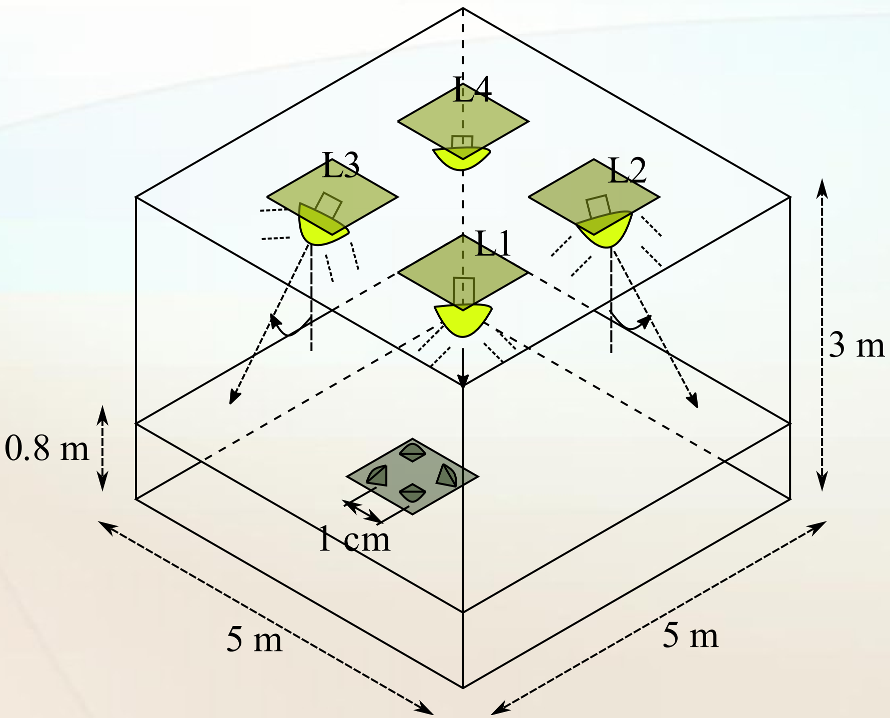
- Bit loading is based on the water filling technique [28][29]



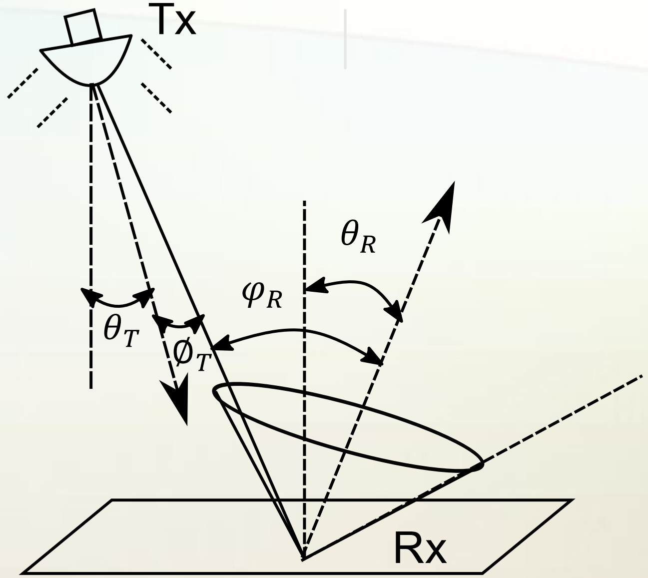
Note:
- σ_i = the spatial channel gain or singular value on subcarrier i

System Model

Configuration of Indoor MIMO OWC system



Configuration of the indoor MIMO OWC system

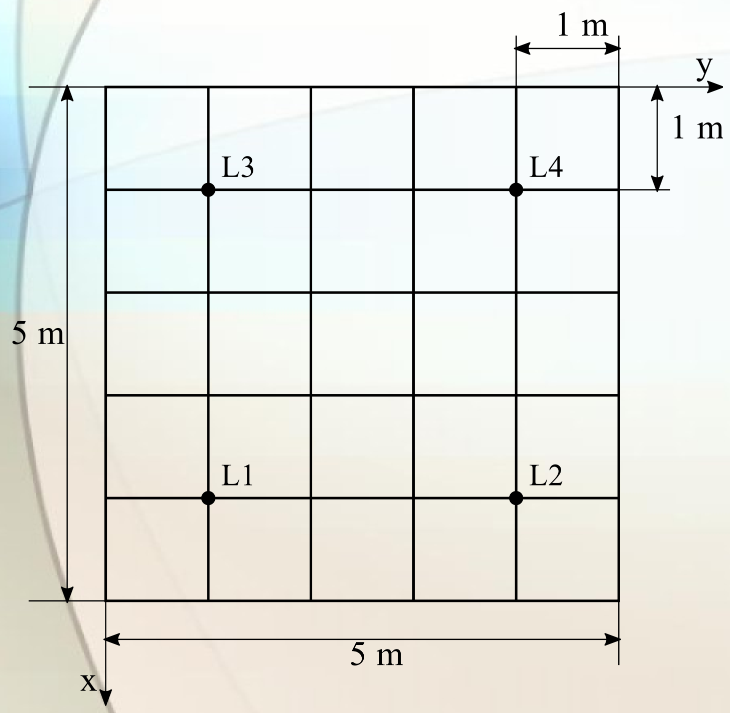


Note:

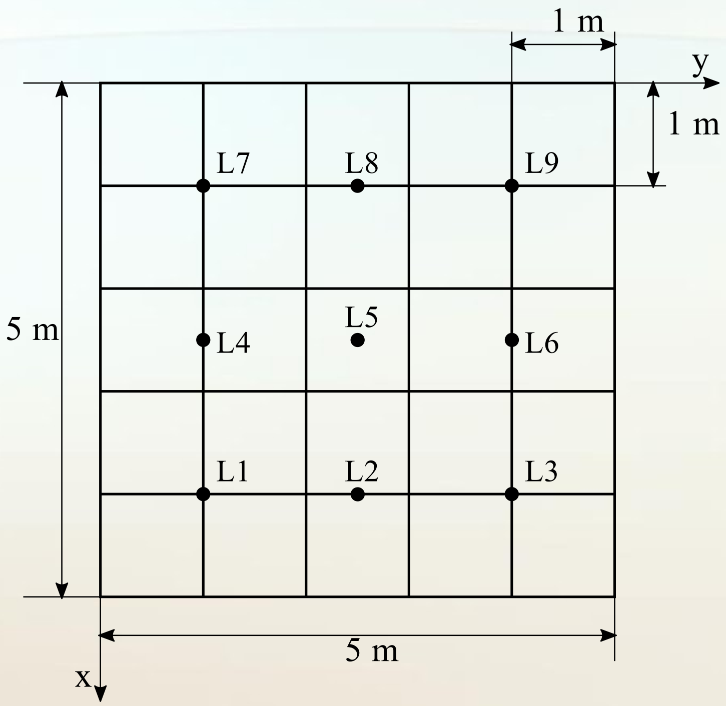
- θ_T, θ_R = the tilled angles of the LED and PD,
- $\emptyset_T$ = **the emission angle at transmit antenna,**
- φ_R = **the incident angle at receive antenna.**

Proposed transceiver systems

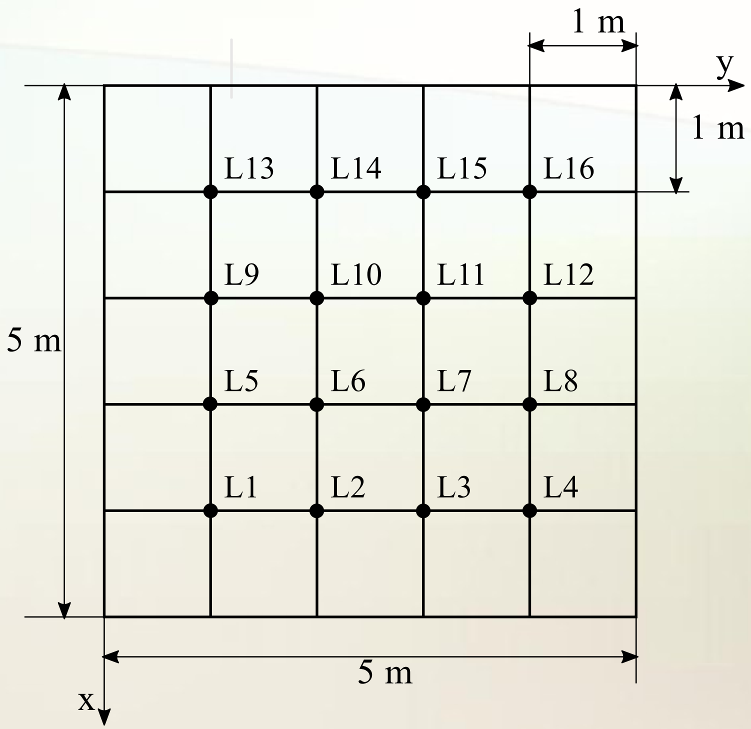
System Model
Position of Lighting Equipments



4x4-MIMO flip-OFDM



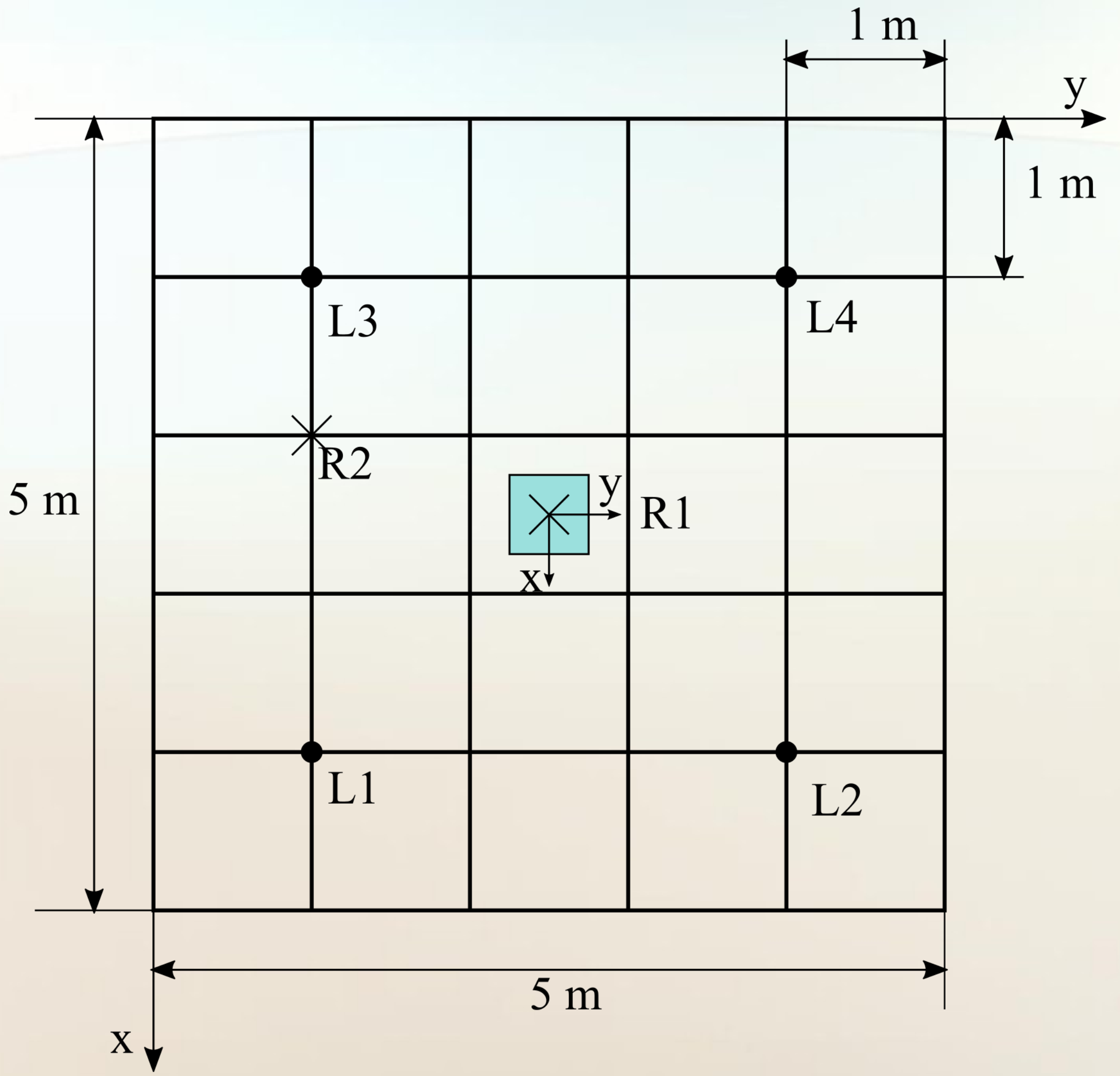
9x4-MIMO flip-OFDM



16x4-MIMO flip-OFDM

System Model

Top view of the room of 4x4 MIMO flip-OFDM

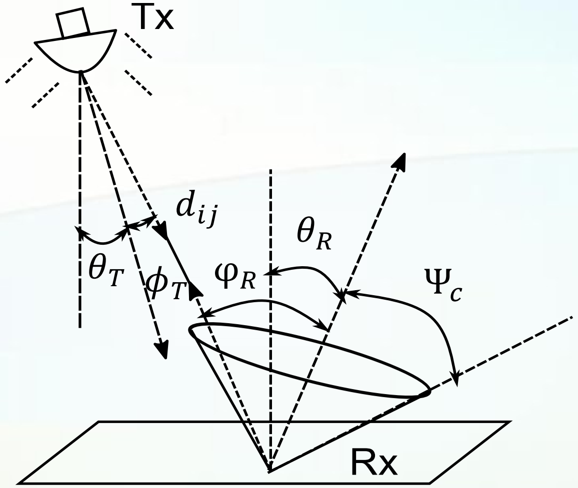


- LED1: (1,1)
- LED2: (1,4)
- LED3: (4,1)
- LED4: (4,4)

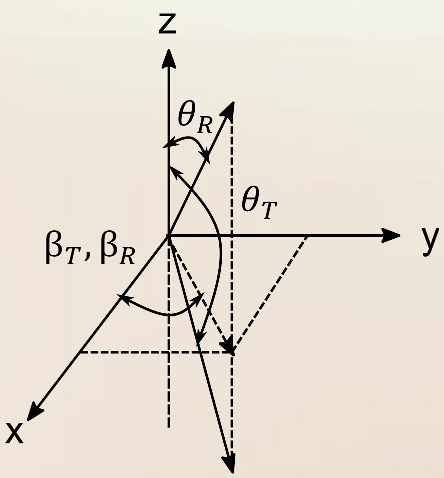
- R1: (2.5,2.5)
- R2: (1,1)

System Model

Configuration of Indoor MIMO OWC system



The configuration of the proposed transceiver orientation model



The coordinate of the proposed transceiver orientation model

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

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,
- Ψ_c = the FOV of the PD where$\Psi_c \leq \pi/2$,
- $\emptyset_T$ = 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 ad PD,
- β_T, β_R = the azimuthal angle values of the four LEDs and the four PDs.

Preliminary Results of Mathematical Analysis

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

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

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

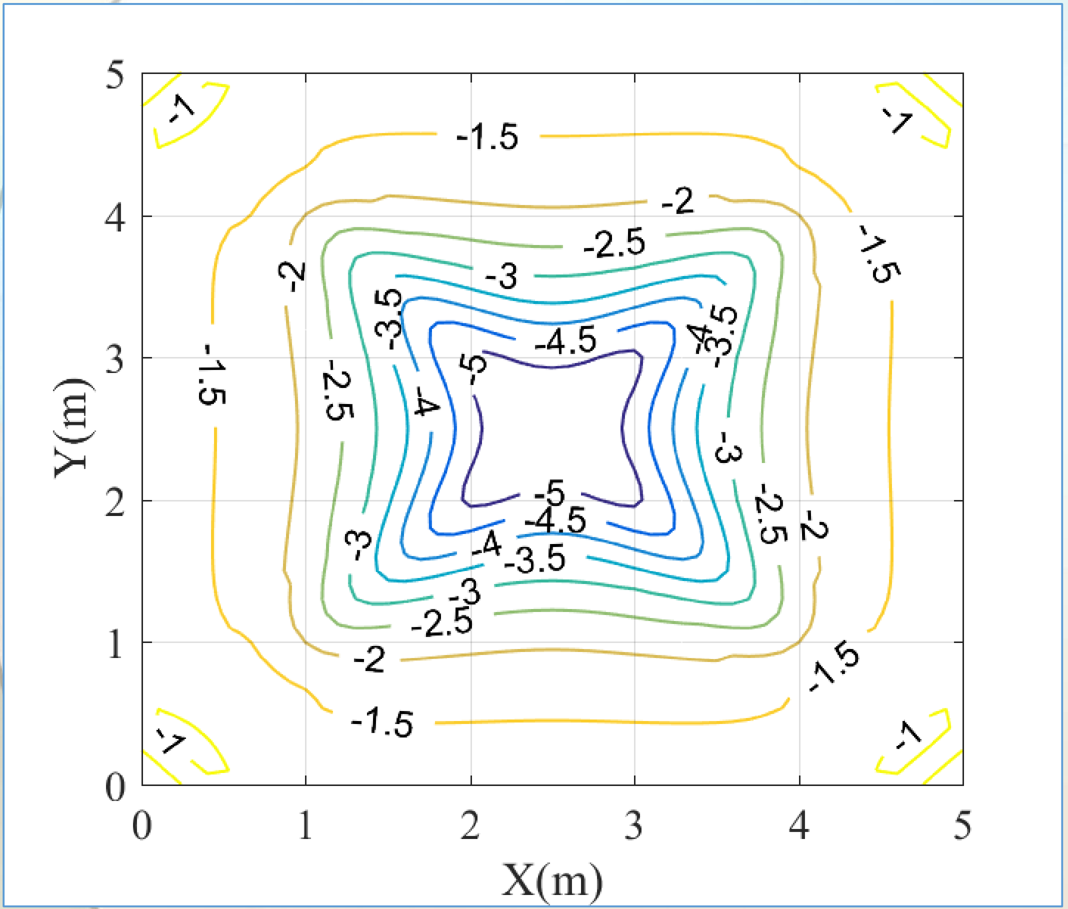
Note:

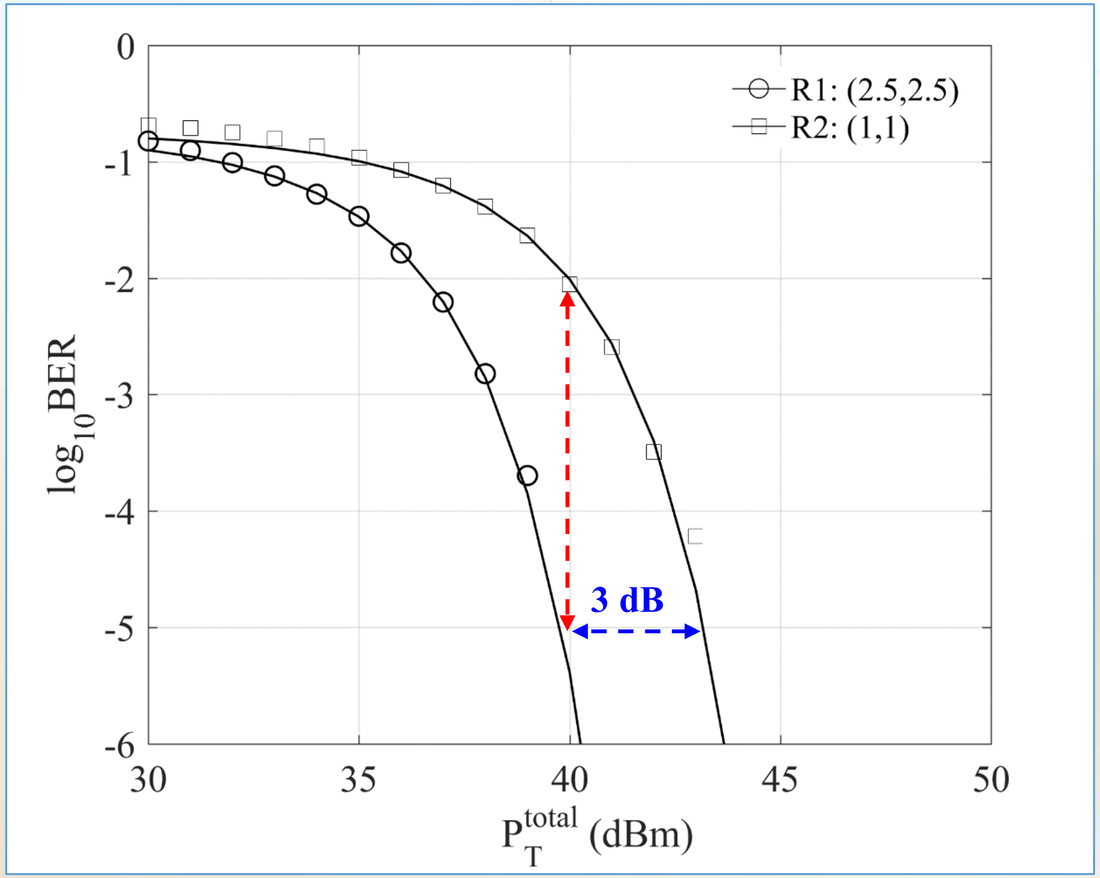
- BER = bit error rate,
- b_{total} = No. of bits transmitted on all spatial channels and subcarriers,
- P_{total} = total transmit optical power of all transmit antenna,
- R = bit rate,
- M_t= No. of transmit antenna,
- $M_{g,k}$ = QAM constellation on subcarrier k on spatial channel g,
- d = the minimum 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
Bit Rate	R	5 Mbps
Transmit optical power	P_{opt}	0-50 dBm
Number of OFDM subcarriers	N	64 [6][10]
Number of transmitted OFDM symbol	-	10^2
DC gain of CIR	H_0	10^{-6} [16]
Maximum M × M QAM constellation size	M	16
Number of bits/ OFDM symbol	b_{OFDM}	496
PSD of AWGN	N_0	3.05×10^{-23} A^2/Hz [16]
Conversion factor	$\alpha_{W/A}$	1 W/A [18]
Receiver responsivity	$\alpha_{A/W}$	0.53 A/W [16]
Target BER in bit loading algorithm	-	10^{-5}

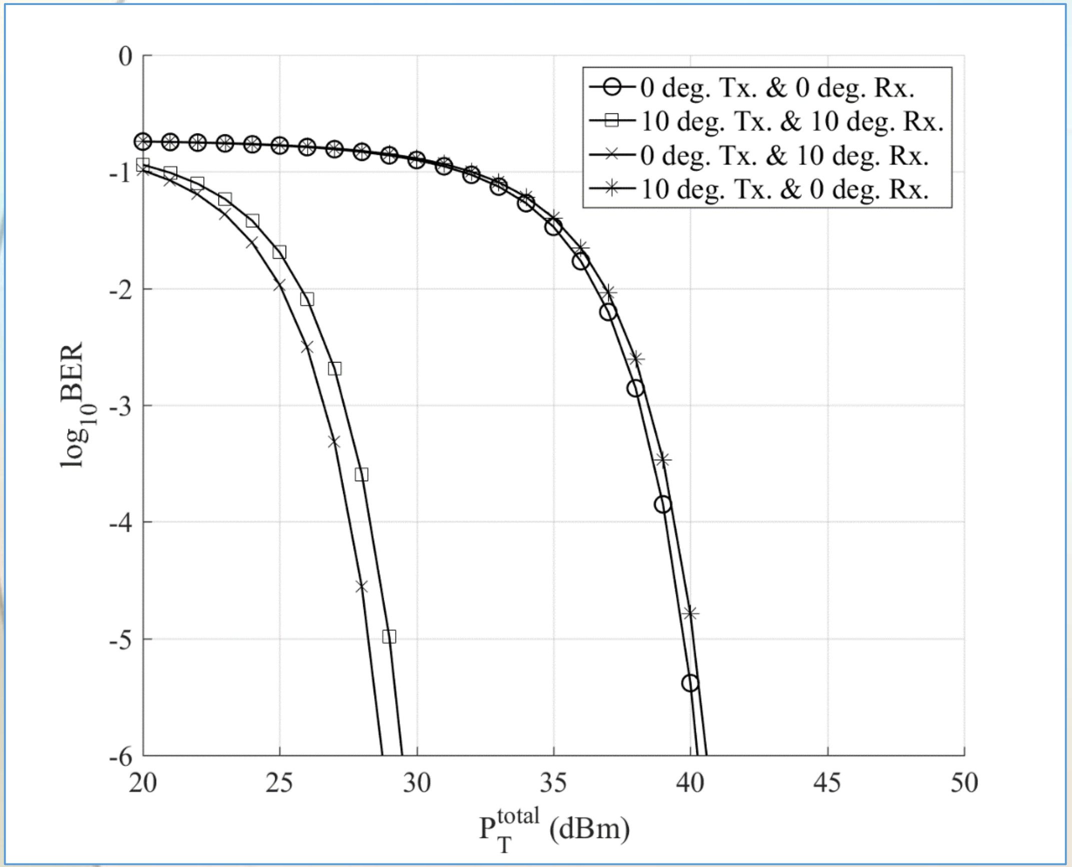
Preliminary Results



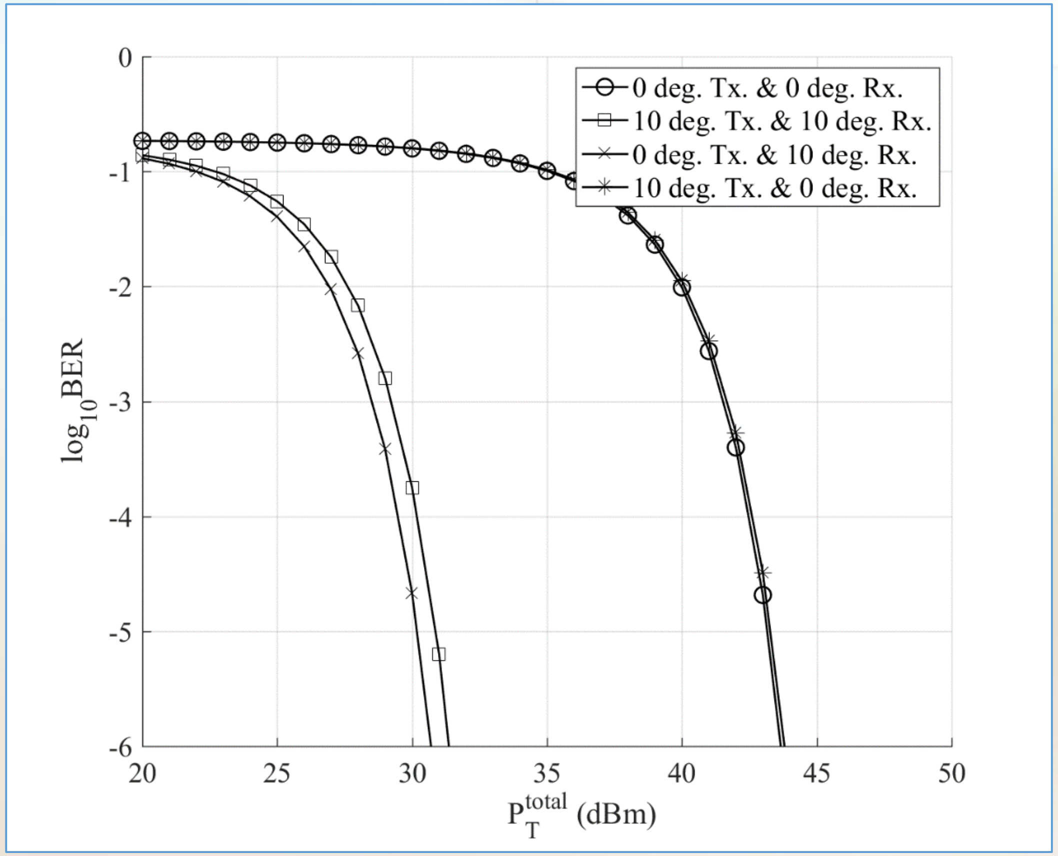


Total transmit optical power = 40 dBm

Preliminary Results

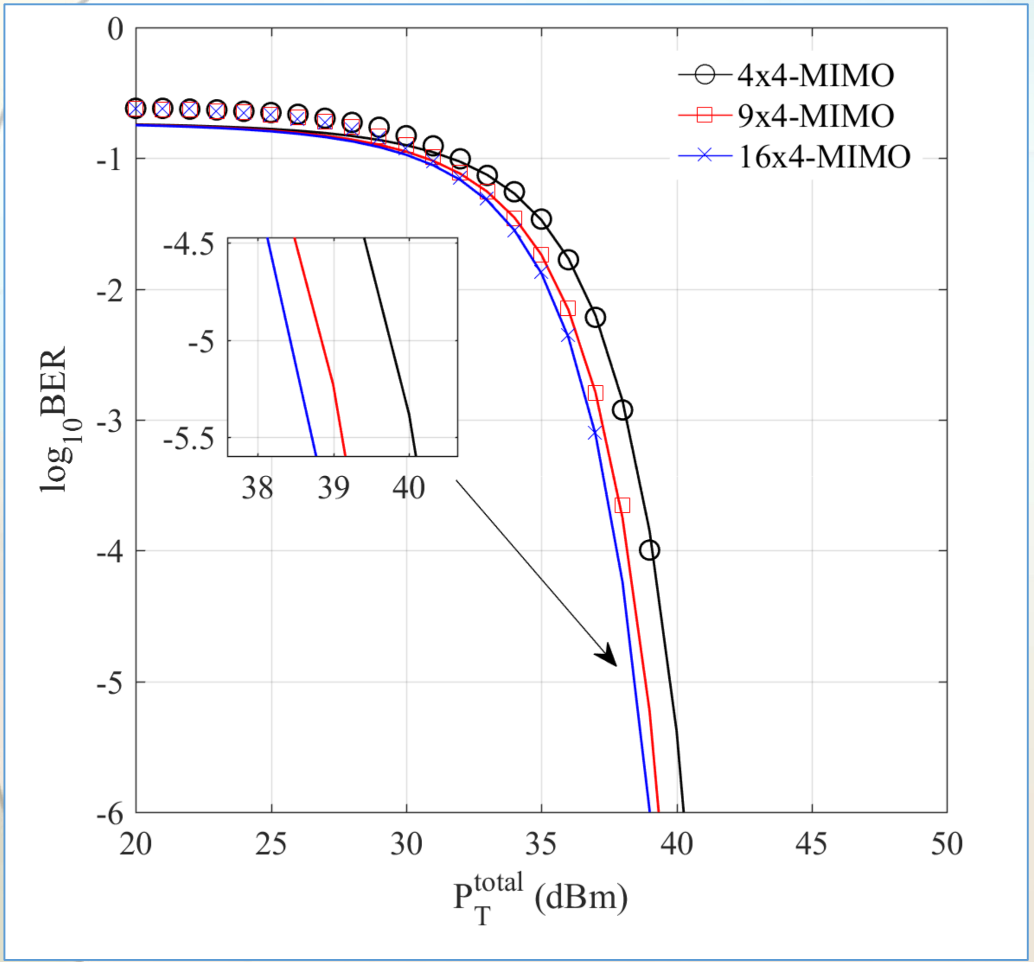


R1: (2.5, 2.5)

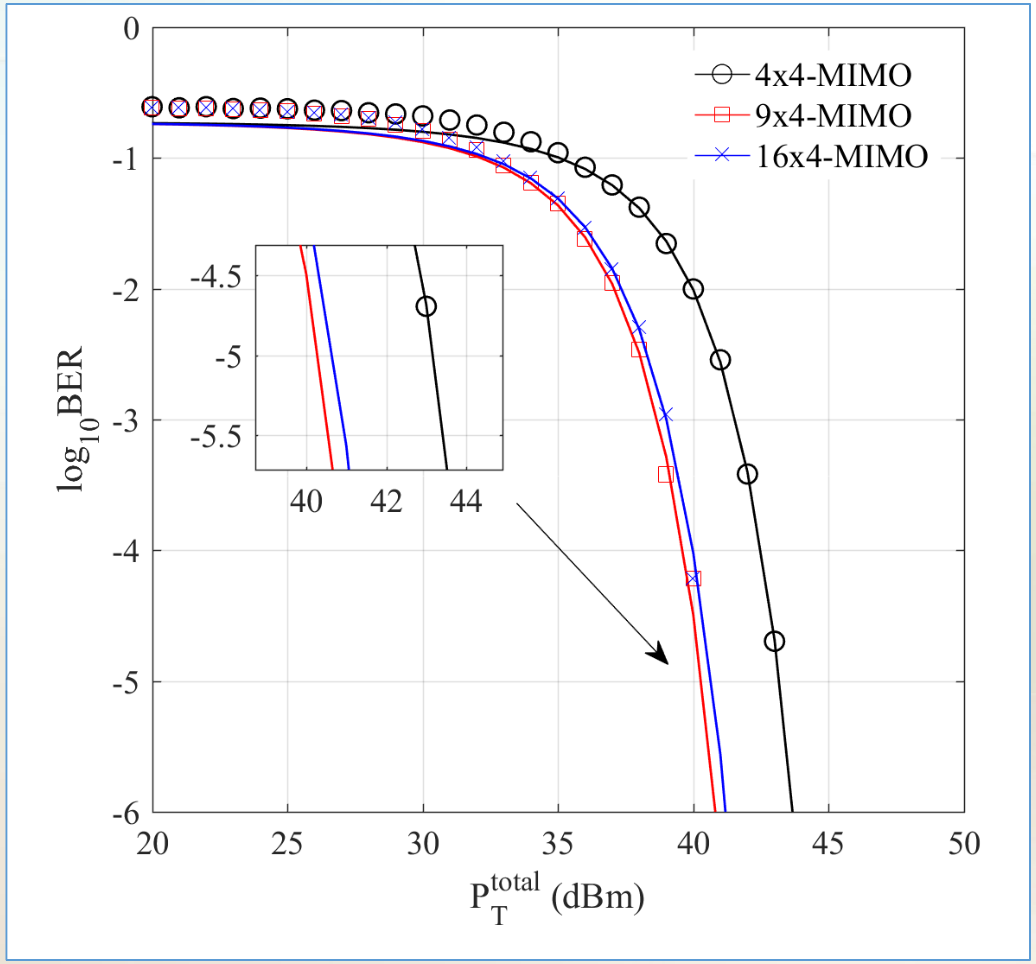


R2: (1, 1)

Preliminary Results

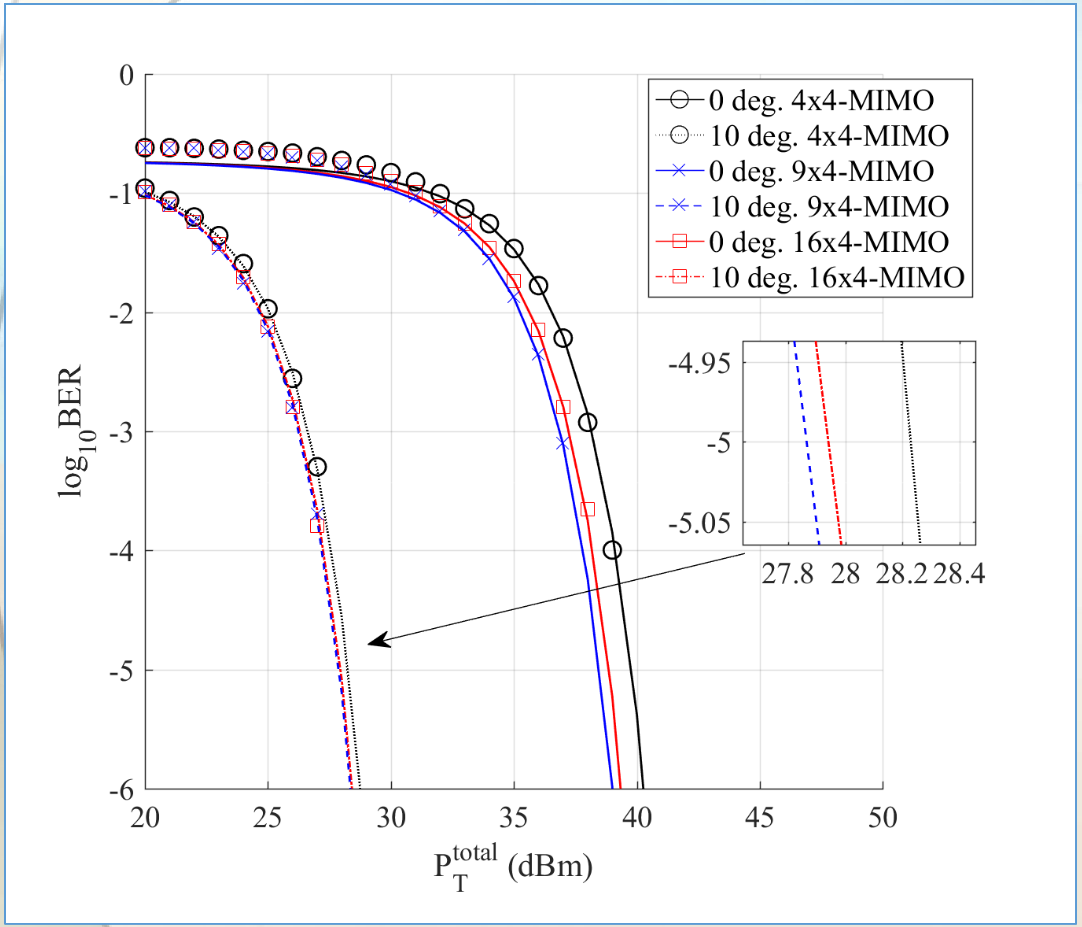


R1: (2.5, 2.5)

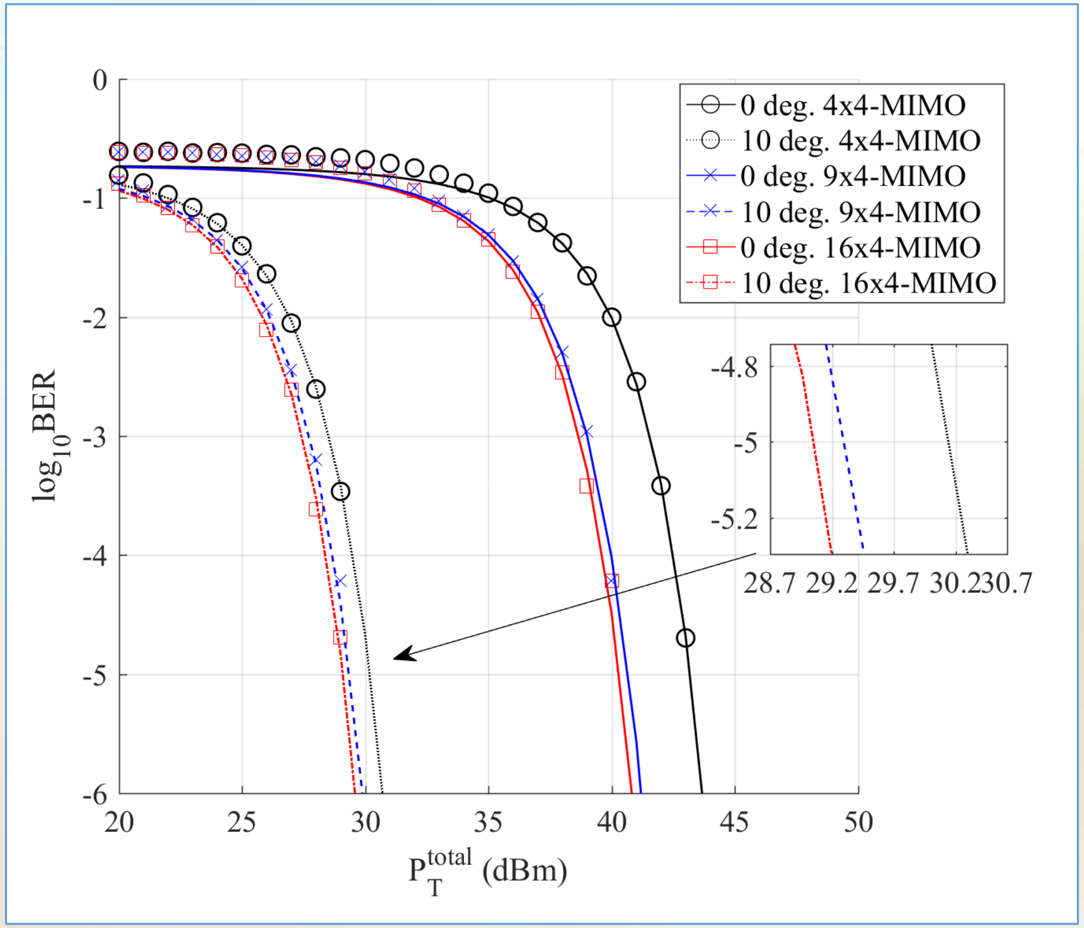


R2: (1, 1)

Preliminary Results

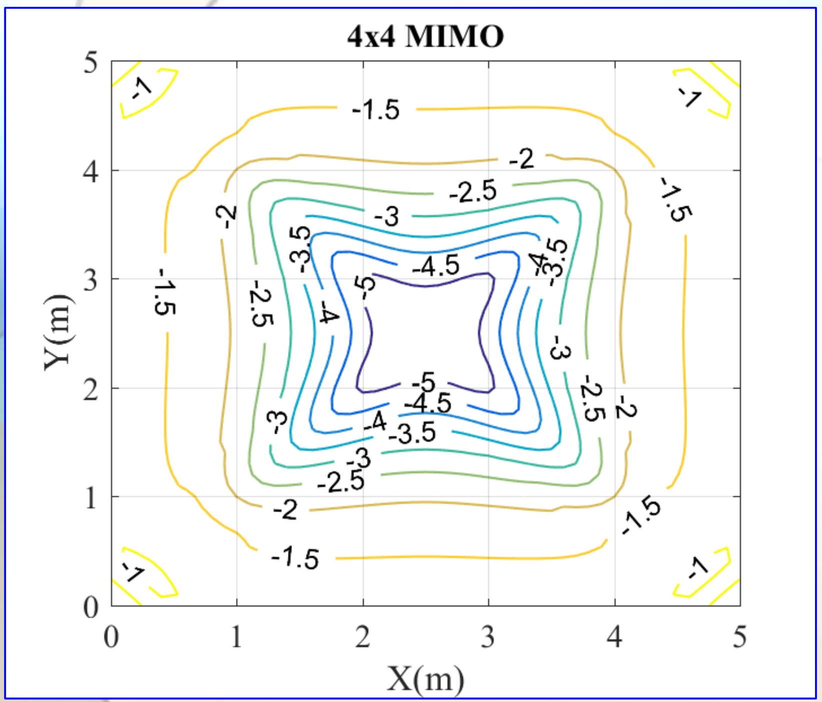


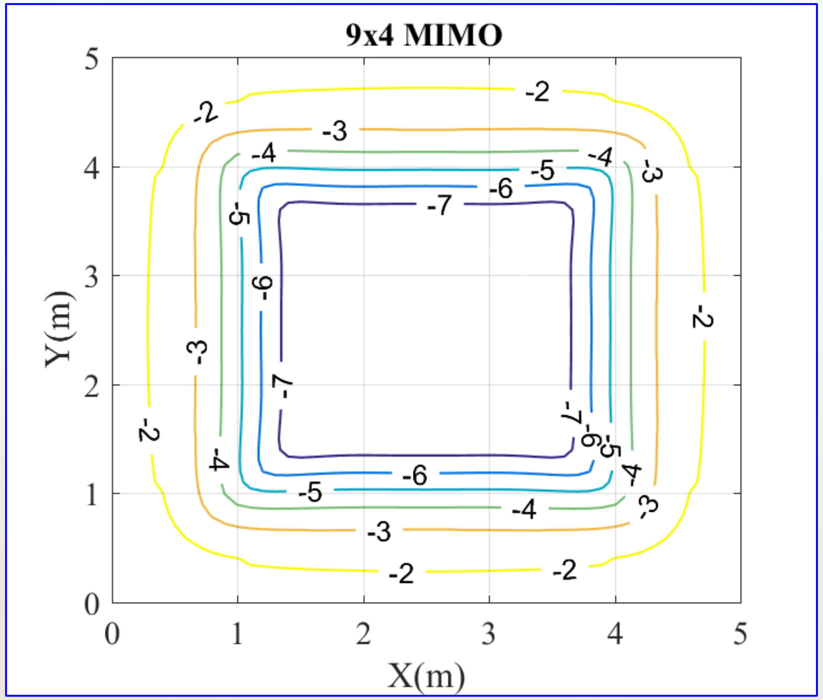
R1: (2.5, 2.5)

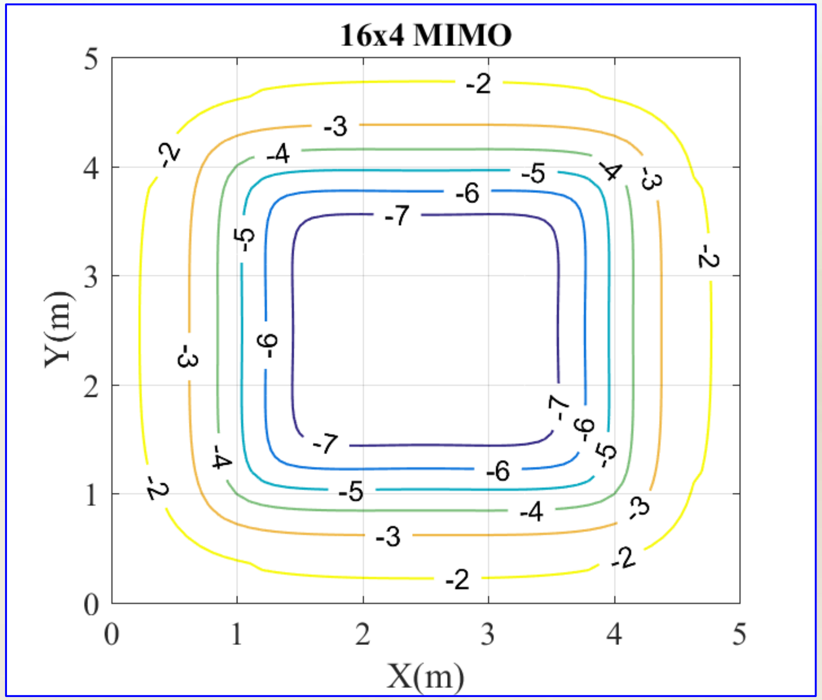


R2: (1, 1)

Preliminary Results

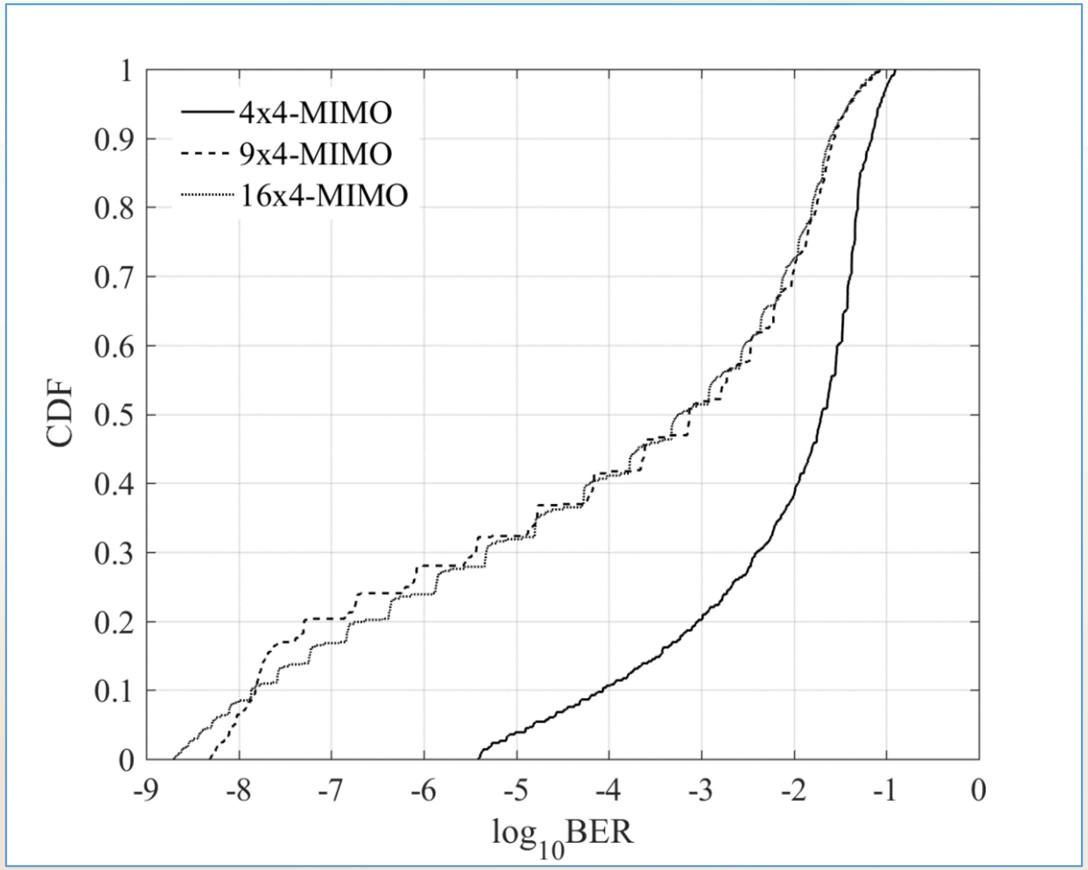






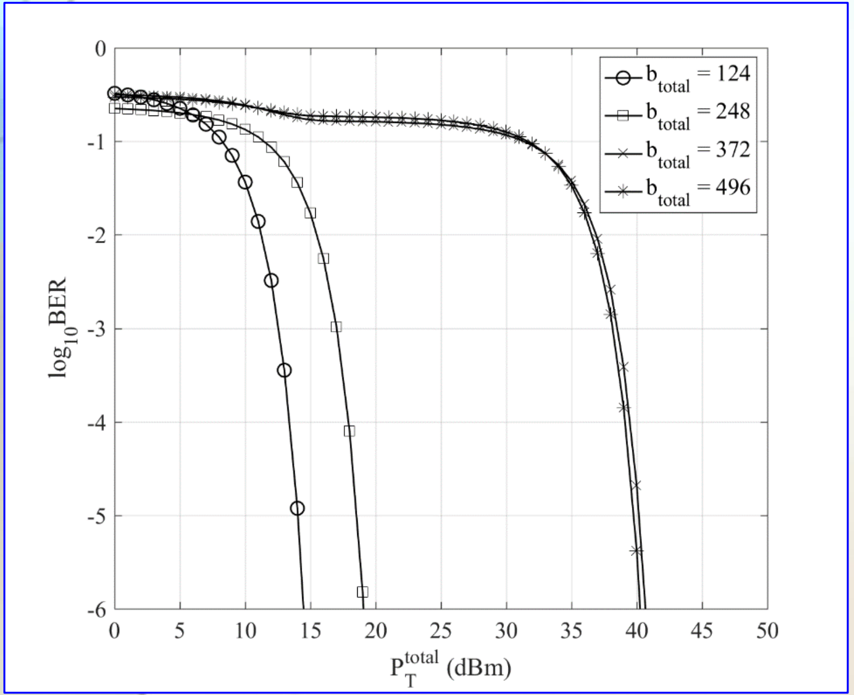
Total transmit optical power = 40 dBm

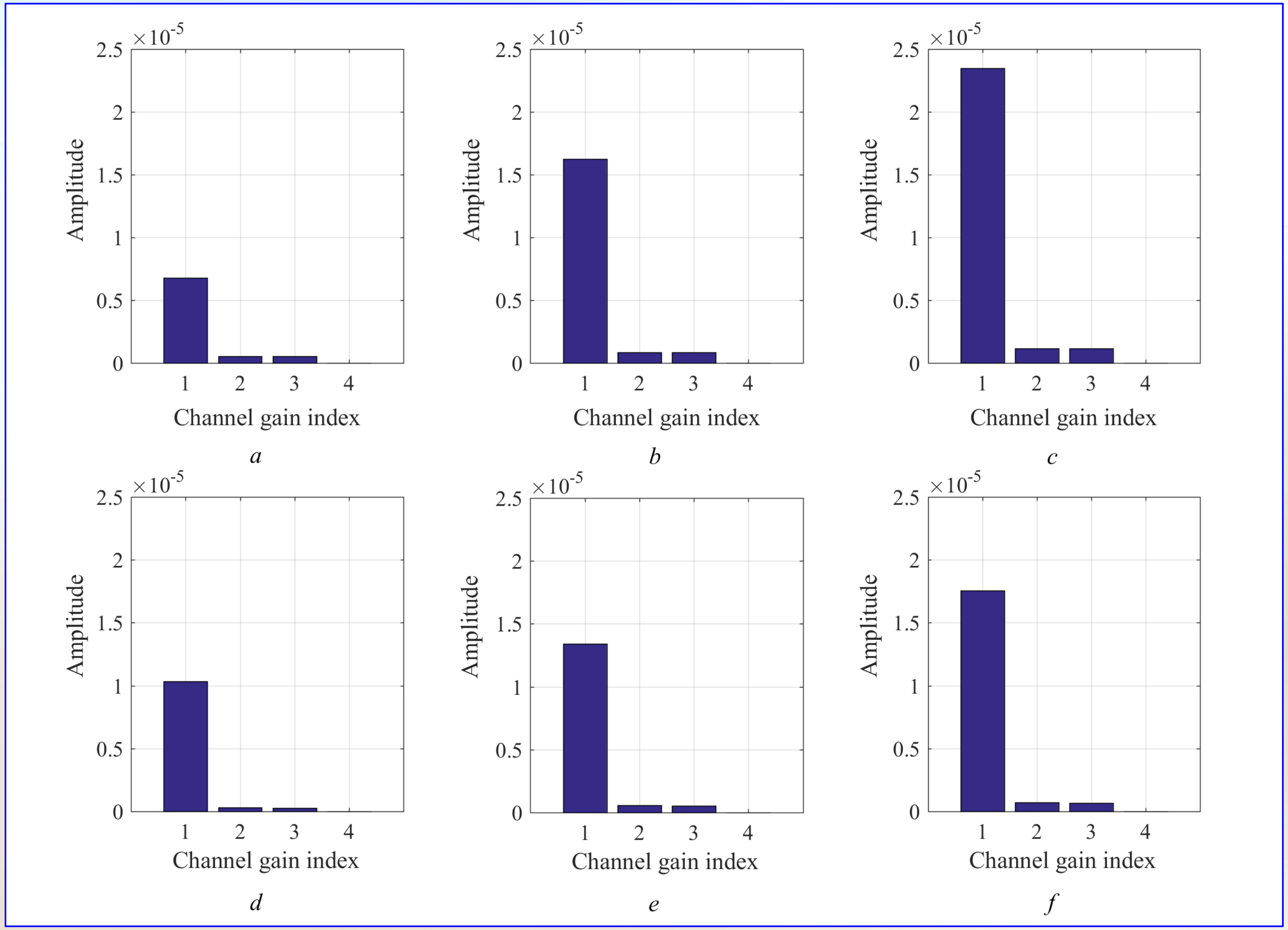
Preliminary Results



Total transmit optical power = 40 dBm

Preliminary Results





Conclusion and Future work

Conclusion

- Proposed adjusting orientation of transceivers on MIMO flip-OFDM using SVD
  - ✓ Quantified the performances of the system through bit loading for different LED and 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

Future Work

- Compare the analytical results with the simulation results for the previous cases
- Analyze the BER performance of ZF and MMSE
- Quantify the system performances using ZF and MMSE

Time schedule

Tasks	Plan start	Plan finish
Research Planning	**August 2016**	**August 2020**
1. 1st paper publication	June 2019	November 2019
2. 2nd paper publication (conference)	June 2019	July 2019
2. 3rd paper publication	August 2019	March 2020
3. Final defense (preparing, writing, editing)	September 2019	August 2020

References

[1] H. Elgala, R. Mesleh and H. Haas, "Indoor broadcasting via white LEDs and OFDM," in IEEE Transactions on Consumer Electronics, vol. 55, no. 3, pp. 1127-1134, August 2009.

[2] http://www.ieee802.org/15/pub/TG7.html

[3] http://www.jeita.or.jp/cgi-bin/standard_e/list.cgi?cateid=1&subcateid=50

[4] http://www.ednasia.com/news/article/lifi-paves-way-for-light-enabled-internet?utm_source= EDNA+News+Blast&utm_medium= Article+Alert&utm_campaign=2016-09-27

[5] www.bemri.org/visible-light-communication/...in-japan/file.html

[6] Armstrong, J., "OFDM for Optical Communications," Journal of Lightwave Technology, vol.27, no.3, pp.189-204, Feb. 2009

[7] Dissanayake, S.D.; Armstrong, J., "Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD Systems," Journal of Lightwave Technology, vol.31, no.7, pp.1063-1072, Apr. 2013.

[8] Armstrong, J.; Schmidt, B., "Comparison of Asymmetrically Clipped Optical OFDM and DC-Biased Optical OFDM in AWGN," IEEE Communications Letters, vol.12, no.5, pp.343-345, May 2008.

[9] Mesleh, R.; Elgala, H.; Haas, H., "On the Performance of Different OFDM Based Optical Wireless Communication Systems," IEEE/OSA Journal of Optical Communications and Networking, vol.3, no.8, pp.620-628, Aug. 2011.

[10] Xia Li; Vucic, J.; Jungnickel, V.; Armstrong, J., "On the Capacity of Intensity-Modulated Direct-Detection Systems and the Information Rate of ACO-OFDM for Indoor Optical Wireless Applications," IEEE Transactions on Communications, vol.60, no.3, pp.799-809, Mar. 2012.

[11] Fernando, N.; Yi Hong; Viterbo, E., "Flip-OFDM for optical wireless communications," 2011 IEEE Information Theory Workshop (ITW), vol., no., pp.5-9, Oct. 2011.

[12] Fernando, N.; Yi Hong; Viterbo, E., "Flip-OFDM for Unipolar Communication Systems," IEEE Transactions on Communications, vol.60, no.12, pp.3726-3733, Dec. 2012.

References(cont.)

[13] Goldsmith, A. *Wireless Communications* (2005). USA: Stanford University.

[14] http://www.gaussianwaves.com/2014/08/mimo-diversity-and-spatial-multiplexing/

[15] P. H. Pathak, X. Feng, P. Hu and P. Mohapatra, "Visible Light Communication, Networking, and Sensing: A Survey, Potential and Challenges," in IEEE Communications Surveys & Tutorials, vol. 17, no. 4, pp. 2047-2077, Fourthquarter 2015.

[16] J.M. Kahn and J.R. Barry, “Wireless infrared communications,” Proc. Of IEEE, vol. 85, no. 2, pp. 265-298, Feb. 1997.

[17] T. Fath and H. Haas, "Performance Comparison of MIMO Techniques for Optical Wireless Communications in Indoor Environments," in IEEE Transactions on Communications, vol. 61, no. 2, pp. 733-742, February 2013.

[18] T. Q. Wang, R. J. Green and J. Armstrong, "MIMO Optical Wireless Communications Using ACO-OFDM and a Prism-Array Receiver," in IEEE Journal on Selected Areas in Communications, vol. 33, no. 9, pp. 1959-1971, Sept. 2015.

[19] C. He, T. Q. Wang and J. Armstrong, "MIMO Optical Wireless Receiver Using Photodetectors with Different Fields of View," 2015 IEEE 81st Vehicular Technology Conference (VTC Spring), Glasgow, 2015, pp. 1-5.

[20] T. Q. Wang, C. He and J. Armstrong, "Angular diversity for indoor MIMO optical wireless communications," 2015 IEEE International Conference on Communications (ICC), London, 2015, pp. 5066-5071.

[21] C. He, T. Q. Wang and J. Armstrong, "Performance comparison between spatial multiplexing and spatial modulation in indoor MIMO visible light communication systems," 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, 2016, pp. 1-6.

[22] T. Q. Wang, C. He and J. Armstrong, "Performance Analysis of Aperture-Based Receivers for MIMO IM/DD Visible Light Communications," in Journal of Lightwave Technology, vol. 35, no. 9, pp. 1513-1523, 1 May1, 2017.

[23] Zhen Zhan et al., "1.2 Gbps non-imaging MIMO-OFDM scheme based VLC over indoor lighting LED arrangments," 2015 Opto-Electronics and Communications Conference (OECC), Shanghai, 2015, pp. 1-3.

[24] Y. Hong, T. Wu and L. K. Chen, "On the Performance of Adaptive MIMO-OFDM Indoor Visible Light Communications," in IEEE Photonics Technology Letters, vol. 28, no. 8, pp. 907-910, April15, 15 2016.

References(cont.)

[25] Qing-Feng Liu, Shuai-Fang Xiao, Kai-Zhi Huang, and Zhou Zhong, "A SVD-Based Optical MIMO Precoding Scheme in Indoor Visible Light Communication," International Journal of Future Computer and Communication vol. 3, no. 6, pp. 421-426, 2014.

[26] Y. Hong, J. Chen, Z. Wang and C. Yu, "Performance of a Precoding MIMO System for Decentralized Multiuser Indoor Visible Light Communications," in IEEE Photonics Journal, vol. 5, no. 4, pp. 7800211-7800211, Aug. 2013.

[27] O. Narmanlioglu, R. C. Kızılırmak, F. Miramirkhani and M. Uysal, "Rate-adaptive OFDM MIMO VLC system," 2017 10th International Conference on Electrical and Electronics Engineering (ELECO), Bursa, 2017, pp. 676-680.

[28] S. K. Wilson and J. Armstrong, "Transmitter and receiver methods for improving asymmetrically-clipped optical OFDM," in IEEE Transactions on Wireless Communications, vol. 8, no. 9, pp. 4561-4567, September 2009.

[29] J.G.ProakisandM.Salehi,DigitalCommunications.McGraw-Hill,2008.

[30] Dehao Wu, Zabih Ghassemlooy, Wen-De Zhong, Mohammad-Ali Khalighi, Hoa Le Minh, et al.. Effect of optimal Lambertian order for cellular indoor optical wireless communication and positioning systems. Optical Engineering, SPIE, 2016, Optical Engineering, 55 (6), pp.066114.

Thank you

Question & Suggestion