Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: High-speed VLC modulation formats and MIMO transmission
Date Submitted: March 2016
Source: Prof. Nan Chi, Dr. Junwen Zhang, Mr. Yiguang Wang **Company:** Fudan Univerisity
Address: Fu Dan University, 220 Handan Rd., Yangpu District, Shanghai
Voice: Tel: 0086-21-65642983, E-Mail: nanchi@fudan.edu.cn; hustzjw@gmail.com; 12110720015@fudan.edu.cn;

Abstract: In response to «Call for Proposals for OWC Channel Models» issued by 802.15.7r1, this contribution presents the PHY technologies proposal of high-speed VLC modulation formats and MIMO transmission.

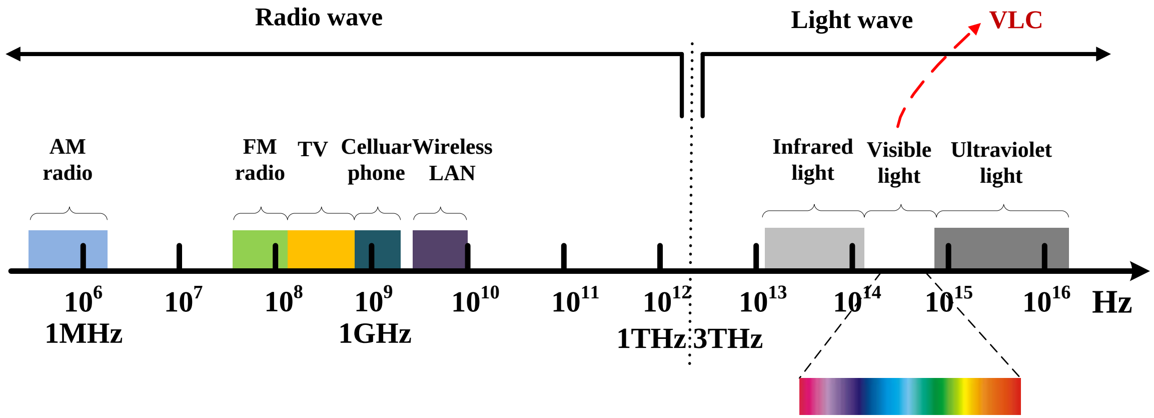
Purpose: Call for Proposal Response

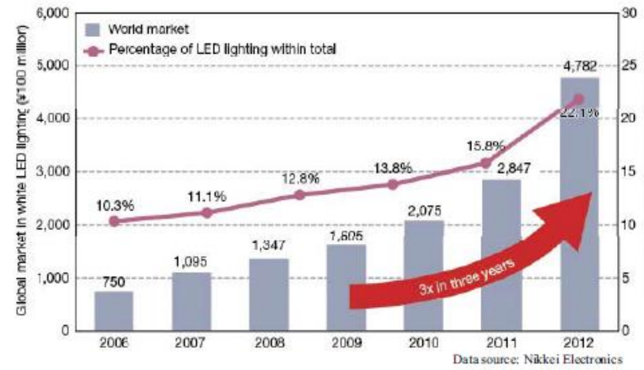
High-speed VLC modulation formats and MIMO transmission

Outlines

- Background and Introduction
- Scenario Targets
- Description of Proposed Solutions
- Some Experiment Results
- Conclusions

Background





LED lighting in the global market

- Expand the spectrum for the next generation of broadband communications
- Combine lighting with communication, bringing unique advantages

By 2018, the semiconductor lighting penetration will reach 80%. With the popularity of LED lighting process, VLC will be standing on the shoulders of giants.

Targets

- High-speed VLC MIMO transmission
- Data Rates Speed: **~Gbps**
- Distance: **3m~5m**
- Environment: indoor public space for multiple users
- Link: non-imaging MIMO, imaging MIMO

To provide a high-speed VLC free-space link for multi-user access.

Proposal Research Route

High-speed VLC modulation formats

Bit and power loading based adaptive OFDM	SC-FDMA	ACO-OFDM

↓

VLC MIMO transmission modes

Non-imaging MIMO & time-multiplexed TS	Imaging MIMO	PDM transmission

↓

VLC channel coding for MIMO

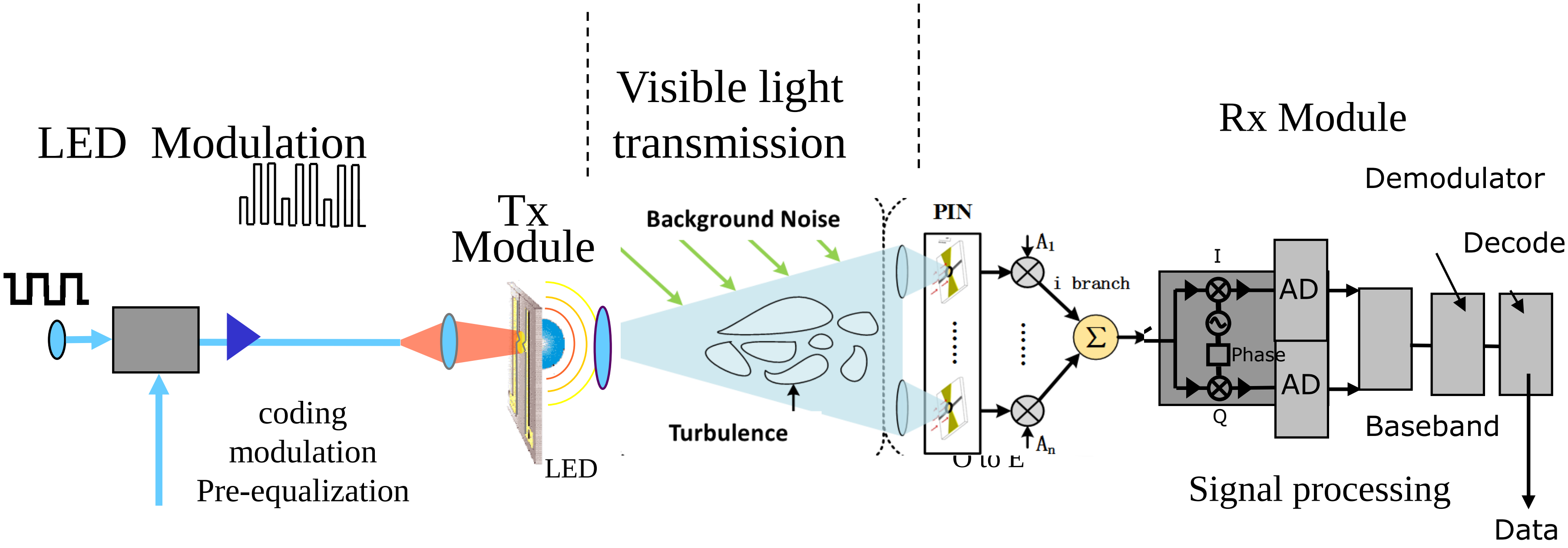
STBC coding for MISO	MRC based receiver diversity

↓

MIMO Transmission Experiments

System Structure	Results and Analysis

Physical Layer of VLC system



- TX：
  - electronics：LED driving circuit，**coding**, **modulation,** Pre-equalization
  - optics：transmitter antenna (**Multiple Input**)
- RX：
  - optics：receiver antenna (**Multiple Output**)
  - electronics： signal processing (decoding, demodulation, equalization),

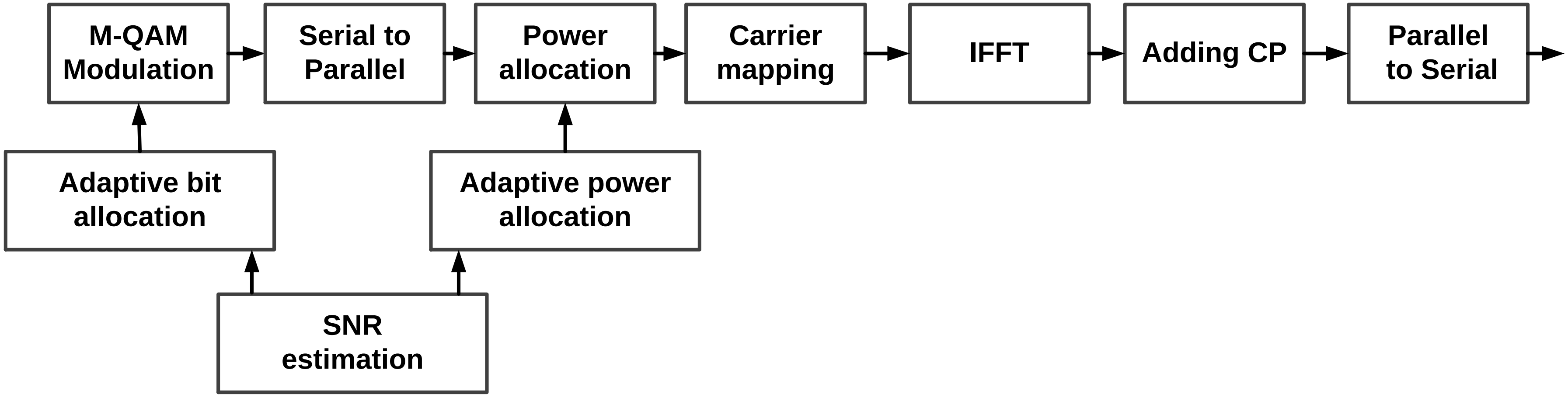
To achieve the high speed VLC

- Modulation formats:
  - Bit and power loading based adaptive OFDM
  - Single-carrier FDMA (optional)
  - Asymmetrically-clipped optical OFDM (optional)

- MIMO transmission modes
  - Non-imaging MIMO with time-multiplexed training symbols
  - Imaging MIMO
  - Polarization division multiplexing (PDM) transmission

- Channel coding for MIMO
  - Self-adaptive space-time block coding (STBC) for MISO
  - Maximal ratio combining (MRC) based receiver diversity

Bit and power loading based adaptive OFDM modulation



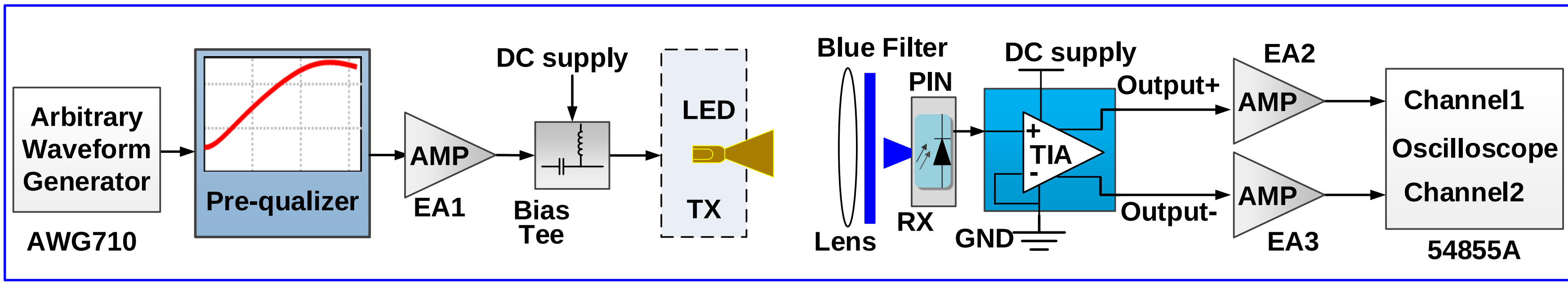
Bit and power loading is used in adaptive OFDM signal generation to maximum system capacity

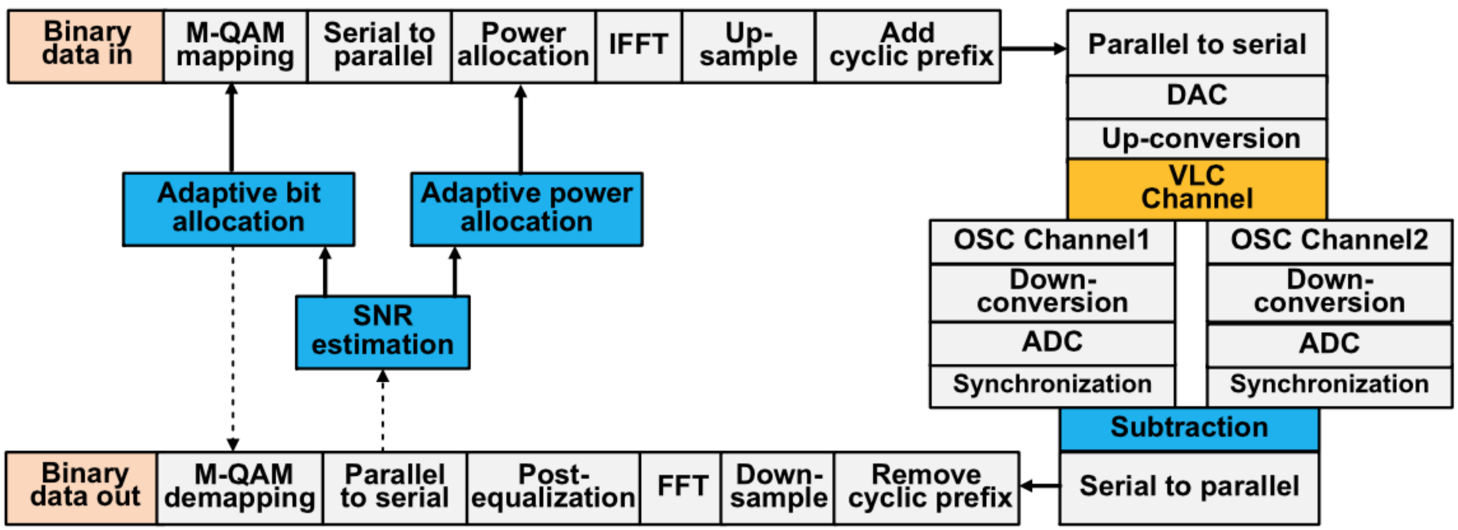
$$R = \frac{B(\sum_{k=1}^{N} \log_2 M_k)}{N}$$

Before applying bit and power allocation, the SNR of the channel is estimated through EVM method

$$EVM = \frac{\sum_{n=1}^{M} \left| S_n - S_{0,n} \right|^2}{\sum_{n=1}^{M} \left| S_{0,n} \right|^2} \qquad SNR = \frac{1}{EVM^2}$$

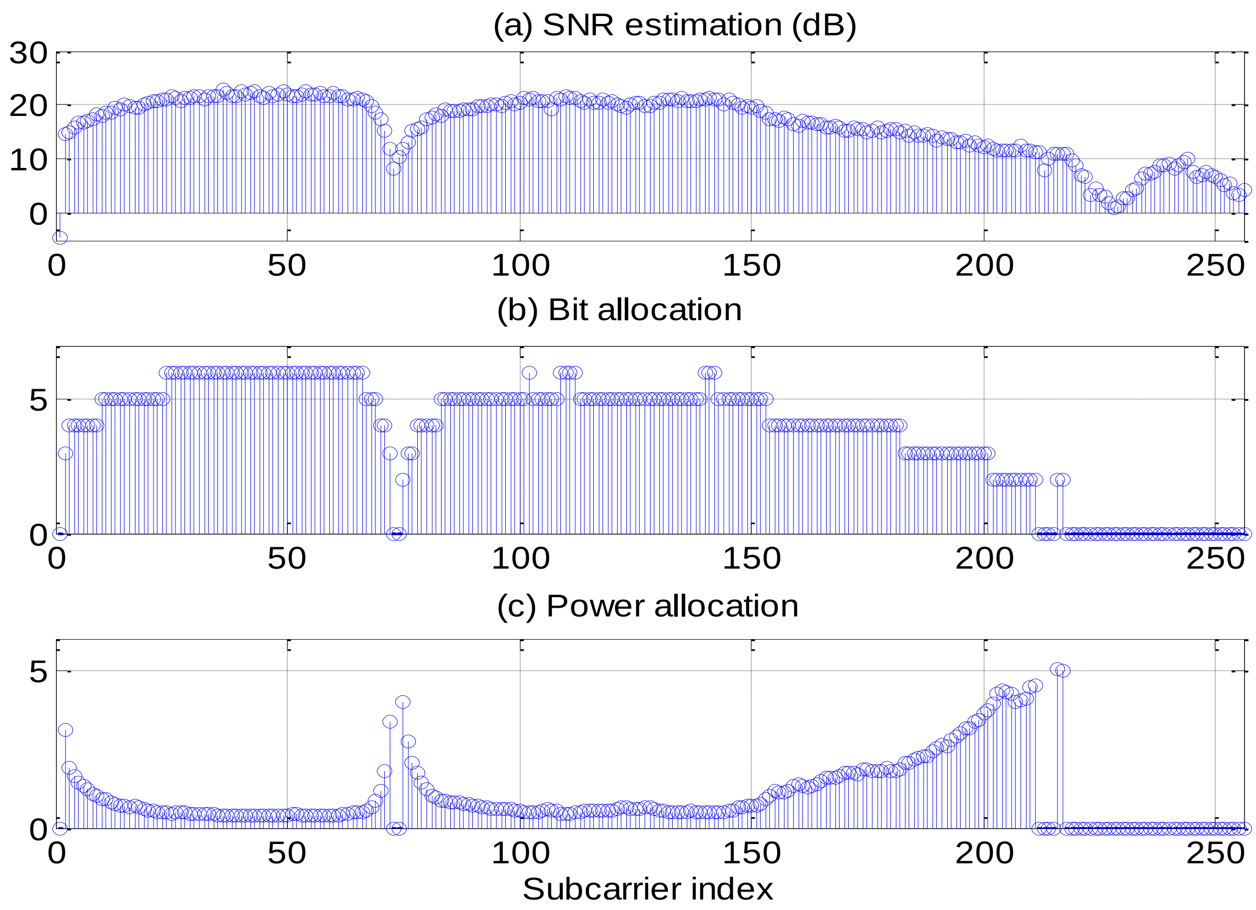
Bit and power loading based adaptive OFDM modulation





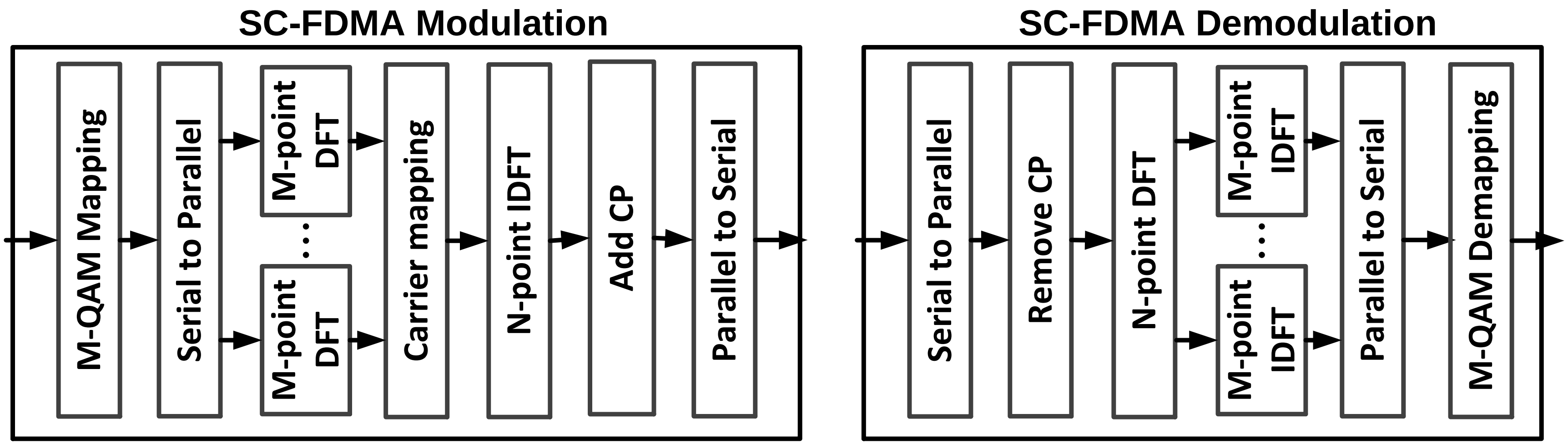
X. Huang, et al, IEEE Photonics Journal, 2015

Bit and power loading based adaptive OFDM modulation



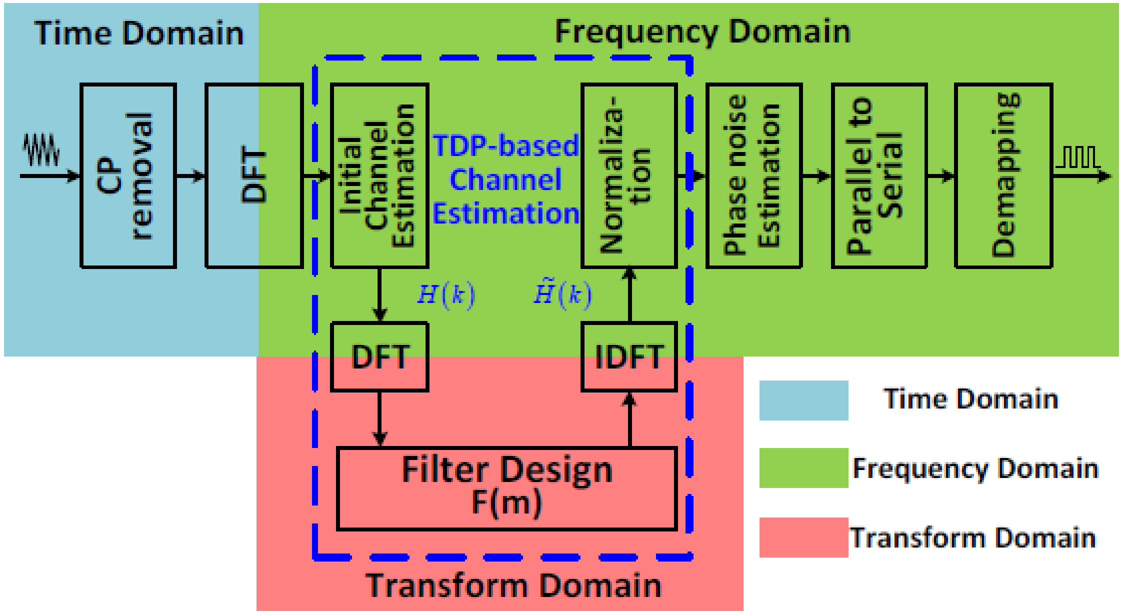
X. Huang, et al, IEEE Photonics Journal, 2015

Single carrier modulation (optional): Single-carrier frequency division multiple access (SC-FDMA)



- SC-FDMA can be an optional choice for uplink, due to its advantage to provide low PAPR for the transmit waveform;
- SC-FDMA divides the transmission bandwidth into multiple parallel subcarriers, which adds a DFT block before the subcarrier mapping

Transform domain processing (TDP) based channel estimation method for SC-FDMA



Transform domain processing (TDP) can be used for channel estimation:

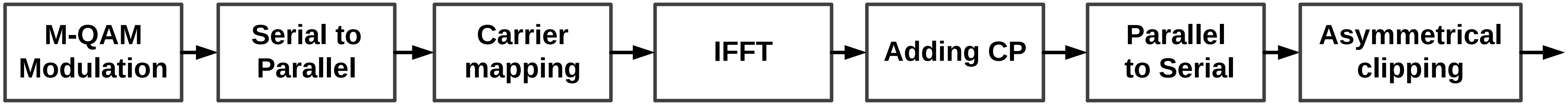
- improve the accuracy of channel estimation
- reduce the length of overhead

H(k) is transformed to $H_T(m)$ by employing another DFT. $H_T(m)$ is in transform domain and expressed as

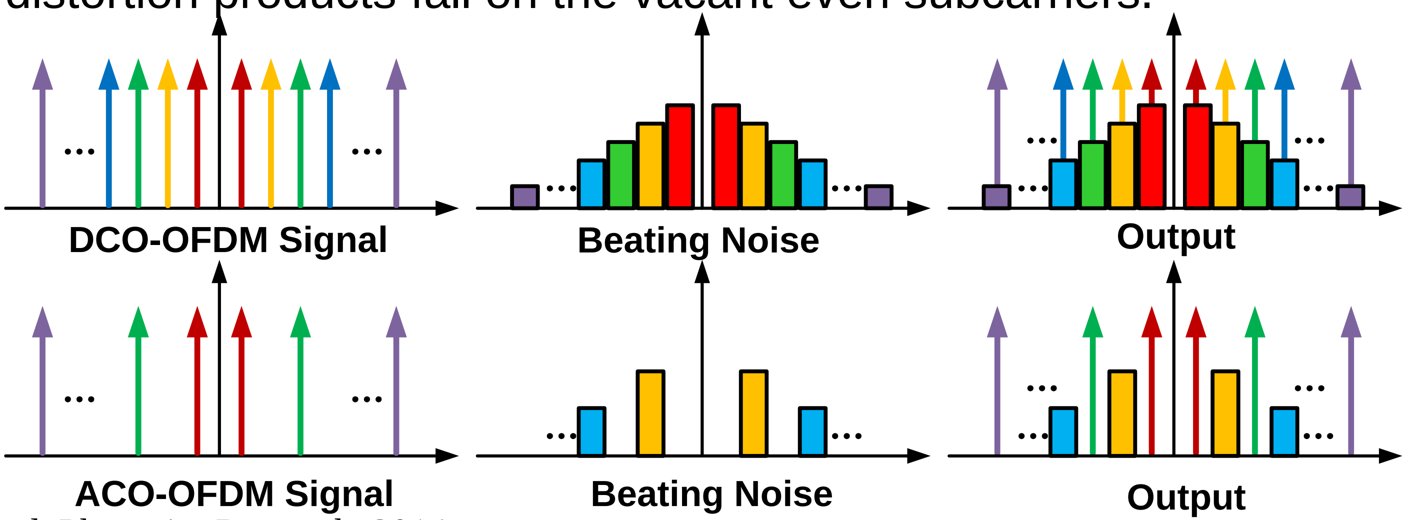
$$H_T(m) = \sum_{k=0}^{N-1} (H(k)) \cdot \exp(-j2\pi mk / N)$$

L. Tao, et al, Optics Express, 2013

Unipolar modulation (optional): Asymmetrically-Clipped Optical OFDM (ACO-OFDM)

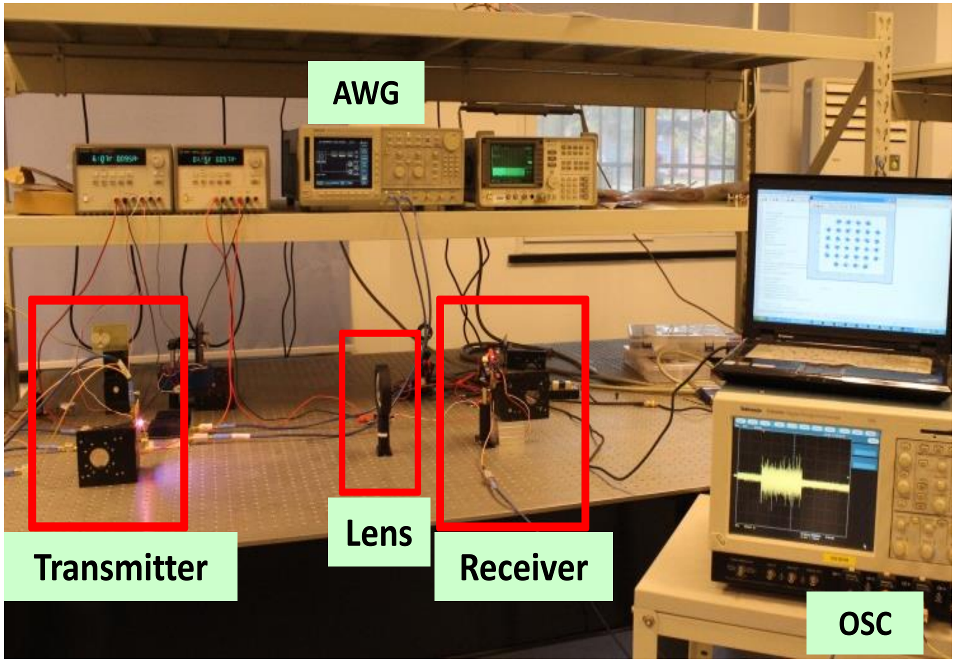


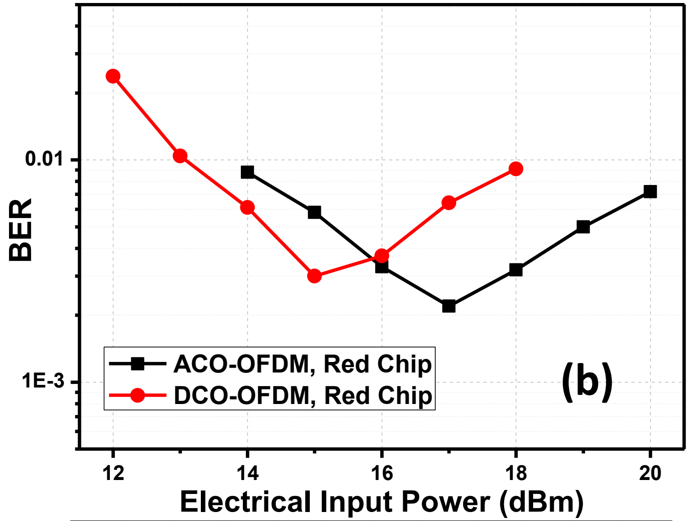
- ACO-OFDM can be used as a unipolar modulation scheme to further improve the power efficiency.
- The time domain signal is made unipolar by simply clipping the negative part at the zero level.
- Only odd subcarriers are modulated by signals, and all of the clipping distortion products fall on the vacant even subcarriers.

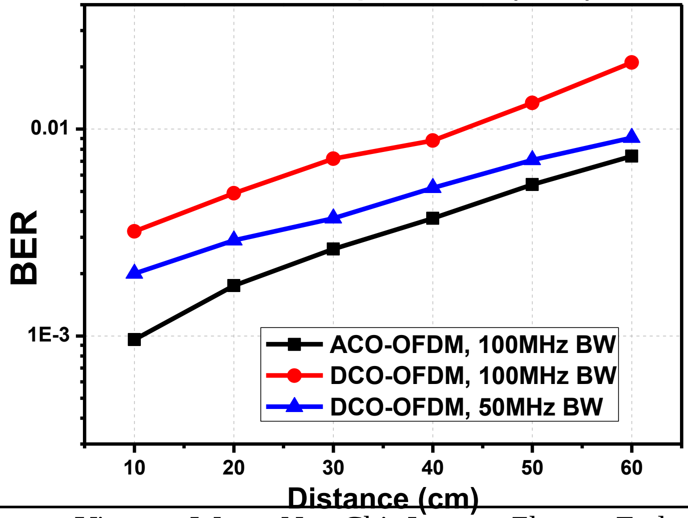


Y. Wang, et al, Photonics Research, 2014

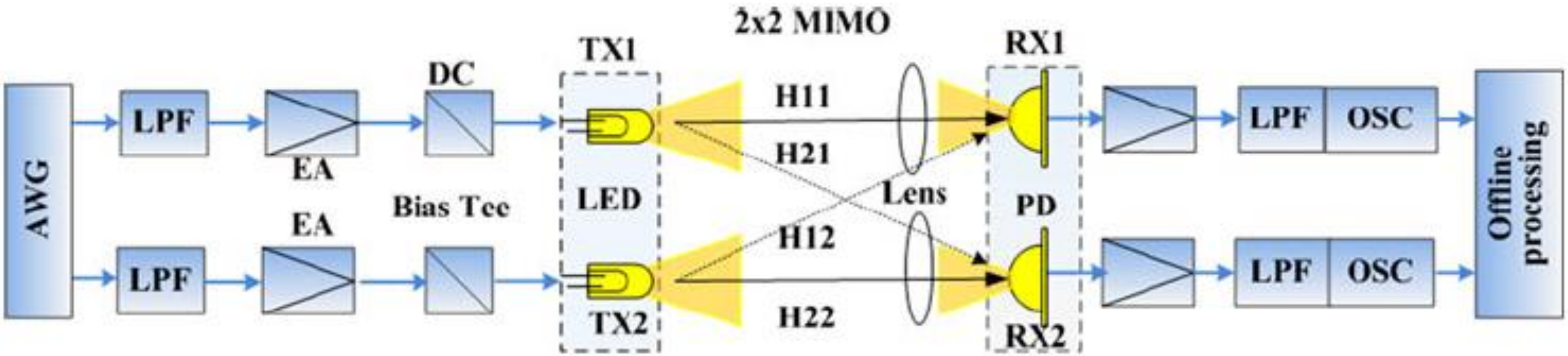
Unipolar modulation (optional): Asymmetrically-Clipped Optical OFDM (ACO-OFDM)







MIMO transmission modes: Non-imaging MIMO

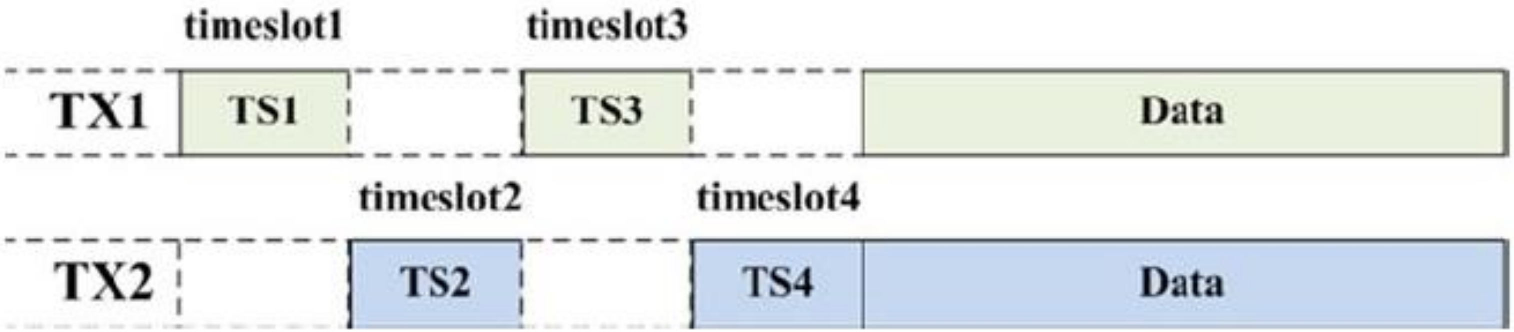


Light from each of the LED arrays is received by all the separate receivers, but with different strengths

$$\begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ X_2 \end{pmatrix} + \begin{pmatrix} N_1 \\ N_2 \end{pmatrix}$$

Y. Wang, et al, IEEE Journal of Lightwave Technology, 2014

Time-multiplexed training symbols for non-imaging MIMO de-multiplexing



The time-multiplexed TS based frequency domain equalization can be used for MIMO channel estimation and de-multiplexing

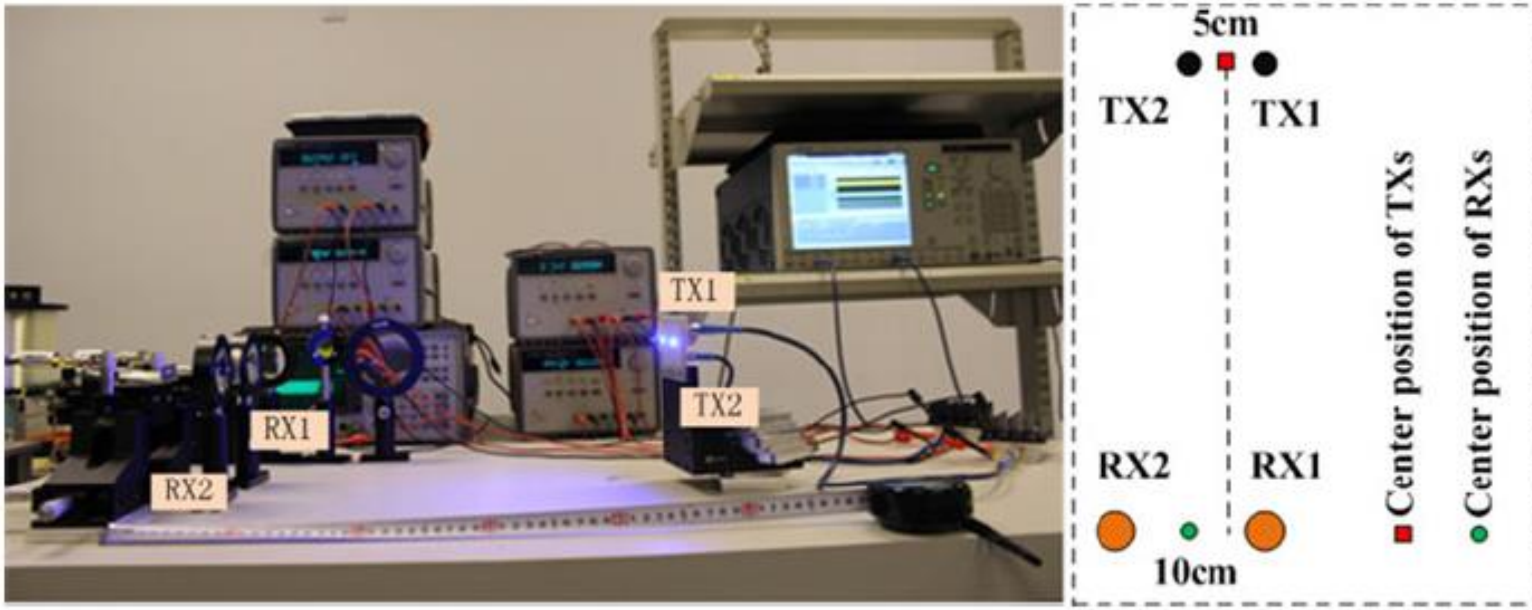
$$T_1 = \begin{pmatrix} TS_1 \\ 0 \end{pmatrix}, T_2 = \begin{pmatrix} 0 \\ TS_2 \end{pmatrix} \xrightarrow{\text{Zero forcing}} H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} Y_{11}/TS_1 & Y_{12}/TS_2 \\ Y_{21}/\mathrm{TS}_1 & Y_{22}/TS_2 \end{pmatrix}$$

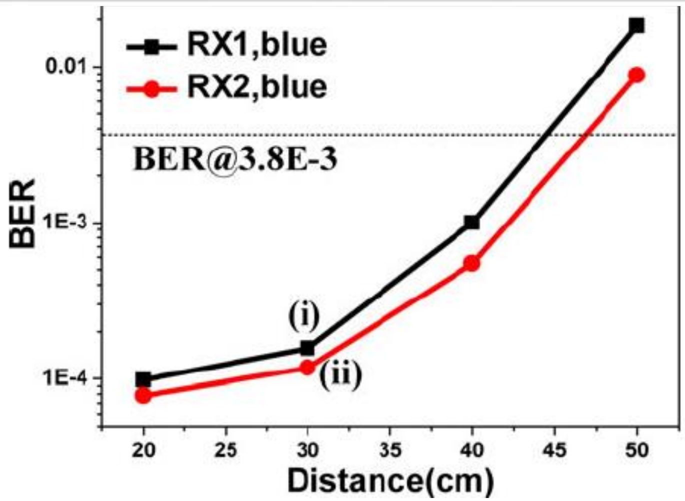
$$X_1 = (H_{22} * Y_1 - H_{12} * Y_2)/(H_{22} * H_{11} - H_{12} * H_{21})$$

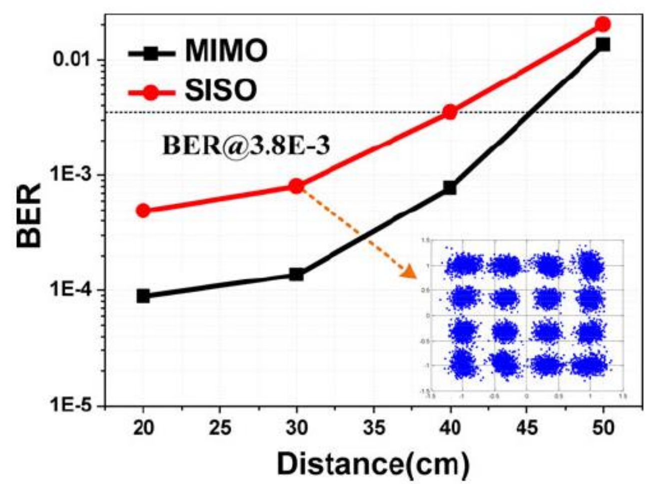
$$X_2 = (H_{11} * Y_2 - H_{21} * Y_1)/(H_{22} * H_{11} - H_{12} * H_{21})$$

Y. Wang, et al, IEEE Journal of Lightwave Technology, 2014

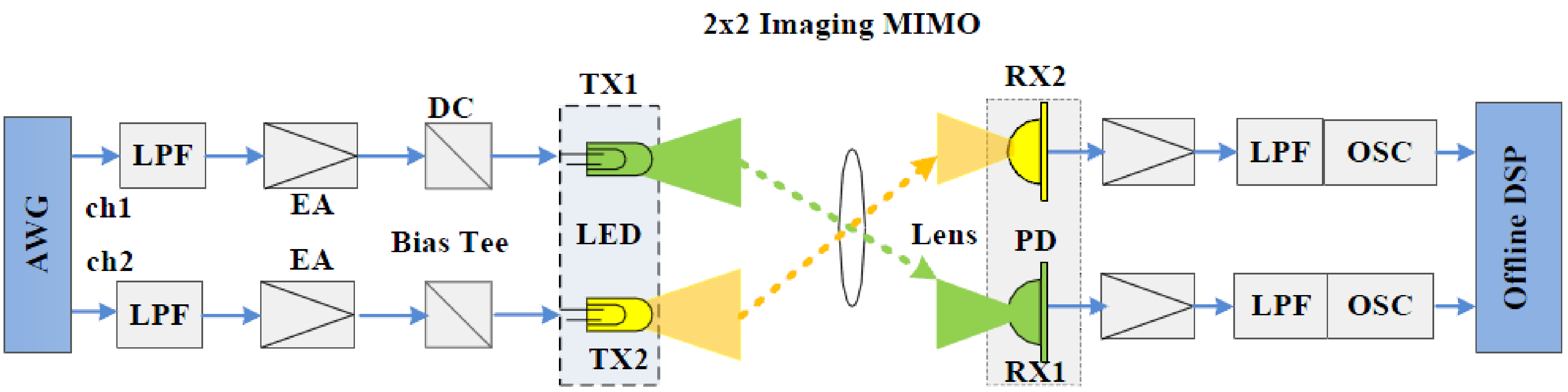
MIMO transmission modes: Non-imaging MIMO







MIMO transmission modes: Imaging MIMO



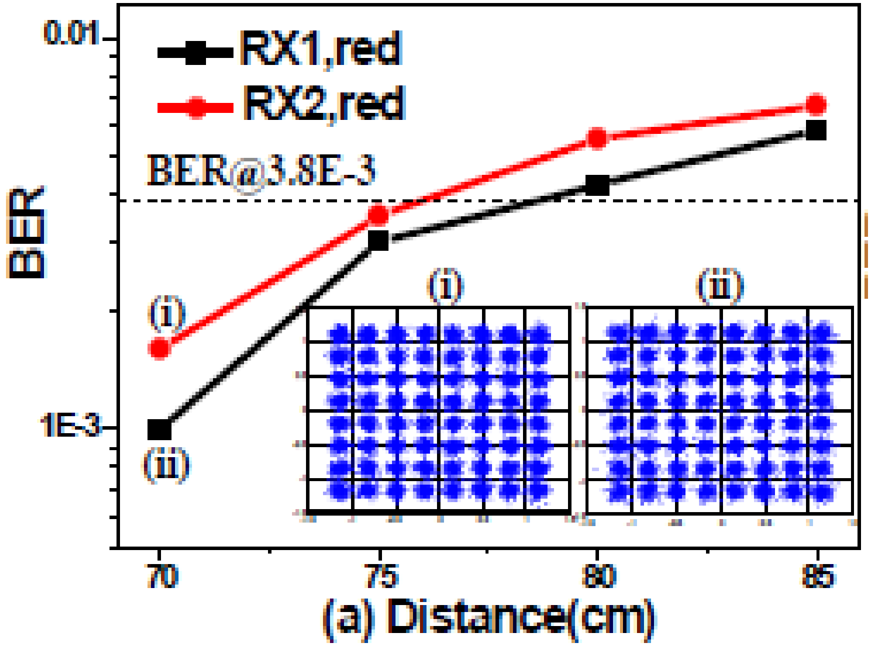
Imaging MIMO requires each LED array imaging onto a detector array, and the light propagates directly to the corresponding detector

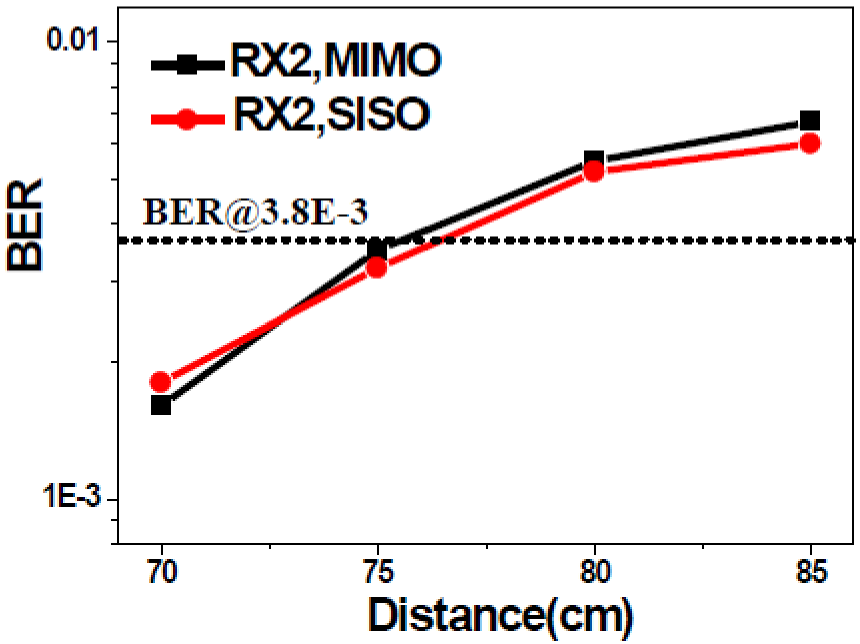
Channel crosstalk can be neglected, and the channel matrix can be simplified

$$H = \begin{pmatrix} H_{11} & 0 \\ 0 & H_{22} \end{pmatrix} = \begin{pmatrix} Y_{11} / TS_1 & 0 \\ 0 & Y_{22} / TS_2 \end{pmatrix}$$

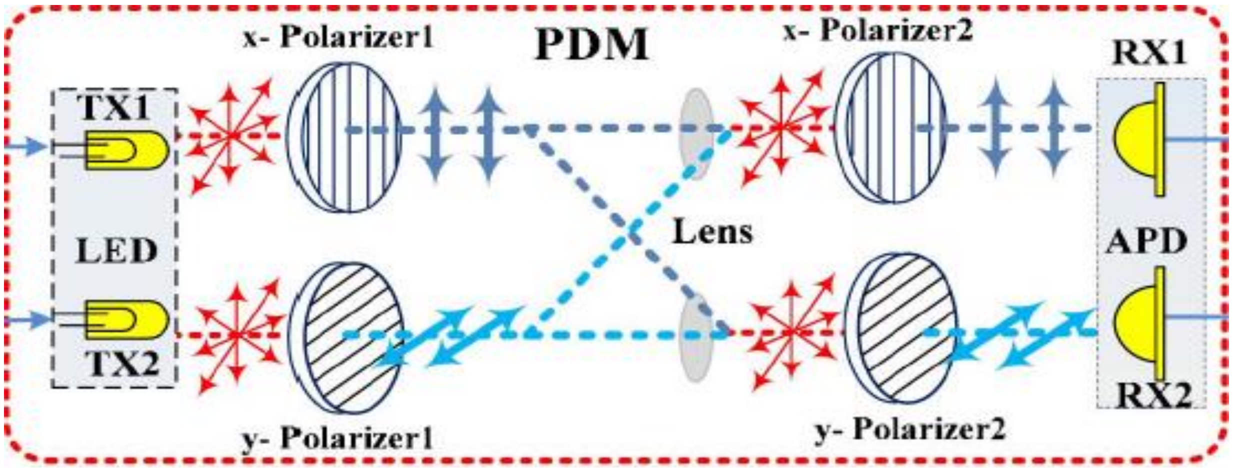
Y. Wang, et al, Chinese Optics Letters, 2014

MIMO transmission modes: Imaging MIMO





Polarization division multiplexing (PDM) transmission



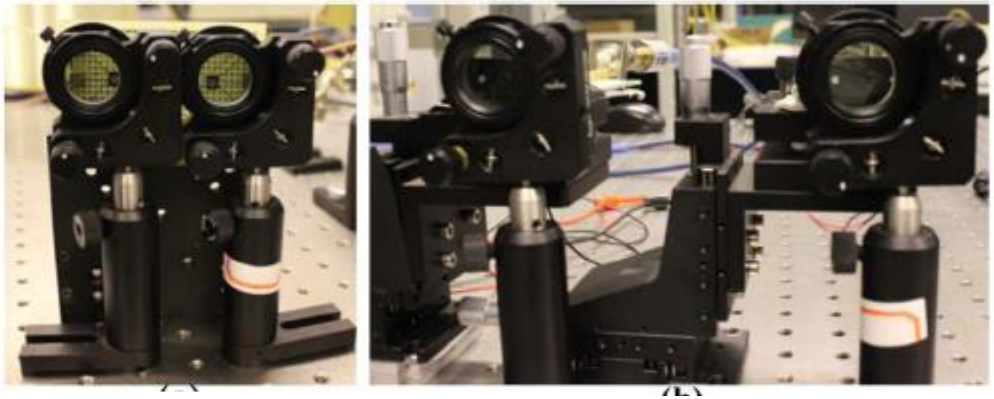
As the lights emitting from incoherent LEDs are natural lights, they can be decomposed as two orthogonal bases of x polarization and y polarization by polarizers.

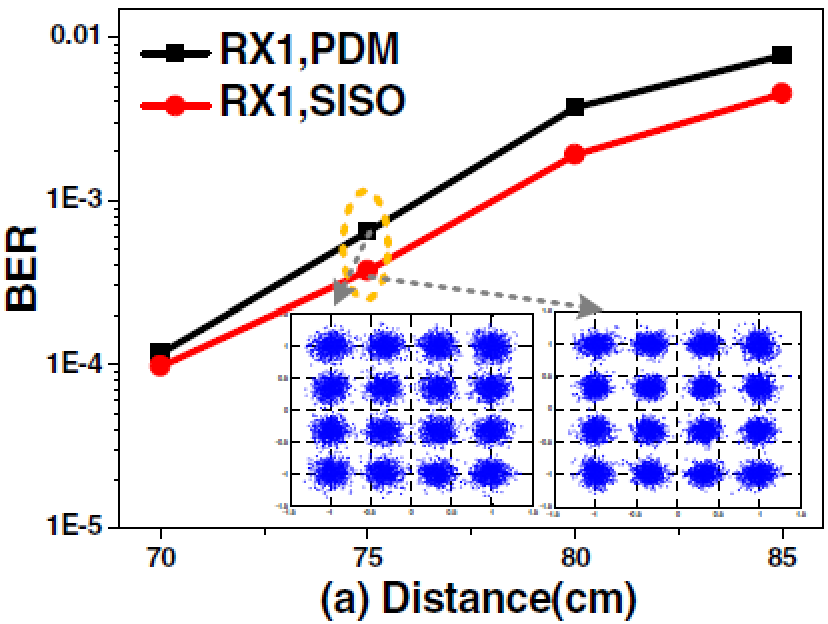
The received optical intensity can be expressed as

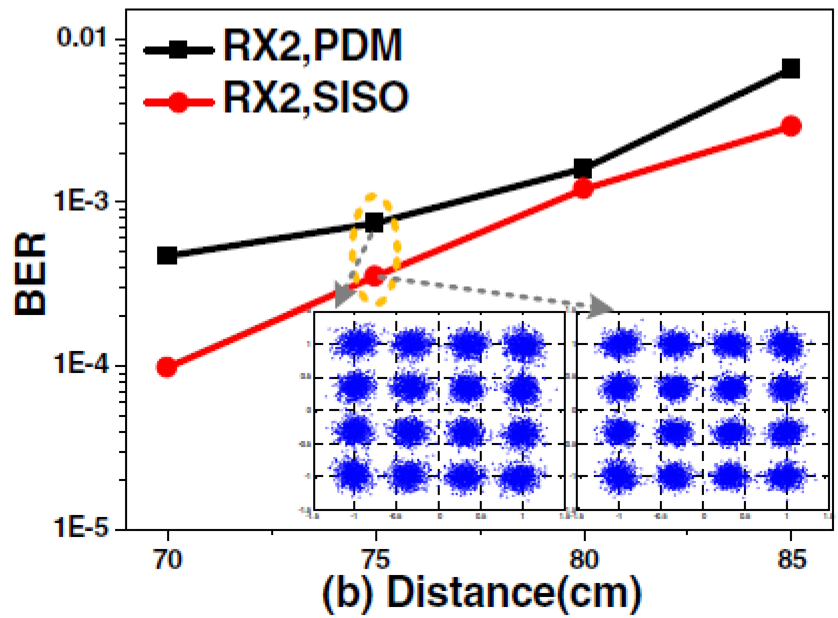
$$\begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix} = H \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} + N = \frac{1}{2} \begin{pmatrix} \cos^2 \alpha_{11} & \cos^2 \alpha_{12} \\ \cos^2 \alpha_{21} & \cos^2 \alpha_{22} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} + N$$

Y. Wang, et al, Optics Letters, 2014

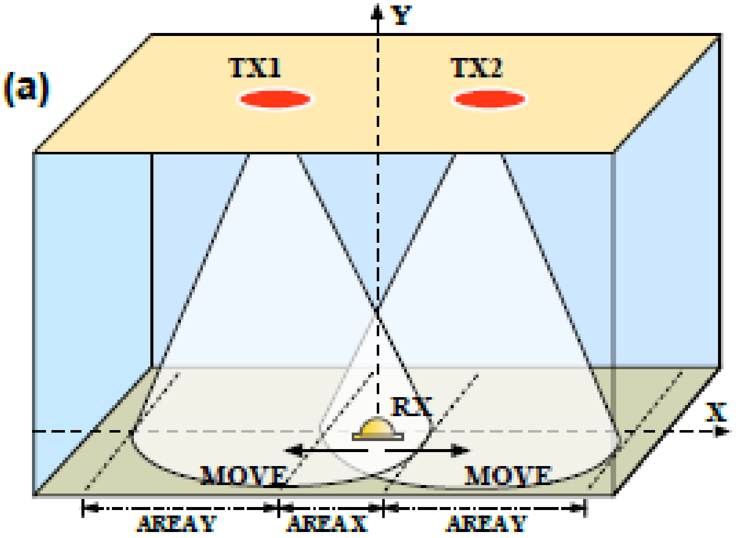
Polarization division multiplexing (PDM) transmission







Channel coding for MIMO: Self-adaptive space-time block coding (STBC) for MISO



STBC technique can easily provide the diversity at receiver for MISO VLC transmission

Alamouti's STBC scheme is employed to encode the data with two transmit LEDs and one receiver. Space-time encoding as:

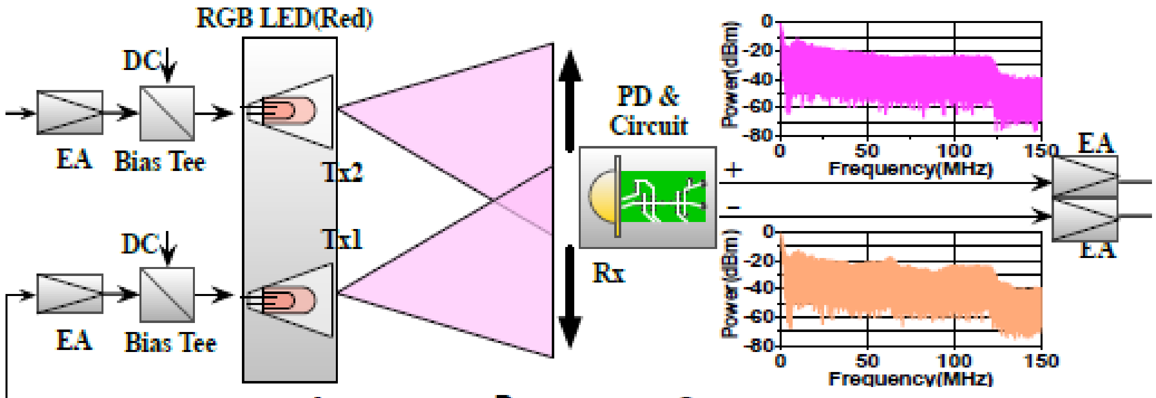
$$\begin{bmatrix} c_1 & c_2 \\ -c_2^* & c_1^* \end{bmatrix}$$

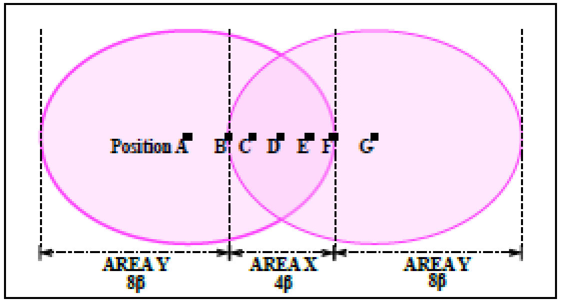
the decoded signal can be obtained as

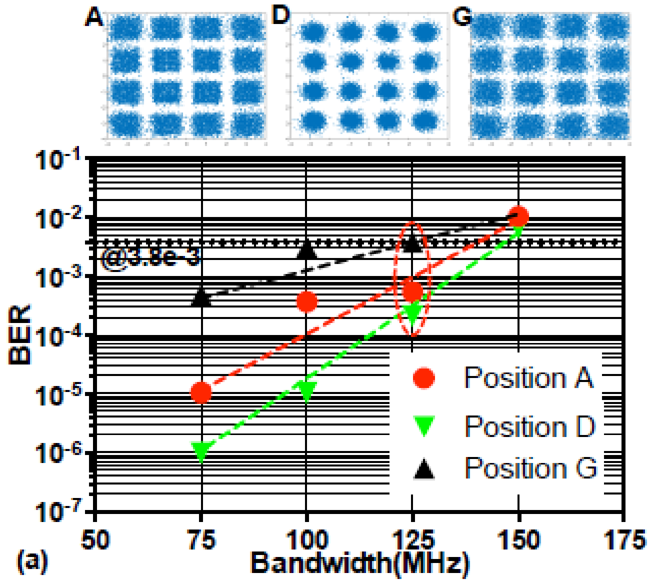
$$r = \begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} + \begin{bmatrix} \eta_1 \\ \eta_2^* \end{bmatrix} = Hc + n \quad \Longrightarrow \quad \tilde{r} = \tilde{H}^H r = \tilde{H}^H Hc + \tilde{H}^H n$$

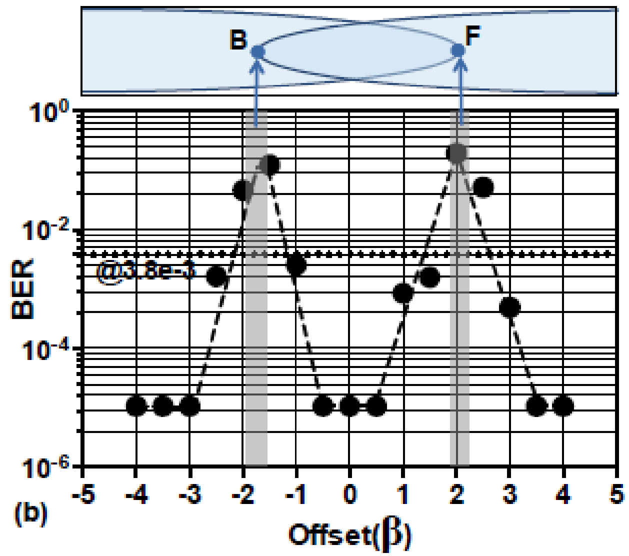
J. Shi, et al, IEEE MOTL, 2015

Channel coding for MIMO:
Self-adaptive space-time block coding (STBC) for MISO



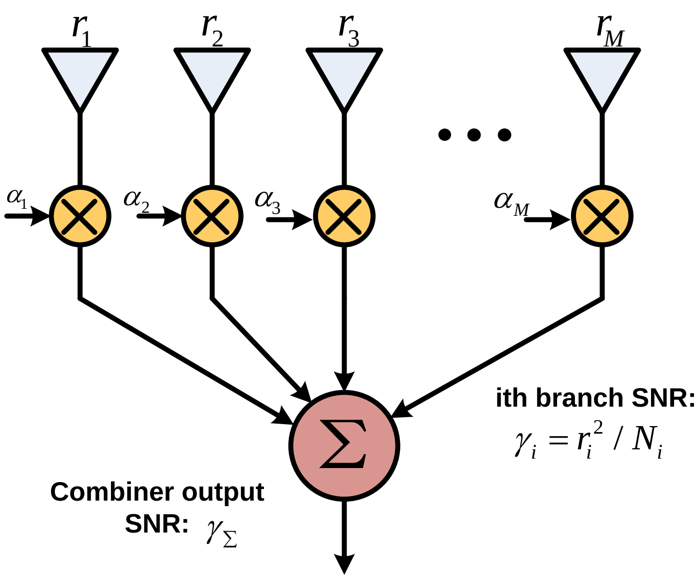






J. Shi, et al, OFC, 2016

Channel coding for MIMO: Maximal ratio combining (MRC) based receiver diversity



- In receiver diversity, the outputs of multiple receivers are combined which is a weighted sum of the different branches

$$\gamma_\Sigma = \frac{r^2}{N_{tot}} = \frac{\left[\sum_{i=1}^{M} \alpha_i r_i\right]^2}{\sum_{i=1}^{M} \alpha_i^2 N_i}$$

- The goal of MRC is to find the weight to maximize the output SNR
- According to the Schwarz inequality: the maximum SNR of the combiner output is the sum of SNRs in each branch:

$$\gamma_\Sigma = \sum_{i=1}^{M} r_i^2 / N_i = \sum_{i=1}^{M} \gamma_i$$

J. Li, et al, Optical Engineering, 2015

Conclusion

In this contribution, we propose several general technique considerations for high-speed VLC modulation formats and MIMO transmission.

- Modulation formats:
  - Bit and power loading based adaptive OFDM
  - Single-carrier FDMA (optional)
  - Asymmetrically-clipped optical OFDM (optional)

- MIMO transmission modes
  - Non-imaging MIMO with time-multiplexed training symbols
  - Imaging MIMO
  - Polarization division multiplexing (PDM) transmission

- Channel coding for MIMO
  - Self-adaptive space-time block coding (STBC) for MISO
  - Maximal ratio combining (MRC) based receiver diversity