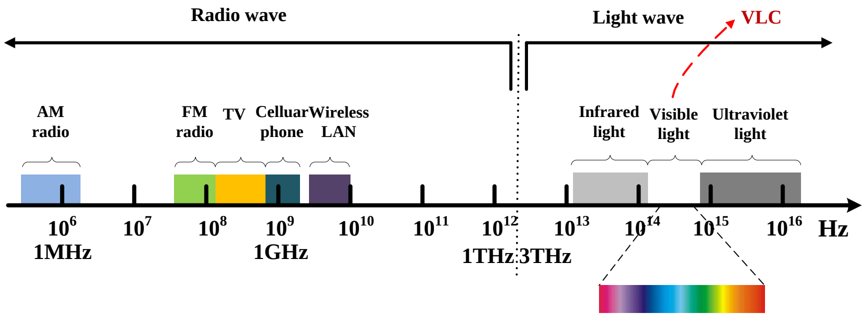
Signal Processing Techniques based on Machine Learning for Visible Light Communications

Dr.LU Xingyu

Outline

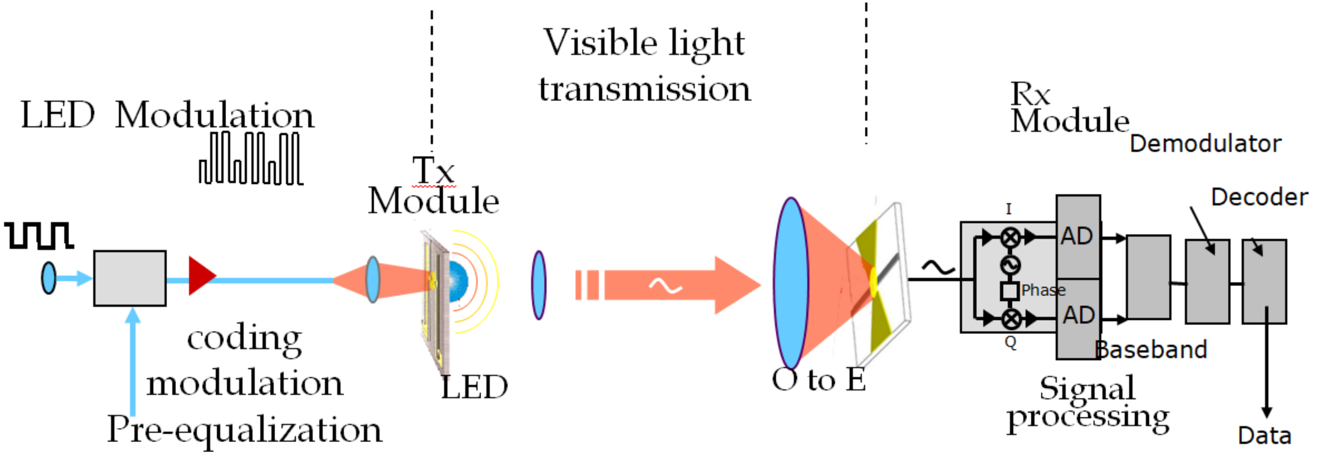
Part I: Introduction

Research Motivation of VLC



1. The white light is safe for human eyes
2. No electromagnetic interference, applications in the electromagnetic-sensitive environment (airplane, hospital, etc)
3. Energy conservation because of providing with functions of illumination, communication and control positioning
4. Spectrum license free
5. Suitable for security communication

Schematics of VLC system



- TX：
  - electronics：LED driving circuit，signal processing (coding, modulation, equalization)
  - optics：transmitter antenna
- RX：
  - optics：receiver antenna，PD
  - electronics：signal processing (decoding, demodulation, equalization)

LED Based VLC

Modulation

- OOK
- PPM
- OFDM: ACO, DFTS, 2FFT, PTS, SLM, PC
- CAP
- SC-FDE

Equalization

- Software equalization
- Hardware equalization

Multiplexing

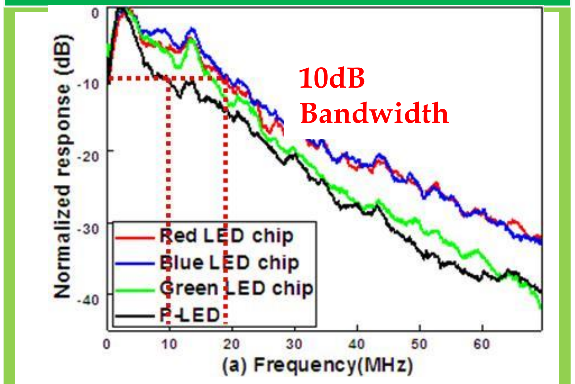
- Frequency division: SCM
- Wave division: RGB
- Imaging VLC MIMO
- Non-imaging VLC MIMO

Material

- Micro-LED
- GaN-LED
- GaAlAs based blue light Narrow band detector
- LED array
- Detector array

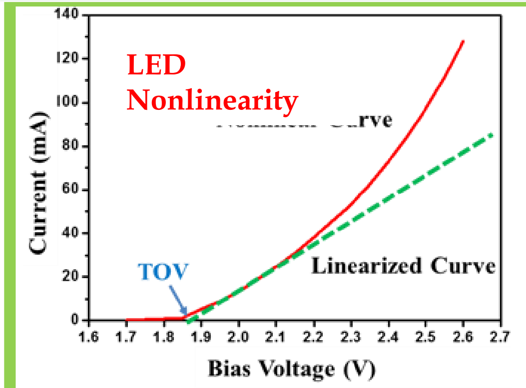
The key problem limiting the high-speed VLC system

1. LED bandwidth limitations



- Blue LED 10dB bandwidth<15MHz
- RGB LED 10dB bandwidth<25MHz

2. VLC system damage



- Inter-symbol interference
- LED nonlinearity

Solutions

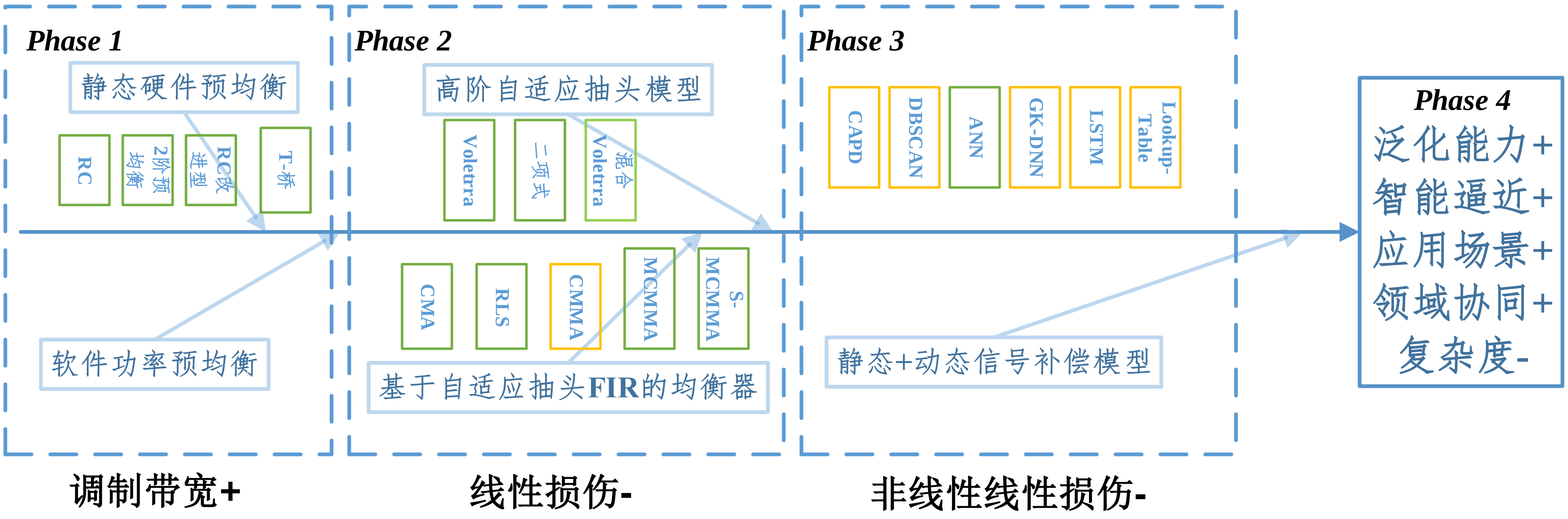
High spectral efficiency higher order modulation

- PAM、OFDM
- Single Carrier、CAP and so on

Advanced post-equalization techniques

- ZF、DFE、RLS、DD-LMS
- CMMA、M-CMMA
- Volterra、 Machine learning

Advances of DSP in VLC systems

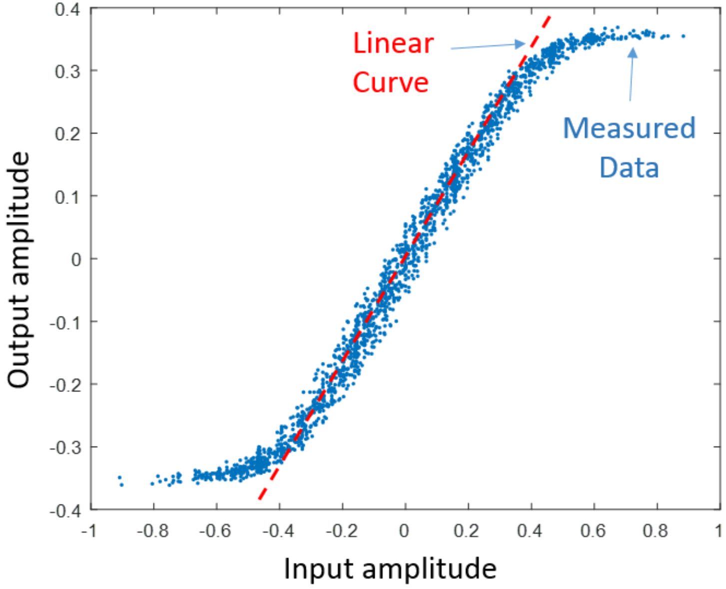


重庆邮电大学
Chongqing University of Posts and Telecommunications

Part II: Application of ML in VLC Systems

- 2.1 A blind post-equalization scheme of mulit-CAP
- 2.2 A pre-distortion scheme of mulit-CAP
- 2.3 Amplitude Jitter Compensation scheme of PAM Systems
- 2.4 DBSCAN scheme of CAP (QAM) Systems

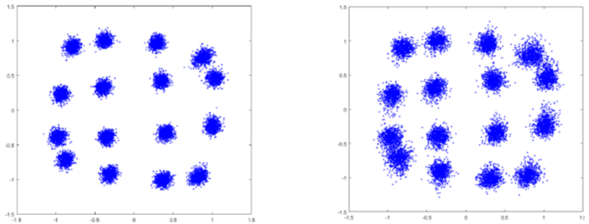
Non-linearity of CAP VLC systems (1/4 of 2.1)



Transfer curve of Multi-Band **CAP** VLC system.

Reasons for the non-linearity of the VLC system[1~2]：

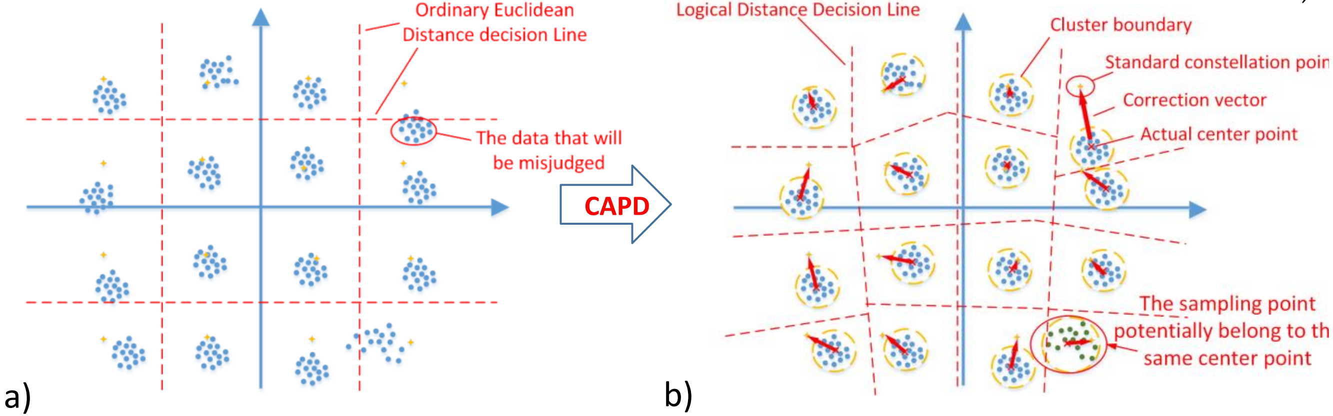
- V-I model in LED (Current and Voltage);
- PIN photodetector;
- Transmitter driving circuits and the amplifier.

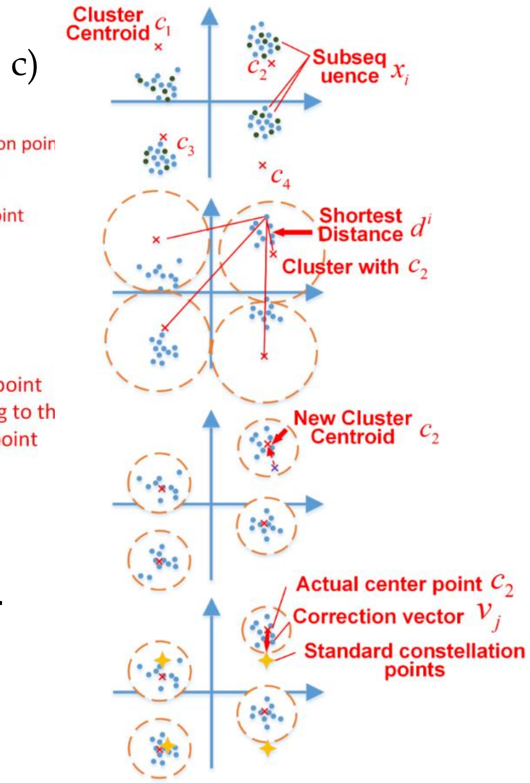


Constellation diagrams of 2 sub-band **after CMMA linear equalizer.**

[1]:I. Stefan, H. Elgala, and H. Haas. "Study of dimming and LED nonlinearity for ACO-OFDM based VLC systems," in Wireless Communications and Networking Conference (WCNC), 2012, pp. 990-994.
[2]: G. Stepniak, J. Siuzdak, P. Zwierko. "Compensation of a VLC Phosphorescent White LED Nonlinearity by Means of Volterra DFE"

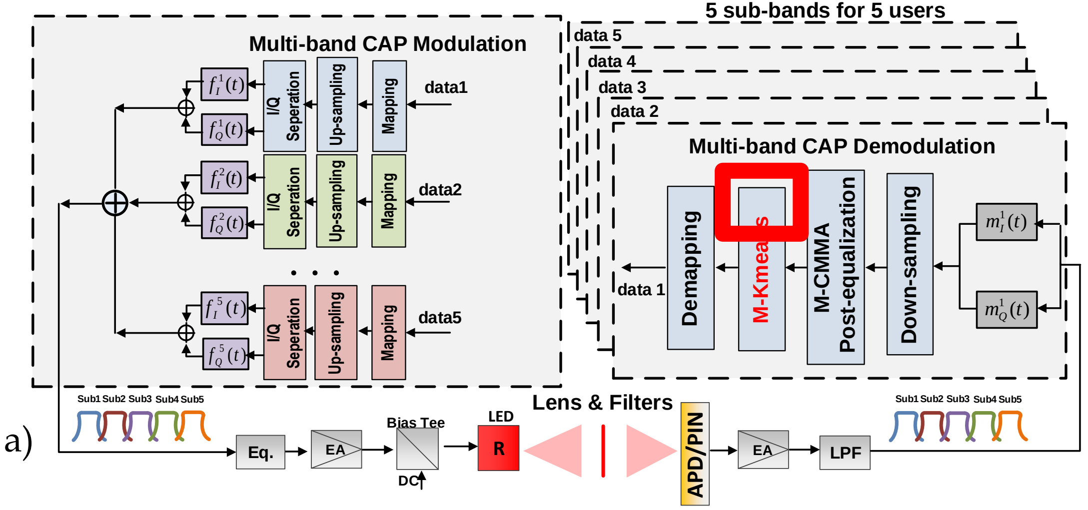
Principle of K-means Based Perception Decision (2/4 of 2.1)



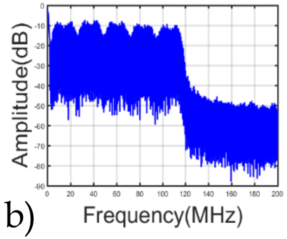


a) Traditional decision principle. b) K-means based perception decision.
c) Flowchart of K-means Based Perception Decision

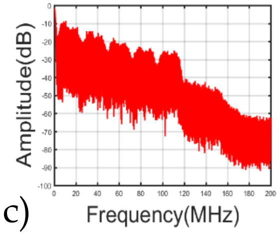
Experiment of K-means Based Perception Decision (3/4 of 2.1)



a) The experimental setup



b)

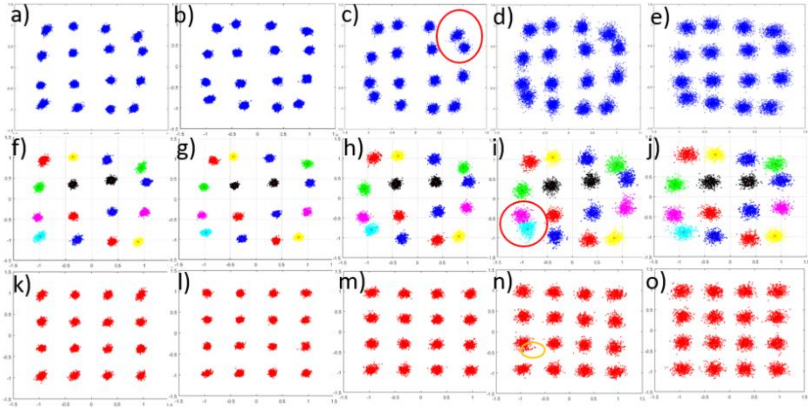


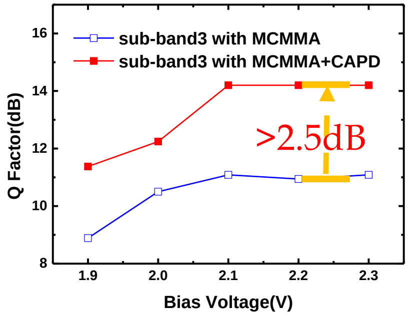
c)

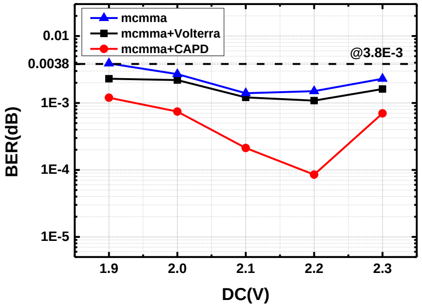
b) the transmitted spectra;
c) the received spectra.

- The 5-band CAP16 VLC system employing clustering algorithm-based perception decision.
- The transmitted spectra and the received spectra.

Experiment of K-means Based Perception Decision (4/4 of 2.1)





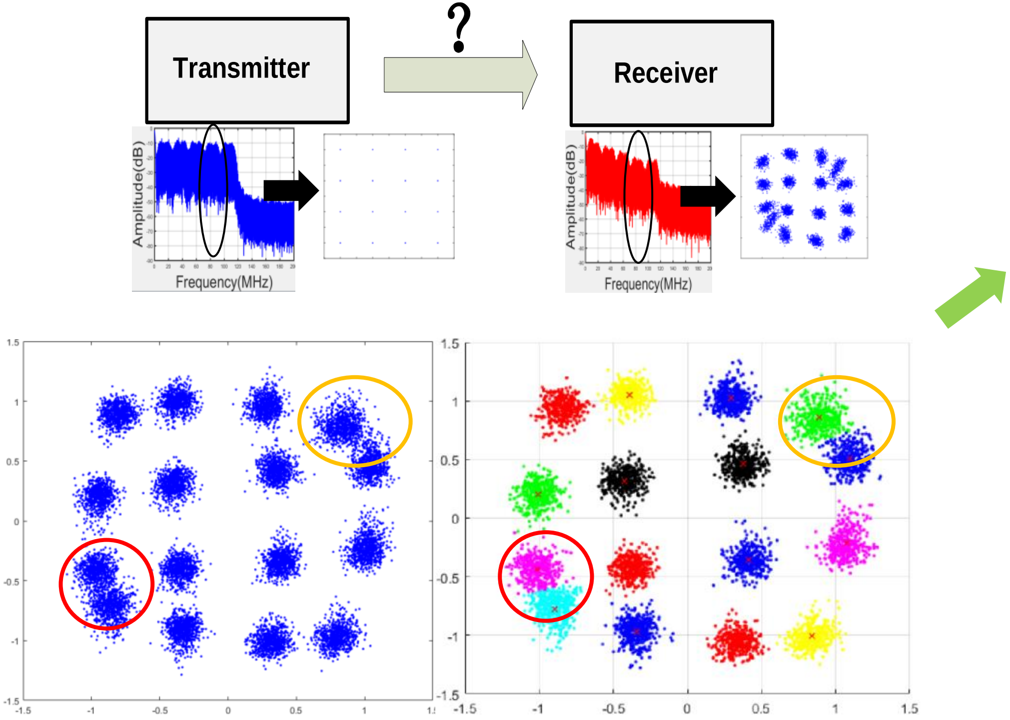


Compensation Method	M-CMMA（CAP16）	Volterra Equalizer(2-Order)	Volterra Equalizer(3-Order)	CAPD
Multiplier	8N+16	$2N^2$	$3N^3+2N^2$	$I*(L^2/2)$
Adder	8N+20	N^2-1	N^3+N^2-2	I*L
Comparator	6	0	0	I*32
Iterations	all Rx data	all Rx data	all Rx data	L=2000~3000
Data aided	No	No	No	No

- The Q factor of each sub-band is improved by 1.6~2.5 dB
- Lower computational complexity than Volterra equalizers

Xingyu Lu, et al., Photonics Journal, Vol. 9, No. 5

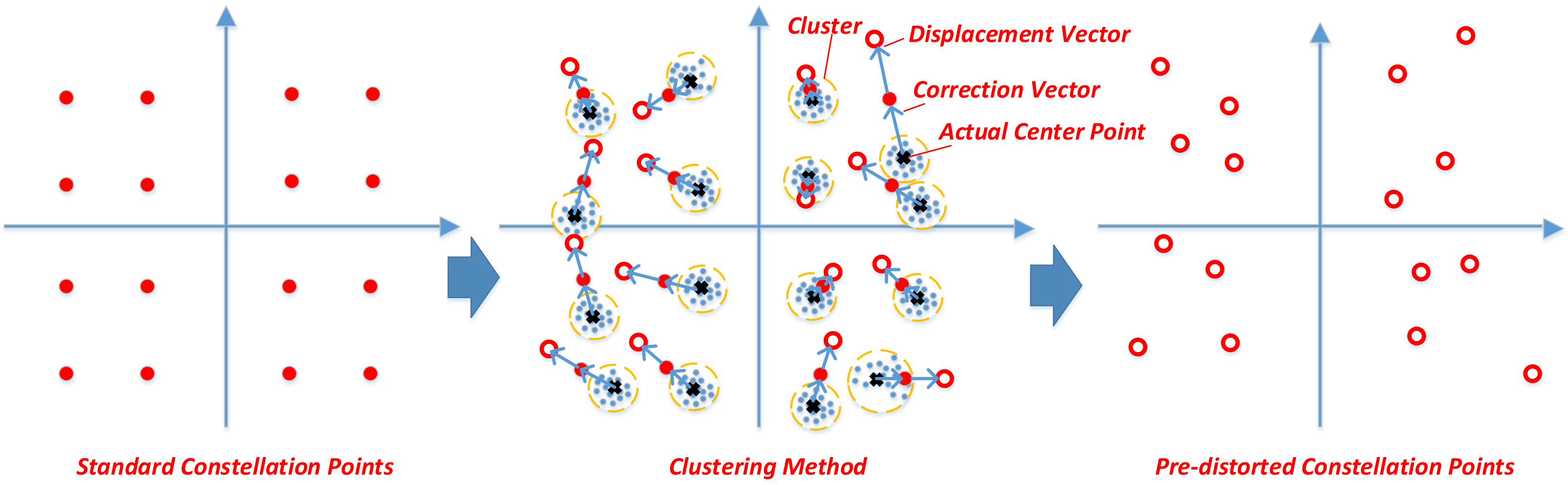
Defect of Post-Equalization scheme (1/4 of 2.2)



The confused constellation points cannot be distinguished.

What/How can we do before transmission?

Principle of pre-distortion scheme (2/4 of 2.2)



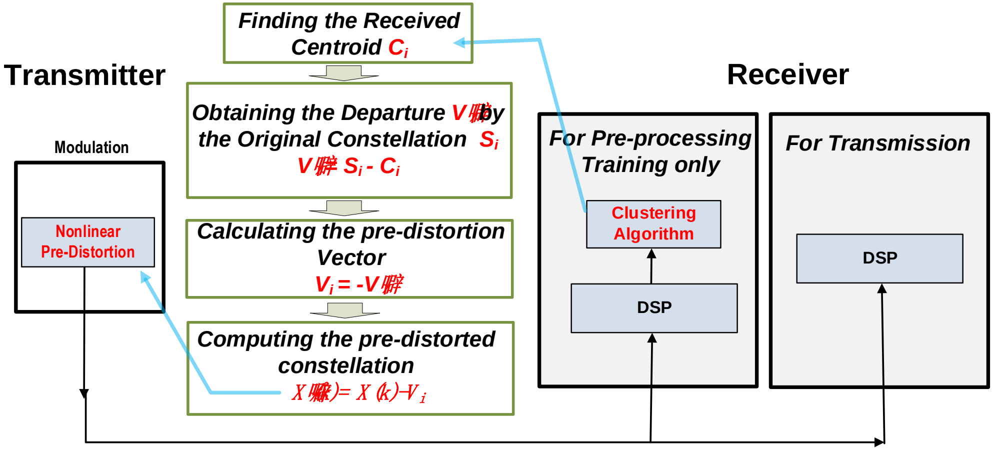
Specific steps:

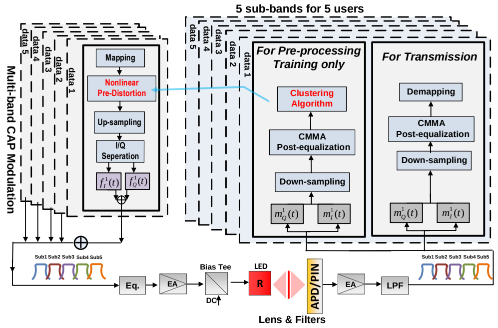
1. Find the actual centroids by analyzing the statistical properties (Training process);

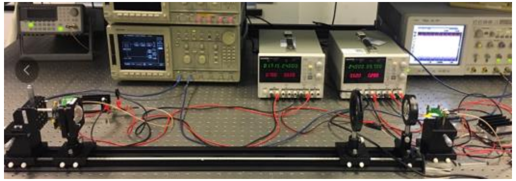
2. Calculating **correct vector** is obtained from the original constellation and the actual center point;

3. Send pre-distorted symbols (Transmission process)

Experiment of pre-distortion scheme (3/4 of 2.2)

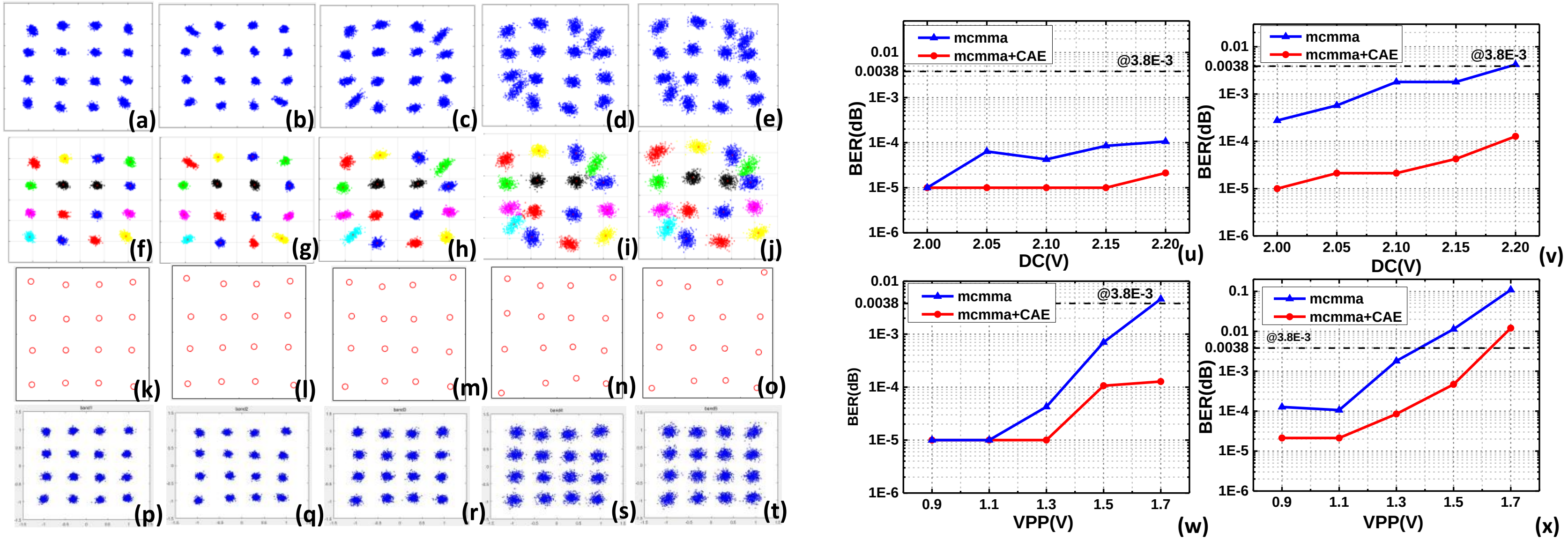






- Finding Constellation Centers By K-means algorithm;
- Pre-distortion with training process

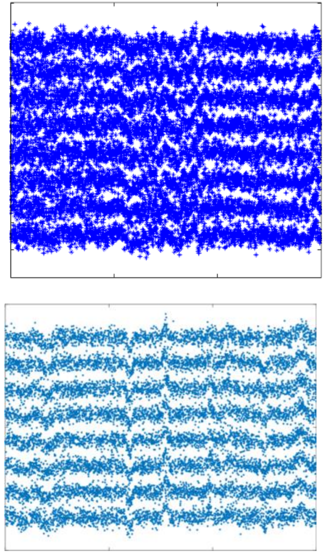
Experimental results of pre-distortion scheme (4/4 of 2.2)



Constellation diagrams of different sub-band after (a~e) CMMA linear equalizer; (f~j) k-means clustering algorithm results (different clusters are represented by different colors, red crosses in cluster is the cluster centers); (k~o) the displacement vector; (p~t) the final data corrected. (u~x) BER comparison of CMMA, CMMA+CAE

Xingyu Lu, et al., OFC 2018, M2K.1

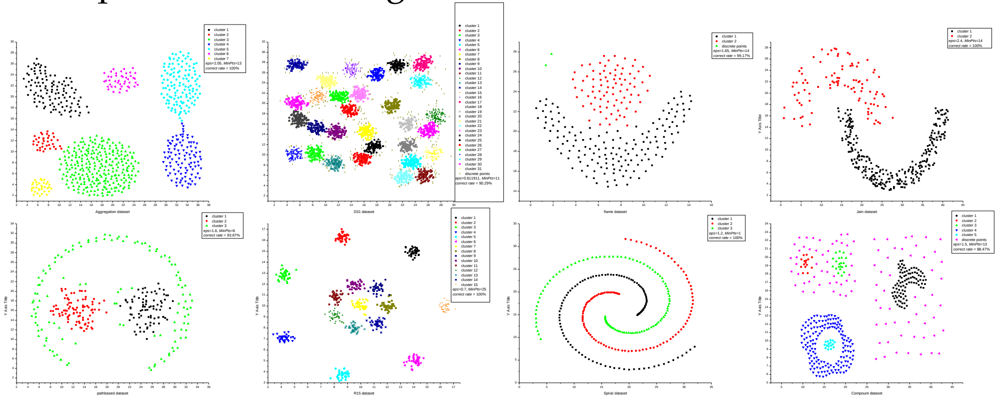
Background and Motivation of DBSCAN (1/3 of 2.3)



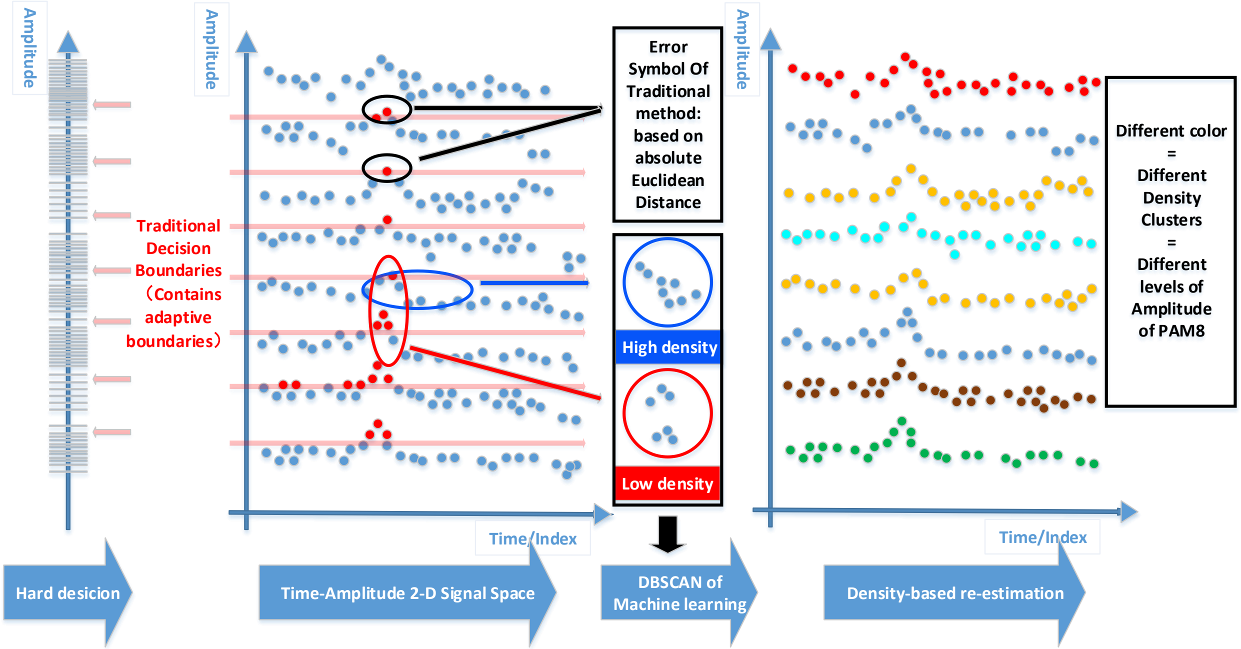
Constellations of PAM-8 VLC systems with Amplitude jitter.

- Amplitude jitter affects the performance of the PAM systems
- Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm is suitable for clustering without geometric center

Principle of DBSCAN algorithm

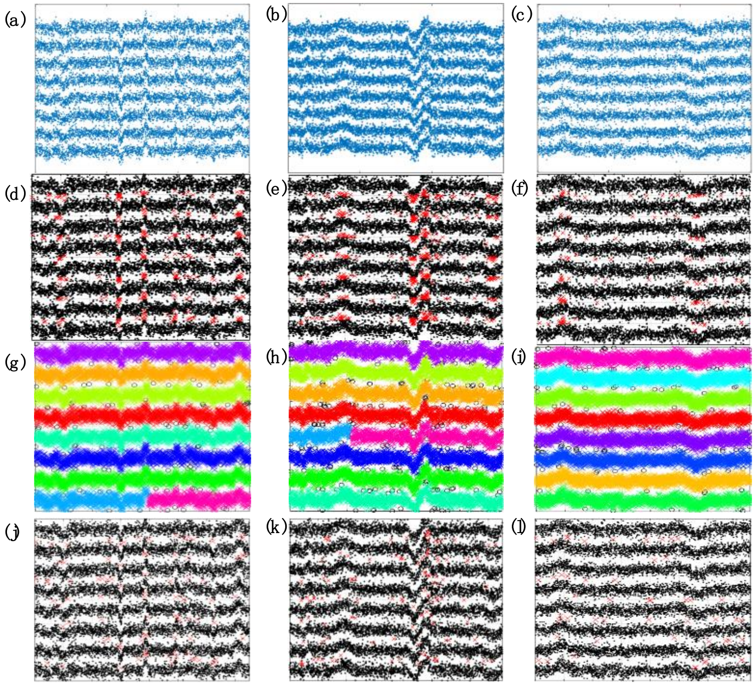


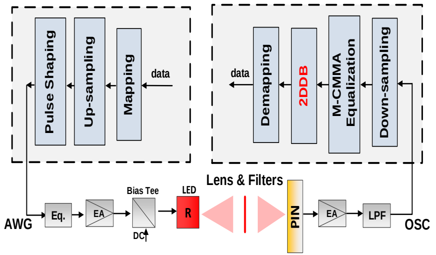
Principle of DBSCAN in PAM systems (2/3 of 2.3)

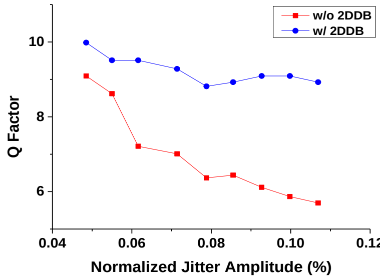


- Amplitude-only signal extended to time-amplitude dimension;
- Using density gaps to distinguish different symbols by DBSCAN algorithm.

Experiment and results of DBSCAN in PAM (3/3 of 2.3)





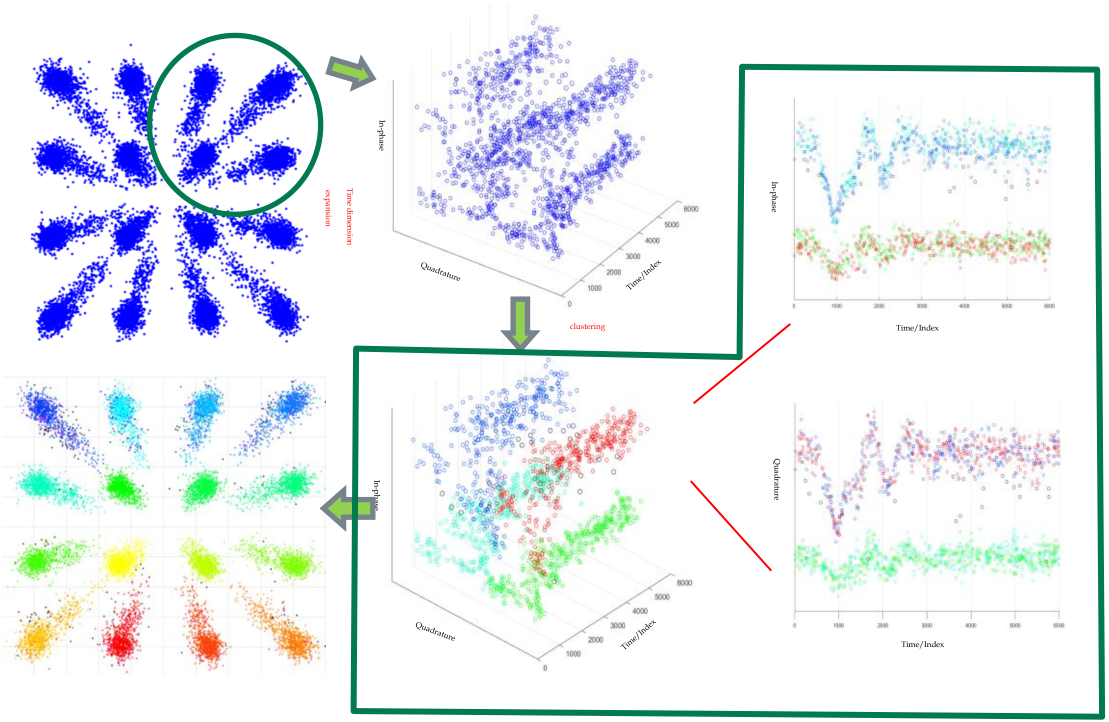


With DBSCAN:

- The Q factor of the PAM VLC systems with jitter is improved by 1.6 ~ 3.2 dB;
- BER has a 7% HD-FEC (3.8x10-3) limitation at 10% jitter.

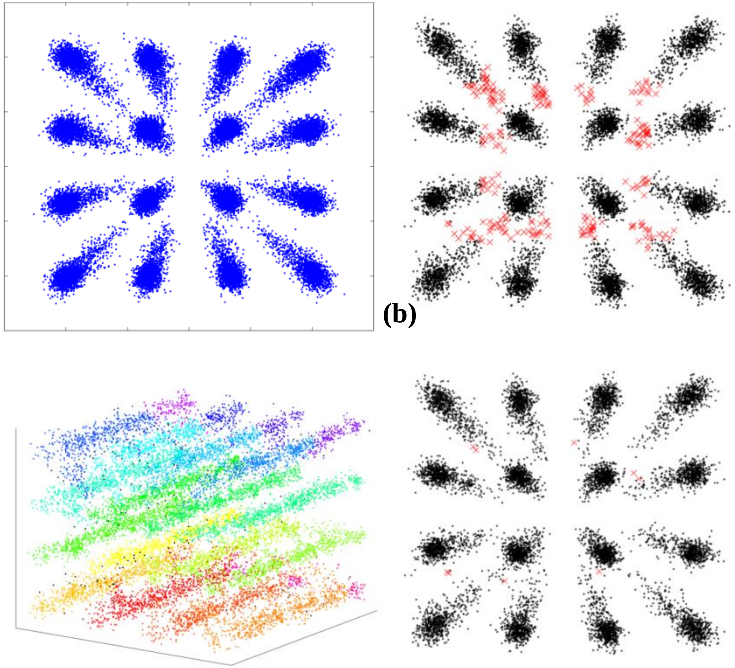
(amplitude jitter peak exceeds 5%:the performance of the traditional decision-making mode drops sharply)

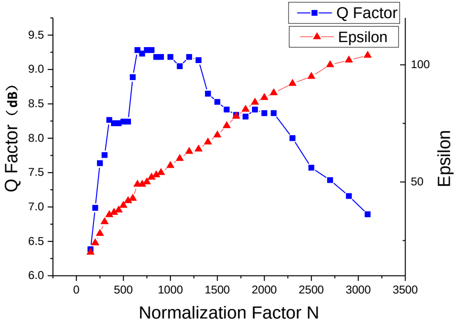
DBSCAN in CAP systems (1/2 of 2.4)

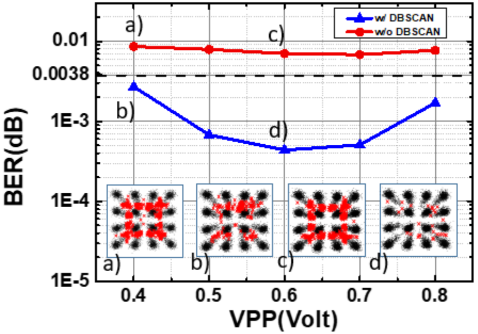


- In-phase-quadrature (IQ) 2 dimensional space to the in-phase-quadrature-time (IQT) 3 dimensional space
- Euclidean distance to Density
- Post-equalization scheme based on DBSCAN algorithm

Experiment and results of DBSCAN in CAP (2/2 of 2.4)







With DBSCAN:

- Traditional scheme: well solve the situation when the noise amplitude below 50% of Euclidean distance;
- DBSCAN scheme: noise jitter is as large as more than 70%;
- Q factor of the system with jitter improves by 3.5 dB.

Part III: Application of NNs in VLC Systems

Motivation and past research (1/3 of part 3.1)

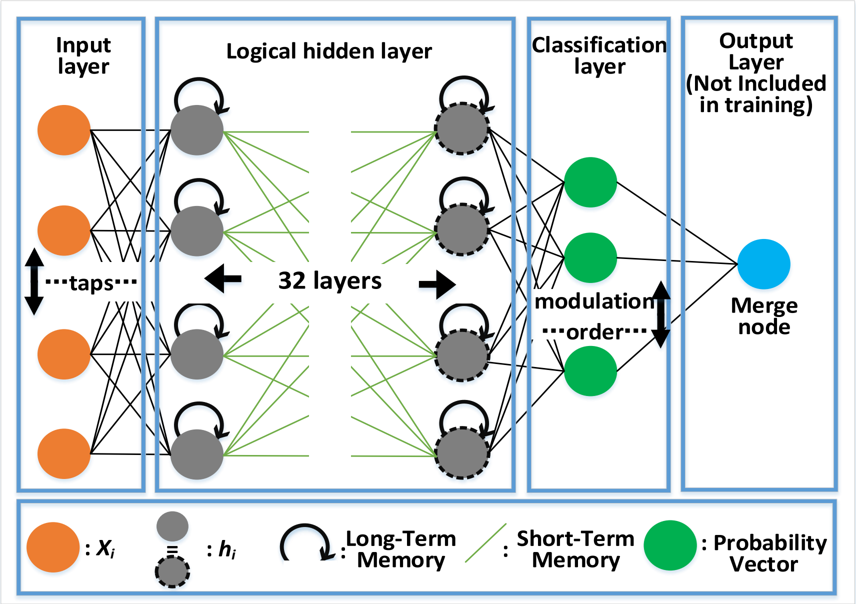
Why need NNs?

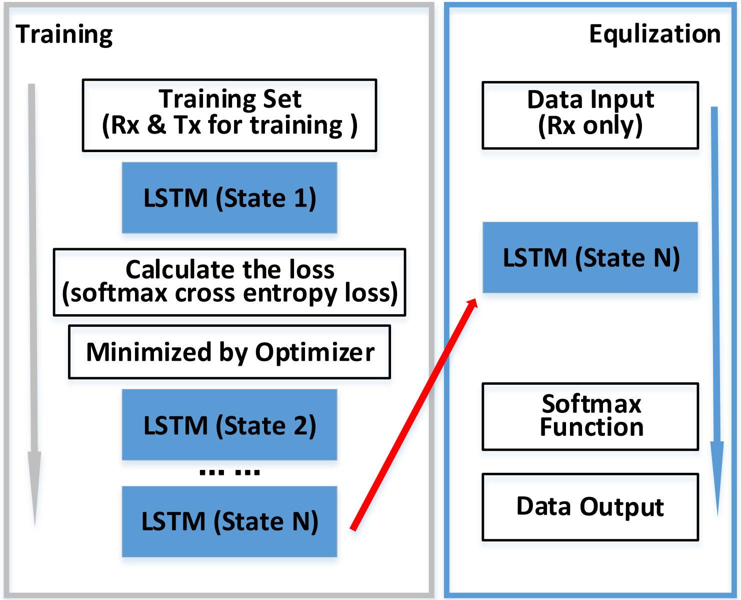
- Increase capacity: higher order modulation over limited bandwidth;
- Trade off of complexity and performance;
- Considering Linear and Non-Linear mutual damage in a model.

A review of NNs in Equalization?

- ANN, MLP, DNN and RNN in Equalization (review in 2010)
- ANN in Short-range fiber IM/DD Systems(ECOC 2016)
- ANN in VLC (JLT 2014)
- DNN, CNN, LSTM (2018~now)

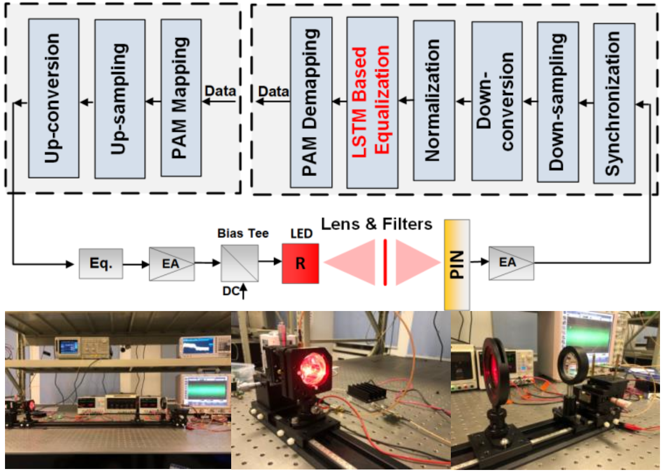
A LSTM equalizer in VLC (2/3 of part 3.1)

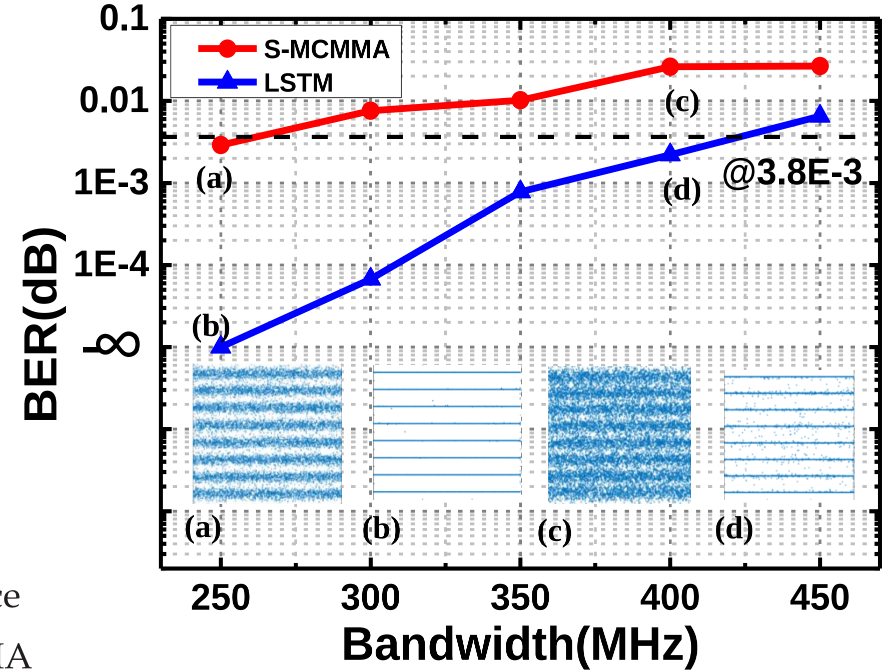




- a time-domain Long Short-Term Memory (LSTM) neural network based equalization scheme

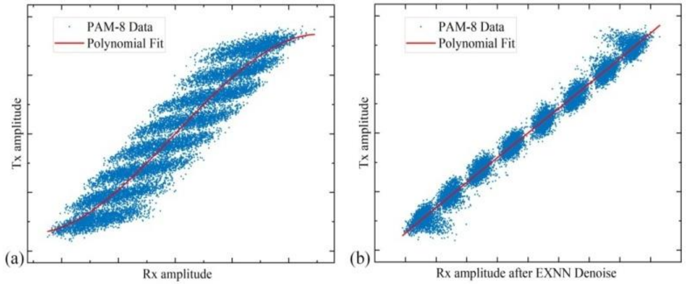
Experiment and results LSTM in PAM-8 (3/3 of part 3.1)

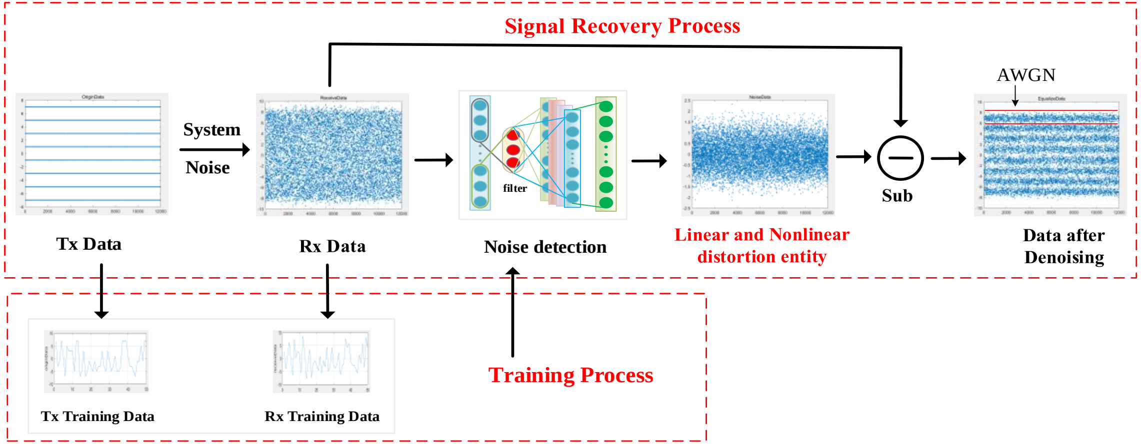




- Proving up to 10~100x BER performance improvement than traditional S-MCMMA equalizer

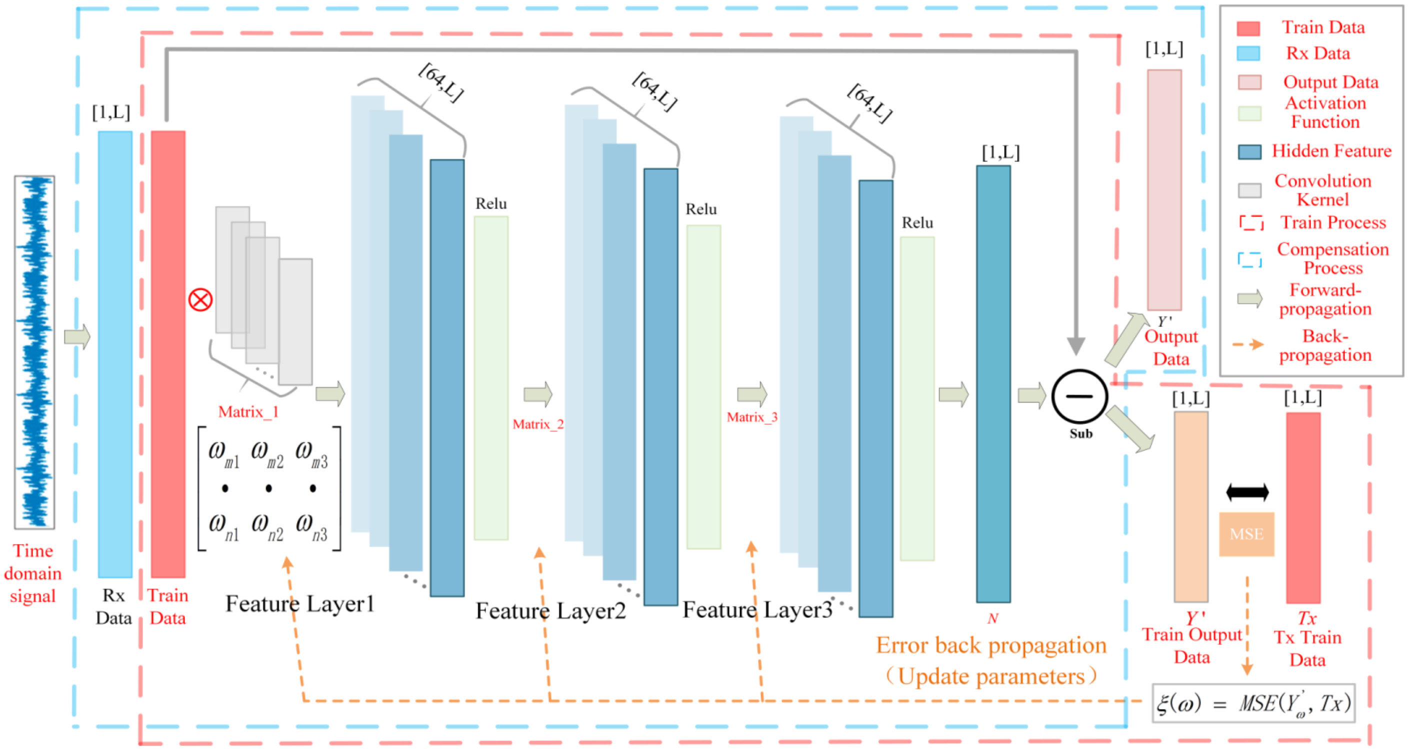
EXNN equalizer in VLC (1/3 of part 3.2)





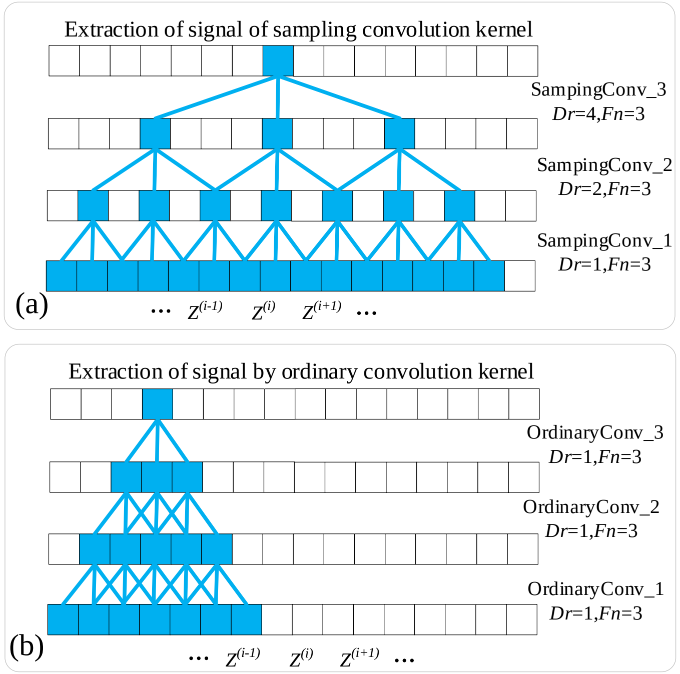
■ Illustration of the EXNN signal recovery principle

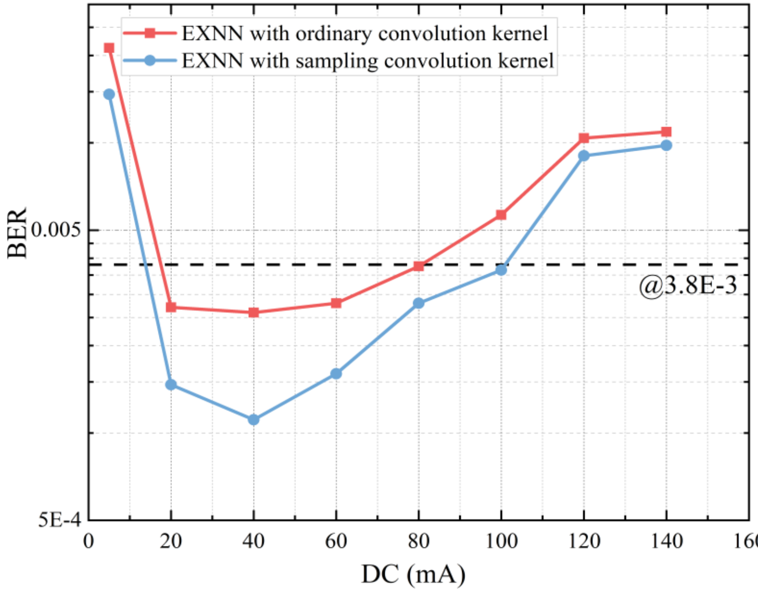
EXNN equalizer in VLC (2/3 of part 3.2)



■ EXNN structure and training process

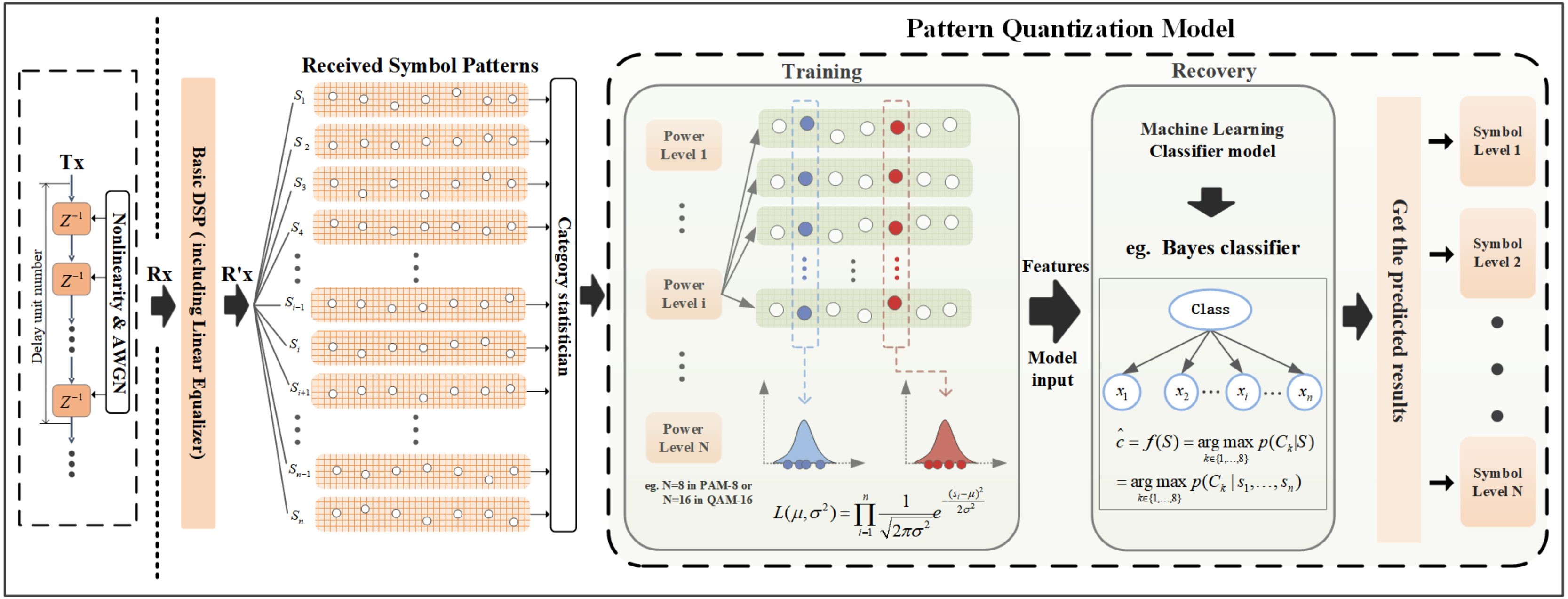
EXNN equalizer in VLC (3/3 of part 3.2)





- Signal extraction using (a) a sampling convolutional kernel and (b) a conventional convolutional kernel

Patterns Quantization with Noise (1/1 of part 3.3)



- Patterns Quantization with Noise Using Gaussian Features (JLT2022)

Part IV : Conclusions

Migration of NNs in VLCs

NNs

DNN

- ANN（2017* Fiber)
- GK-DNN（2018)
- AdaNN（2020)
- AANN（2021)
- …

CNN

- CNN（2019)
- VLCnet(2020)
- TFCNN(2021)
- …

RNN

- LSTM(2019)
- LSTM-cls(2019 * Fiber)
- Bi-LSTM(2022)
- …

Othes

- TTHNet（2019)
- TFNet（2020)
- CNN-DE(2019)

Conclusions and recent researches

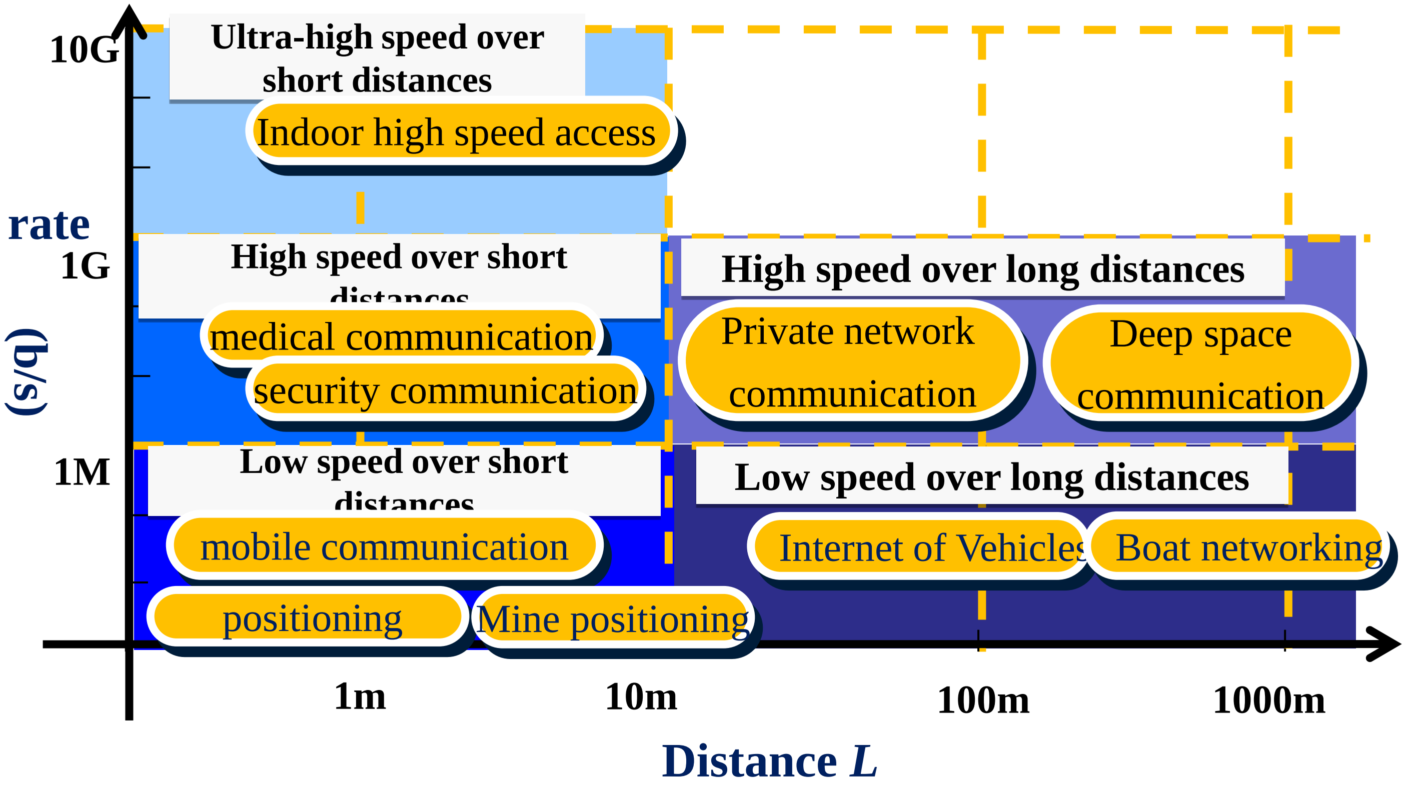
Now:

- It has been experimentally verified that machine learning-based equalization can improve the performance of VLC systems.

And the next：

- Extend the ML algorithms to higher order modulation.
- Compare different algorithms by experiment.
- Theoretically Analyze the potential of machine learning for VLC system performance improvement
- Consider algorithm implementation at the application level.

Application requirements of VLC



Thanks for your attention!