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

Submission Title: High-speed VLC for Wireless backhaul communication
Date Submitted: January 2016
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Abstract: In response to «Call for Proposals for OWC Channel Models» issued by 802.15.7r1, this contribution presents the PHY technologies proposal of outdoor free space VLC long distance transmission for high rate PD communication in wireless backhaul (mobile back haul).

Purpose: Call for Proposal Response

High-speed VLC for Wireless backhaul communication

Outlines

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

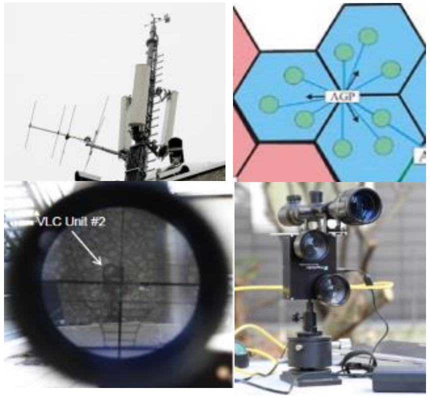
Response to the TCD Document

4.5.1 Applications/Use cases

The following High Speed Photodiode Receiver applications/use cases were presented in response to TG7r1 Call for Applications.

……

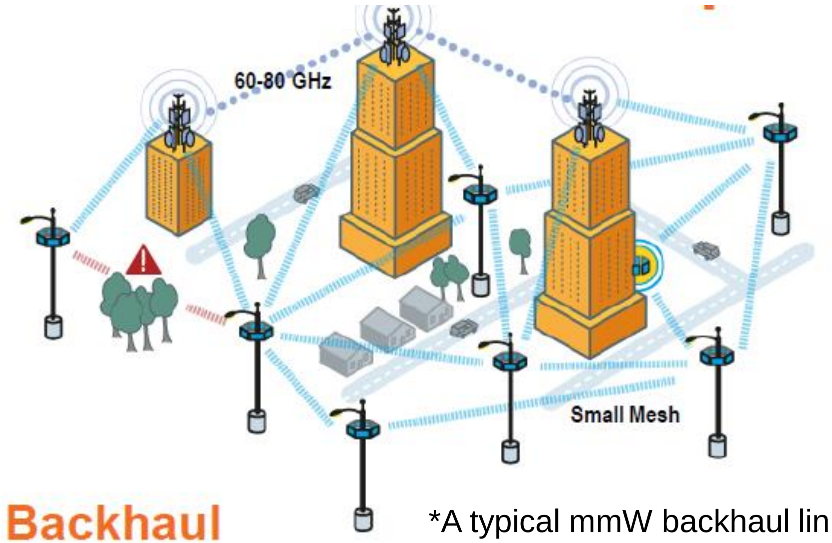
4. *Wireless Backhaul (Small Cell Backhaul, Surveillance Backhaul, LAN Bridging)*



B4: Wireless Backhaul

4.5.3 ……The standard must define a range of data rates with minimum supported connectivity of at least 1 Mbps at the PHY SAP. The standard must support at least one PHY mode that supports peak data rates of 10 Gbps at the PHY SAP.

Application Scenarios: Mobile backhauling



*A typical mmW backhaul link

Backhaul is a top priority for small cell deployments

•80% of small cells will have wireless backhaul

•Cost of fiber is ~4x greater than wireless (cumulative CAPEX/OPEX)

•Small Cell mesh inter-connectivity over ~250m

•Large indoor and outdoor public spaces

** According to InterDigital Whitepaper 2013*

VLC outdoor free-space high speed PD communication for mobile backhaul

- It shares the same CAPEX/OPEX advantages with mmW
- More competitive with lower device cost

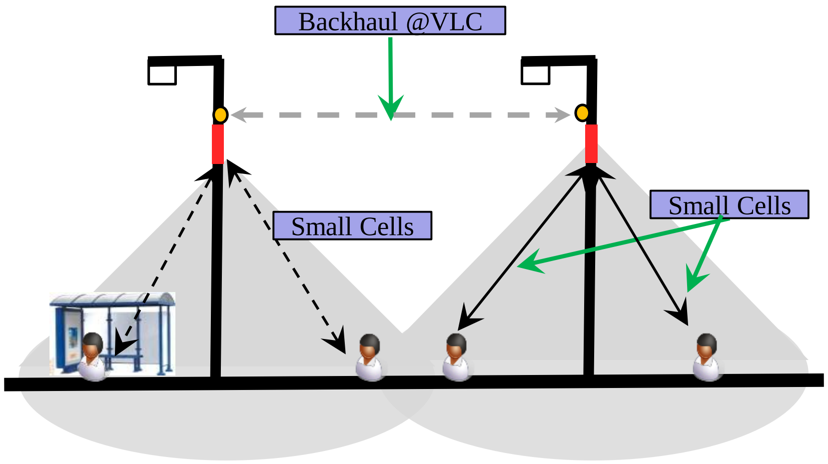
Characters:

- Large indoor/**outdoor public spaces**
- Distance: **~50 m~1 km**
- Speed: **~Gbps**
- Link: **mainly Point-to-point**

Wireless Backhaul

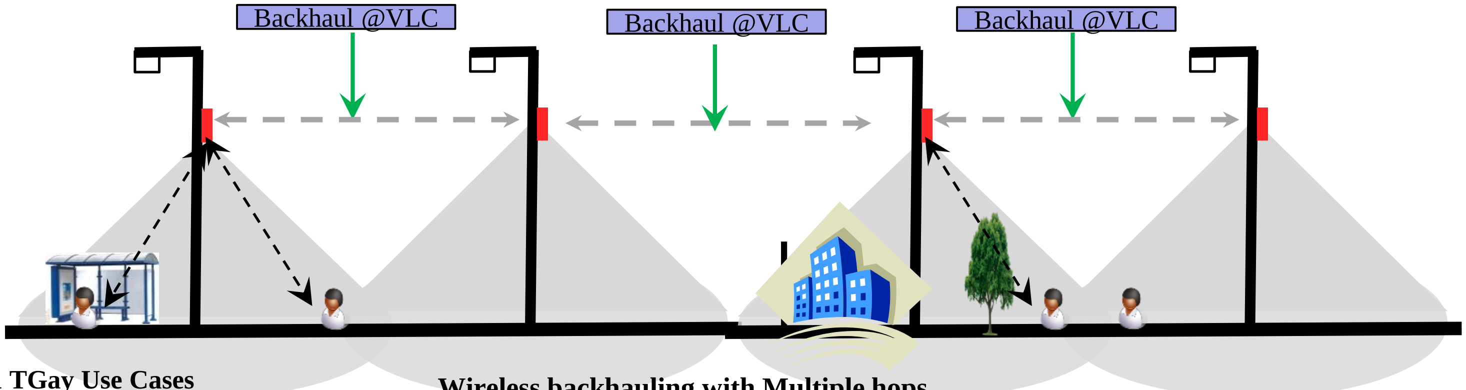
- **Requirements**

	Single Hop Wireless Backhauling	Multiple Hop Wireless Backhauling
# of hops	1	<5
Distance per link	<1km	<150m
Data Rate	~2-20Gbps	~2-20Gbps
Latency	<35ms	<35ms (total)
QoS/QoE	Yes	Yes
Availability	99.99%	99.99%



Wireless backhauling with single hop

Requirements are open for discussion



Source: from 802.11 TGay Use Cases

Wireless backhauling with Multiple hops

Targets

- High-speed VLC Out-door long-distance communication for mobile backhaul
- Data Rates Speed: **~Gbps**
- Distance: **50m~1km**, typical **~50-500 m**
- Environment: Large indoor/outdoor public spaces
- Link: mainly Point-to-point

To provide a Out-door VLC free-space link for high-speed user applications.

Proposal Research Route

VLC Free Space Transmission Channel Model

- LED/PD Modulation Property
- Optics System design
- Free-space channel

Key Technique for High Speed Outdoor VLC Transmission System

- Modulation formats
- Multiplexing Technology
- Pre Equalization and post-equalization
- Diversity reception technology

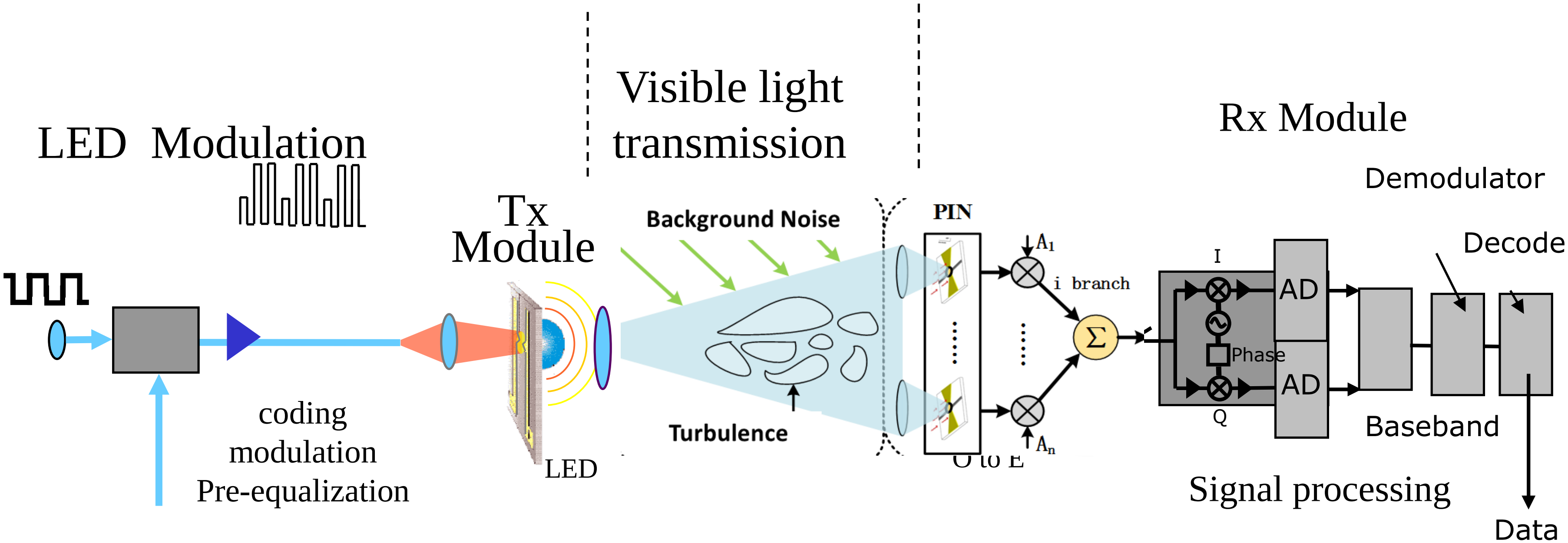
Simulation for Outdoor Long Distance VLC Transmission System

- System Structure and Simulation Parameters
- Simulation Results and Analysis

Outdoor Transmission Experiments

- System Structure
- Results and Analysis

Physical Layer 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),

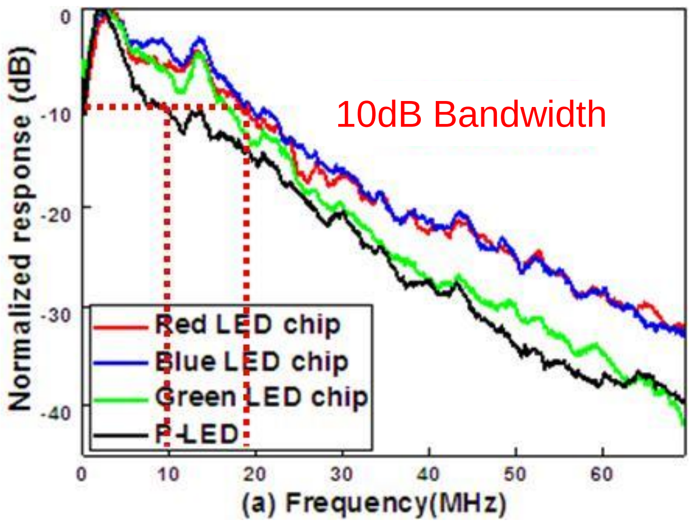
To achieve the high speed VLC

- The pre-equalization and post-equalization technology for the high-speed VLC systems

- Modulation formats:
  - Single-carrier based CAP-QAM
  - Multi-carrier based OFDM or **DMT with bit-loading**

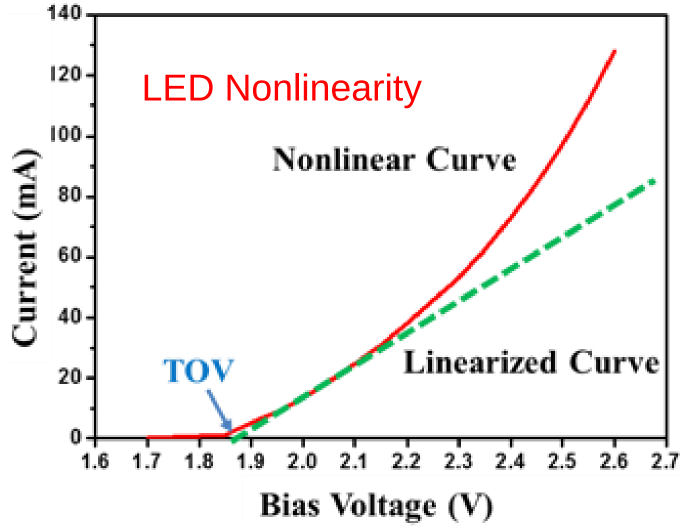
- Multiplexing Technology
  - Multiplexing Technology using different color LED
  - MIMO for multiplexing gain
  - Receiver-diversity reception technology

1. LED bandwidth limitations



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

2. VLC system Nonlinear



- Inter-symbol interference
- LED nonlinearity

Solutions

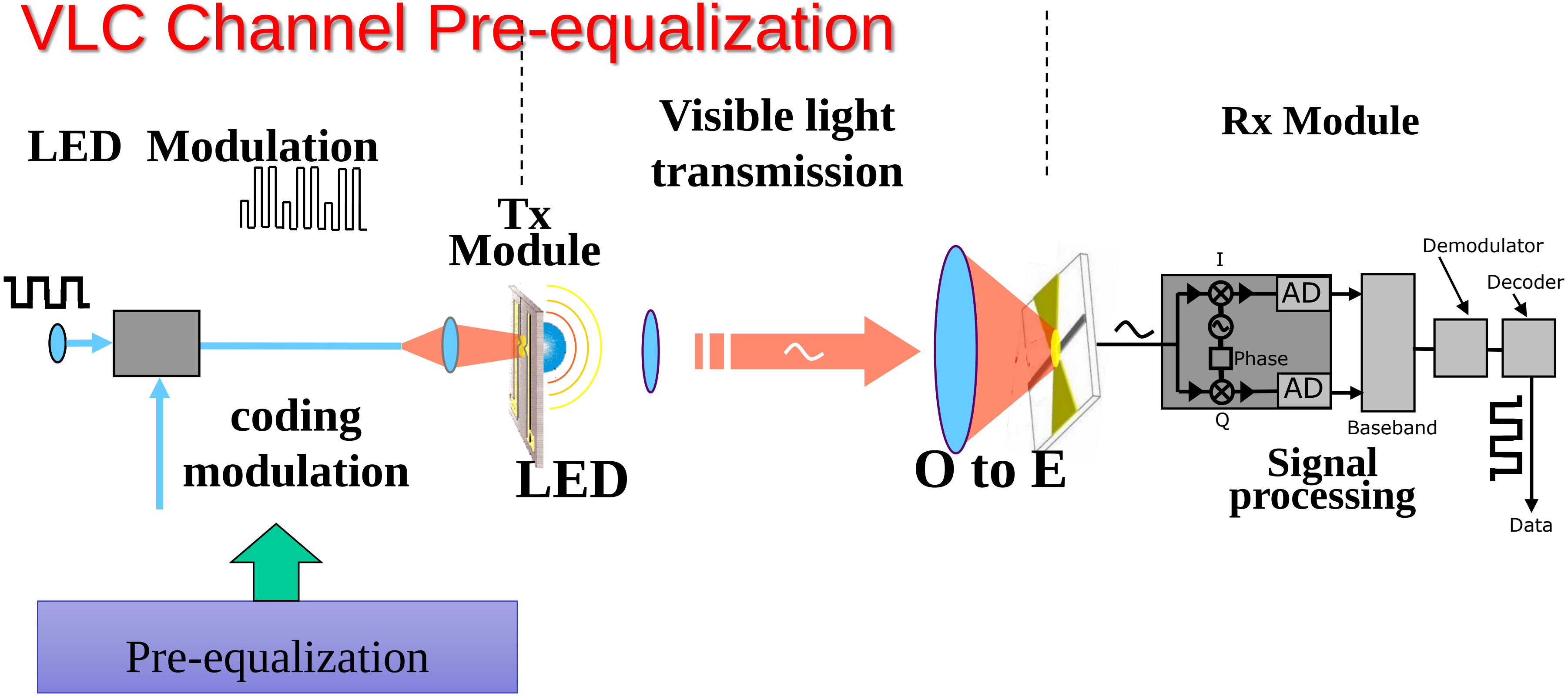
Higher order modulation and pre-equaliztion

- **Software/ hardware pre-equalization**
- **OFDM/DMT**
- **Single Carrier、CAP and so on**

Advanced post-equalization techniques

- **ZF、DFE、RLS、DD-LMS**
- **CMMA、M-CMMA**
- **Volterra**

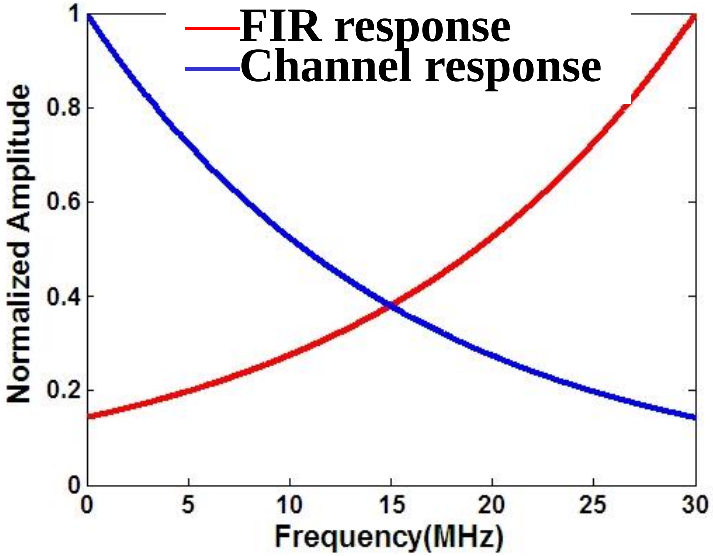
VLC Channel Pre-equalization



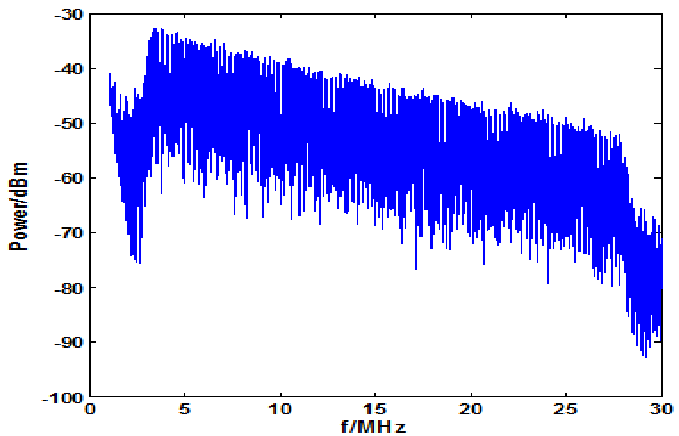
- Pre-equalization schemes:
  - Hardware Equalization：hardware circuit design
  - Software Equalization：digital signal processing

Software Pre-equalization

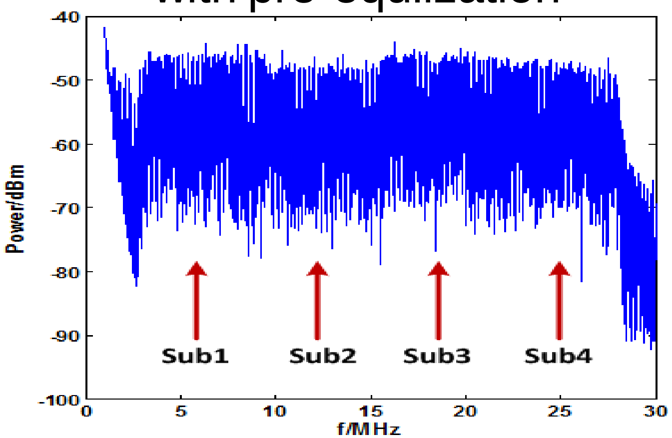
- **Pre-equalization**
  - ✓ Obtain the channel knowledge(H) at the RF domain
  - ✓ Make pre-equalization Tx*1/H at the baseband



w/o pre-equlization

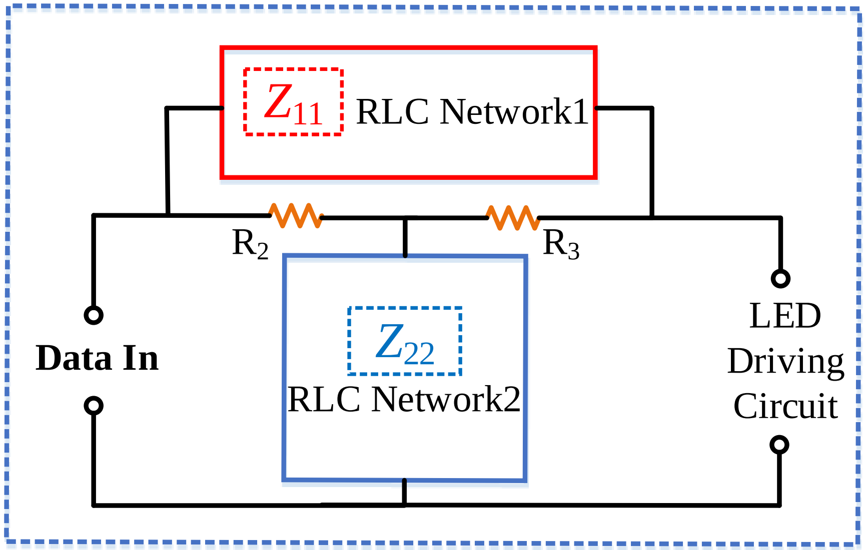


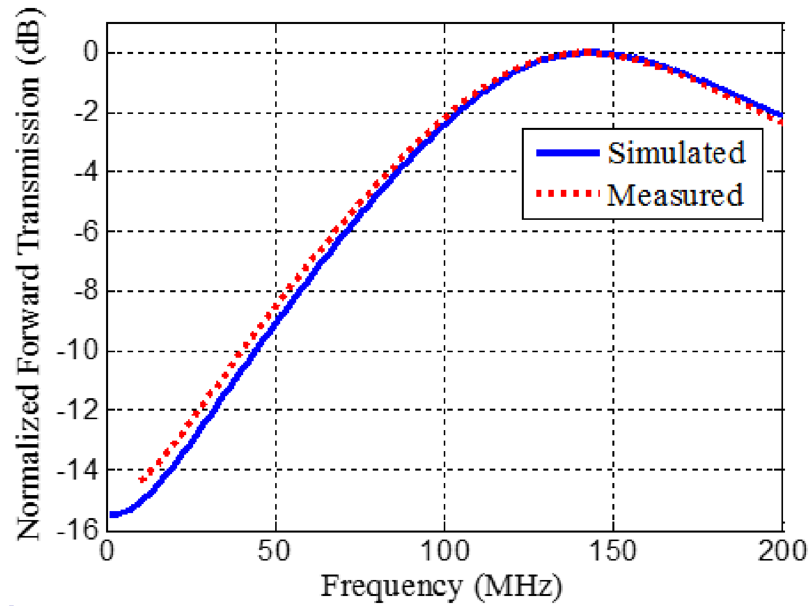
with pre-equlization



Y. Wang, et al, IEEE Communication Letters, Vol. 18, No. 10

Hardware bridged-T amplitude equalizer





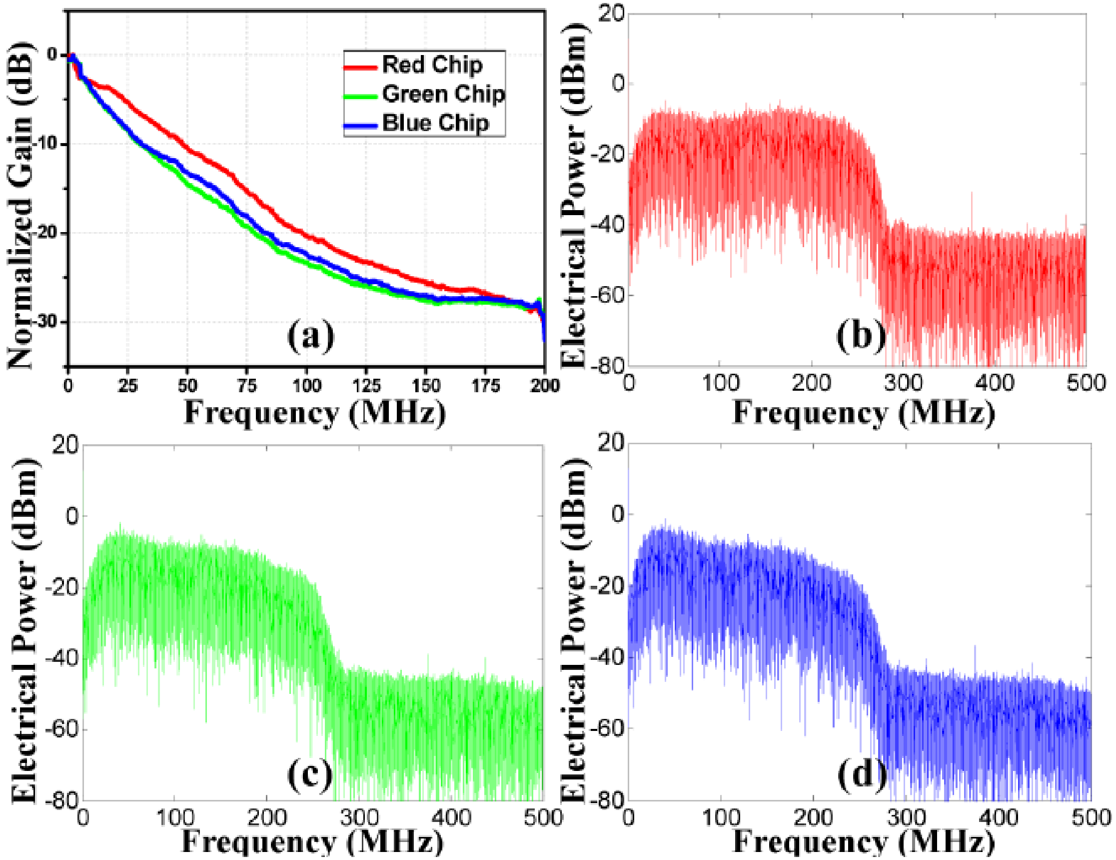
- Z_{11} : RLC network1 (R_1, C_1 and L_1)
- Z_{22} : RLC network2 (R_4, C_2 and L_2)
- $R_2 = R_3 = R_0$

$$Z_{11} * Z_{22} = R_0^2$$

$$S_{21} = 1/(1 + \frac{R_L}{R_4 + \frac{j\omega L_1}{1-\omega^2 C_1 L_1}})$$

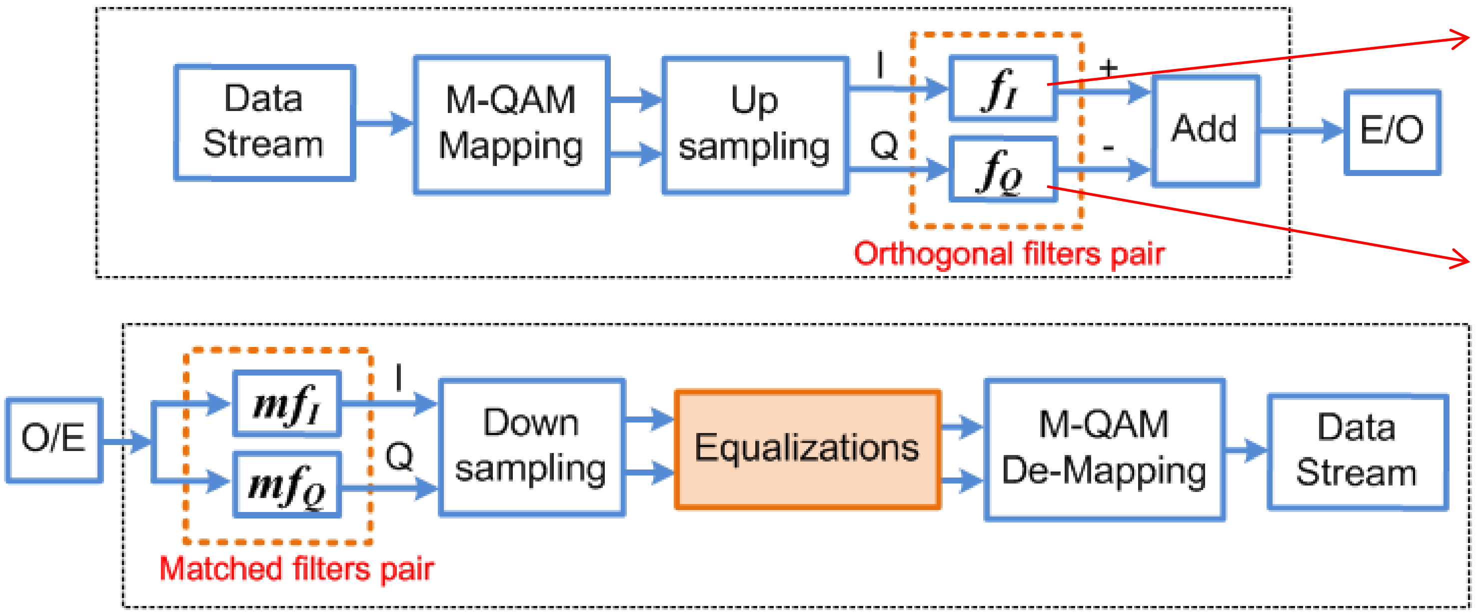
X. Huang, et al, OFC 2015, Tu2G.1

Hardware bridged-T amplitude equalizer Performances

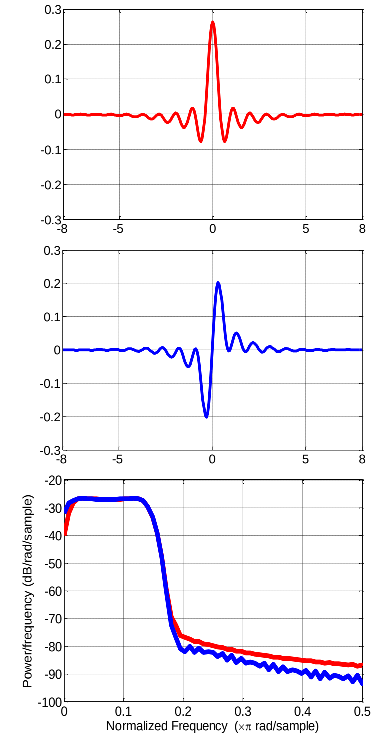


✓Spectrum of a 250-MHz CAP signal after pre-EQ

Carrier-less Amplitude Phase (CAP) modulation format



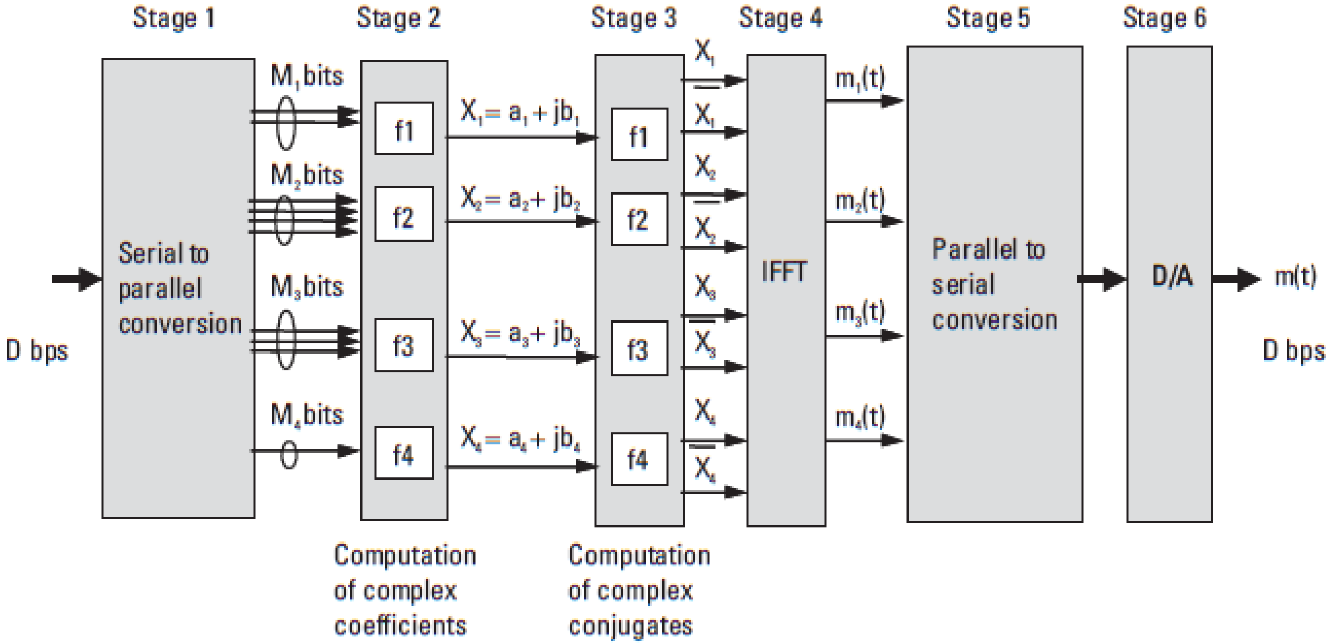
Orthogonal Shaping Filters



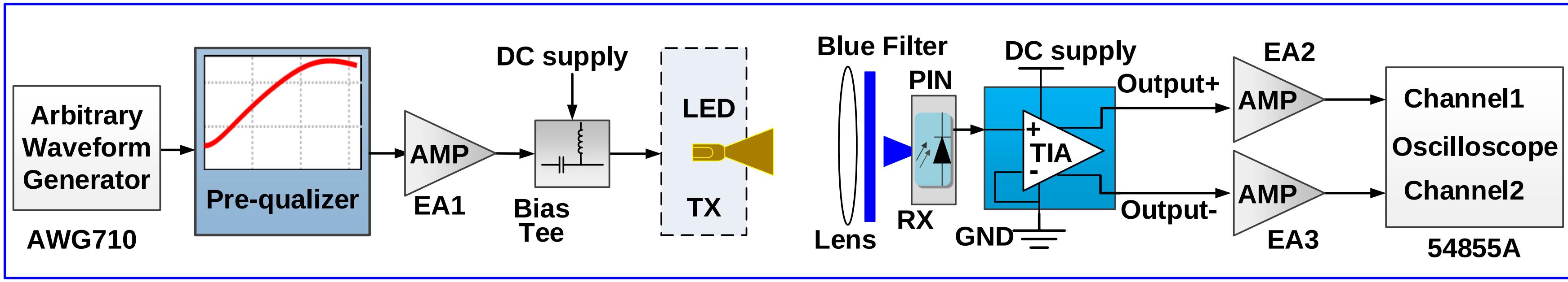
$$s(t) = I(t) \otimes f_I(t) - Q(t) \otimes f_Q(t)$$

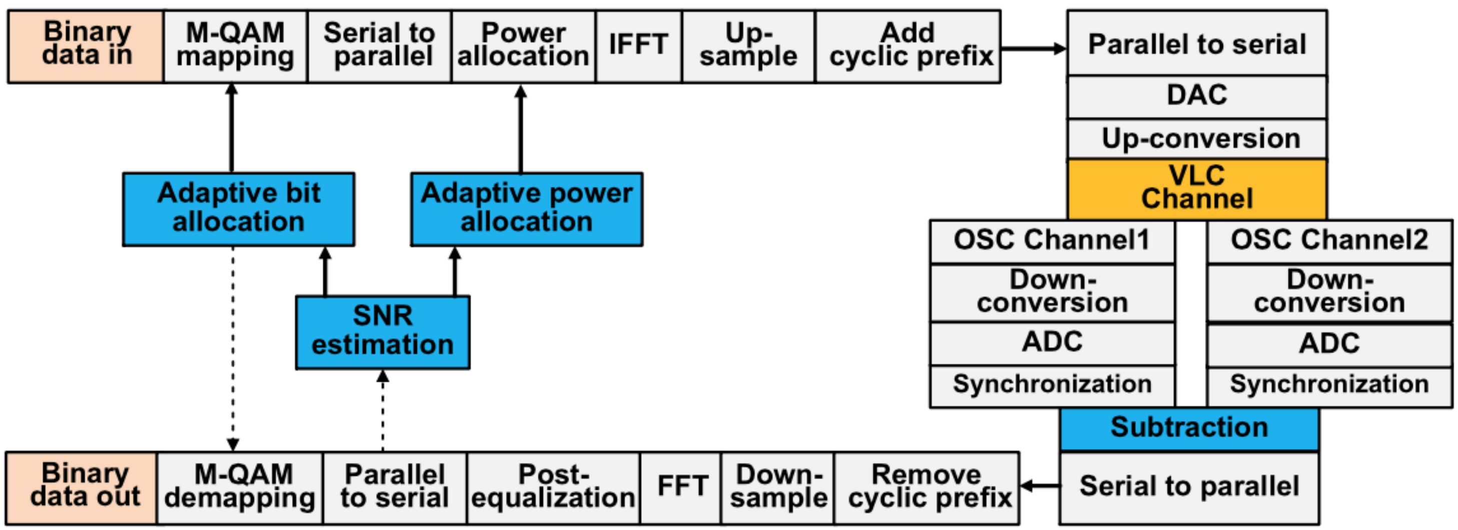
- Carrierless Amplitude and Phase (CAP) is a multi-level modulation scheme proposed by Bell Lad in 1970
- At transmitter a pair of orthogonal filters is used as Hilbert pair for modulation
- At receiver a pair of matched filter is used for demodulation

DMT with Bit-loading Background



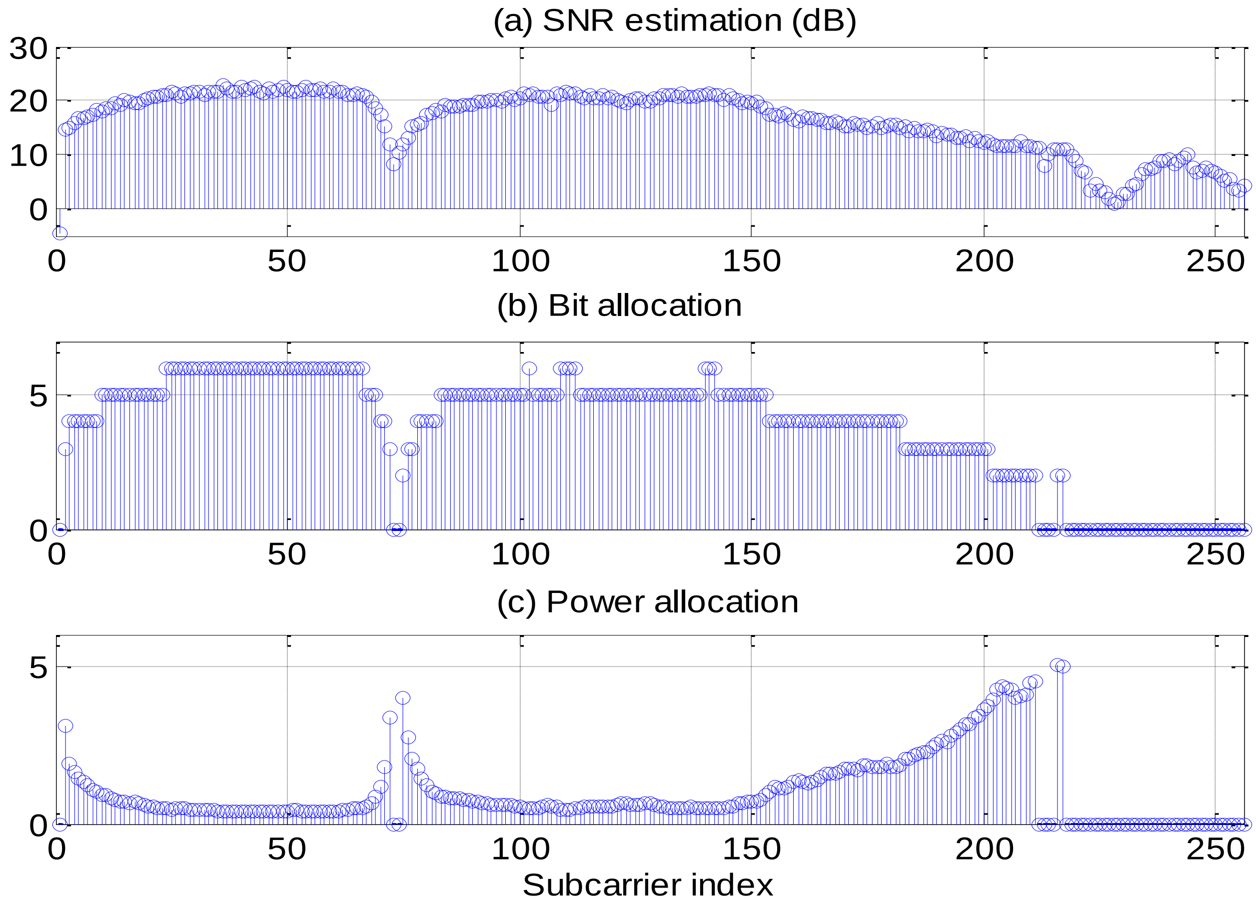
Bit-loading based OFDM-DMT modulation for Gbps VLC





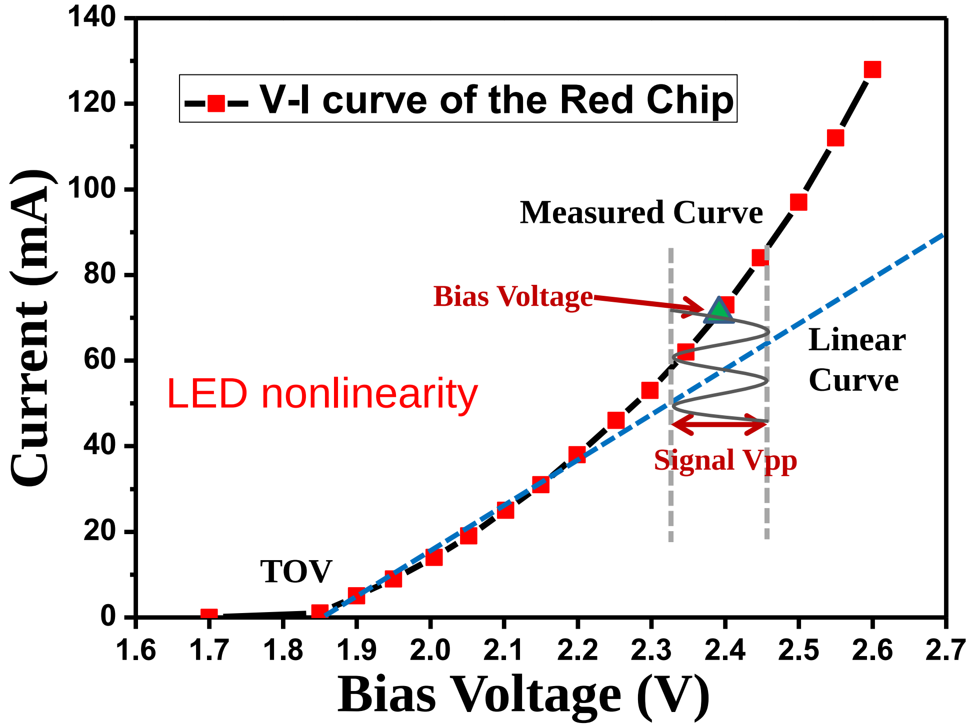
X. Huang, et al, IEEE Photonics Journal, 2015

Bit-loading based OFDM-DMT modulation for Gbps VLC



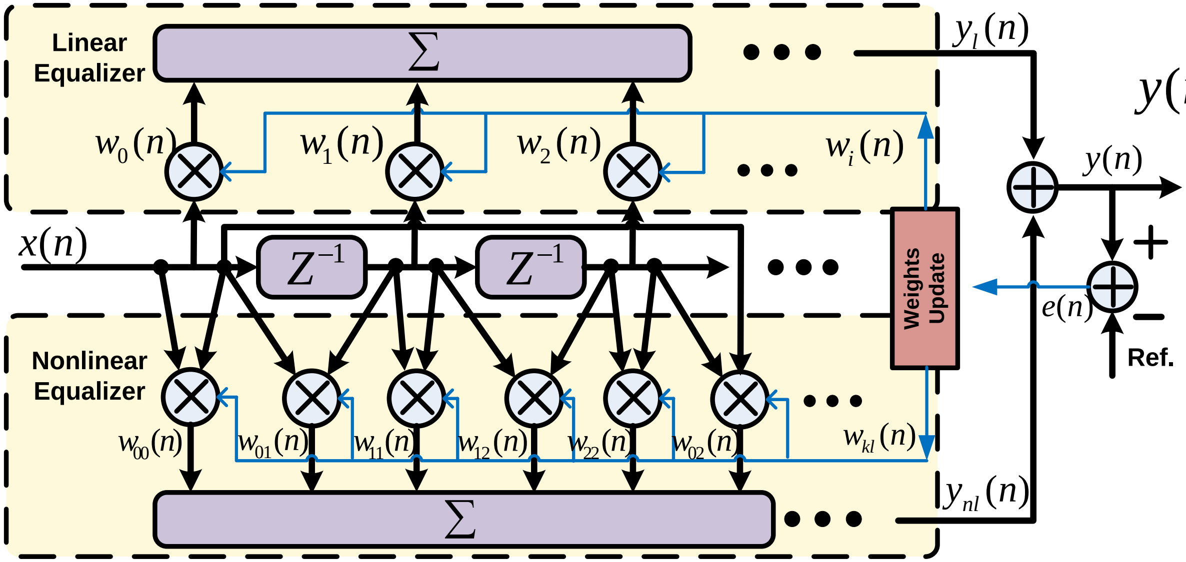
X. Huang, et al, IEEE Photonics Journal, 2015

Volterra nonlinear equalizer



- LED nonlinearity seriously degrades the system performance;
- The LED forward current exhibits strong nonlinearity with the bias voltage;
- Two factors dominate the nonlinear effects: DC bias voltage and the input signal peak-to-peak value (Vpp);

Volterra nonlinear equalizer



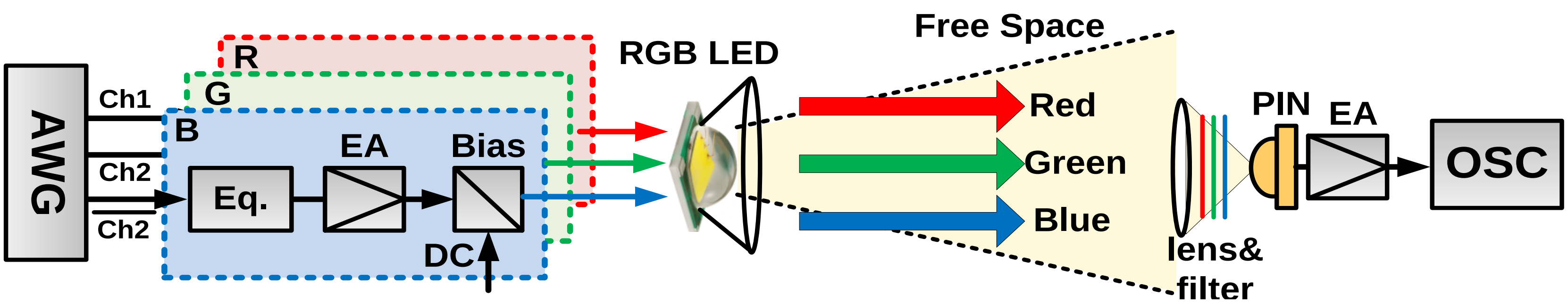
$$y(n) = y_l(n) + y_{nl}(n)$$

$$= \underbrace{\sum_{i=0}^{N-1} w_i(n)x(n-i)}_{y_l(n)} + \underbrace{\sum_{k=0}^{NL-1}\sum_{l=k}^{NL-1} w_{kl}(n)x(n-k)x(n-l)}_{y_{nl}(n)}$$

Principle

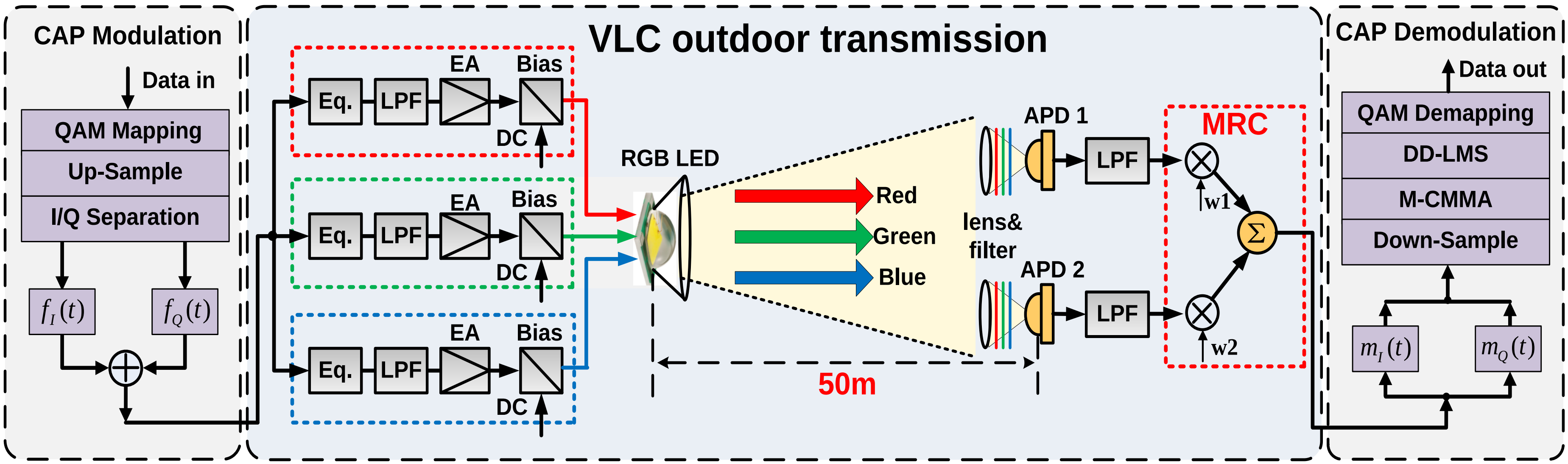
- The Volterra series based equalizer is considered as a promising solution to mitigate the LED nonlinearity;
- The Volterra series expansion contains a linear term and nonlinear series.
- M-CMMA is utilized to update the weights of the nonlinear equalizer without using training symbols

Color-division Multiplexing



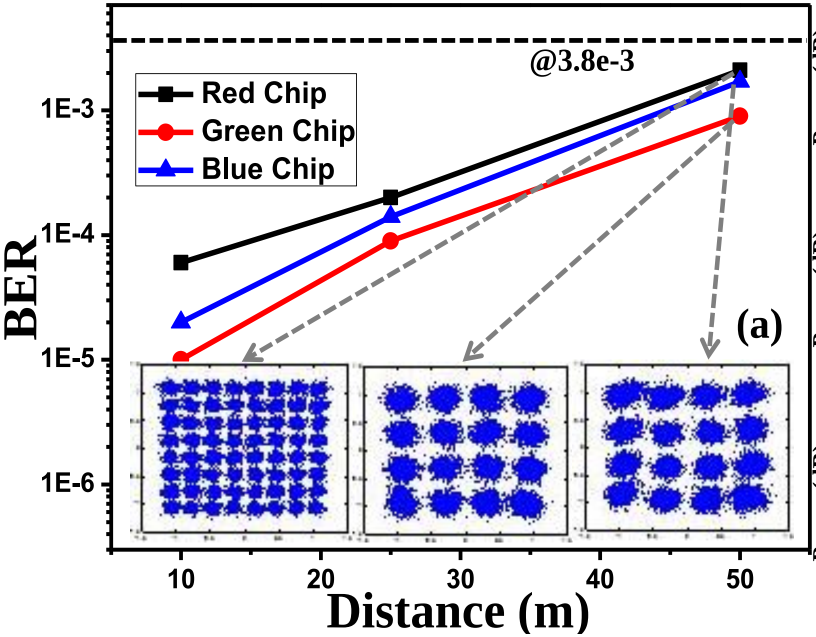
- ➢Same idea of Wavelength-division multiplexing (WDM) used in fiber-optics
- ➢To triple the capacity or speed of VLC system
- ➢RGB bandwidth is larger than the p-LED

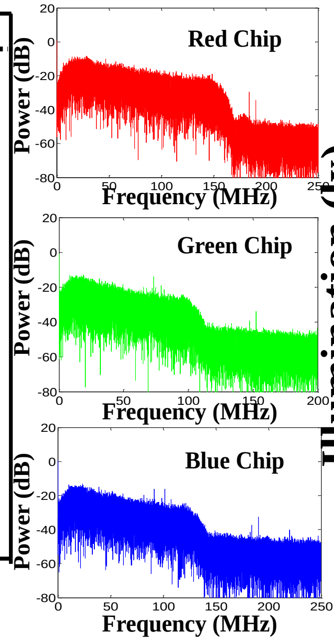
RGB LED (LED Engine) Multiplexing for high-speed VLC (WDM



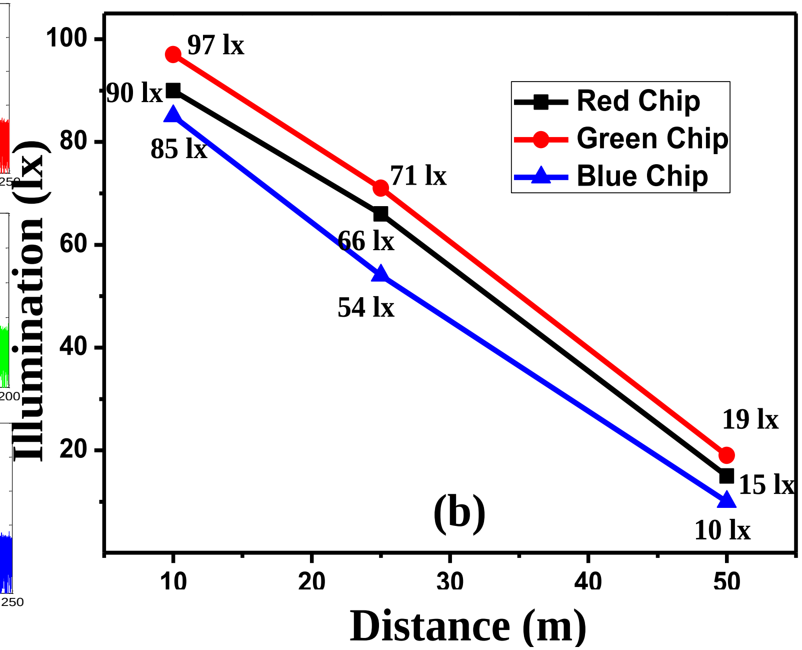
Out-door Long distance testing results

BER vs distance





Illumination vs distance



- At the distance of 50m, the total data rate of 1.8Gb/s can be achieved with the BER less than the 7 % FEC limit of 3.8x10-3.
- The illuminations for each color chip are 15lx, 19lx and 10lx at 50m.
- It should be noted that the experiment is conducted at about 9:00 PM. The ambient light noise mainly comes from the artificial light sources such as the street lights.

LED	Equ.	Modulation	Data rate	receiver	distance	institution	Data source
White light	Pre	OOK-NRZ	40Mbit/s	PIN	2m	**University of Oxford**	PTL2008
Blue light	-	DMT-QAM	200Mbit/s	PIN	2m	**Fraunhofer HHI**	PTL2009
RGB LED	-	DMT-WDM	803Mb/s	APD	12cm	**Fraunhofer HHI**	OFC2011
White light	Post	CAP	1.1Gb/s	PIN	23cm	**National Chiao Tung University**	PTL2012
RGB LED	Post	SC-FDE	3.75Gb/s	APD	1cm	**Fudan University**	COL2013
Micro-LED	Pre/Post	HW OFDM	3 Gb/s	APD	5cm	**Edinbourgh University**	PTL2014
RGB LED	Pre/Post	SC-FDE	4.22Gb/s	APD	10cm	**Fudan Univ.**	OPEX2014
RGBY LED	Pre/Post	DMT	5.6Gb/s	PIN	1.5m	**Scuola Superiore Sant'Anna**	ECOC2014
RGB LED	Pre/Post	CAP	4.5Gb/s	PIN	2m	**Fudan Univ.**	PJ2015
RGB LED	Pre/Post	CAP	1.8Gbb/s	APD	50m	**Fudan Univ.**	OFC 2015
RGBY LED	Pre/Post	CAP	8Gb/s	PIN	1m	**Fudan Univ.**	PTL 2015
RGBY LED	Pre/Post	DMT-BPL	9.5Gb/s	PIN	1m	**Fudan Univ.**	Newly Achieved

Conclusion

In this contribution, we propose several general technique considerations for high rate PD VLC out-door communications.

- The out-door high-speed VLC modeling including three parts
  - LED/PD Modulation Property
  - Optical system design
  - Free-space channel

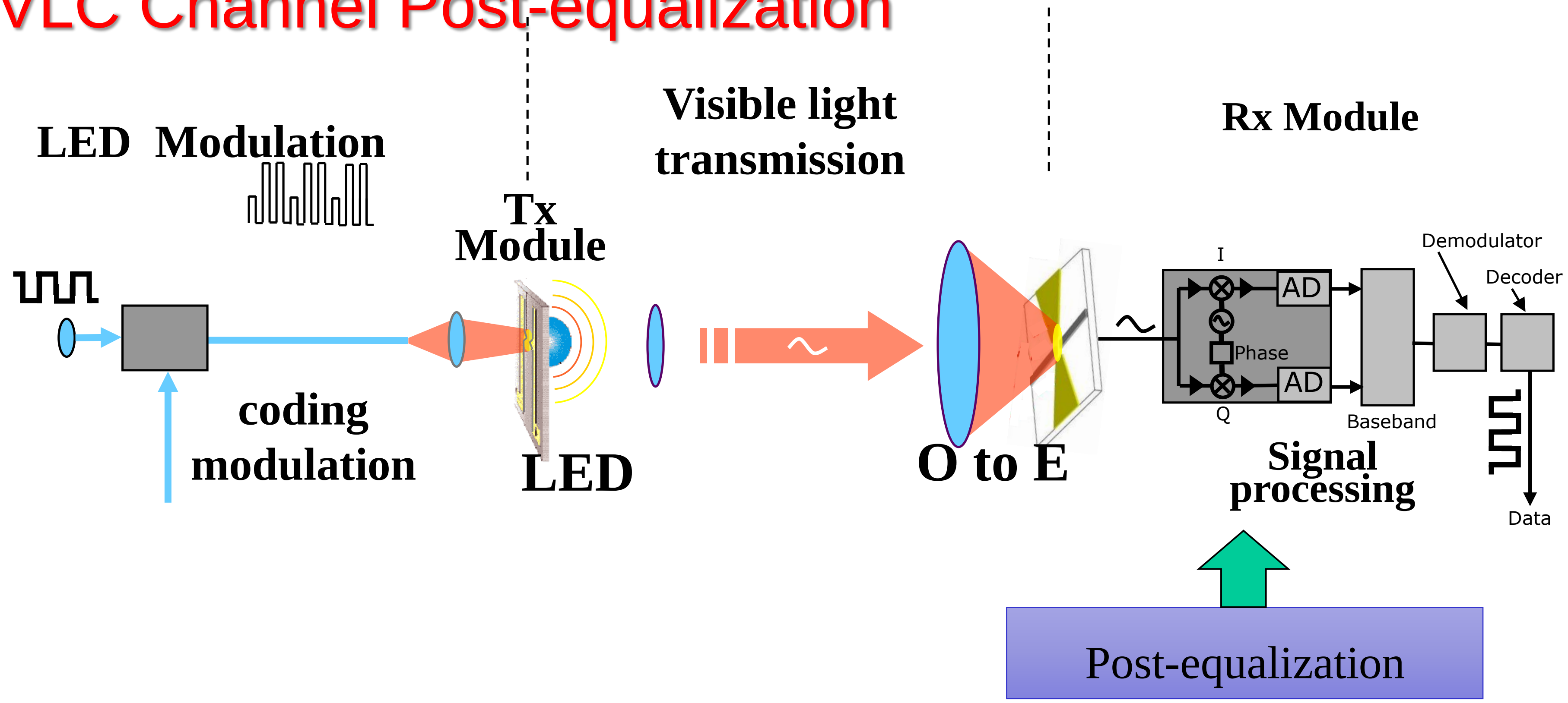
- The pre-equalization and post-equalization technology for the high-speed VLC systems

- Modulation formats:
  - Single-carrier based CAP-QAM
  - Multi-carrier based OFDM or **DMT with bit-loading**

- Multiplexing Technology
  - Multiplexing Technology using different color LED
  - MIMO for multiplexing gain
  - Receiver-diversity reception technology

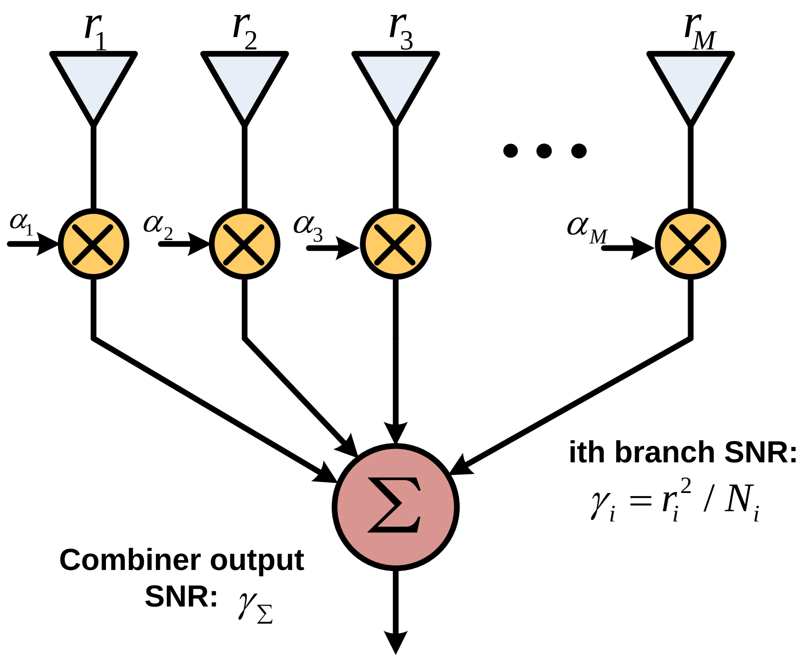
Appendix

VLC Channel Post-equalization



- Post-equalization solutions:
  - ISI Equalization：Classical DFE→ Modified Eqs
  - Nonlinear Compensations：Volterra series

Receiver diversity technology



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

the output SNR:

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

- The goal of MRC is to find the weight to maximize the output SNR

According to the Schwarz inequality, it is found that:
the maximum SNR of the combiner output is the sum of SNRs in each branch:

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