On the Superposition Modulation for OFDM-based Optical Wireless Communication

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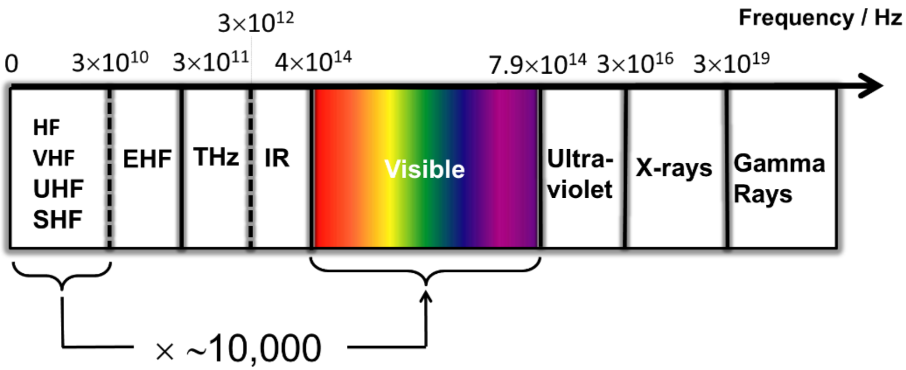
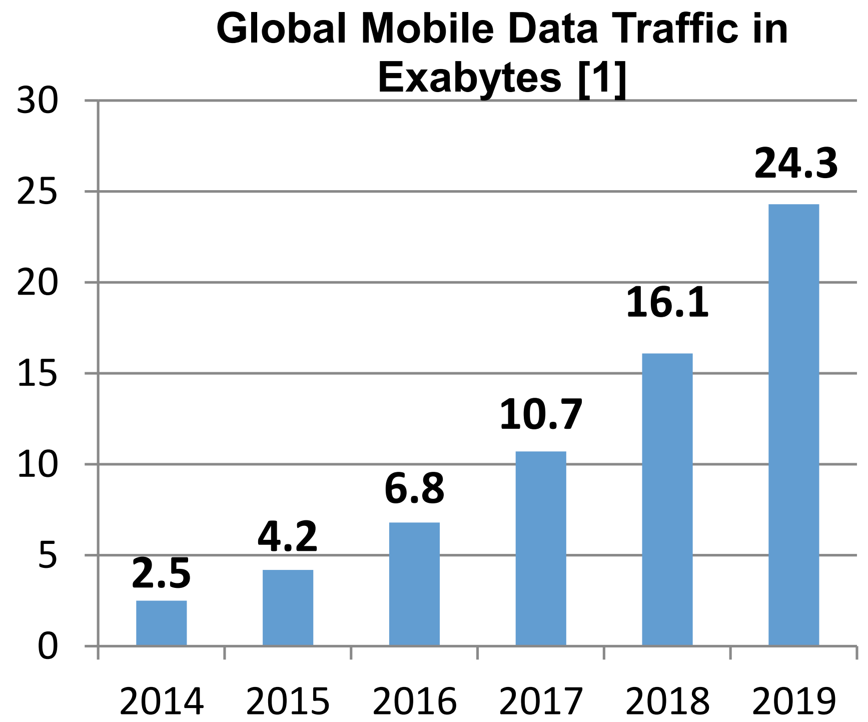
- Introduction
- ACO-OFDM
- Enhanced ACO-OFDM
- Performance Comparison
- Conclusion

Introduction

Looming Spectrum Crisis





- RF spectrum is limited.
- Visible light spectrum is **an unregulated** potential solution to the looming Spectrum Crisis.

[1] Cisco Visual Networking Index, "Global Mobile Data Traffic Forecast Update, 2014-2019," CISCO, White Paper, Feb. 2015. [Online]. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.pdf

Visible Light Communications (VLC)

- Existing lighting infrastructure reuse
- High security, no harmful interference.
- Potential energy savings.
- Remarkable experimental results for VLC:
    - > 3.5 Gbit/s with a single 50-μm LED. [2]
    - > 14 Gbit/s with RGB LD [3]
    - > 224 Gbit/s 3m Li-Fi link [4]

[2] Tsonev et. al., "A 3-Gb/s Single-LED OFDM-based Wireless VLC Link Using a Gallium Nitride μLED", Photonics Technology Letters, 2014

[3] Tsonev et. al., "Towards a 100 Gb/s Visible Light Wireless Access Network," ***Opt. Express*****, vol. 23, no. 2, pp. 1627–1637, Jan 2015.**

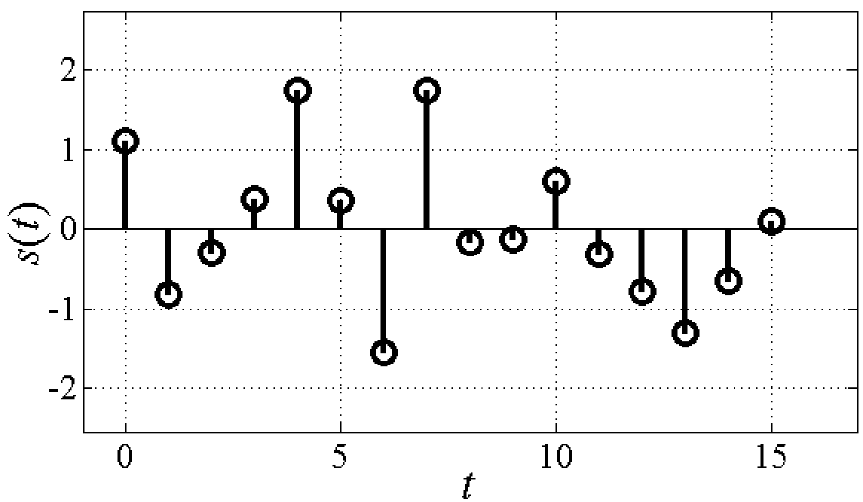
[4] Gomez, A.; Kai Shi; Quintana, C.; Sato, M.; Faulkner, G.; Thomsen, B.C.; O'Brien, D., "Beyond 100-Gb/s Indoor Wide Field-of-View Optical Wireless Communications," in Photonics Technology Letters, IEEE , vol.27, no.4, pp.367-370, Feb.15, 15 2015

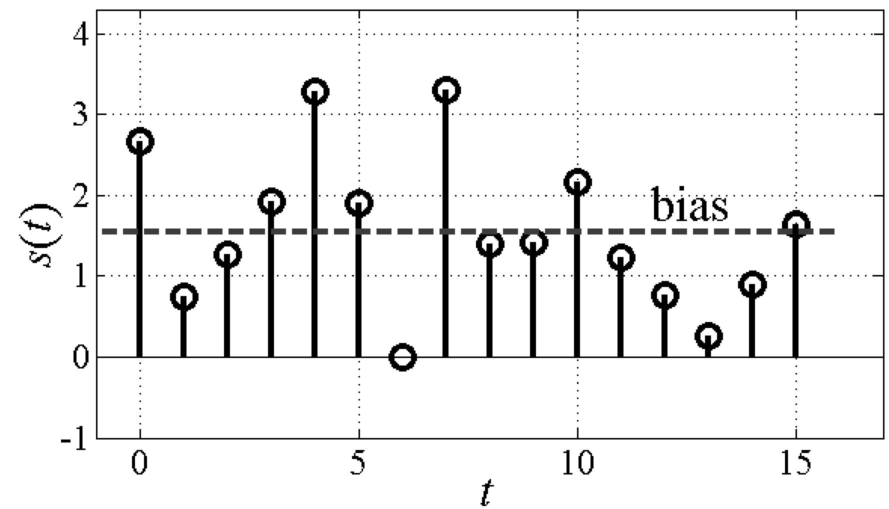
Physical Constraints of VLC

- Incoherent off-the-shelf white LEDs are most likely candidates for front-end devices => Only Intensity modulation and direct detection (IM/DD) is possible.
- OOK, M-PPM, PWM and M-PAM implemented in a straightforward fashion.
- High data rates require ISI-resilient scheme => OFDM is more suitable.
- Conventional OFDM is bipolar and complex => Hermitian symmetry.

DCO-OFDM Signal Generation

- A DC bias required for the generation of unipolar signals.
- DC bias increases the energy consumption.
- Energy saved with inherently unipolar techniques such as: **ACO-OFDM**, PAM-DMT, Flip-OFDM, U-OFDM.



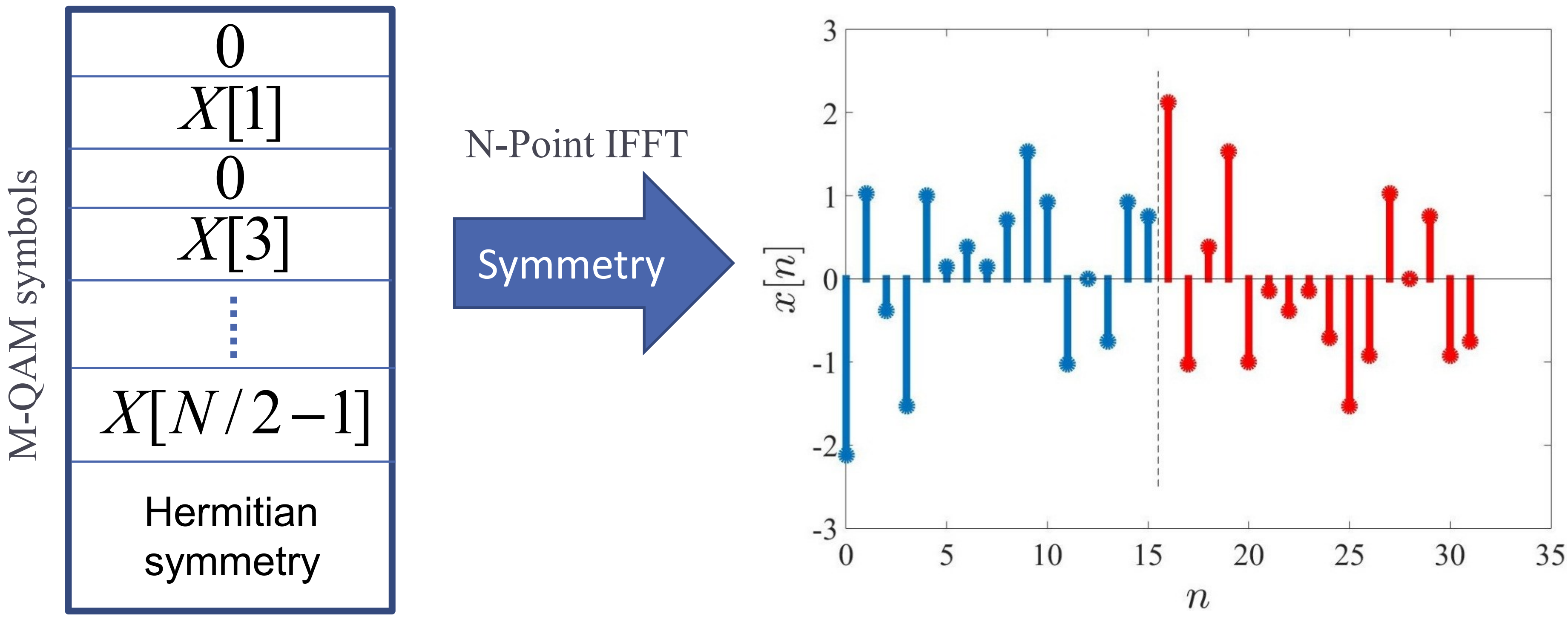


Asymmetrically clipped optical OFDM (ACO-OFDM) (Review)

ACO-OFDM Generation (1/2)

- Sub-carriers are loaded on the odd sub-carriers

$$x[n] = -x[n + N/2]$$



Clipping result in 3dB penalty compared to Bipolar OFDM

N is the size of the OFDM frame

ACO-OFDM Generation (2/2)

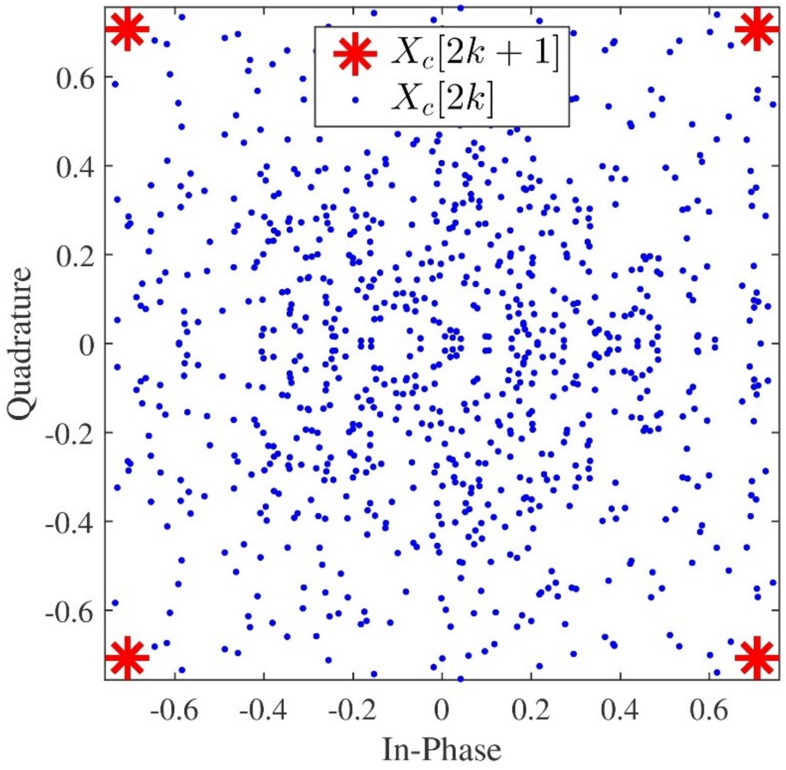
- Clipping distortion affect only the even-indexed sub-carriers [5]:

$$x^{c}(n) = \frac{x(n) + |x(n)|}{2}$$

Distortion term $|x(n)|$ has the property

$$|x(n)| = |x(n + N/2)|$$

Clipping distortion is orthogonal to the information



[5] D. Tsonev, S. Sinanovic, and H. Haas, “Complete Modelling of Nonlinear Distortion in OFDM-based Optical Wireless Communication,” *J. Lightw. Technol., vol. 31, no. 18, pp. 3064–3076, Sep. 15 2013.*

Enhanced ACO-OFDM

Spectral/Power efficiency problem

- The spectral efficiency of ACO-OFDM is half of the spectral efficiency of DCO-OFDM:

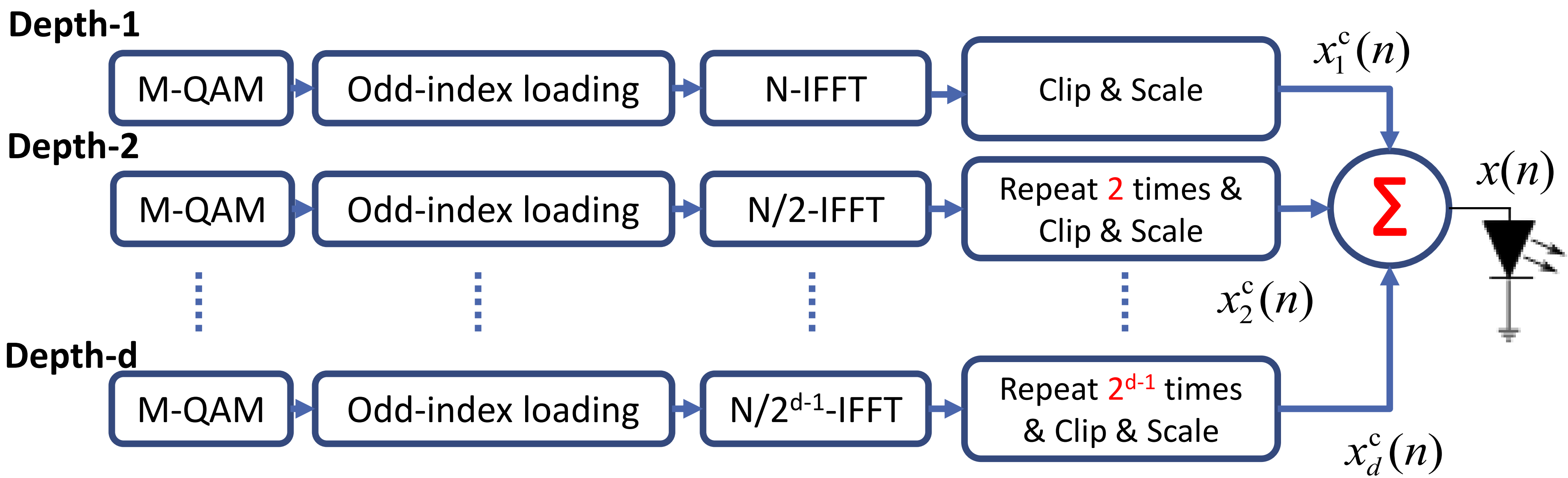
$$\eta_{\mathrm{ACO}} = \frac{\eta_{\mathrm{DCO}}}{2} = \frac{\log_2(M)N}{4(N + N_{\mathrm{CP}})}$$

- The performance of M-QAM DCO-OFDM is equivalent to the performance of M^2 –QAM ACO-OFDM, therefore, the performance of ACO-OFDM degrades as the spectral efficiency increases.

- For example: The BER performance of 32-QAM DCO-OFDM is equivalent to the BER performance of 1024-QAM ACO-OFDM.

System Design (eACO-OFDM Tx)

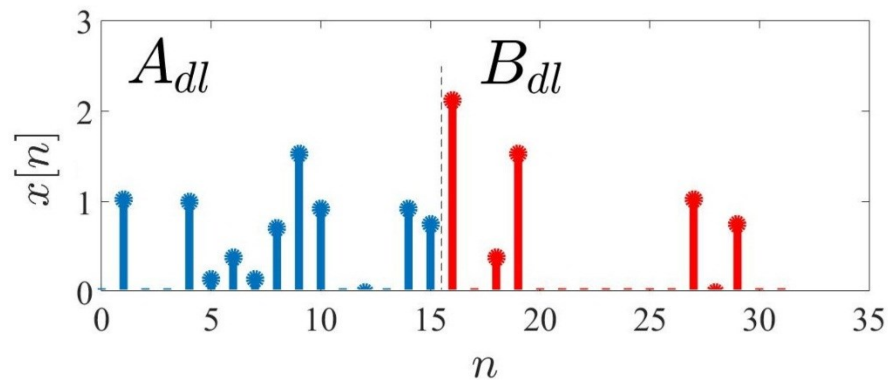
- Multiple information streams of ACO-OFDM can be combined as long as the Inter-Stream-Interference falls into the even-indexed subcarriers. $|x(n)| = |x(n+N/2)|$

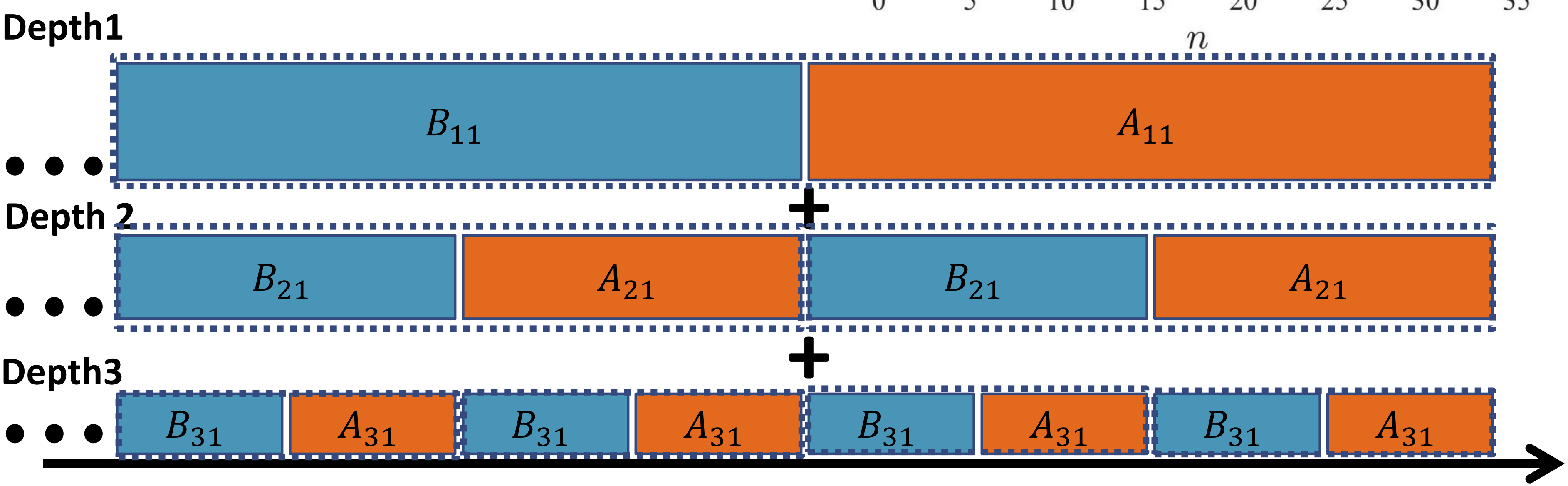


Cyclic prefixes are ignored in this illustration

System Design (eACO-OFDM waveforms)

- *Notations:* A_{dl} and B_{dl} are the first and second subframes of the l-th frame time domain ACO-OFDM waveform at depth-d.

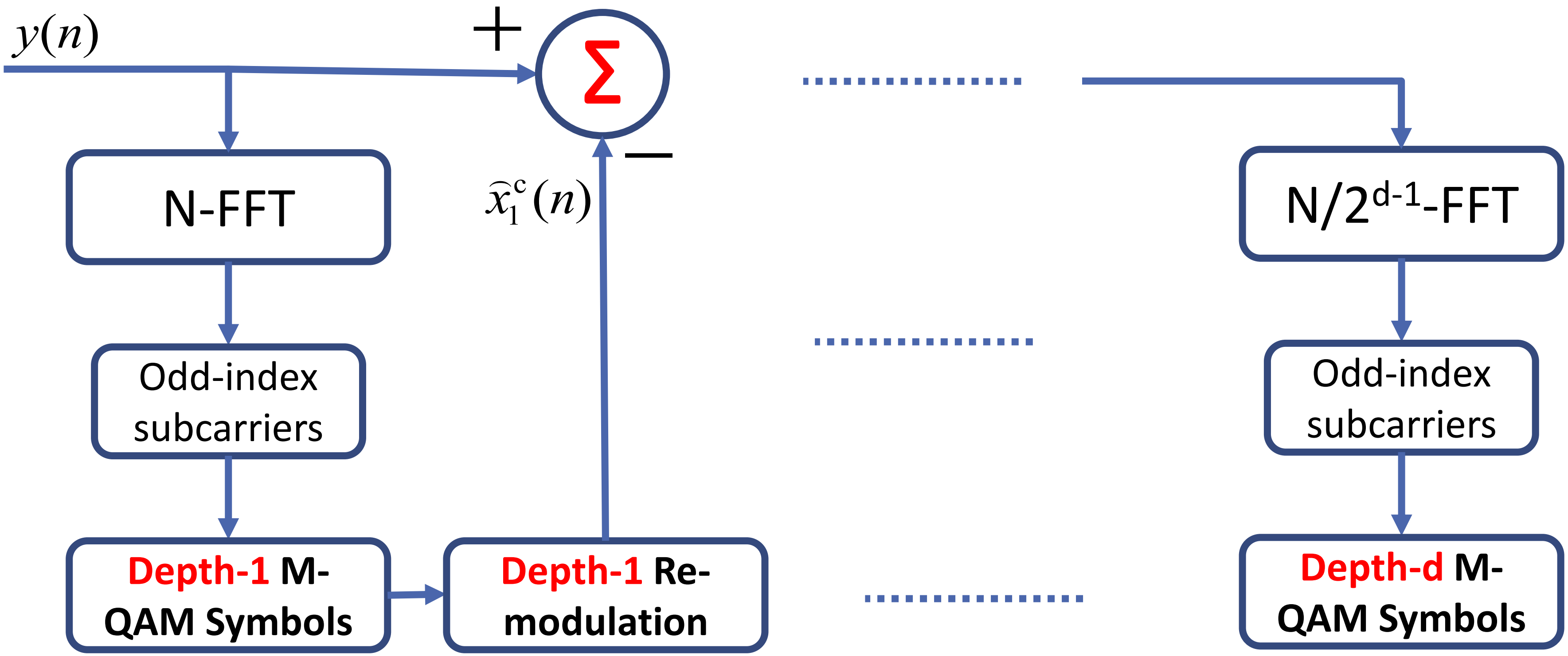




- All additional streams should have the symmetry: $|x(n)| = |x(n+N/2)|$

Cyclic prefixes are ignored in this illustration

System Design (eACO-OFDM Rx)



Spectral efficiency

- The spectral efficiency at each depth is:

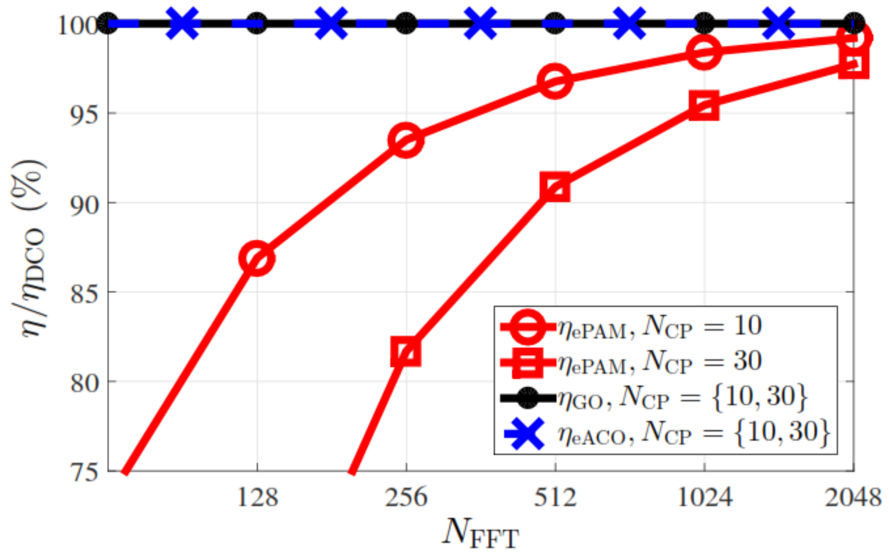
$$\eta_{\mathrm{ACO}}(d) = \frac{\log_2(M_d)N}{2^{d+1}(N+N_{\mathrm{CP}})} \text{ bits/s/Hz},$$

- The spectral efficiency of eACO-OFDM is:

$$\eta_{\mathrm{eACO}}(D) = \sum_{d=1}^{D} \eta_{\mathrm{ACO}}(d)$$

- In order to match the spectral efficiency of DCO-OFDM, the constellation sizes at each depth should follow the constraint:

$$\log_2(M_{\mathrm{DCO}}) = \sum_{d=1}^{D} \frac{\log_2(M_d)}{2^d},$$



The ratio of the spectral efficiency of eACO-OFDM to the spectral efficiency of DCO-OFDM

Performance Comparison

Theoretical Performance Model

- Theoretical performance bound has been established for BER at depth-d:

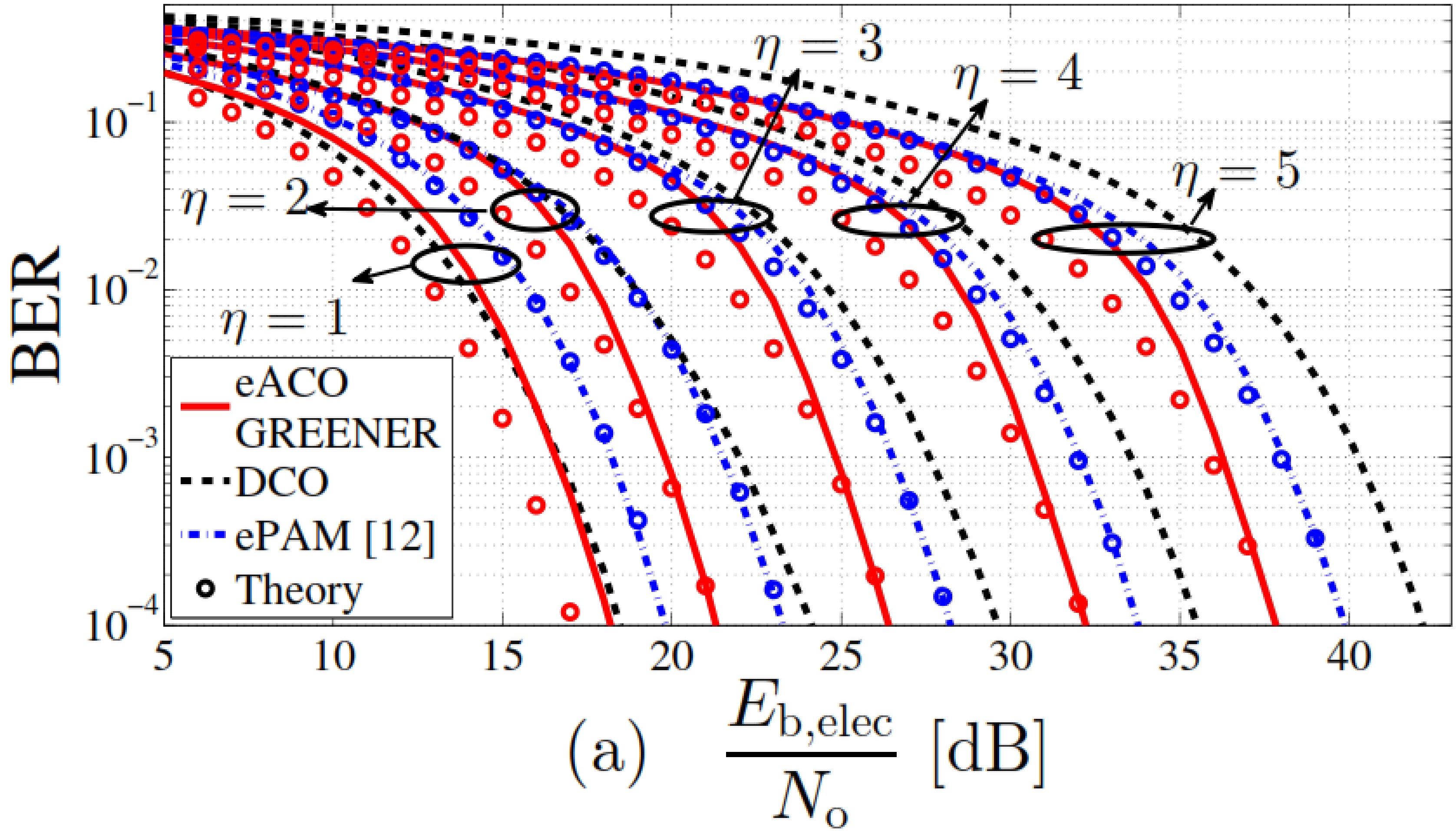
$$\mathrm{BER}^{\mathrm{eACO}}_{(D,d,\underline{\gamma})} \cong \frac{4}{\log_2(M_d)}\left(1-\frac{1}{\sqrt{M_d}}\right)\times\sum_{l=1}^{R}\sum_{k=1}^{N}\mathrm{Q}\left((2l-1)\sqrt{\frac{3|\Lambda_k|^2 E_{\mathrm{b,elec}}\log_2(M_d)}{2\alpha^{\mathrm{eACO}}_{\mathrm{elec}}(D,d)(M_d-1)N_{\mathrm{o}}}}\right)$$

where $E_{\mathrm{b,elec}}/N_o$ is the electrical SNR of real OFDM, $R=\min\left(2,\sqrt{M_d}\right)$, $\mathbf{\Lambda}$ is an $N\times N$ diagonal matrix with the Eigen values of the channel, and $\alpha^{\mathrm{eACO}}_{\mathrm{elec}}(D,d)$ is the eACO-OFDM SNR penalty per bit compared to ACO-OFDM:

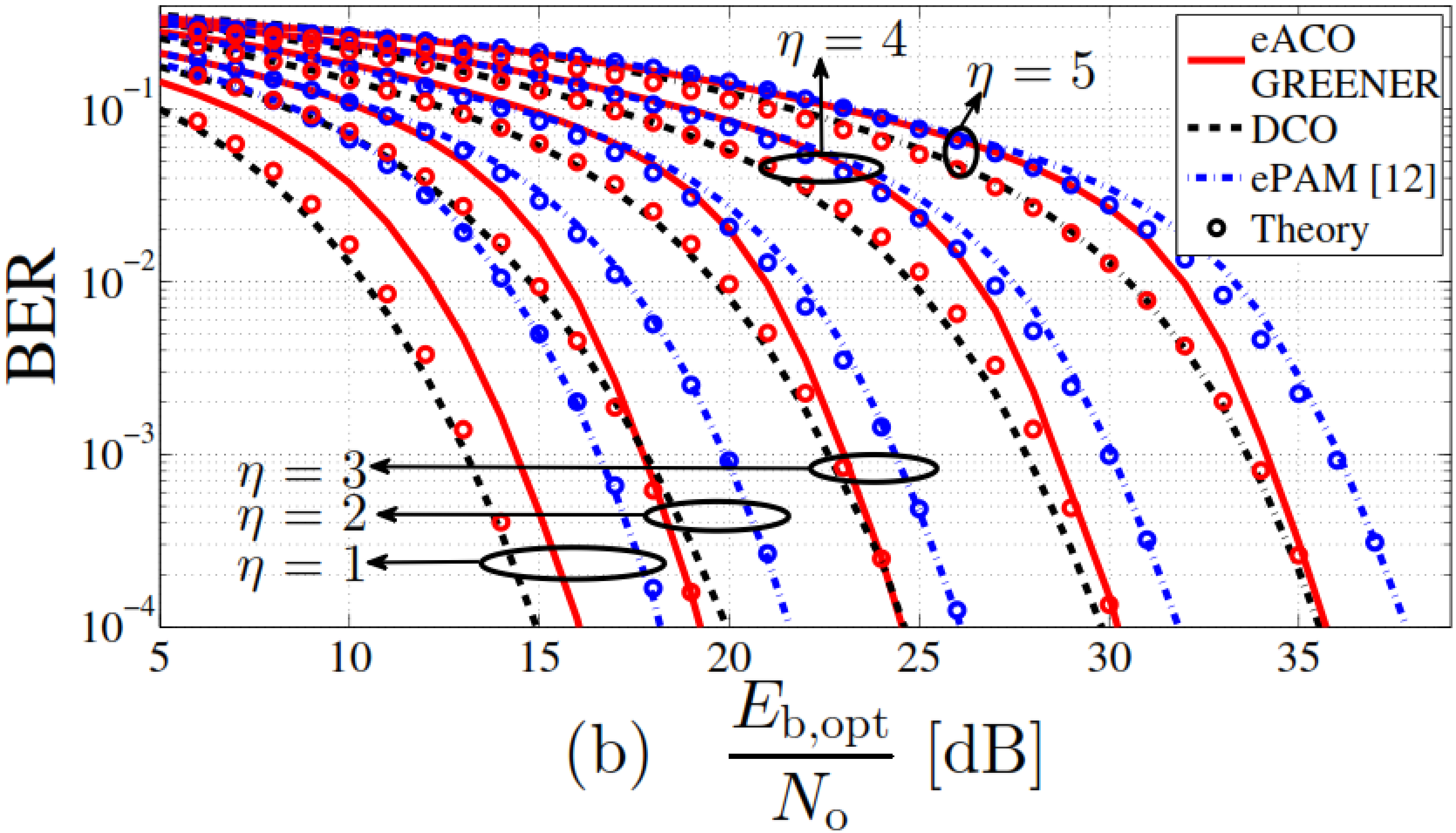
The average BER can derived by taking into account the spectral contribution of each depth ξ_d:

$$\mathrm{BER}^{\mathrm{eACO}} \cong \sum_{d=1}^{D}\left(\mathrm{BER}^{\mathrm{eACO}}_{(D,d,\underline{\gamma})}\xi_d\right)$$

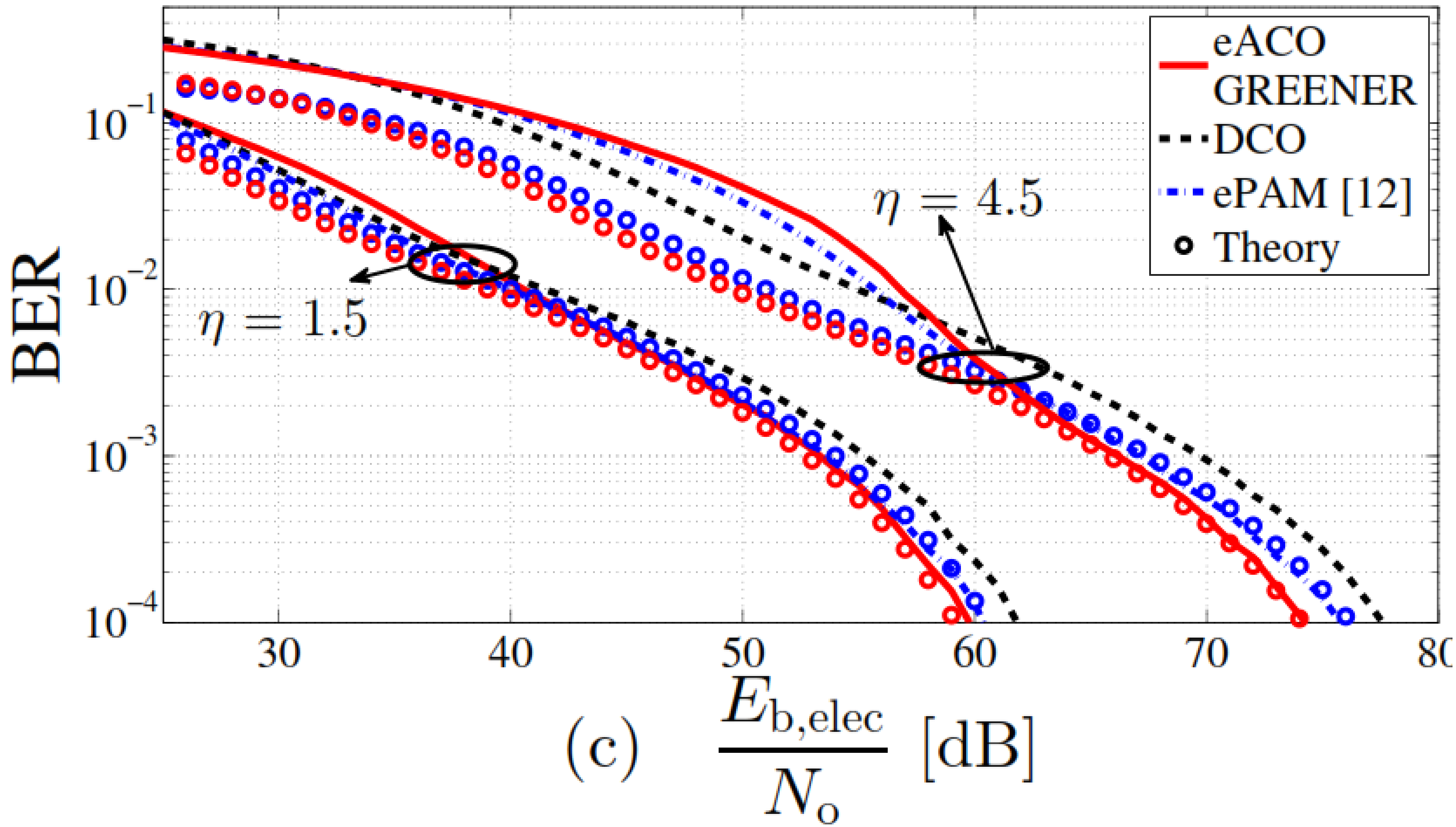
Electrical Energy Efficiency (Flat ch.)



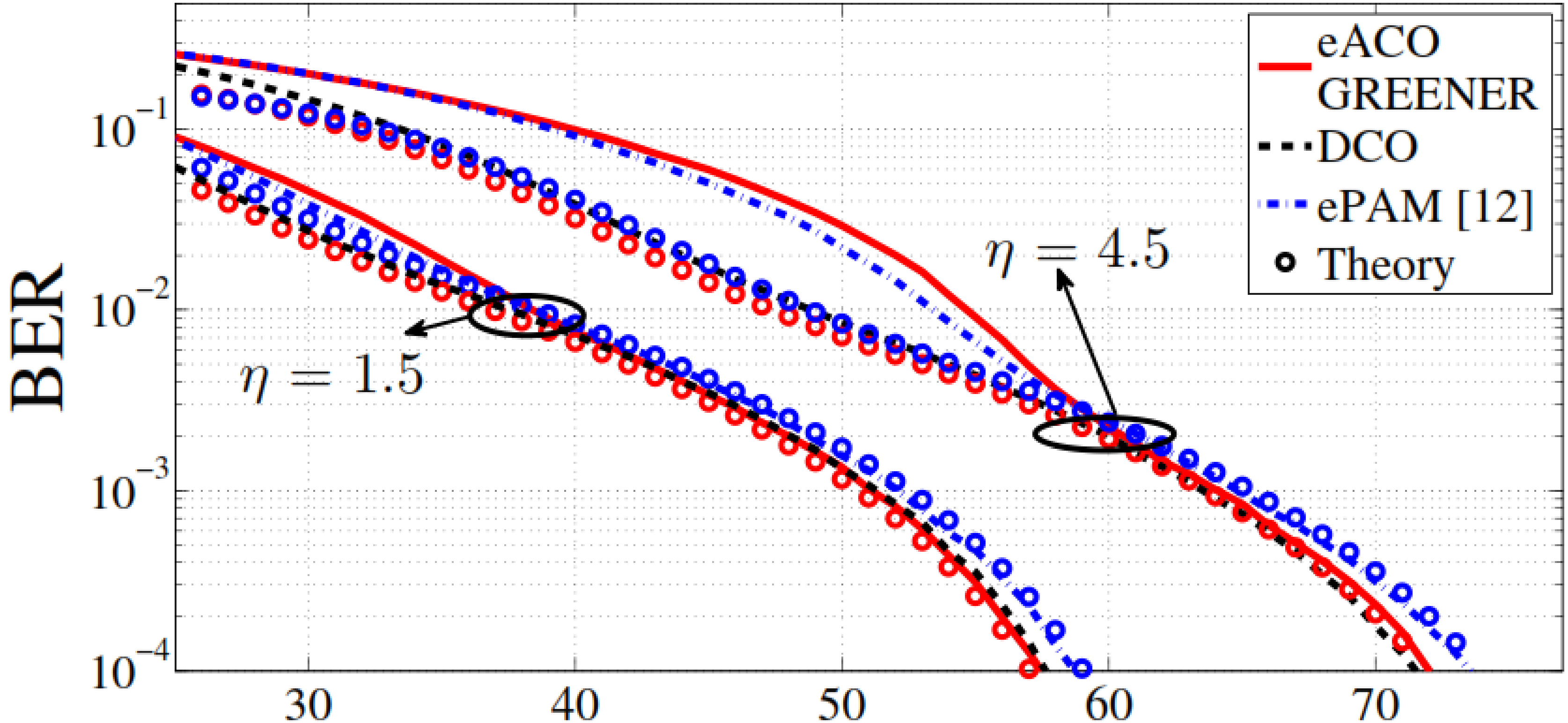
Optical Power Efficiency (Flat ch.)



Electrical Energy Efficiency (Nonflat ch.)



Optical Power Efficiency (Nonflat ch.)



(d) $\frac{E_{\mathrm{b,opt}}}{N_{\mathrm{o}}}$ [dB]

Conclusion

- The ACO-OFDM modulation scheme BER performance degrades as the spectral efficiency increases.
- The enhanced ACO-OFDM proposes a significant electrical energy savings at an equivalent optical energy dissipation (Illumination).
- The optimal combinations of constellation sizes at each depth and their corresponding scaling factors have been determined at different spectral efficiencies.
- The modulation scheme is not limited to OWC only, but applies to any IM/DD system.

Thank you!!!

Questions?