Li-Fi modulation and networked Li-Fi attocell concept

Tutorial

Professor Harald Haas

23 December, 2013

Contributions by…

- Svilen Dimitrov,
- Thilo Fath,
- Irina Stefan,
- Dobroslav Tsonev,
- Stefan Videv,
- Wasiu Popoola,
- Enrique Poves,
- Harald Burchardt,
- Sinan Sinanovic
- Nikola Serafimovski,
- Abdelhamid Younis,
- Mostafa Afgani,
- Cheng Chen,
- Yichen Li,
- John Fakidis,

Wireless data is growing exponentially …

YouTube

- In 2011, ~ 140 views for every person on earth (over 1 Trillion views
- More video is uploaded to YouTube in one month than the 3 major US networks created in 60 years
- 72 hours of video are uploaded to YouTube every minute
- 25% of global YouTube views come from mobile devices

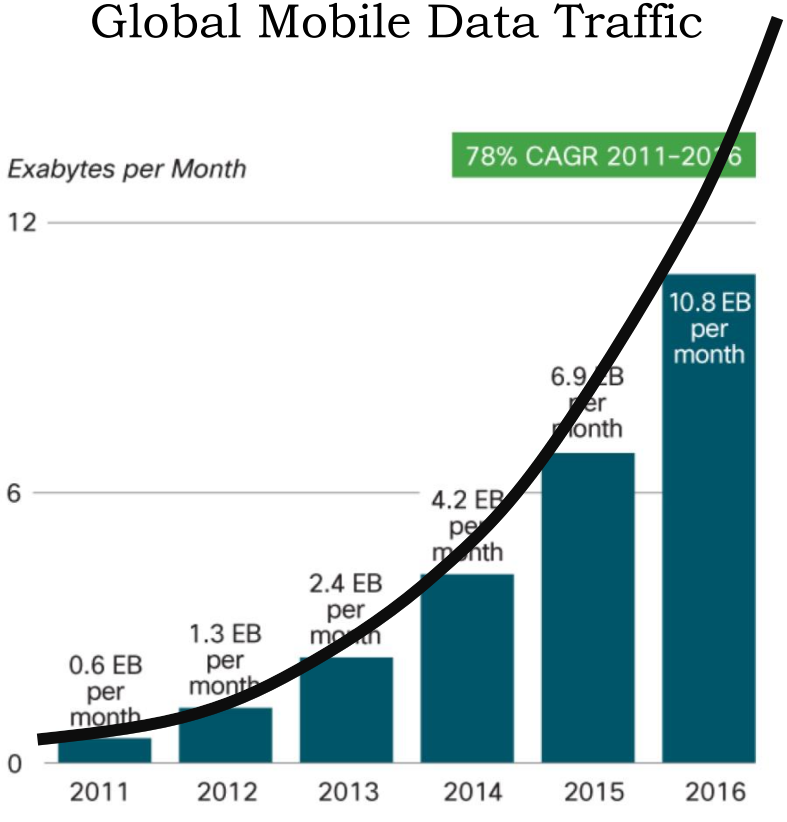
Source - http://www.youtube.com/t/press_statistics

Internet video traffic is growing at 48% CAGR

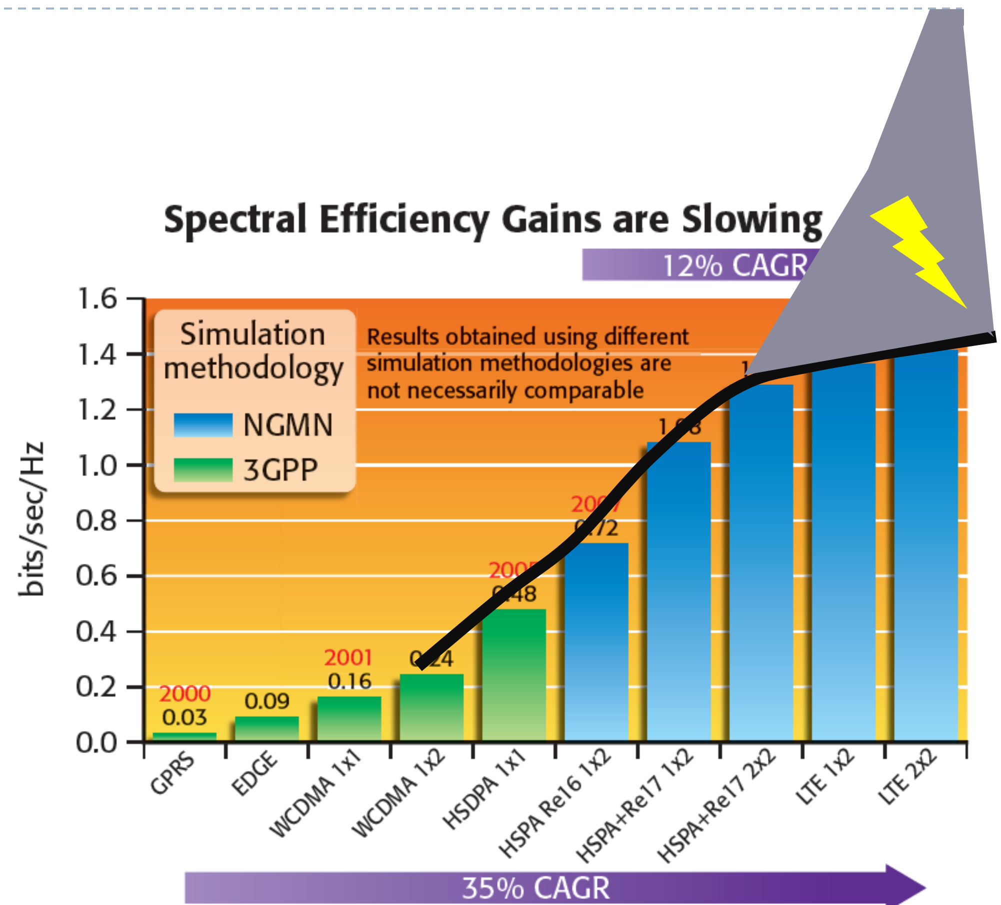
Source - Cisco Visual Networking Index: Forecast and Methodology, 2010-2015

… leading to RF Spectrum Shortage

Global Mobile Data Traffic



Source: Cisco VNI Mobile, 2012

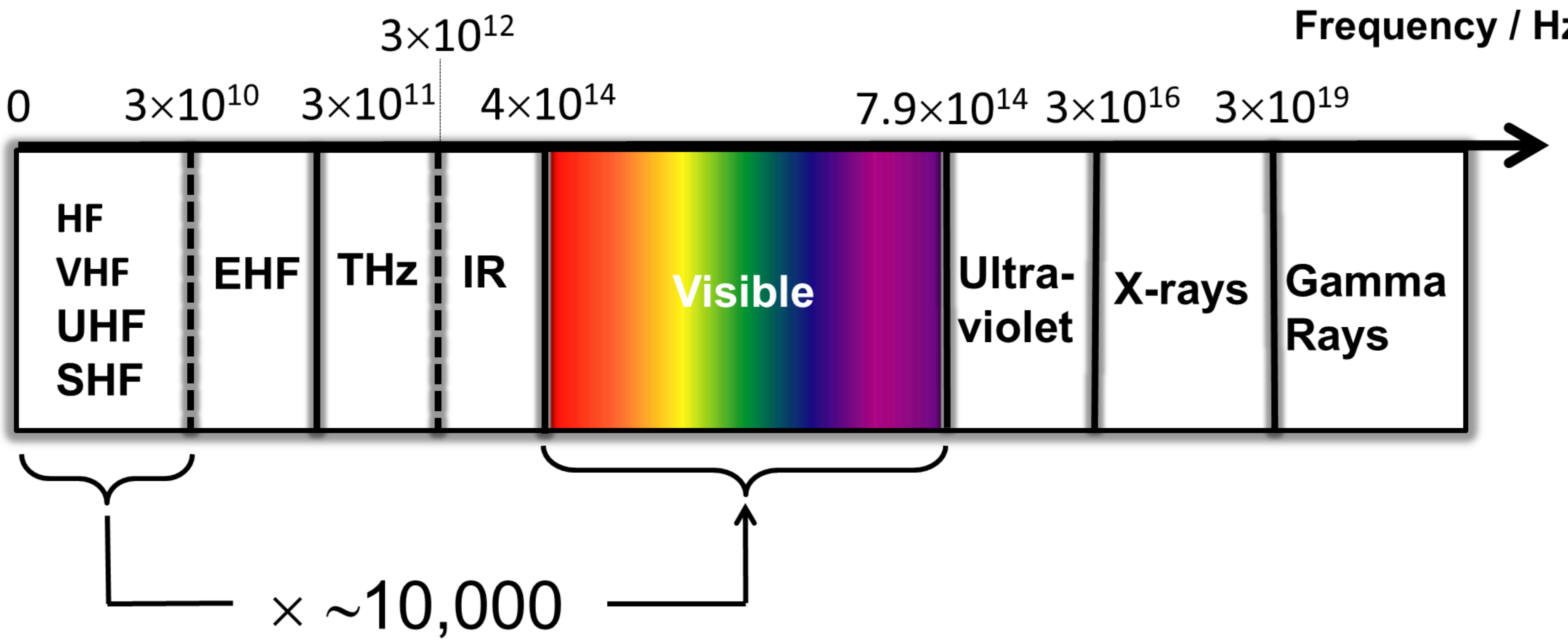


Source: Qualcomm

How fix the problem?

1. Identify new spectrum, and/or
2. Enhance spectrum reuse (smaller cells)

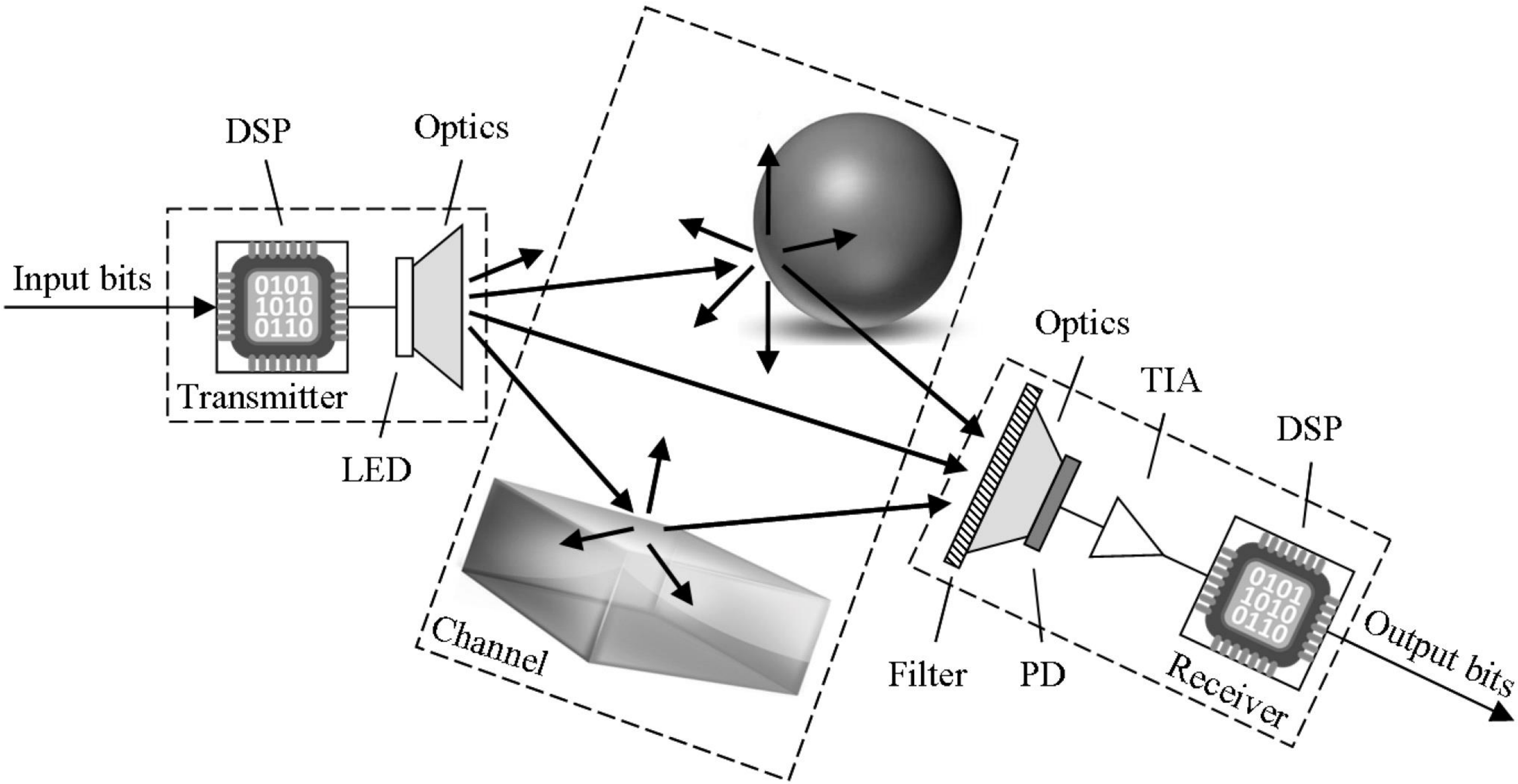
The electromagnetic spectrum



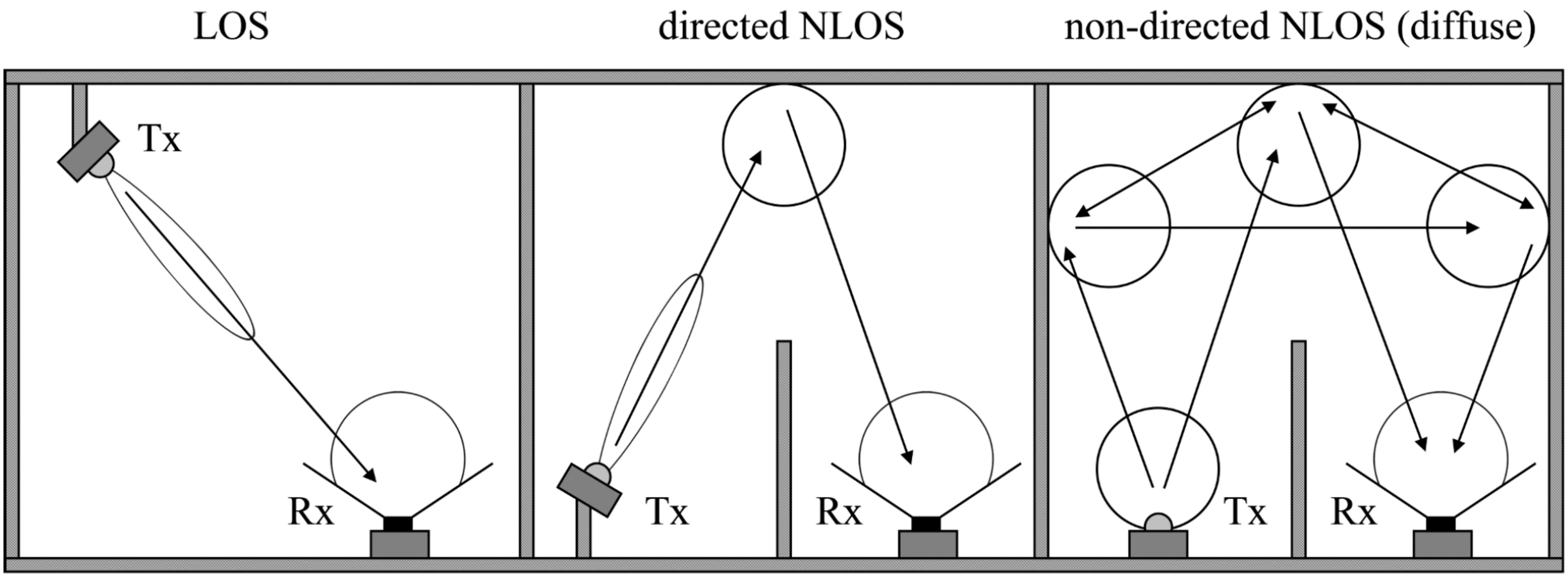

Li-Fi
0 1 1 1 0 0 0 1 1 0 1 0 1 0 0 0 0 1 0
1 1 0 0 0 1 1 0 1 0 1 0 0 0 0 1 0

Optical Attocell Concept

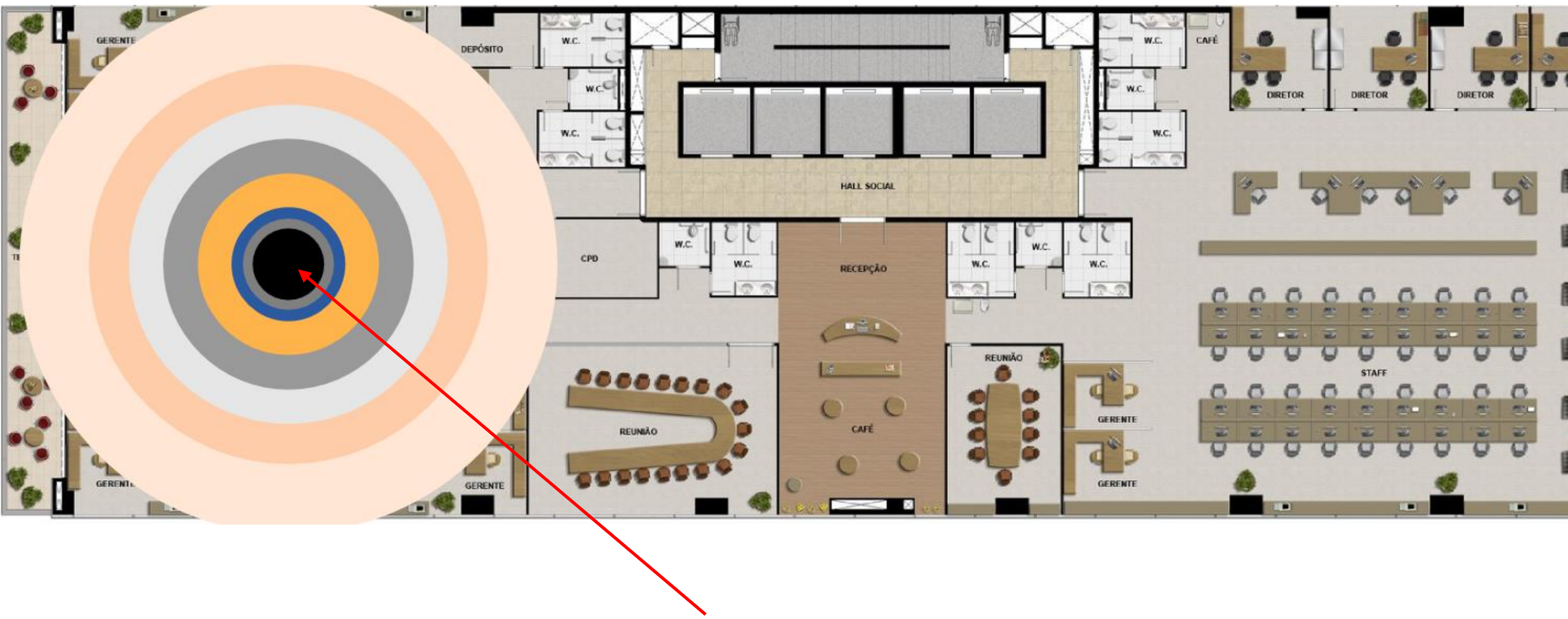
Link-Level Communication System



Communication Scenarios

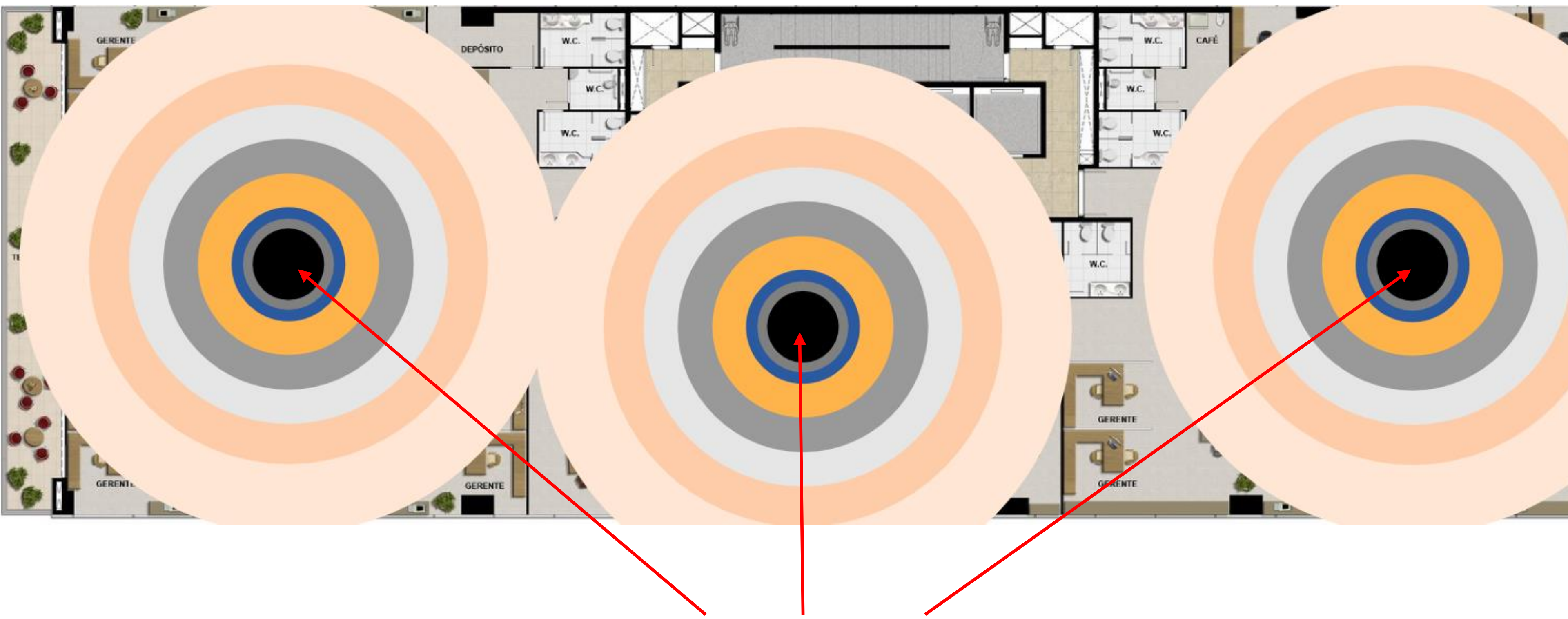


State-of-the-Art: Wi-Fi



Wi-Fi Router Location

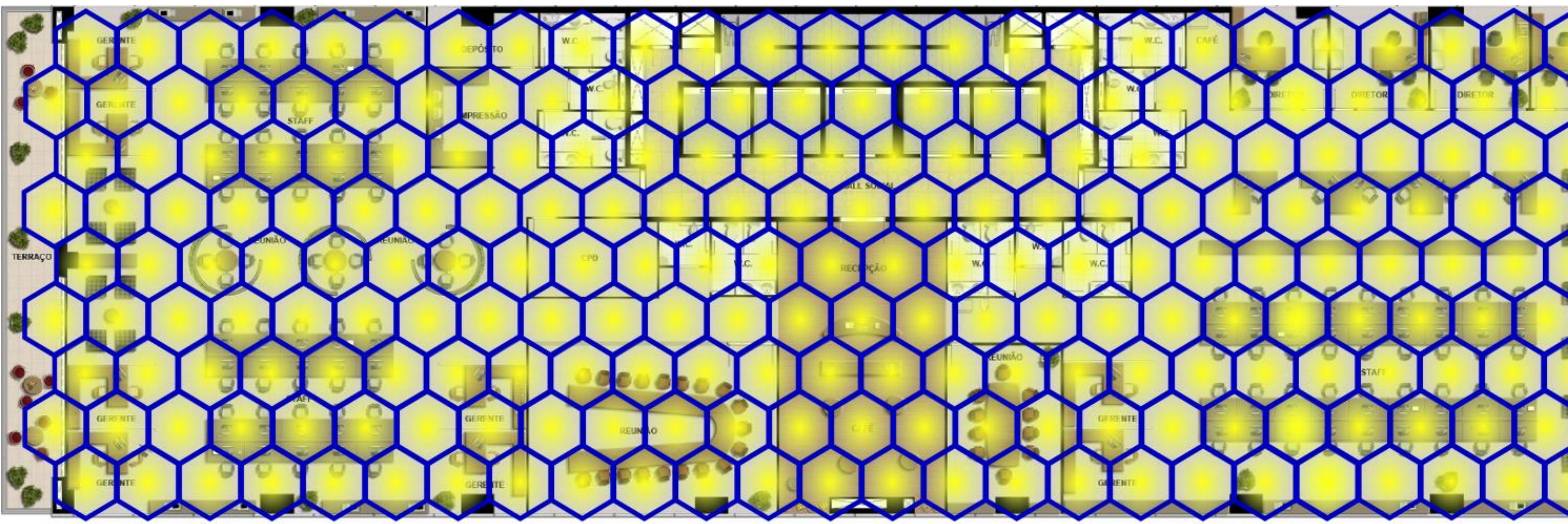
State-of-the-Art: Wi-Fi



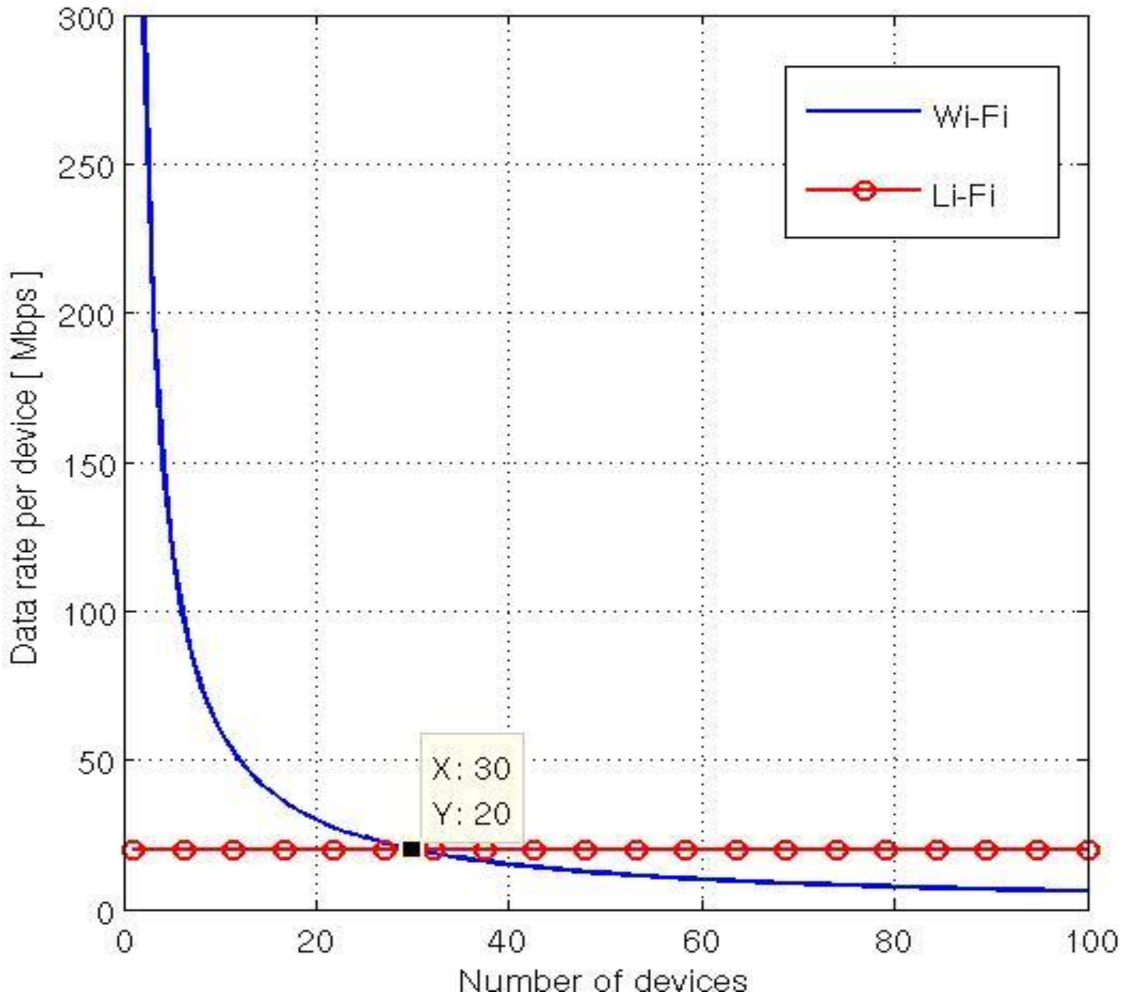
Wi-Fi Router Location


GERENTE
GERENTE
STAFF
TERRAÇO
REUNIÃO
REUNIÃO
STAFF
GERENTE
GERENTE
DEPÓSITO
IMPRESSÃO
W.C.
W.C.
W.C.
HALL SOCIAL
CPD
W.C.
W.C.
RECEPÇÃO
CAFÉ
REUNIÃO
GERENTE
GERENTE
W.C.
W.C.
W.C.
W.C.
W.C.
W.C.
CAFÉ
DIRETOR
DIRETOR
DIRETOR
REUNIÃO
GERENTE
GERENTE
STAFF

Optical Attocell Network

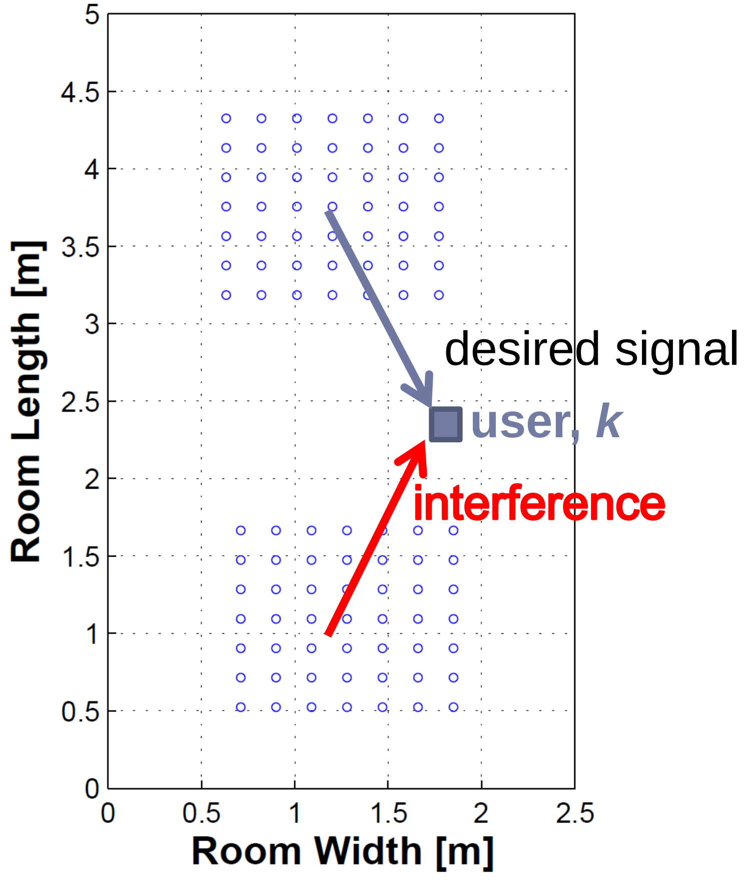


Data rates per device



- Space per desk 4 m^2
- 100 employees per floor
- Assume a uniform distribution of employees
- 20m x 20m floor = 400 m^2
- Area can be covered by a single Wi-Fi AP
- Each Li-Fi AP can cover around 4 m^2
- Wi-Fi data rate 600 Mbps
- Li-Fi data rate 20 Mbps

Interference Scenario



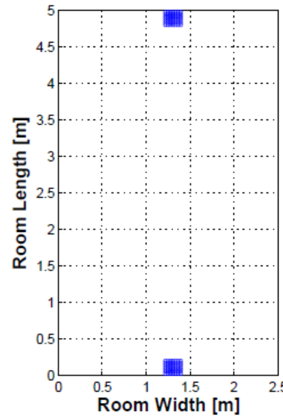
$$A_e = \frac{\sum_{k=1}^{K_u} W_k \log_2(1 + \gamma(u_k))}{W A_r}$$

I. Stefan, et al., *VTC 2013-Spring*, 2013

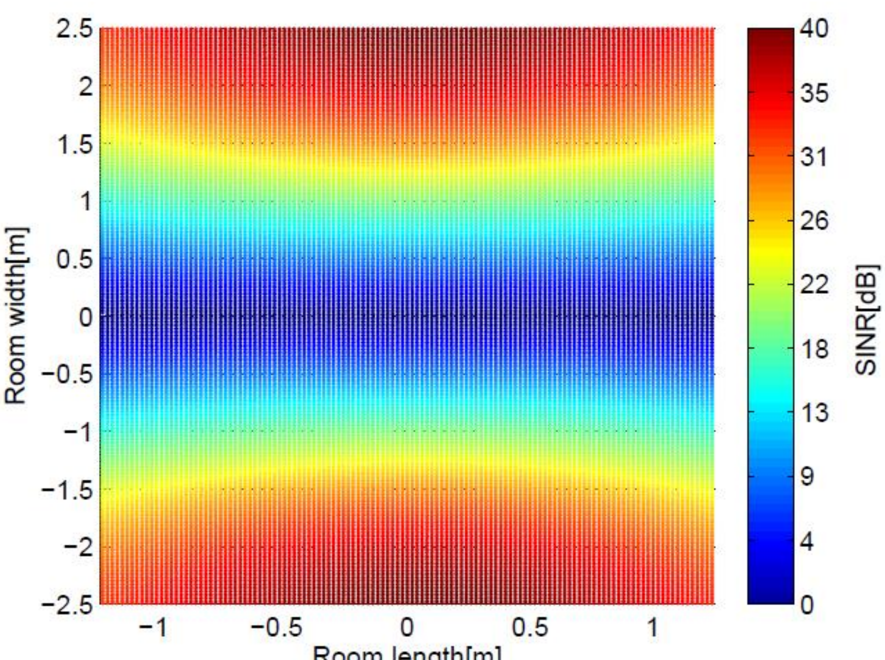
Optimisation Framework

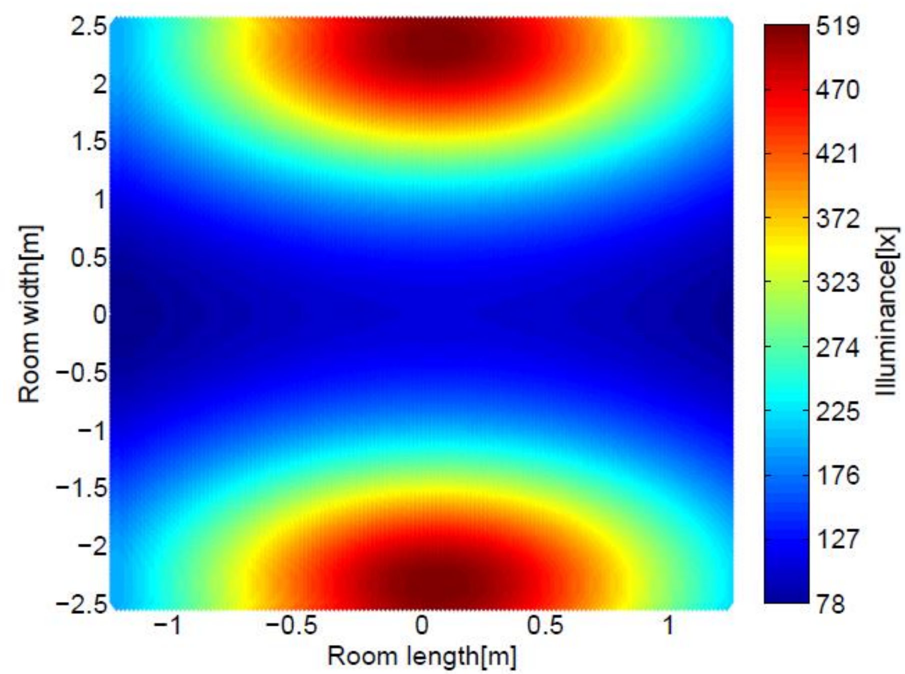
Find variables:	$x_{c1},\ y_{c1},\ x_{c2},\ y_{c2}, \ldots, x_{cL},\ y_{cL},\ d$
Criteria:	$\max \mathrm{E}[A_e]$
Constraints:	$\frac{-\text{Length.Room}}{2} < x_{c1}, x_{c2}, \ldots, x_{cL} < \frac{\text{Length.Room}}{2}$ $\frac{-\text{Width.Room}}{2} < y_{c1}, y_{c2}, \ldots, y_{cL} < \frac{\text{Width.Room}}{2}$ $0 < d < \frac{\min(\text{Width.Room,Length.Room})}{N_{\text{led}}}$ $\mathrm{E_h} > 400\,\mathrm{lx}$ for at least 50% of the room area and $\mathrm{E_h} > 100\,\mathrm{lx}$ for the rest of the room

Rx FOV 85° - without lighting constraint



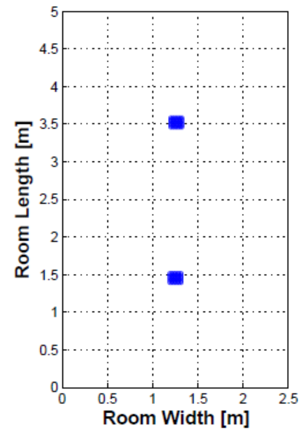
$1.14\,\mathrm{b/s/Hz/m^2}$



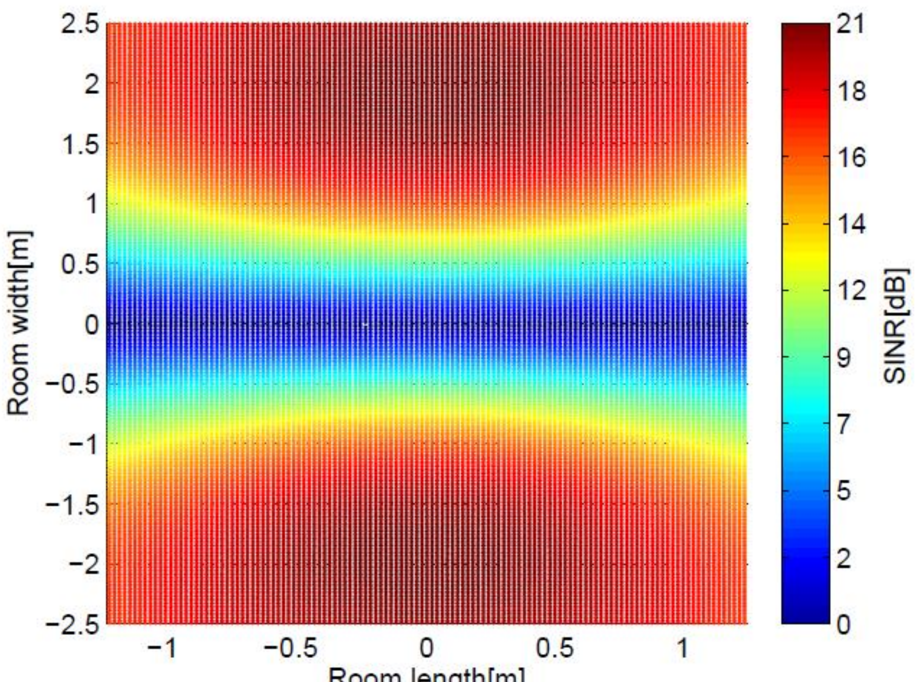


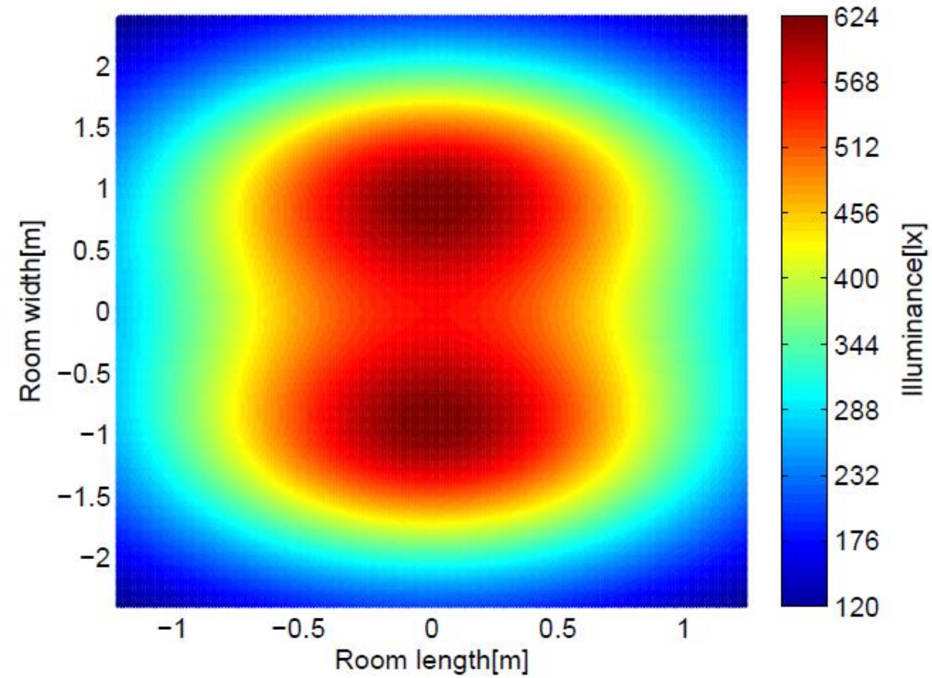
(b)

Rx FOV 85° - with lighting constraint

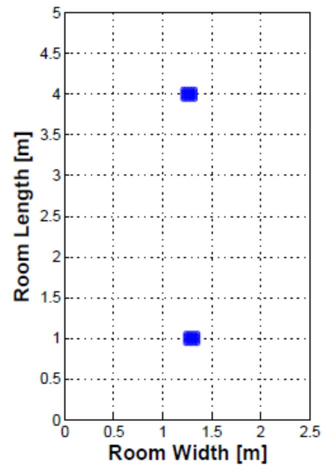


0.76 b/s/Hz/m^2

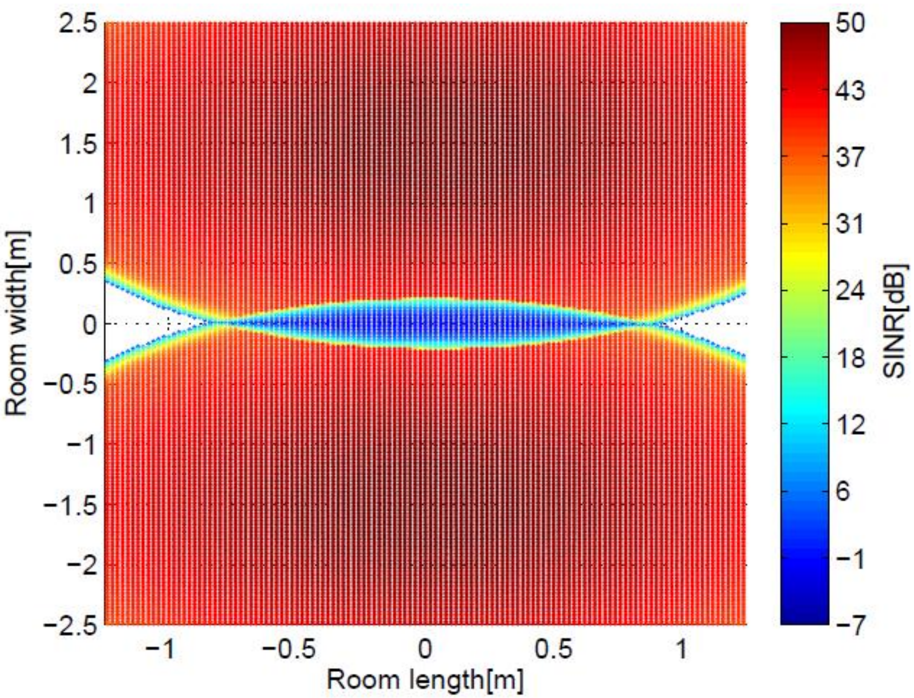


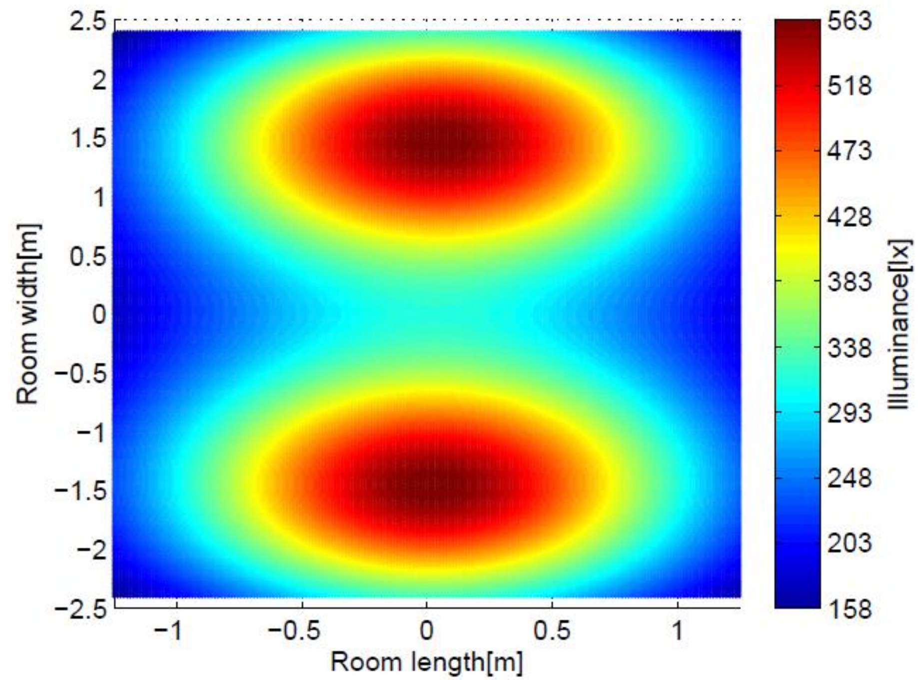


Rx FOV 45° - without lighting constraint

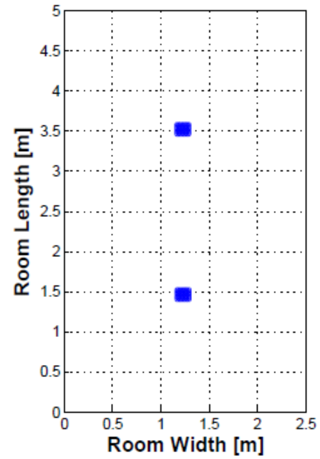


$2.24\ \mathrm{b/s/Hz/m^2}$

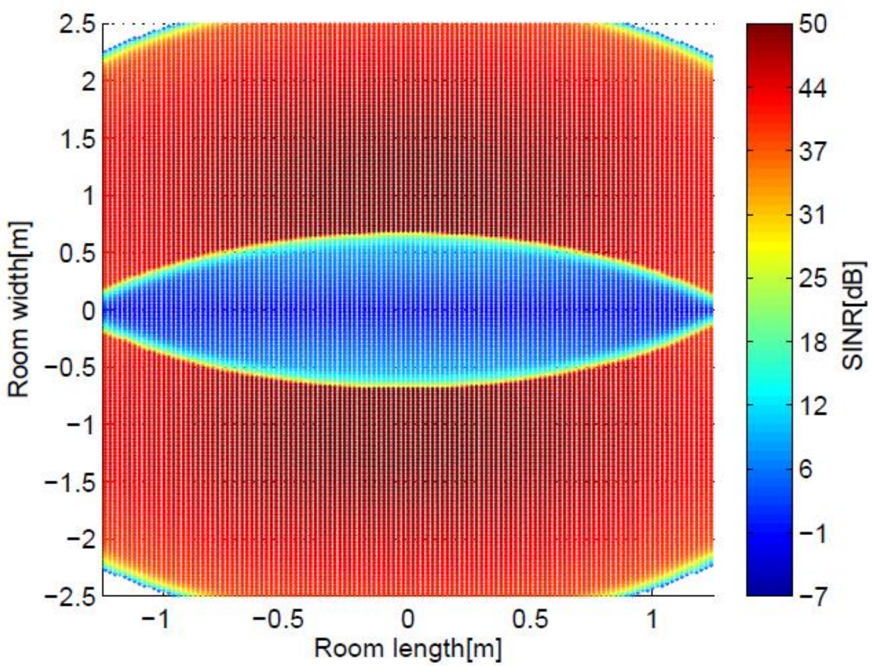


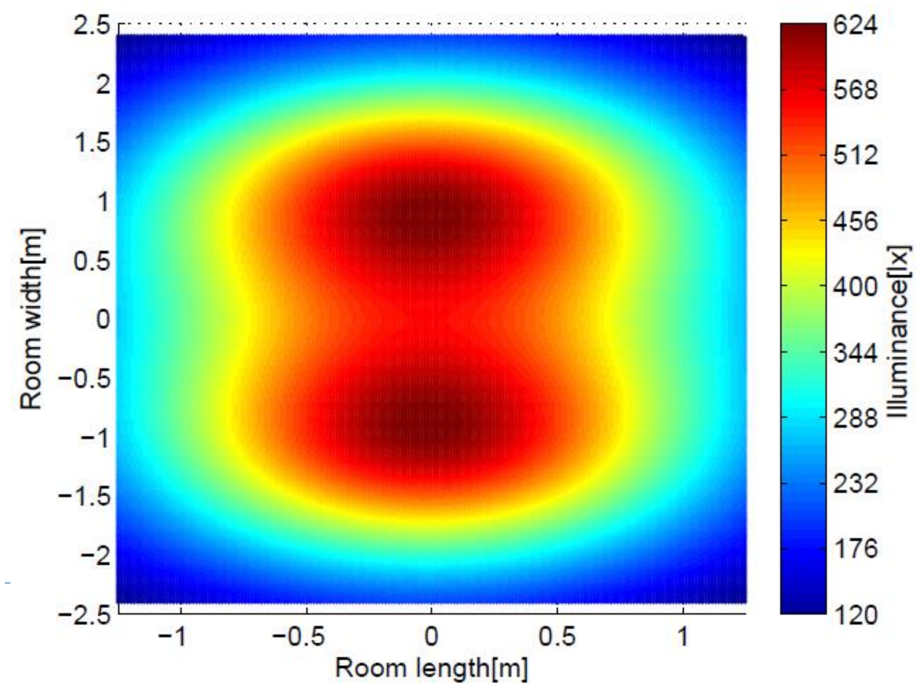


Rx FOV 45° - with lighting constraint



$1.918\,\mathrm{b/s/Hz/m^2}$



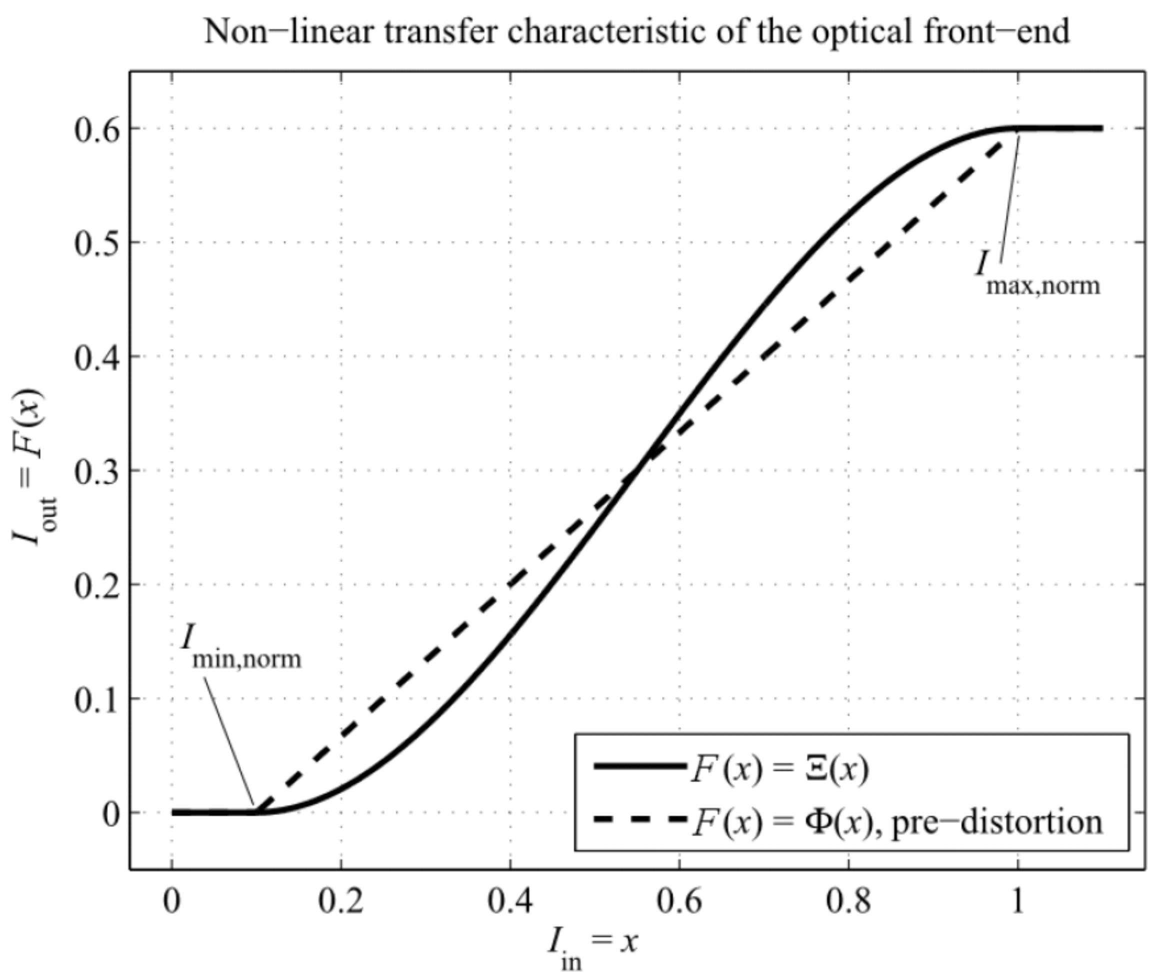


Digital Modulation

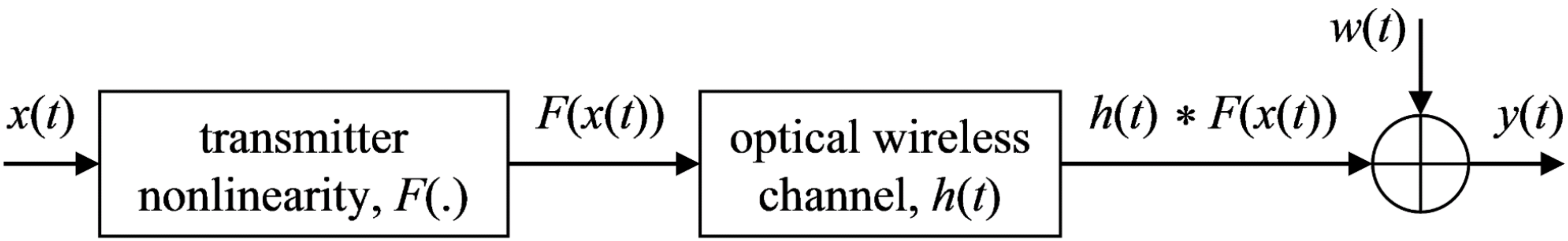
Key differences to RF

System	Information	Signal	
RF	carried on electric field	complex valued	bipolar
Incoherent Optical	carried on optical intensity	real valued	unipolar non-negative

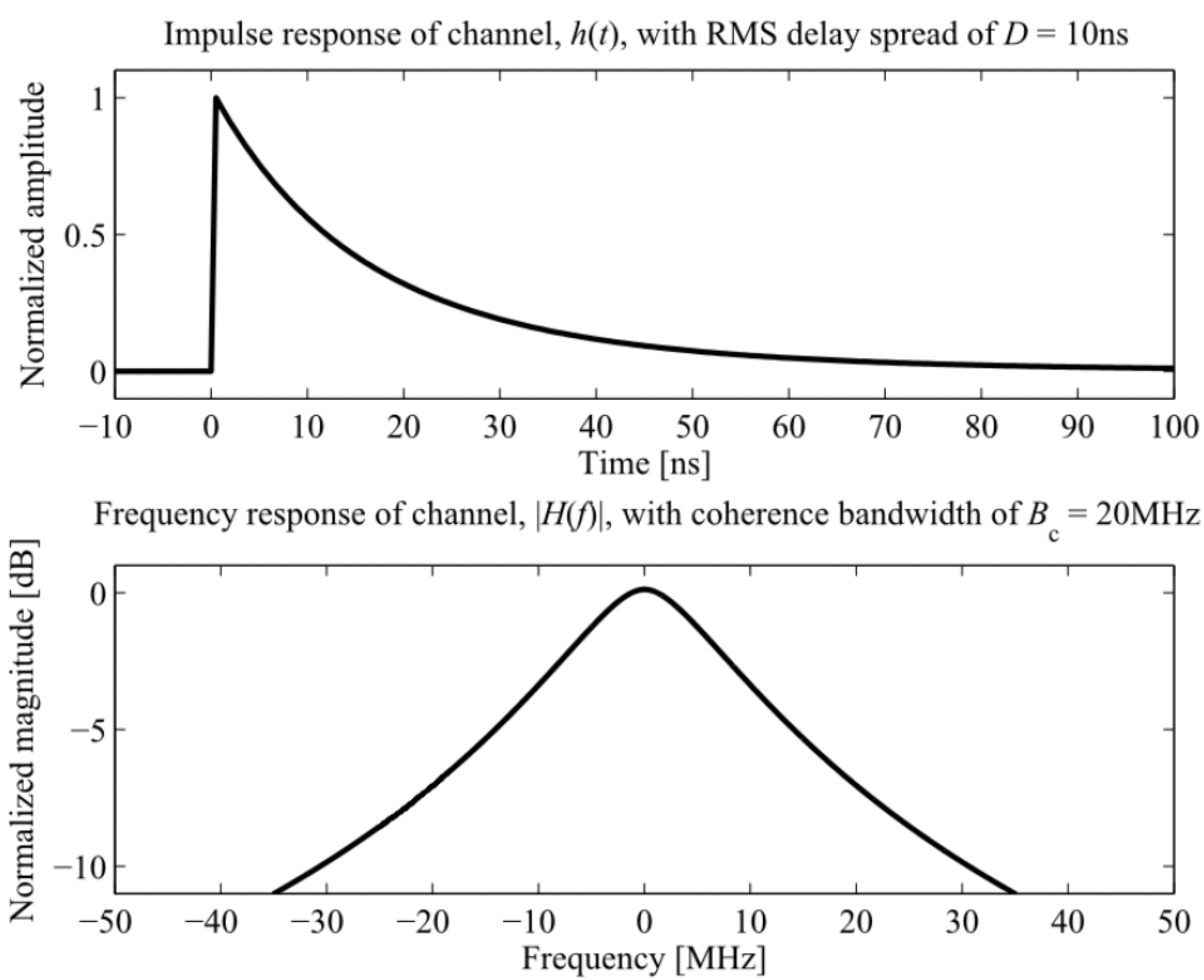
Non-linear Characteristic



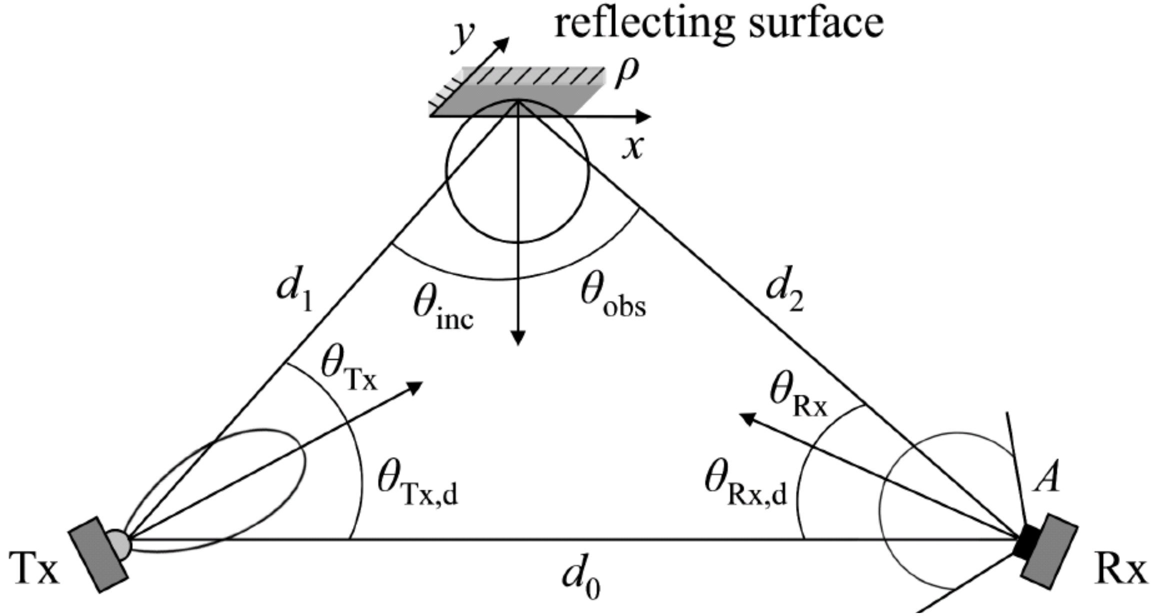
Optical channel



Coherence Bandwidth of Channel



Path loss



$$P_R = \frac{n+1}{2\pi} P_T \cos^n(\theta_{Tx,d}) \frac{A}{d_0^2} \cos(\theta_{Rx,d}) \mathrm{rect}(\theta_{Rx,d})$$
$$+ \frac{n+1}{2\pi} P_T \int_x \int_y \int_\theta \int_\phi \cos^n(\theta_{Tx}) \frac{\rho \mathcal{R}(\theta, \phi)}{d_1^2}$$
$$\times \frac{A}{d_2^2} \cos(\theta_{Rx}) \mathrm{rect}(\theta_{Rx}) \, dx \, dy \, d\theta \, d\phi \; .$$

bi-directional reflectance distribution function (BRDF)

Path loss, cont'd

Optical path gain

$$g_{\mathrm{h(opt)}}(\lambda) = P_{\mathrm{R}}(\lambda) S_{\mathrm{PD}}(\lambda) G_{\mathrm{TIA}} / (P_{\mathrm{T}}(\lambda)\sqrt{r_{\mathrm{load}}})$$

Electrical path gain

$$g_{\mathrm{h(elec)}} = \frac{1}{B}\int_{-B/2}^{B/2} |H(f)|^2 \, df = g_{\mathrm{h(opt)}}^2 \frac{1}{B}\int_{-B/2}^{B/2} |H_{\mathrm{norm}}(f)|^2 \, df$$

Path loss

Detector area

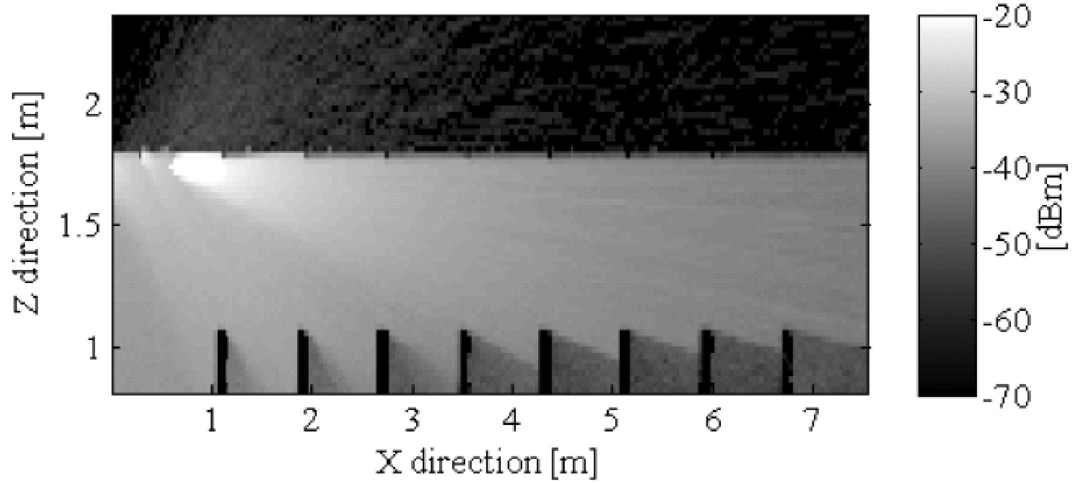
distance

$$\mathrm{PL}(d) = 10\log_{10}\left(\frac{P_{\mathrm{T}}}{E(d_{\mathrm{ref}})A_0}\right) - 10\log_{10}\left(\frac{A}{A_0}\right) + 10\zeta\log_{10}\left(\frac{d}{d_{\mathrm{ref}}}\right) + \xi$$

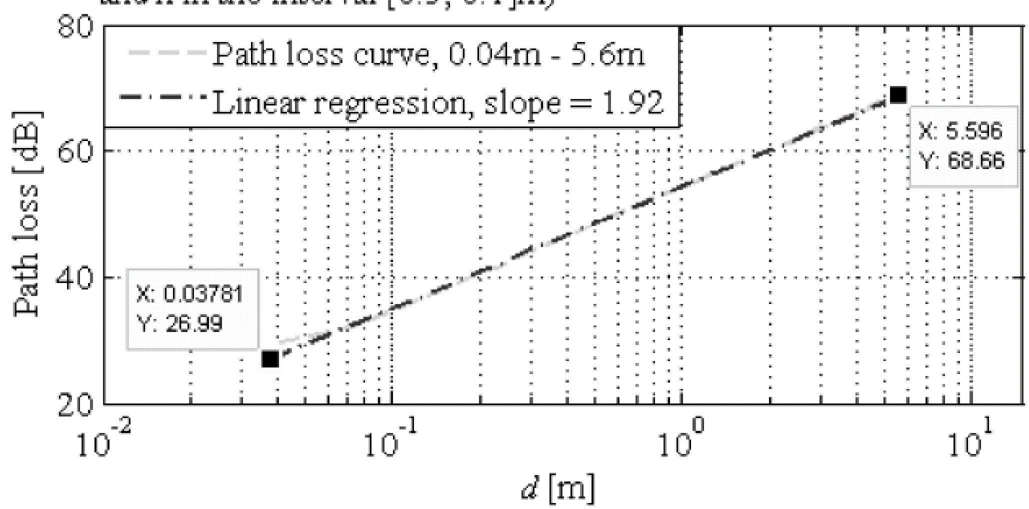
Irradiance

Example: Aircraft cabin / LOS

Received power in the vertical XZ plane along path 4 (y = 6m), backward observer

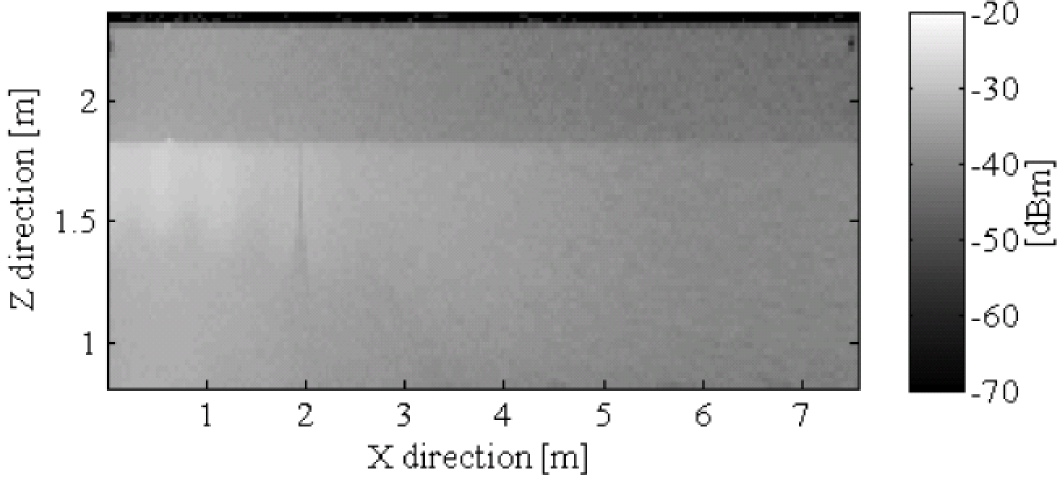


LOS path loss exponent along path 4 (y = 6m, z = 1.7m, and x in the interval [0.5, 6.1]m)

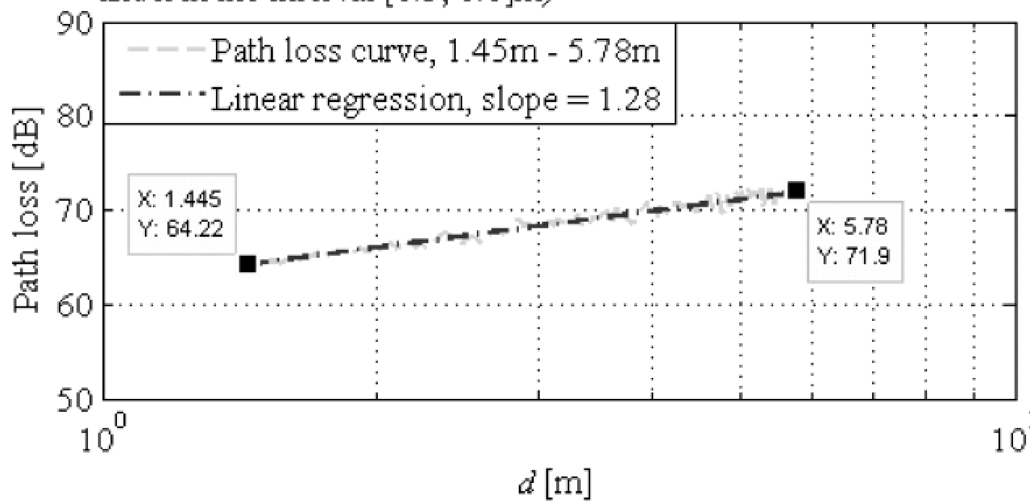


Example: Aircraft cabin / NLOS

Received power in the vertical XZ plane along path 2 (y = 2m); sum of back, front, left and right

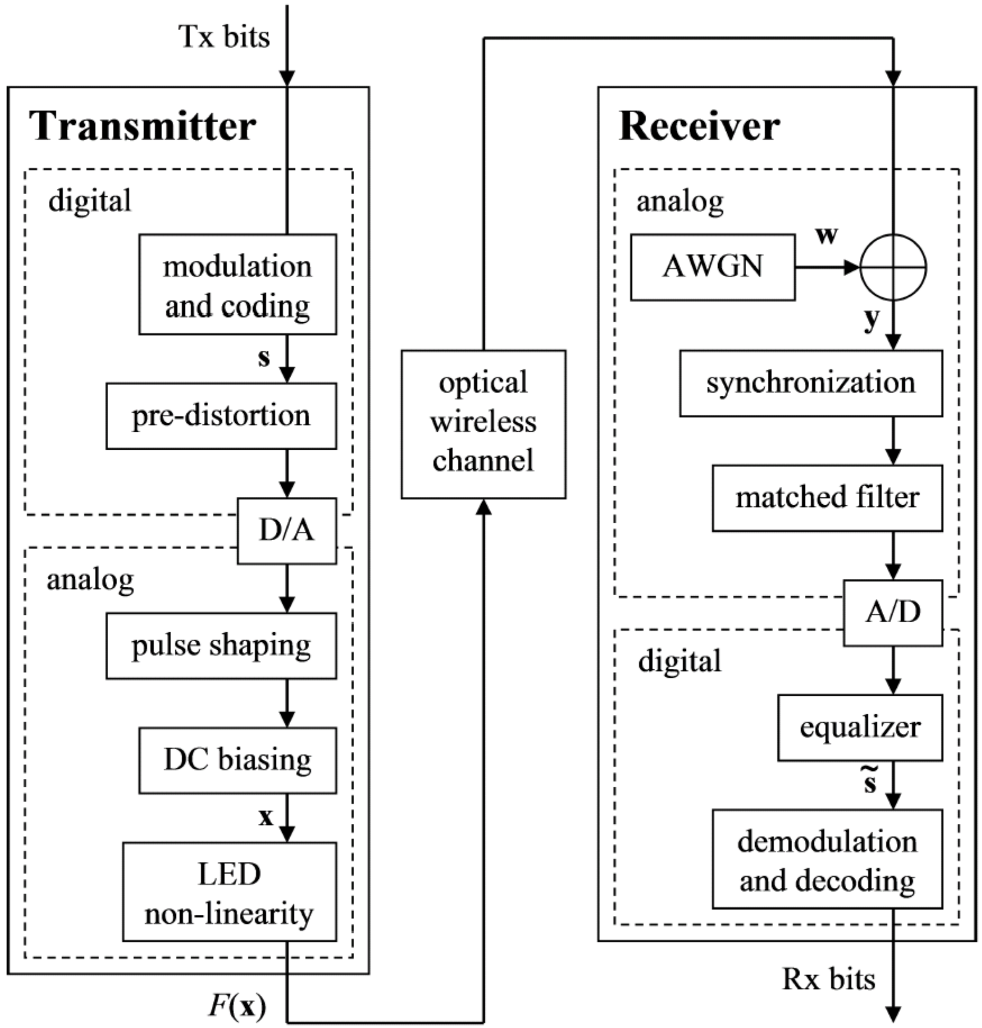


NLOS path loss exponent along path 2 (y = 2m, z = 2m, and x in the interval [0.5, 6.1]m)



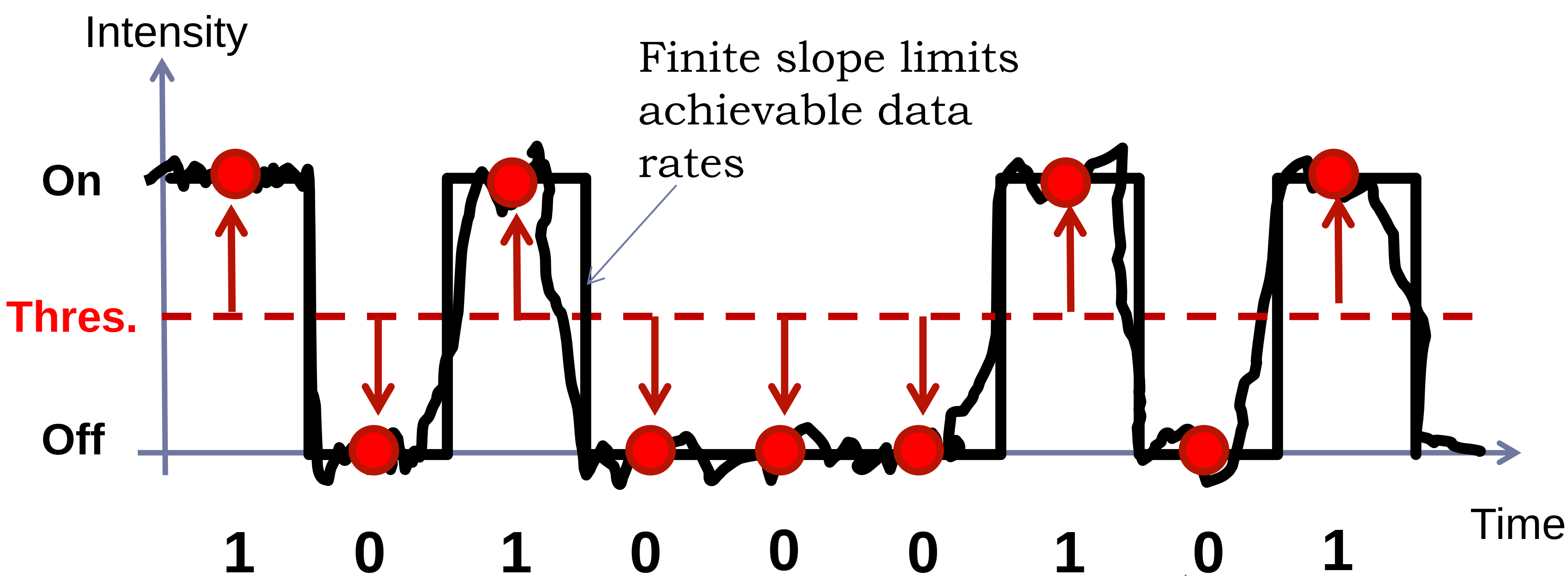
Modulation Techniques

Transceiver building blocks

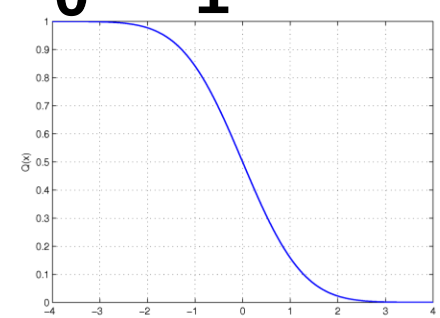


Pulsed Modulation

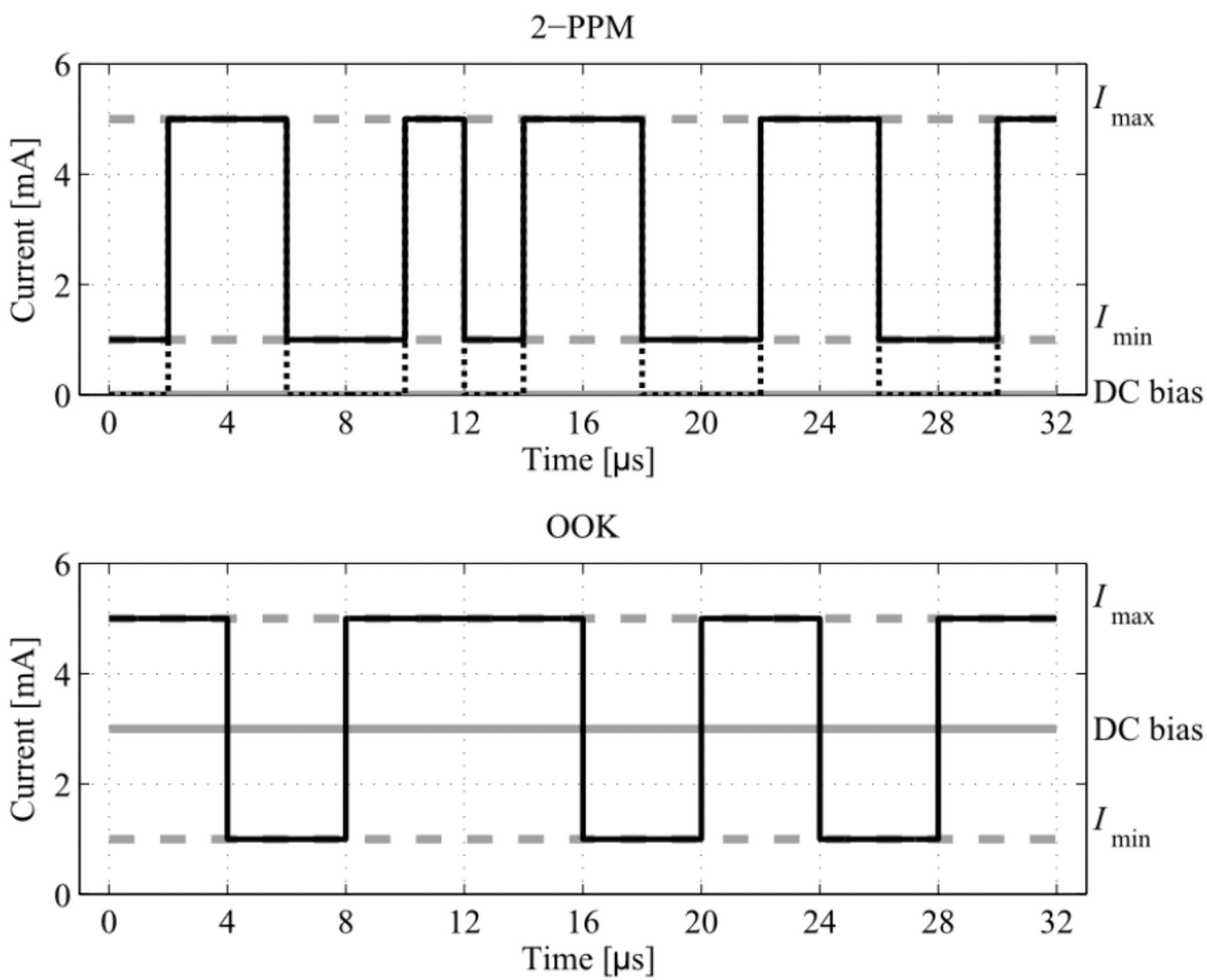
- On-OFF Keying



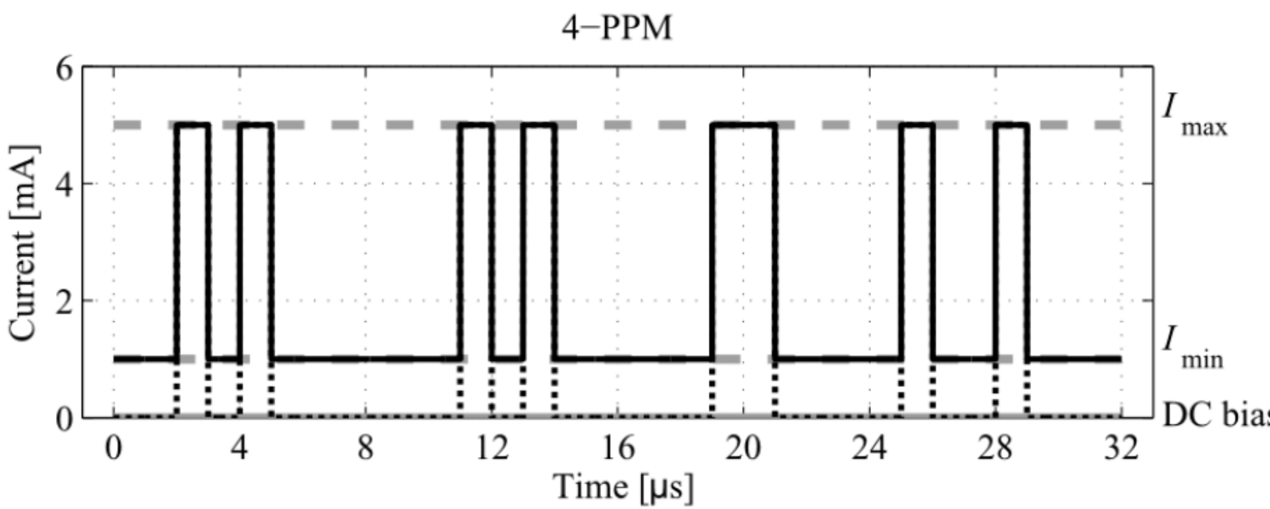
$$\mathrm{BER}_{\mathrm{OOK}} \approx \mathrm{Q}\left(\sqrt{\frac{E_{\mathrm{RX}}}{N_0}}\right) \qquad E_{\mathrm{RX}} = (\rho\, I_{\mathrm{RX}})^2$$

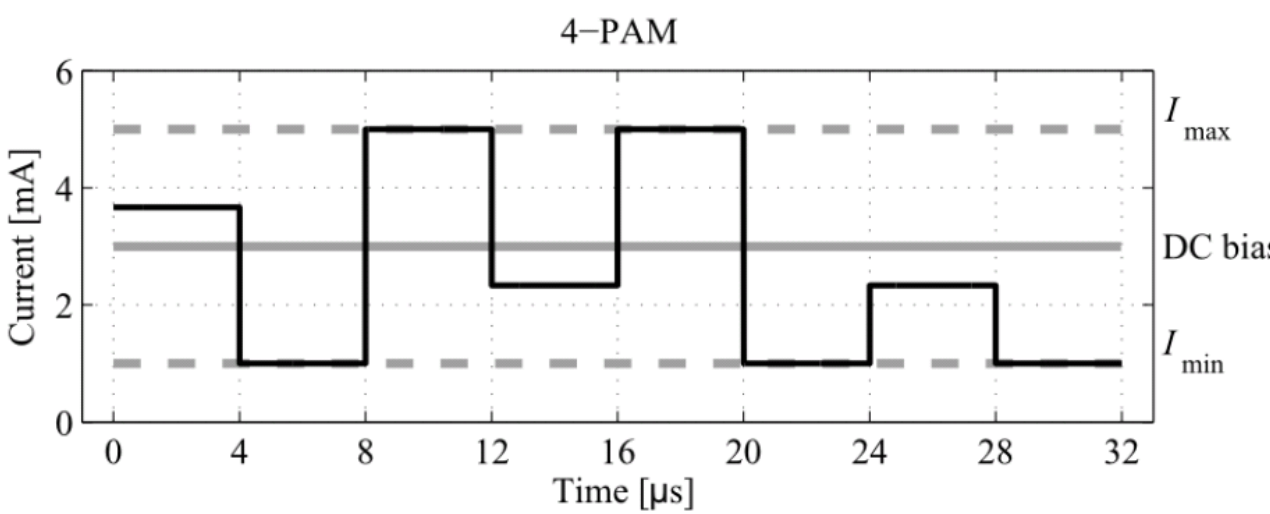


Single Carrier Binary

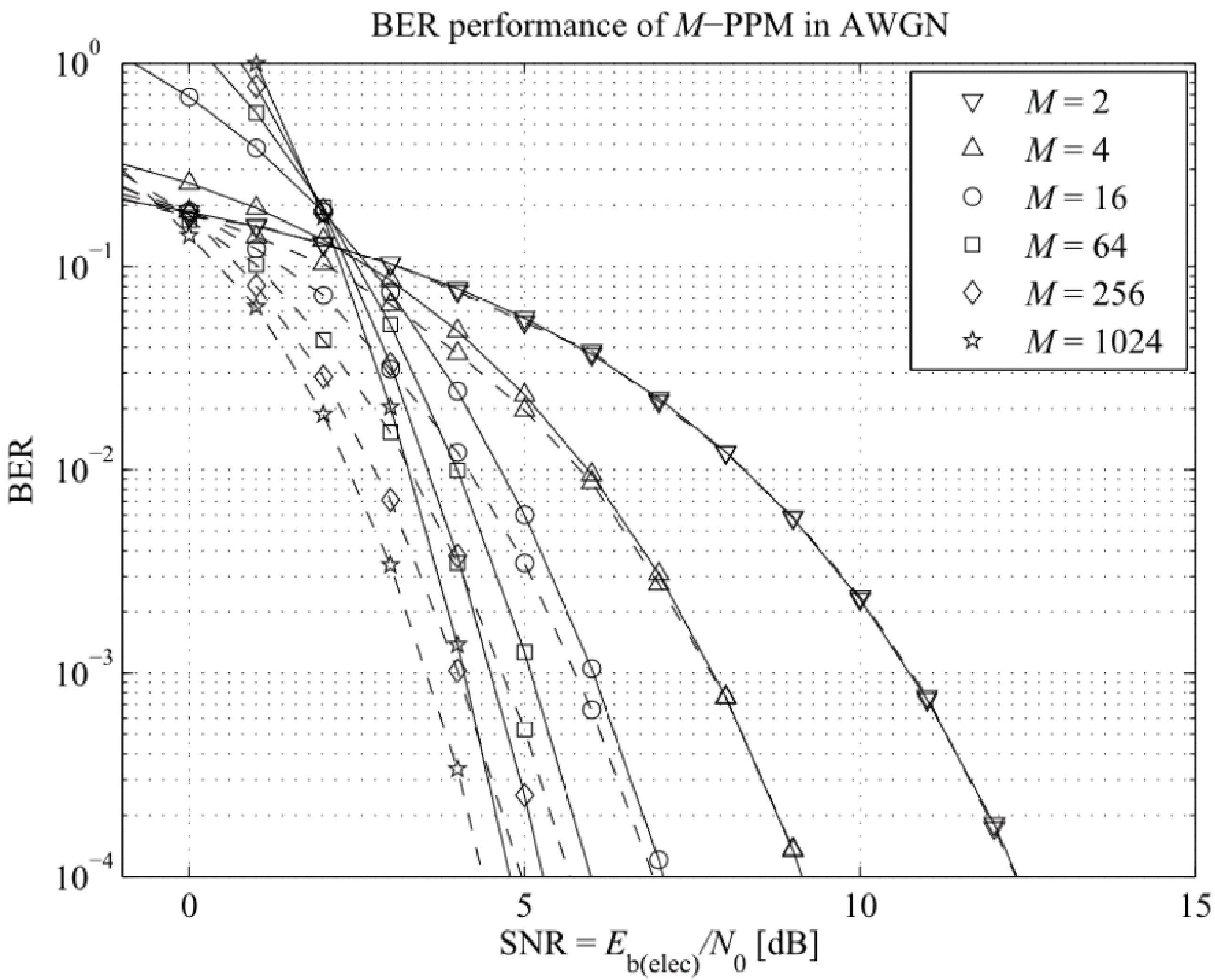


Single Carrier Multi-level





PPM: BER Performance

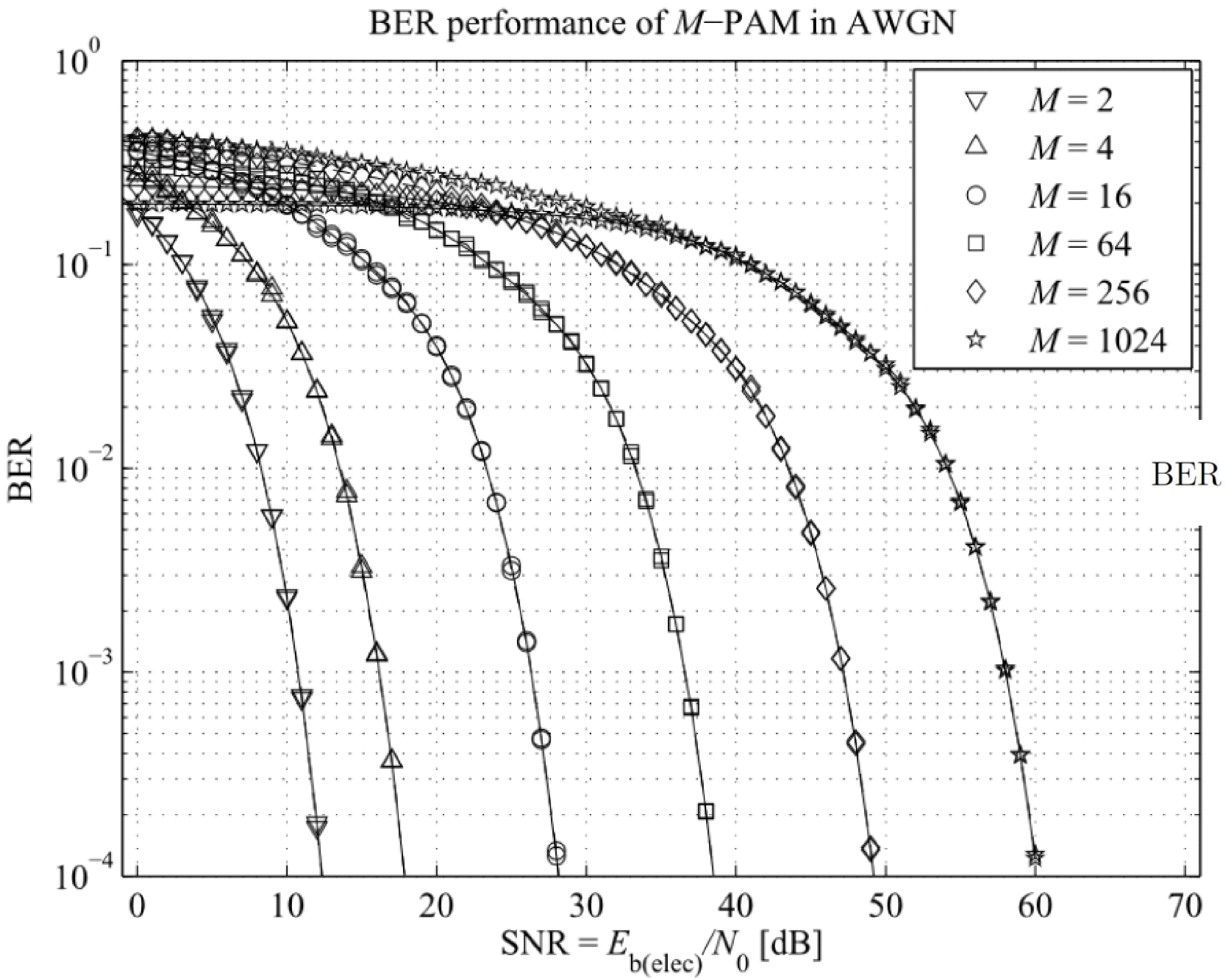


Spectal Efficiency:

$$\log_2(M)/M \ \text{bits/s/Hz}$$

$$\text{BER}_{\text{PPM}} \geq \frac{M}{2}\,Q\left(\sqrt{\frac{M\,E_{\text{RX}}}{2\,N_0}}\right)$$

PAM: BER performance



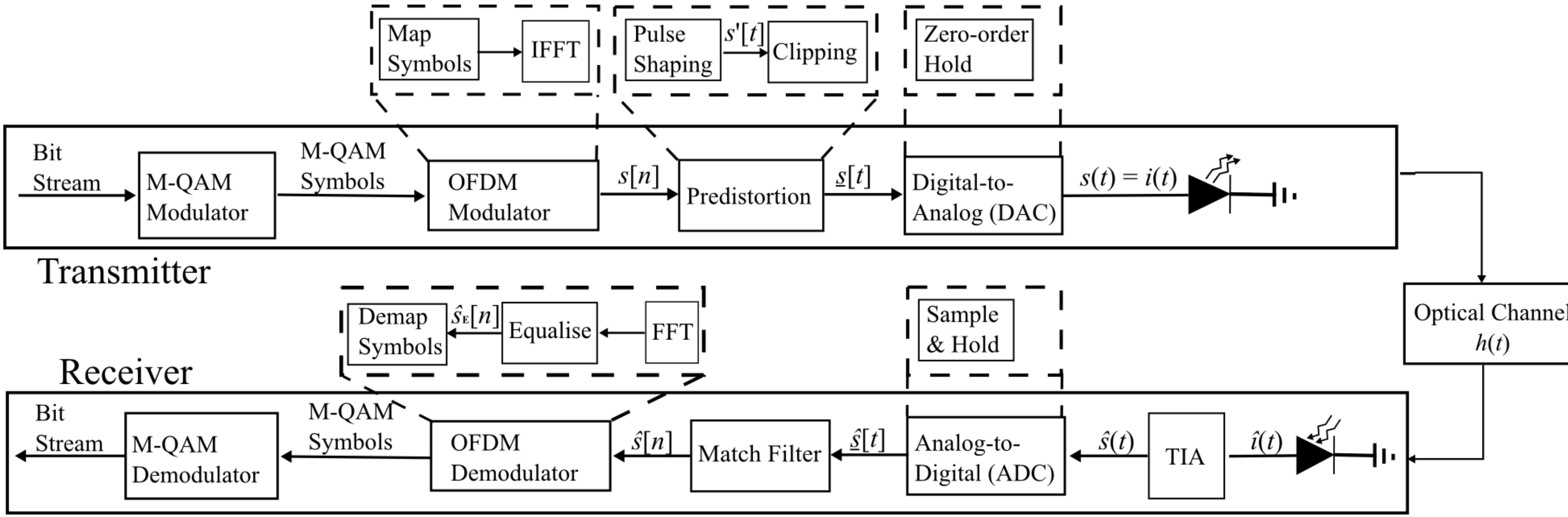
Spectal Efficiency: $\log_2(M)$

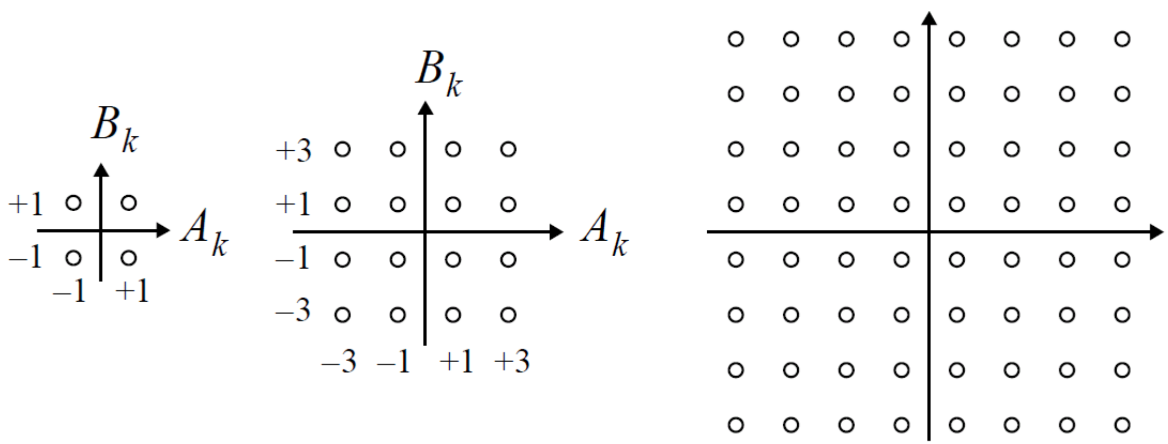
$$\text{BER} = \frac{N_s}{G_{GC}\log_2(M)} Q\left(d_s\sqrt{\log_2(M)\Gamma_{b(elec)}}\right)$$

$$N_s = 2(M-1)/M$$

$$d_s = \sqrt{6/(M^2-1)}$$

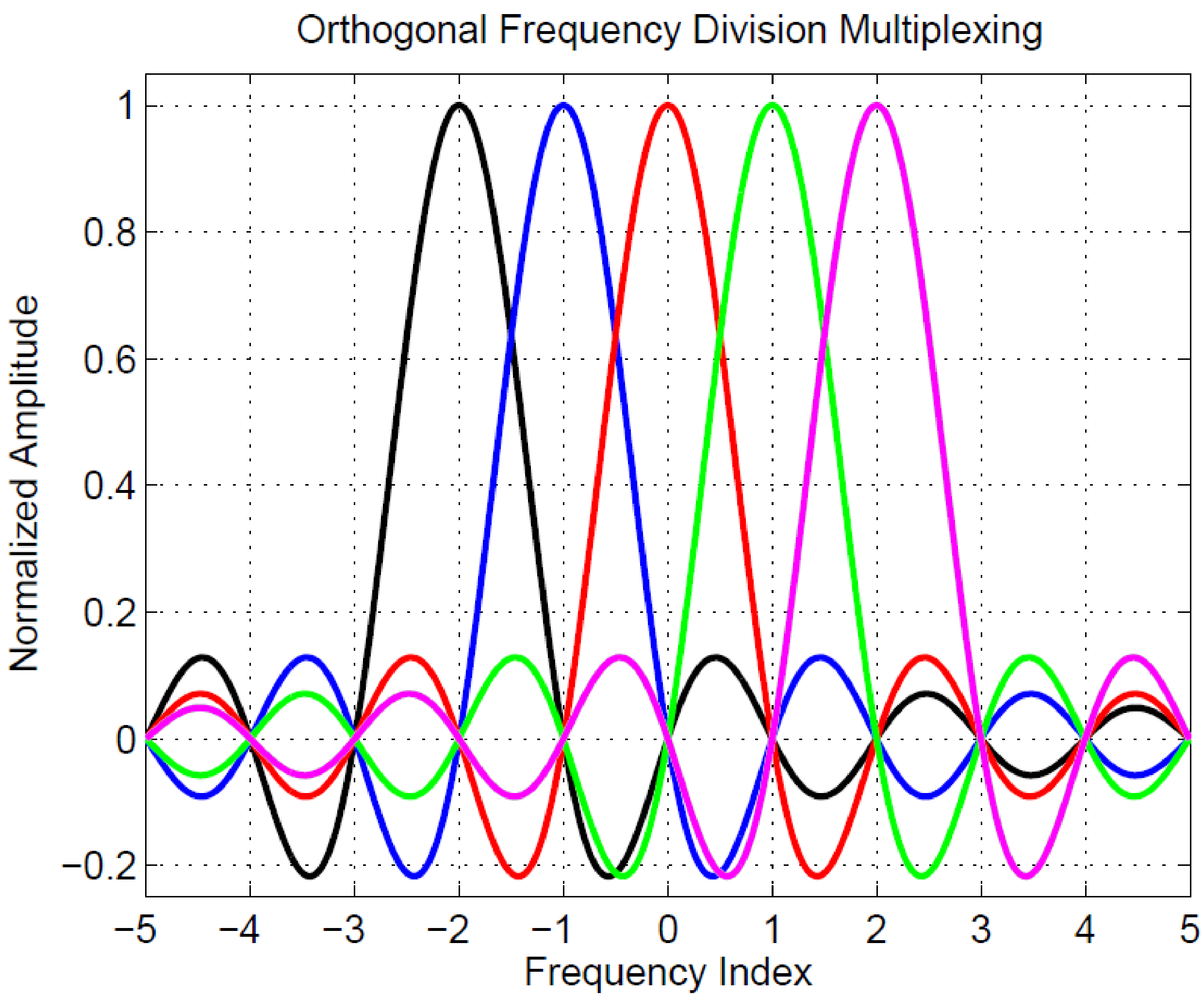
OFDM-based OWC System





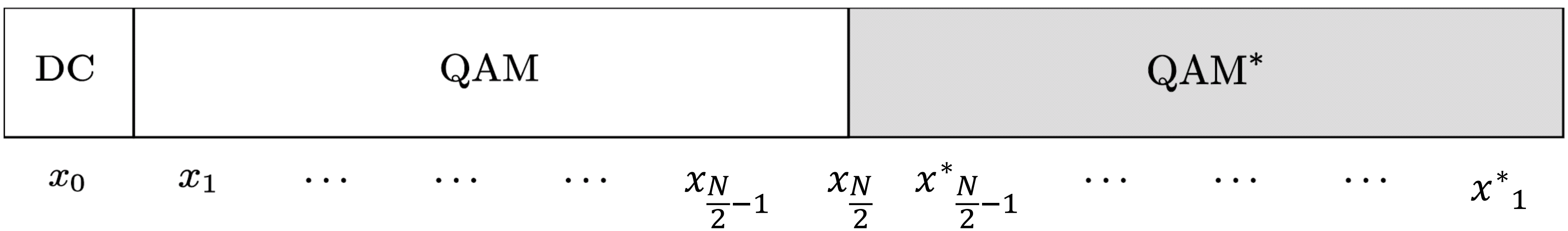
QAM 4 QAM 16 QAM 64

OFDM

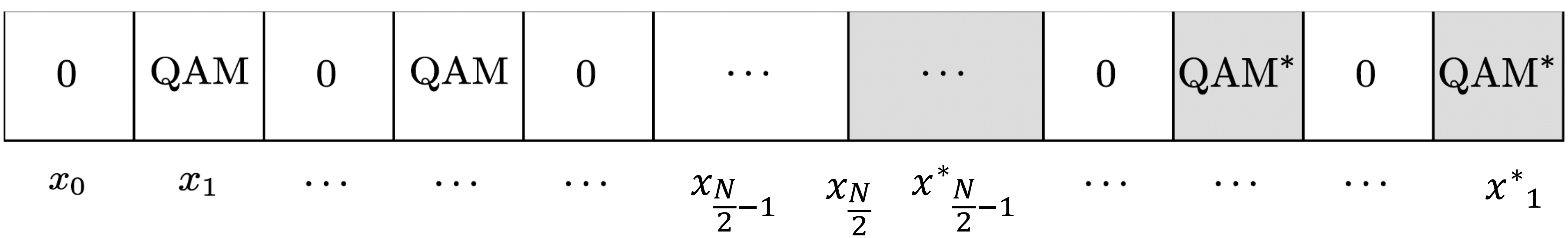

Orthogonal Frequency Division Multiplexing
Normalized Amplitude
1
0.8
0.6
0.4
0.2
0
−0.2
−5
−4
−3
−2
−1
0
1
2
3
4
5
Frequency Index

DCO-OFDM and ACO-OFDM Symbol Structures

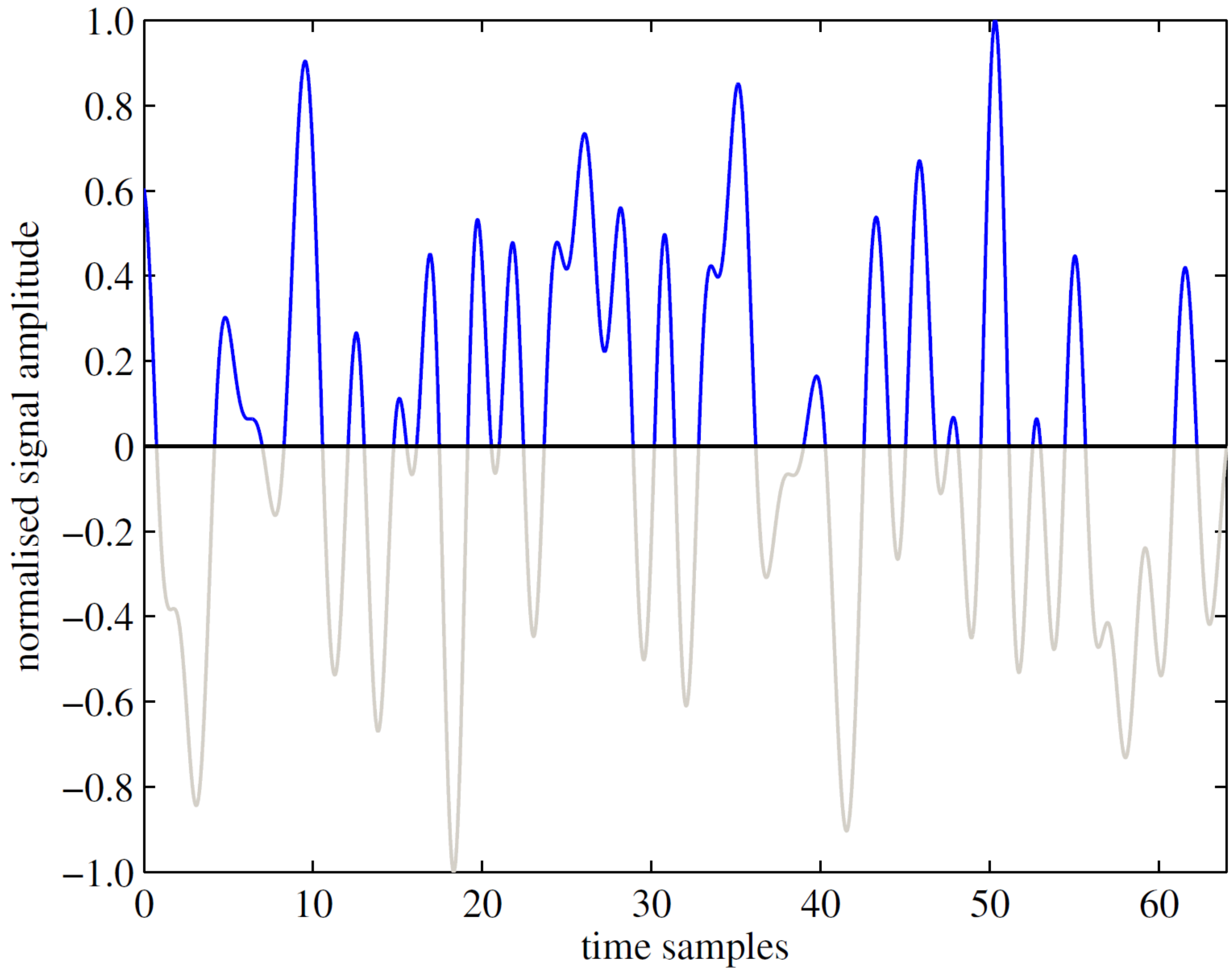
DCO-OFDM



ACO-OFDM

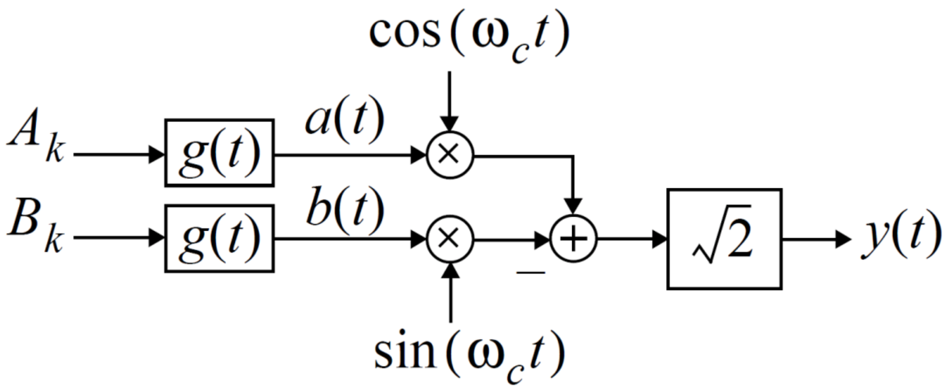


ACO-OFDM Time Domain Signal

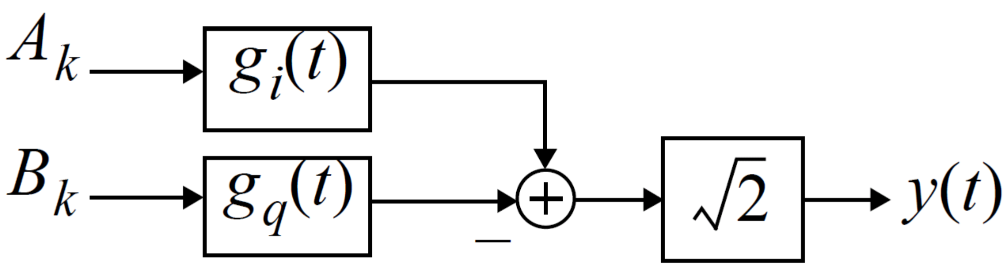


QAM vs. CAP

QAM



CAP



Not feasible if ω_C is much greater than the symbol frequency

$$g_i(t) = g(t)\cos(\omega_c t)$$

$$g_q(t) = g(t)\sin(\omega_c t)$$

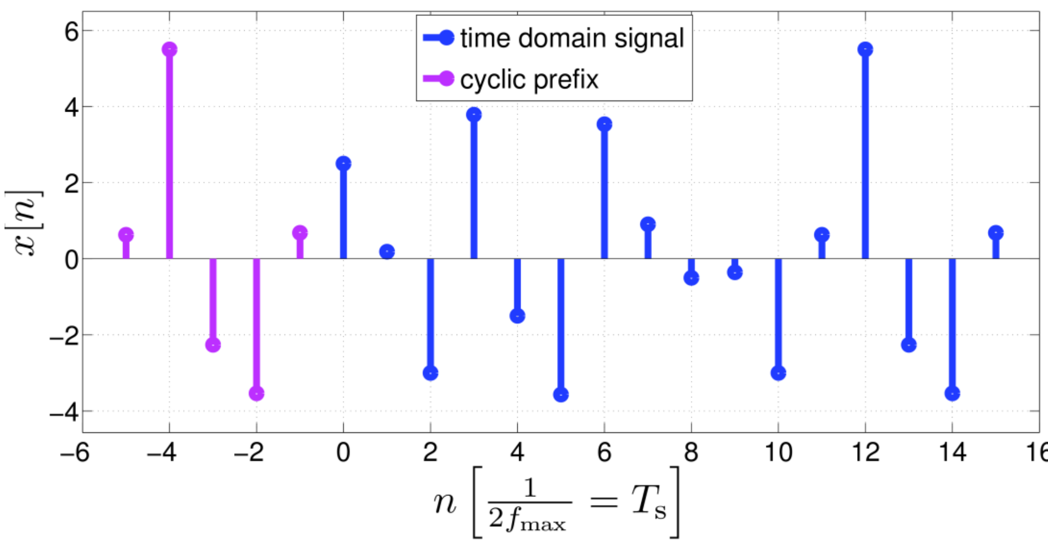
$$\int_{-\infty}^{\infty} g_i(t) g_q(t) dt = 0$$

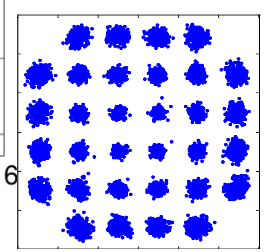
A. H. Abdolhamid, et al. "A Comparison of QAM/CAP Architectures", 1998

OFDM Generation (Time Domain)

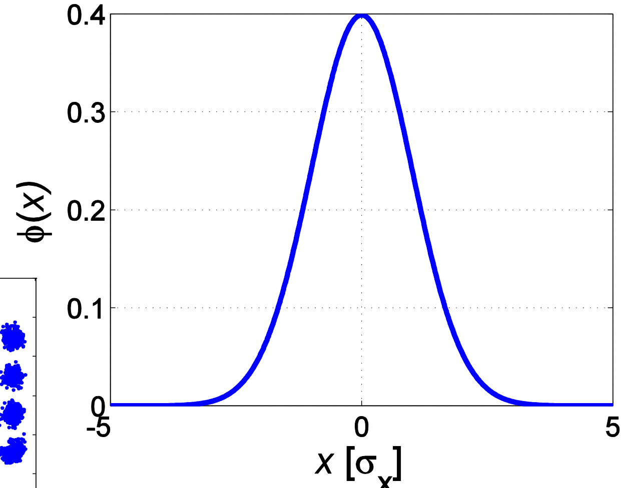
- After the IFFT, the signal follows a zero-mean Gaussian distribution in the time domain:

Time-domain signal





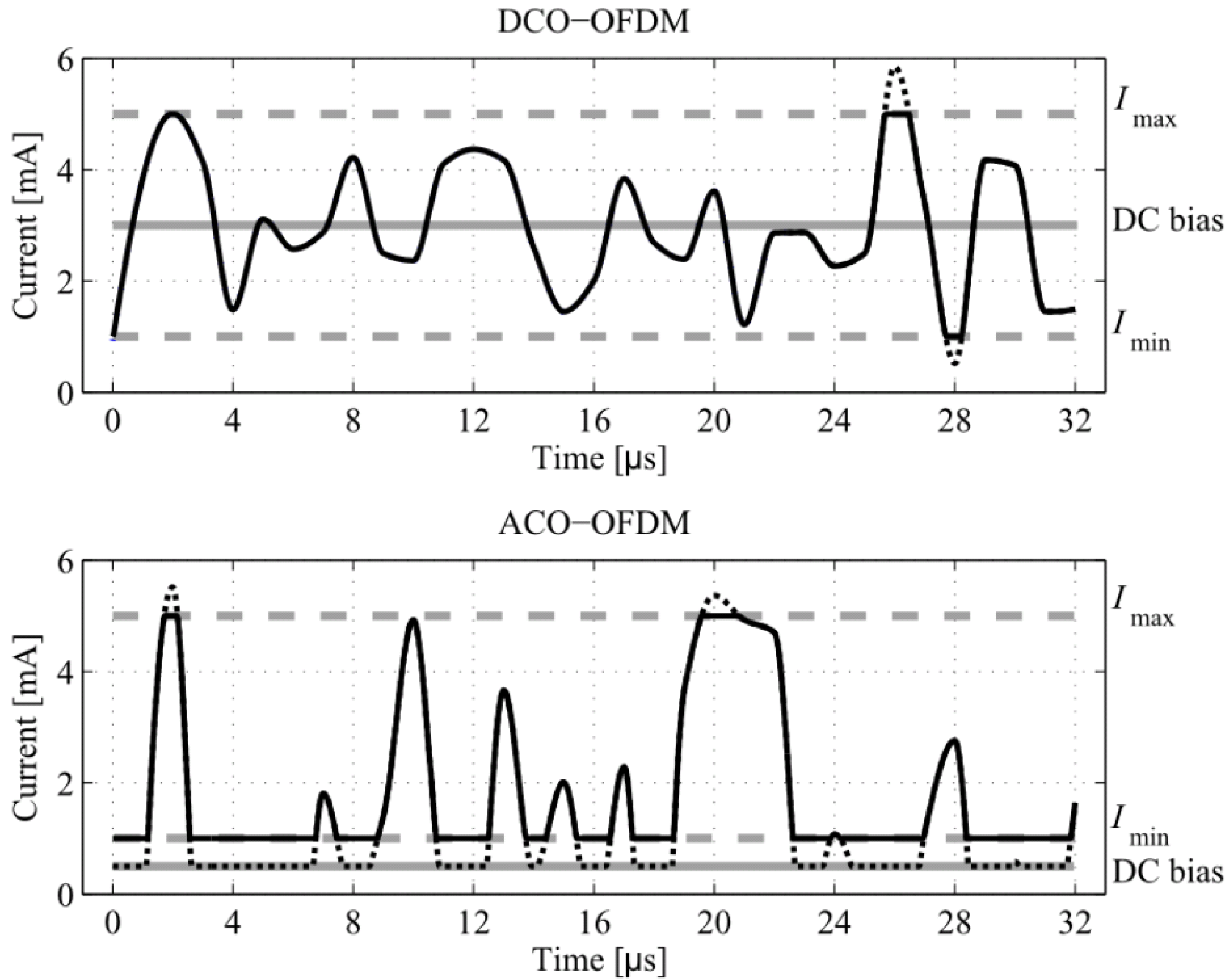
Probability density function



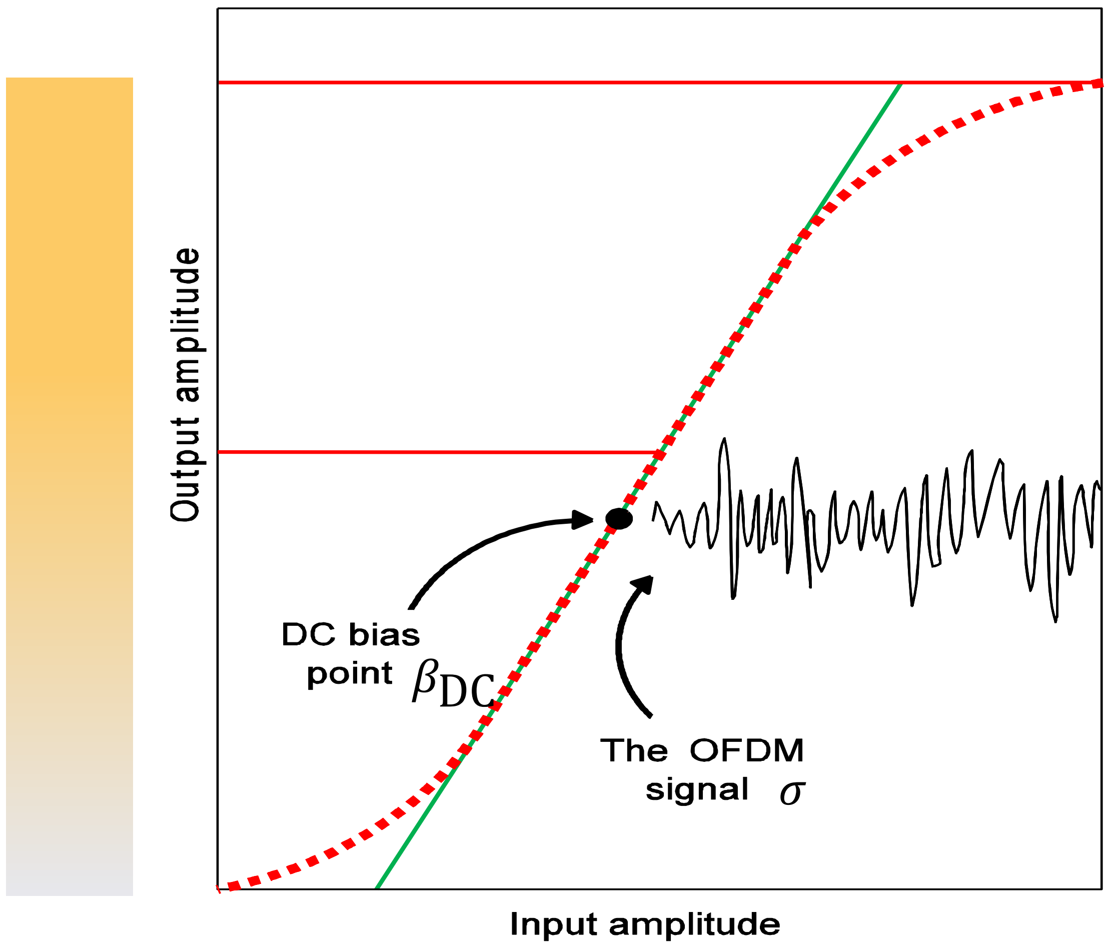
$$\mathrm{BER}_{\mathrm{QAM}} \geq \frac{2\left(\sqrt{M}-1\right)}{\sqrt{M}\ \log_2(\sqrt{M})}\ \mathrm{Q}\left(\frac{1}{\sqrt{M}-1}\sqrt{\frac{E_{\mathrm{RX}}}{4\ N_0}}\right)$$

$$\mathbf{s}_{l,k} = \frac{1}{\sqrt{N}}\sum_{m=0}^{N-1}\mathbf{f}_{l,m}\exp\left(\frac{i2\pi km}{N}\right)$$

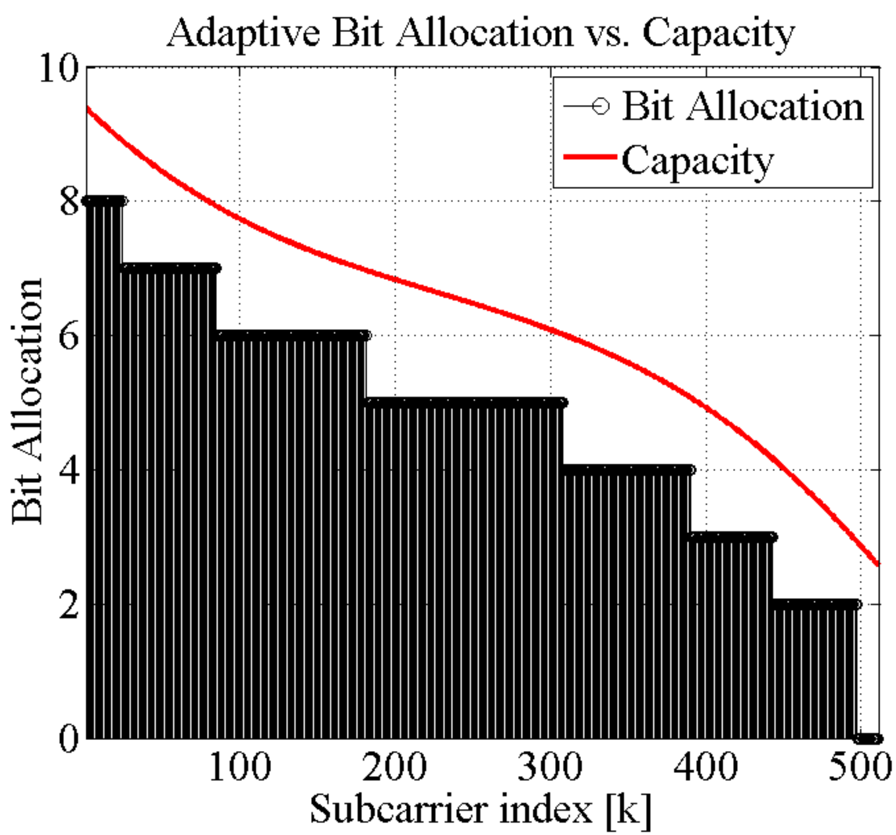
Multi-carrier Multi-level

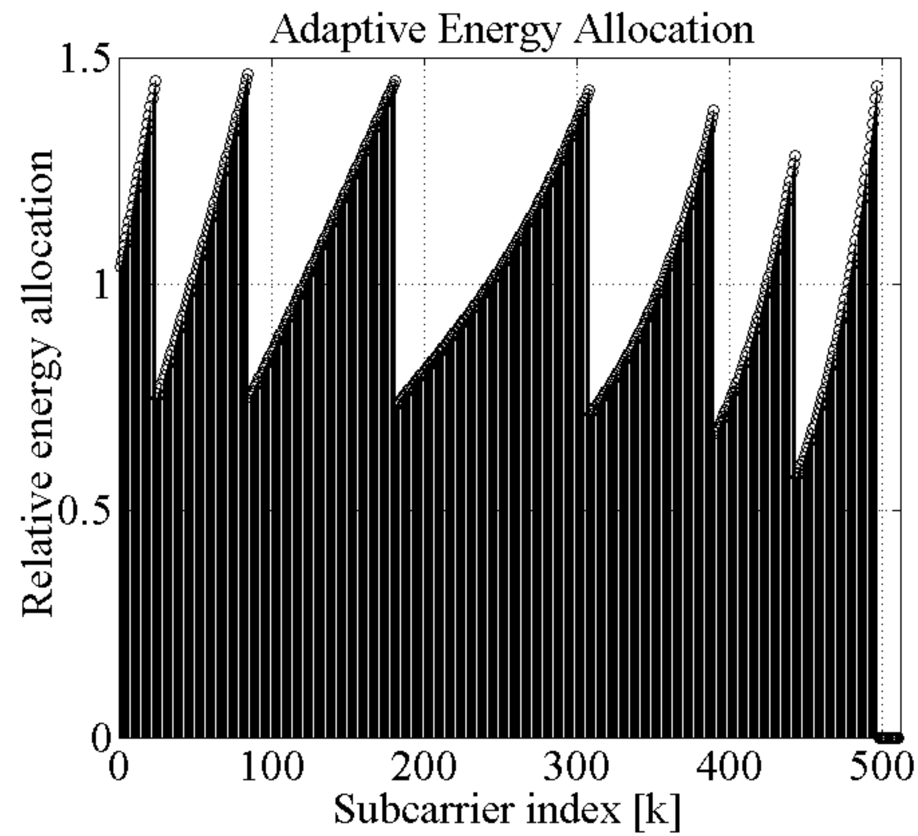


DC Bias and Signal Power



UPVLC Results (assuming single colour μLED)





Bussgang Theorem

- X is a zero-mean Gaussian random variable with variance σ and g(X) is an arbitrary transform on X, which could be linear or nonlinear.
- The Bussgang theorem:

$$g(X) = KX + Y_n$$
$$E[XY_n] = 0$$

- Then:

$$K = \frac{E[X\,g(X)]}{\sigma^2}$$
$$E[Y_n^2] = E[g^2(X)] - K^2\sigma^2$$
$$E[Y_n] = E[g(X)]$$
$$Var[Y_n] = E[Y_n^2] - E[Y_n]^2$$

$$\frac{E_b^{new}}{N_o^{new}} = \frac{K^2 E_b^{old}}{N_o + Var[Y_n]}$$

Redefintion of the Distortion

- Any arbitrary distortion function g(x) can be represented with a set of intervals I and a number of continuous polynomials which describe the function in those intervals.

- Then g(X) becomes:

$$\mathrm{g}(x) = \sum_{k=1}^{|I|} \sum_{j=0}^{n_k} c_{k,j} x^j \left(\mathrm{U}(x - x_{\min,k}) - \mathrm{U}(x - x_{\max,k}) \right)$$

where n_k is the order of the polynomial in interval k, and

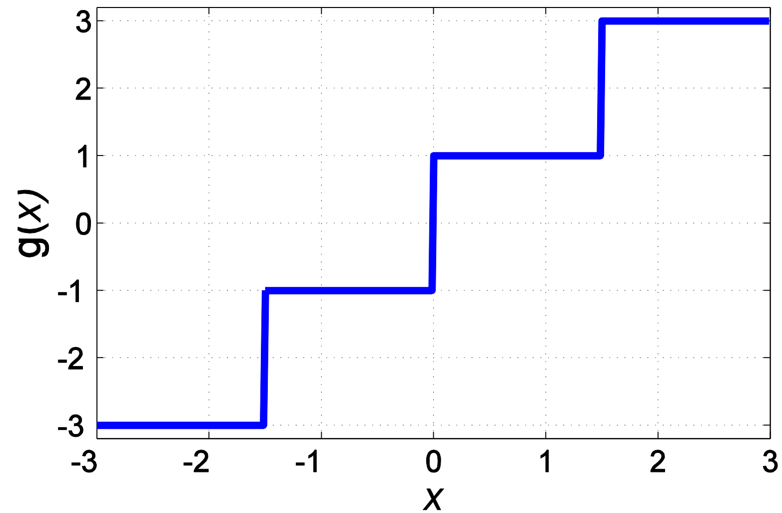
U(x) is the
unit step function:

$$\mathrm{U}(x) = \begin{cases} 0, x < 0 \\ 1, x \geq 0 \end{cases}$$

Examples

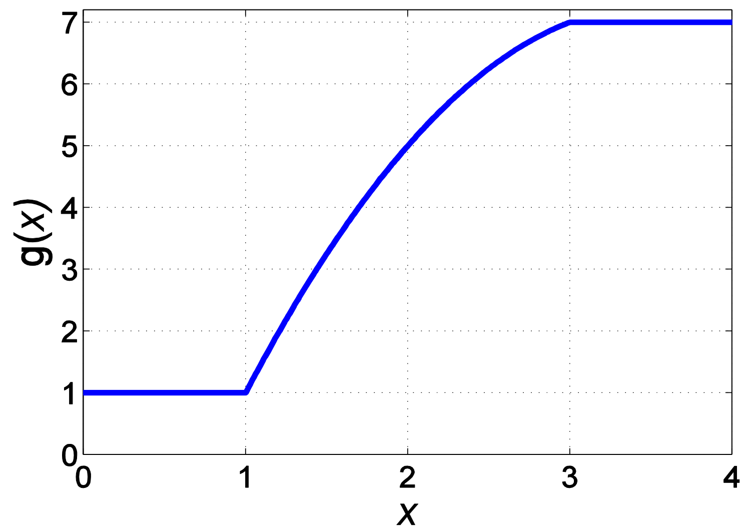
- 3-bit DAC:

$$g(x) = 3(U(x-1.5) - U(x-\infty)) + \\ +1(U(x) - U(x-1.5)) - \\ -1(U(x+1.5) - U(x)) - \\ -3(U(x+\infty) - U(x+1.5))$$



- Clipping and LED current-to-light conversion:

$$g(x) = 3(U(x-3) - U(x-\infty)) + \\ +(-1x^2 + 7x - 5)(U(x-1) - U(x-3)) + \\ +1(U(x+\infty) - U(x-1))$$



Closed Form Solutions

The equations from the Bussgang analysis become:

$$K = \frac{1}{\sigma^2} \sum_{k=1}^{|I|} \sum_{j=0}^{n_k} c_{k,j} \left. \frac{\mathrm{d}^{j+1} \mathrm{D}\left(t, x_{\min,k}, x_{\max,k}, 0, \sigma\right)}{\mathrm{d}t^{j+1}} \right|_{t=0}$$

$$\mathrm{E}\left[g(X)\right] = \sum_{k=1}^{|I|} \sum_{j=0}^{n_k} c_{k,j} \left. \frac{\mathrm{d}^{j} \mathrm{D}\left(t, x_{\min,k}, x_{\max,k}, 0, \sigma\right)}{\mathrm{d}t^{j}} \right|_{t=0}$$

$$\mathrm{E}\left[g^2(X)\right] = \sum_{k=1}^{|I|} \sum_{j=0}^{n_k} \sum_{m=0}^{n_k} c_{k,j} c_{k,m} \left. \frac{\mathrm{d}^{j+m} \mathrm{D}\left(t, x_{\min,k}, x_{\max,k}, 0, \sigma\right)}{\mathrm{d}t^{j+m}} \right|_{t=0}$$

Tsonev, et al., *JLT*, 2013

Channel Capacity: Optimisation Frameworks

Given:

BER, M, $P_{\mathrm{min,norm}}$, $P_{\mathrm{max,norm}}$ and $P_{\mathrm{avg,norm}}$

Find:

$$\underset{\substack{\sigma \geq 0 \\ \beta_{\mathrm{DC}} \geq 0}}{\operatorname{argmin}} \ \gamma_{\mathrm{b(elec)}}(\sigma, \beta_{\mathrm{DC}}) \geq 0$$

where

ZF equalizer

$$\gamma_{\mathrm{b(elec)}} = \frac{G_{\mathrm{B}}}{|H(f_{\mathrm{info}})|^2 G_{\mathrm{T}} G_{\mathrm{DC}}} \left(qK^2 - \frac{G_{\mathrm{B}} \log_2(M) \sigma_{\mathrm{clip}}^2}{P_{\mathrm{s(elec)}}} \right)^{-1}$$

MMSE equalizer

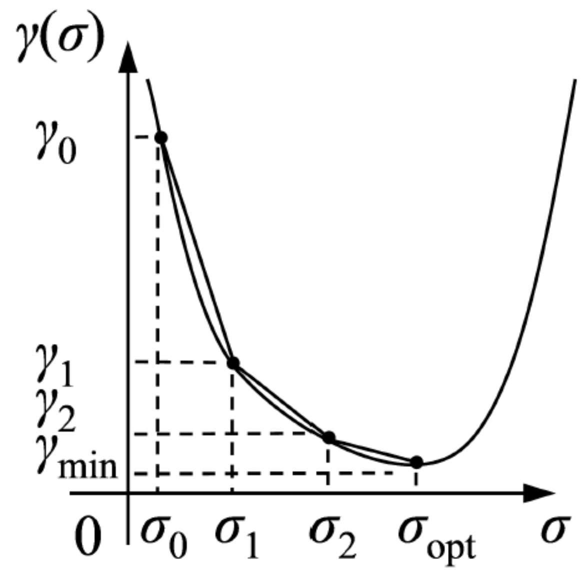
$$\gamma_{\mathrm{b(elec)}} = \frac{\frac{G_{\mathrm{B}}}{G_{\mathrm{T}} G_{\mathrm{DC}}} - \left(qK^2 - \frac{G_{\mathrm{B}} \log_2(M) \sigma_{\mathrm{clip}}^2}{P_{\mathrm{s(elec)}}} \right)}{|H(f_{\mathrm{info}})|^2 \left(qK^2 - \frac{G_{\mathrm{B}} \log_2(M) \sigma_{\mathrm{clip}}^2}{P_{\mathrm{s(elec)}}} \right)}$$

$$q = \frac{3 \log_2(M)}{M-1} \left(Q^{-1} \left(\frac{\mathrm{BER}\sqrt{M} \log_2(M)}{4(\sqrt{M}-1)} \right) \right)^{-2}$$

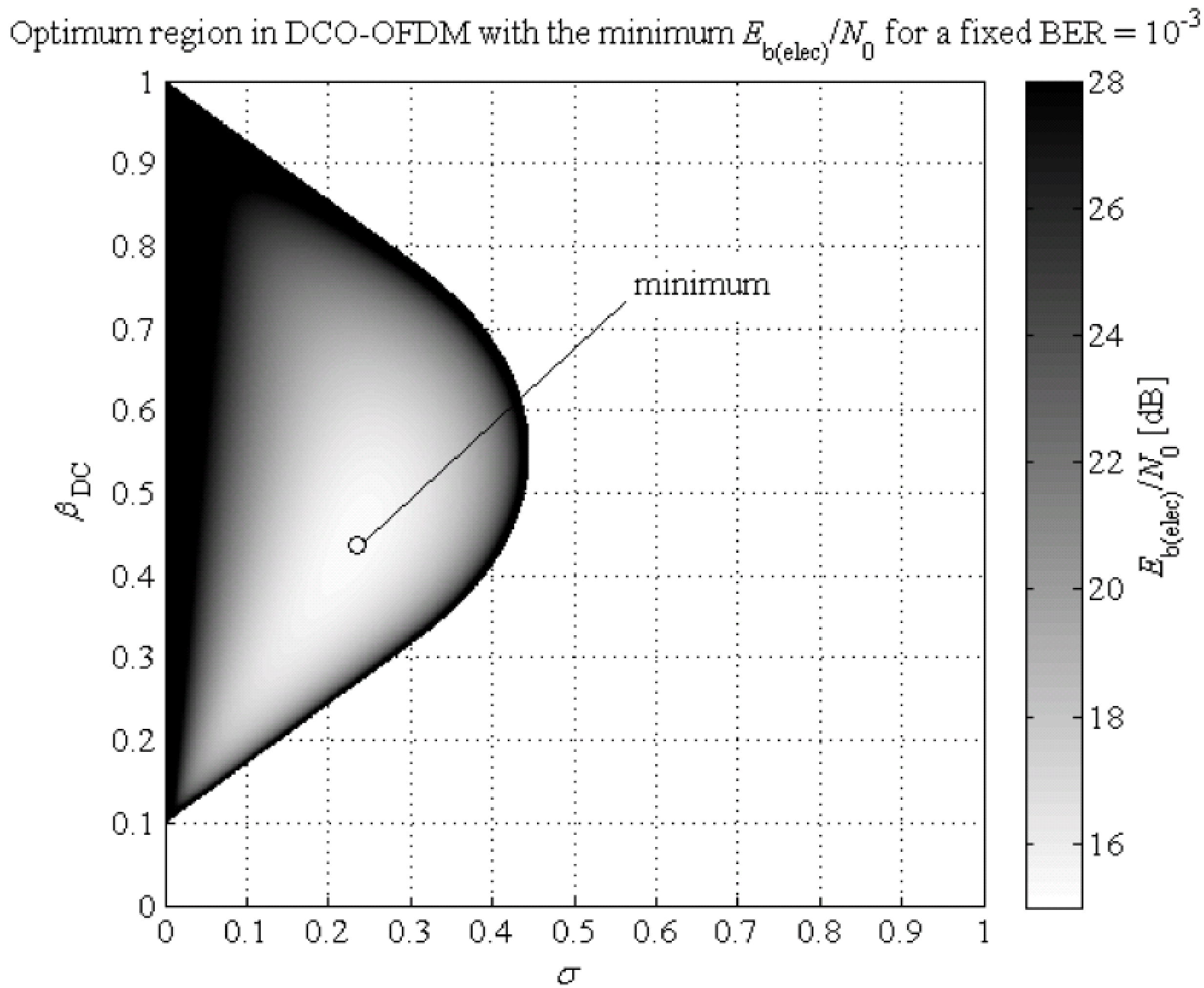
Constraints: $\mathrm{E}\left[\Phi(\mathbf{x}_l)\right] \leq P_{\mathrm{avg,norm}}$

$\lambda_{\mathrm{top}} > \lambda_{\mathrm{bottom}}$ in DCO-OFDM

$\lambda_{\mathrm{top}} > \lambda_{\mathrm{bottom}} \geq 0$ in ACO-OFDM



Results



Optimum region in DCO-OFDM with the minimum $E_{b(elec)}/N_0$ for a fixed BER = 10^{-3}
minimum
β_{DC}
σ
$E_{b(elec)}/N_0$ [dB]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
16
18
20
22
24
26
28

Spectral Efficiencies

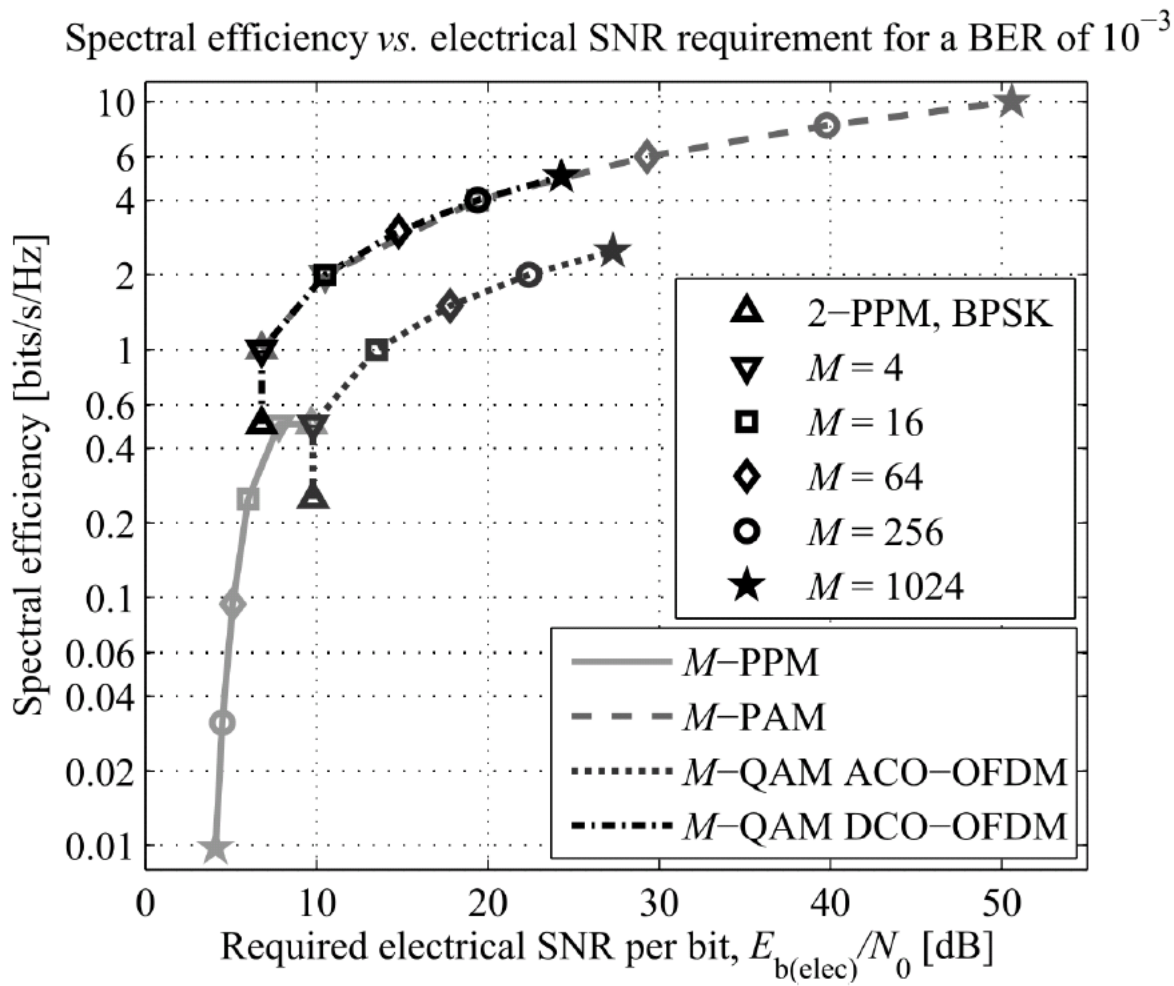


Figure 5.4 Spectral efficiency *vs.* electrical SNR requirement for a 10^{-3} BER of the OWC schemes in a flat fading channel with impulse response $h(t) = \delta(t)$ and a neglected DC-bias power.

Spectral Efficiencies, cont’d

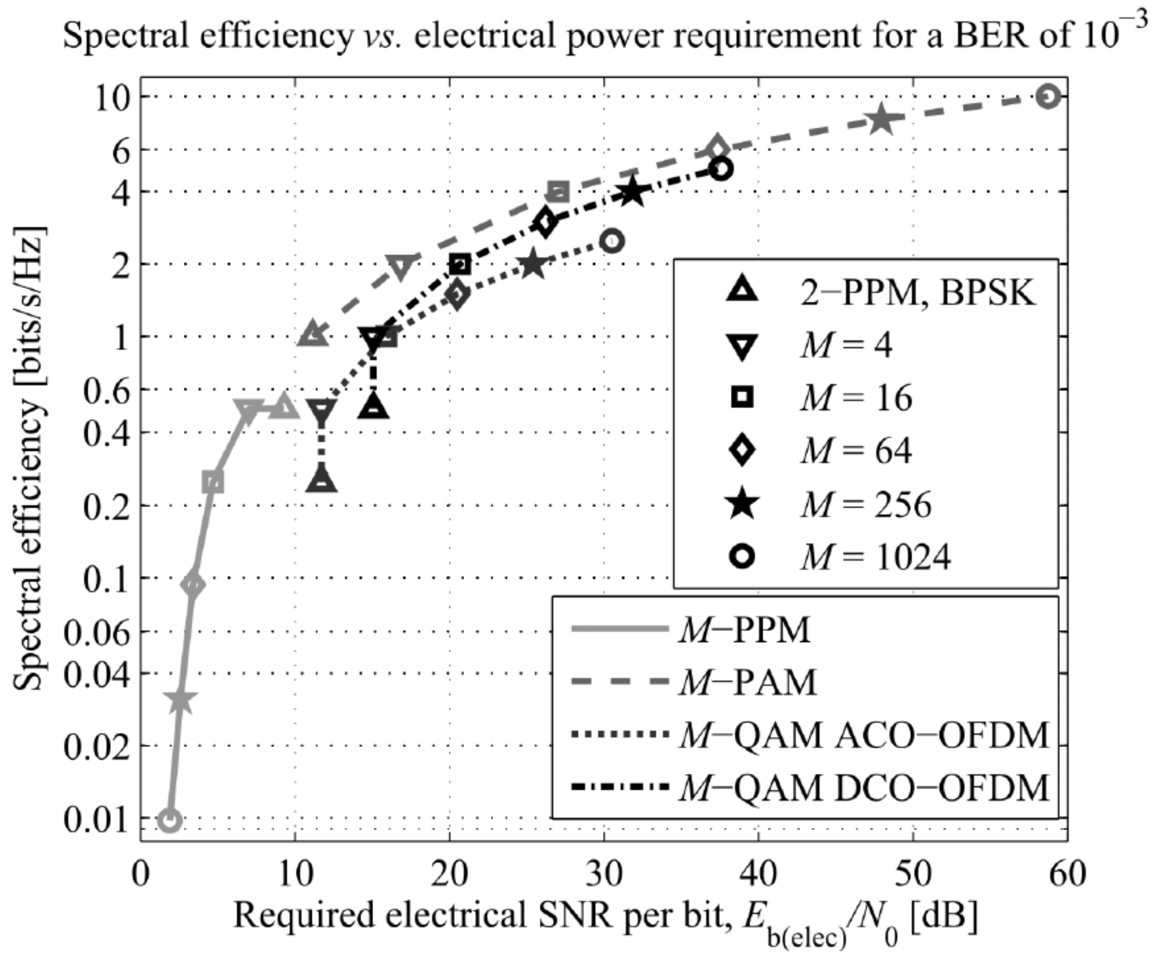
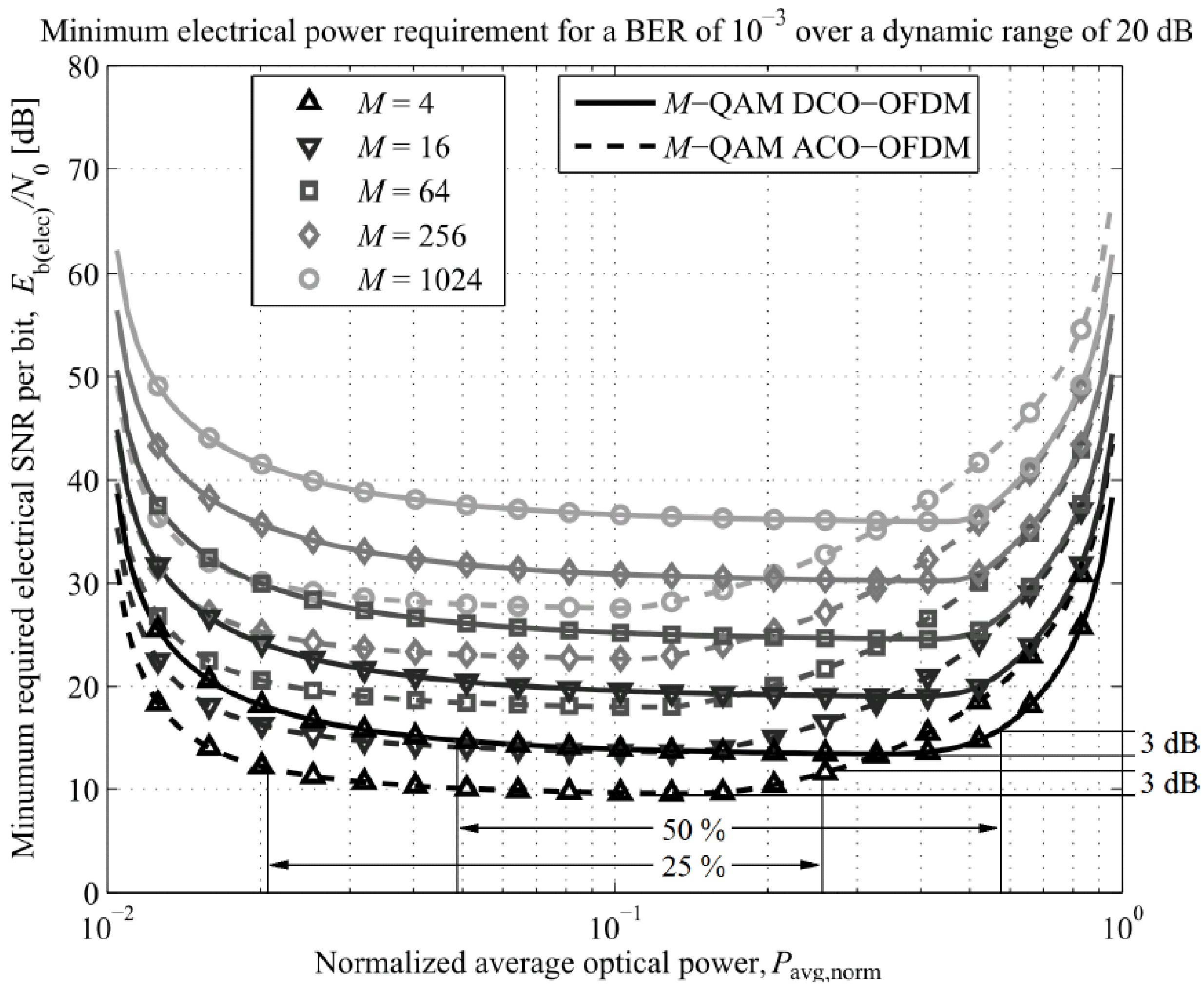
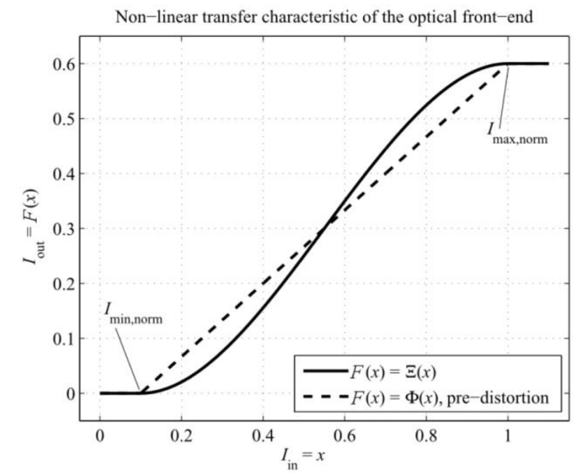


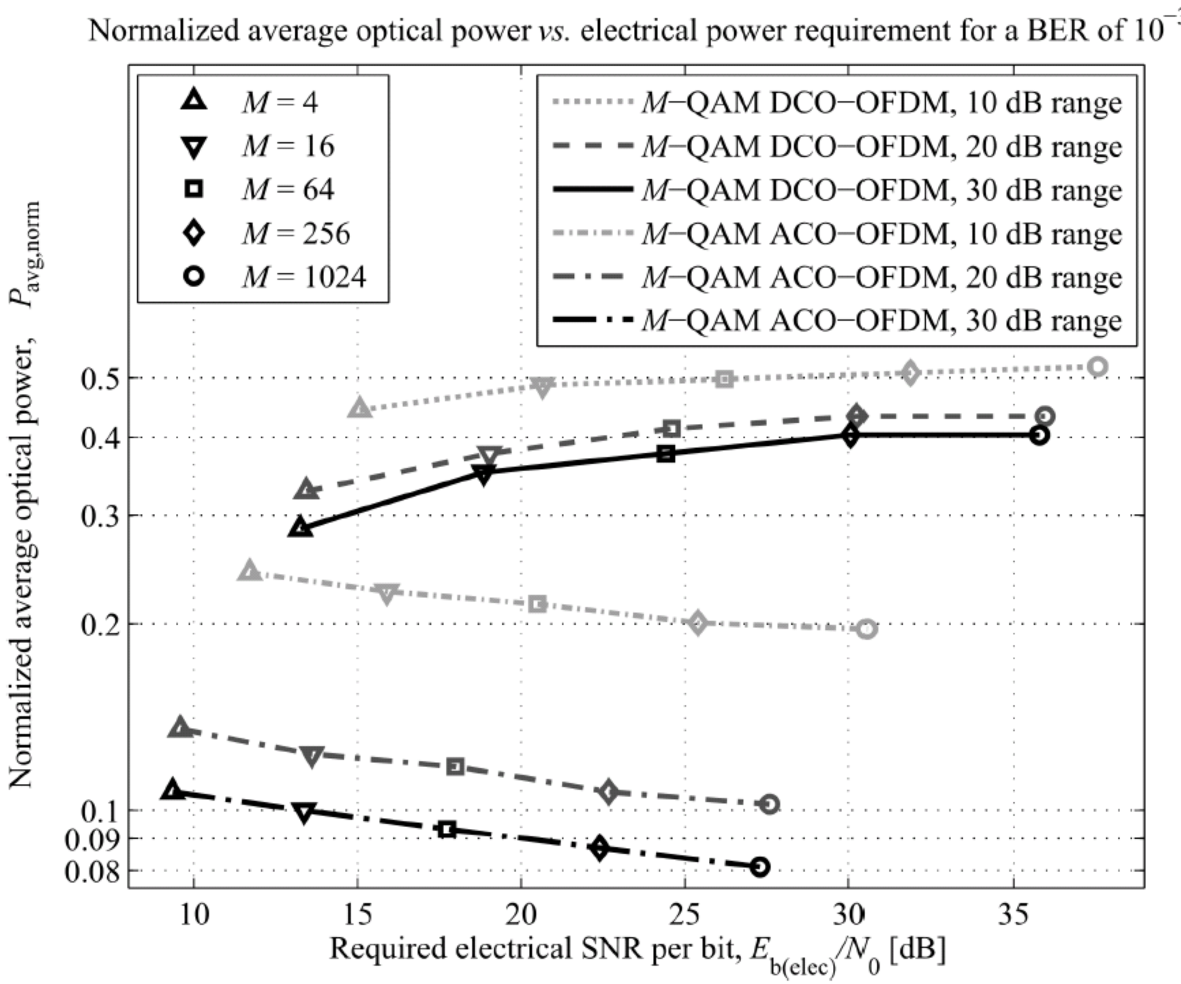
Figure 5.5 Spectral efficiency *vs.* electrical SNR requirement for a 10^{-3} BER of the OWC schemes in a flat fading channel with impulse response $h(t) = \delta(t)$, including the DC-bias power for a 10-dB dynamic range.

Implications on Dimming

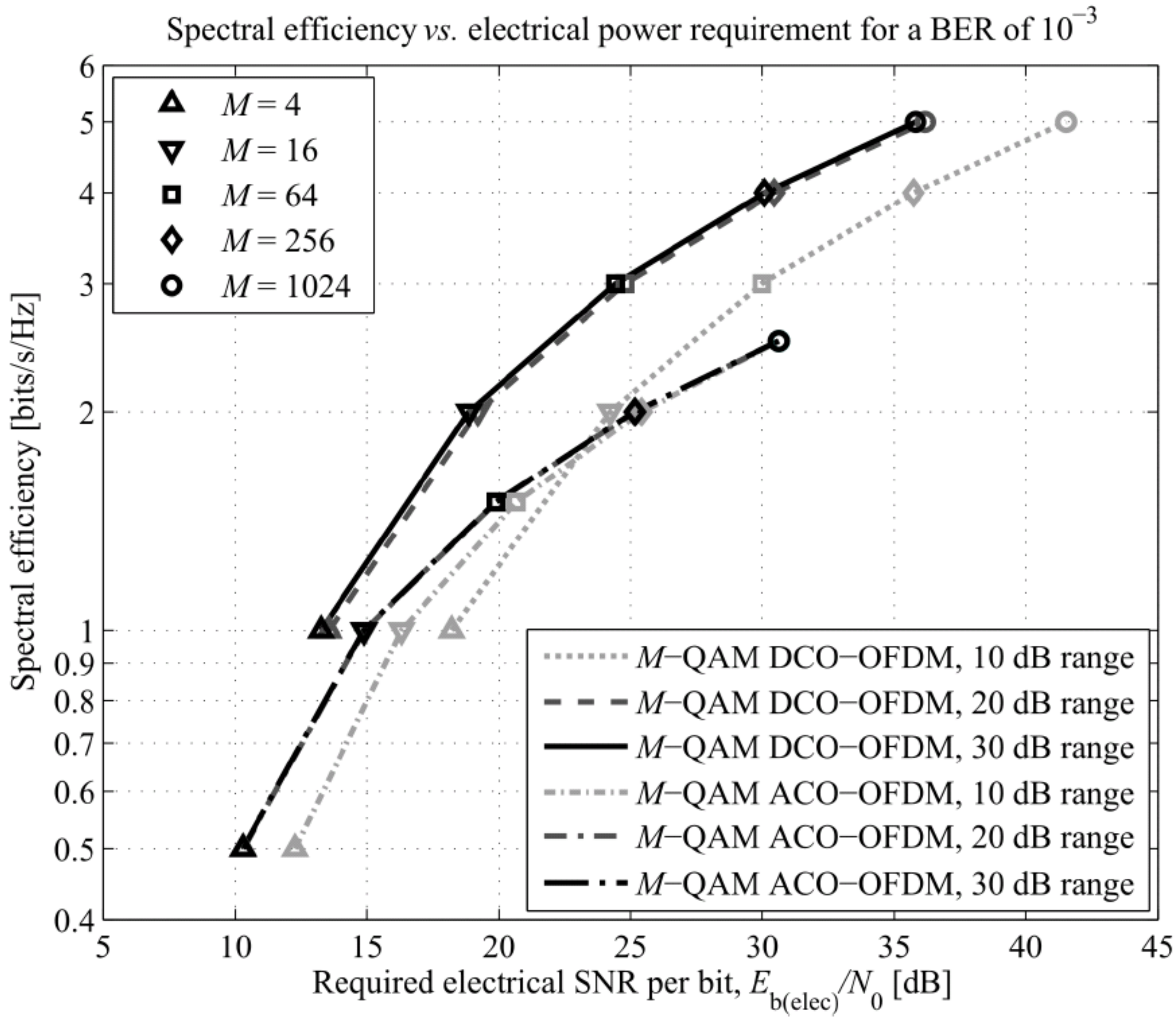




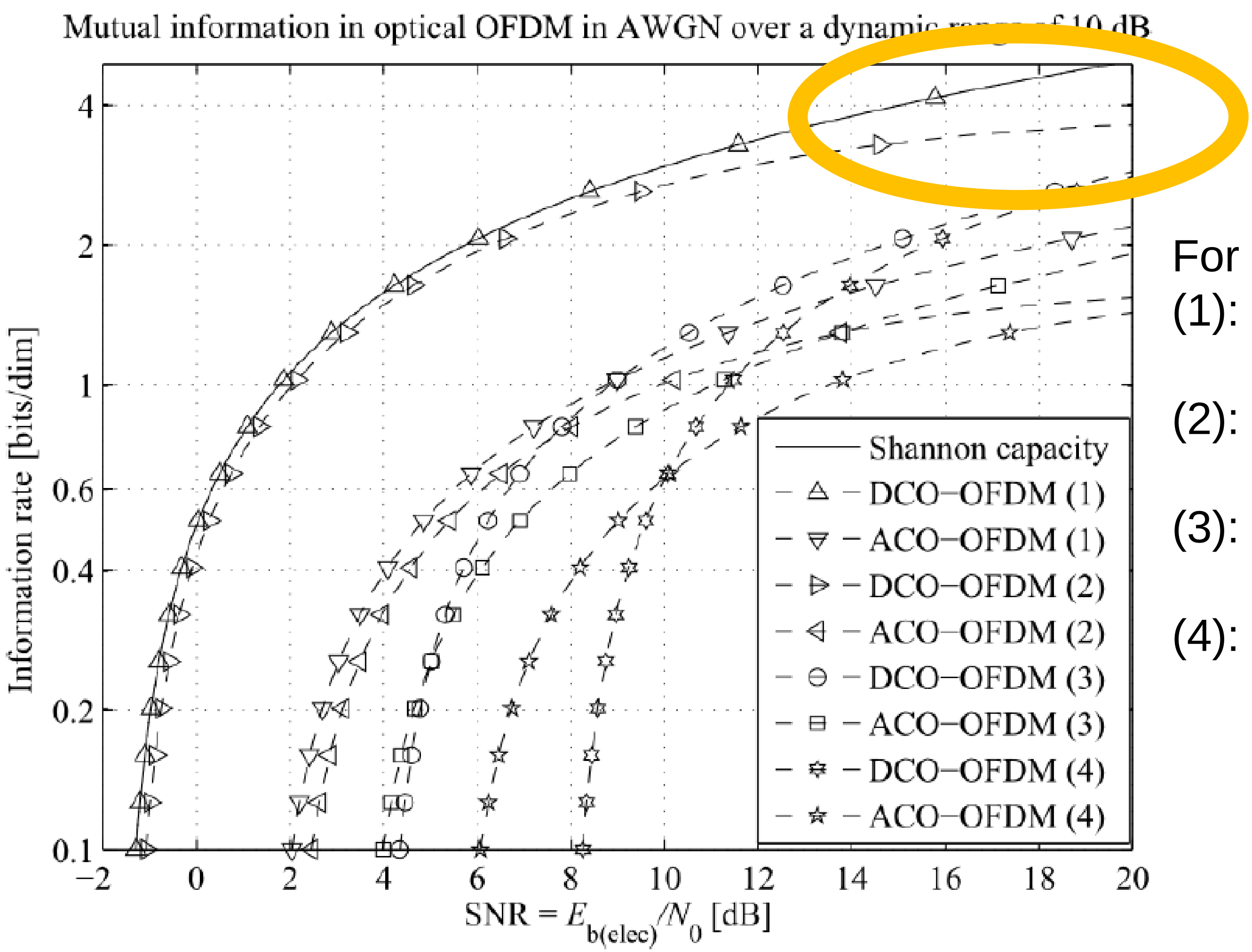
Optical Output Power



Spectral Efficiency of OFDM



Theoretical Capacity limits, cont‘d



For 10 dB dynamic range:

(1): with optimisation, DC bias power **not** included

(2): without optimisation, DC bias power **not** included

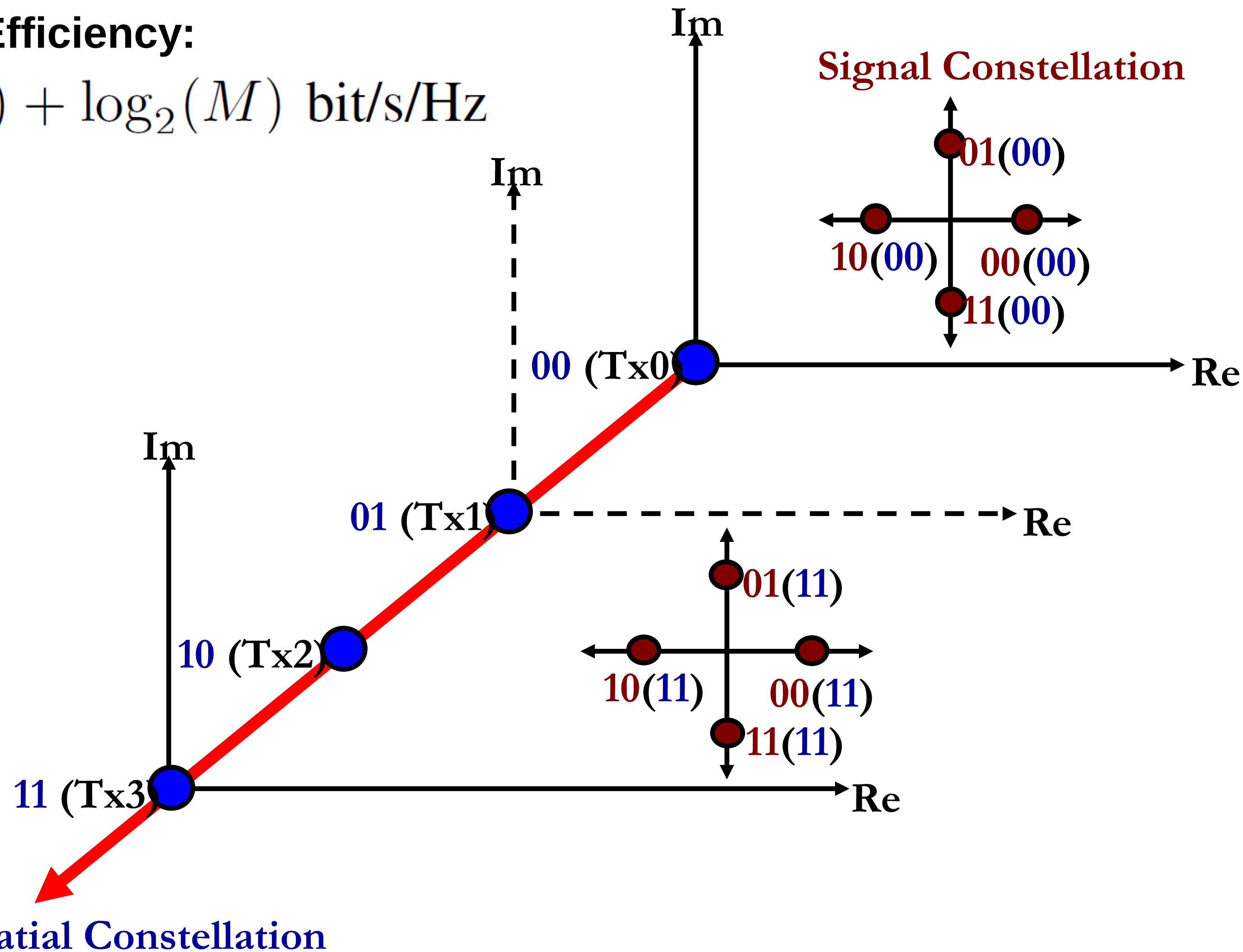
(3): with optimisation, DC bias power included

(4): without optimisation, DC bias power included

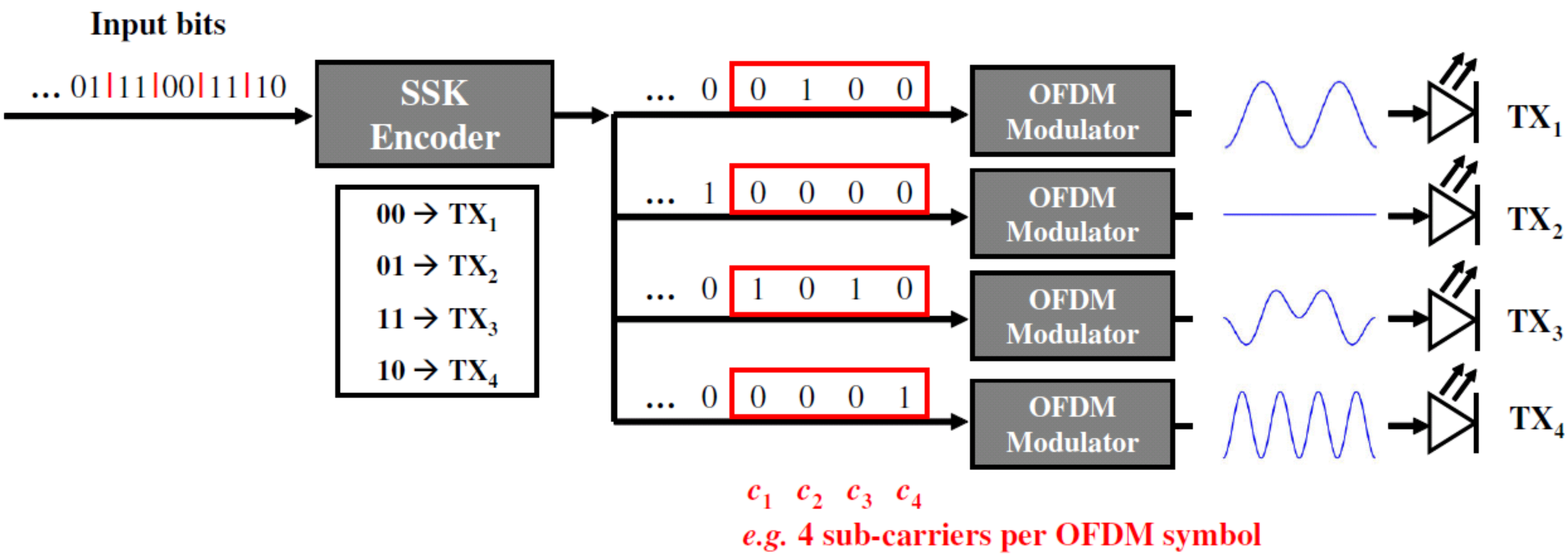
Spatial Modulation: How does it work?

Spectral Efficiency:

$$\log_2(N_t) + \log_2(M) \text{ bit/s/Hz}$$



Spatial Modulation OFDM



$$\mathrm{BER_{SSK}} \leq \frac{1}{N_t \ \log_2\left(N_t\right)} \sum_{n_t^{(1)}=1}^{N_t} \sum_{n_t^{(2)}=1}^{N_t} \mathrm{d_H}\left(b_{n_t^{(1)}}, b_{n_t^{(2)}}\right) \cdot$$

$$\mathrm{Q}\left(\sqrt{\frac{E_s}{4\ N_0} \sum_{n_r=1}^{N_r} \left|h_{n_r n_t^{(2)}} - h_{n_r n_t^{(1)}}\right|^2}\right),$$

Thank You!