Sequential compensation of RF impairments in OFDM systems

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Outline

- Introduction
- System model
- Sequential compensation technique
- Simulations
- Conclusions

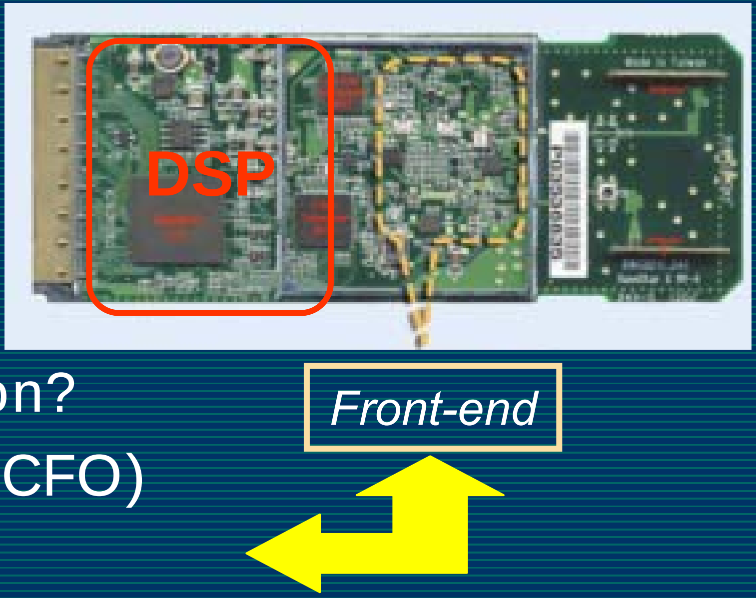
Introduction

- OFDM has gained popularity as a physical layer technique for wideband communication systems
  - High spectral efficiency
  - Low complexity frequency-domain equalization
  - Robustness against multipath channels
  - Adaptive data rate
  - OFDMA for multiuser systems

Introduction

OFDM systems' challenges

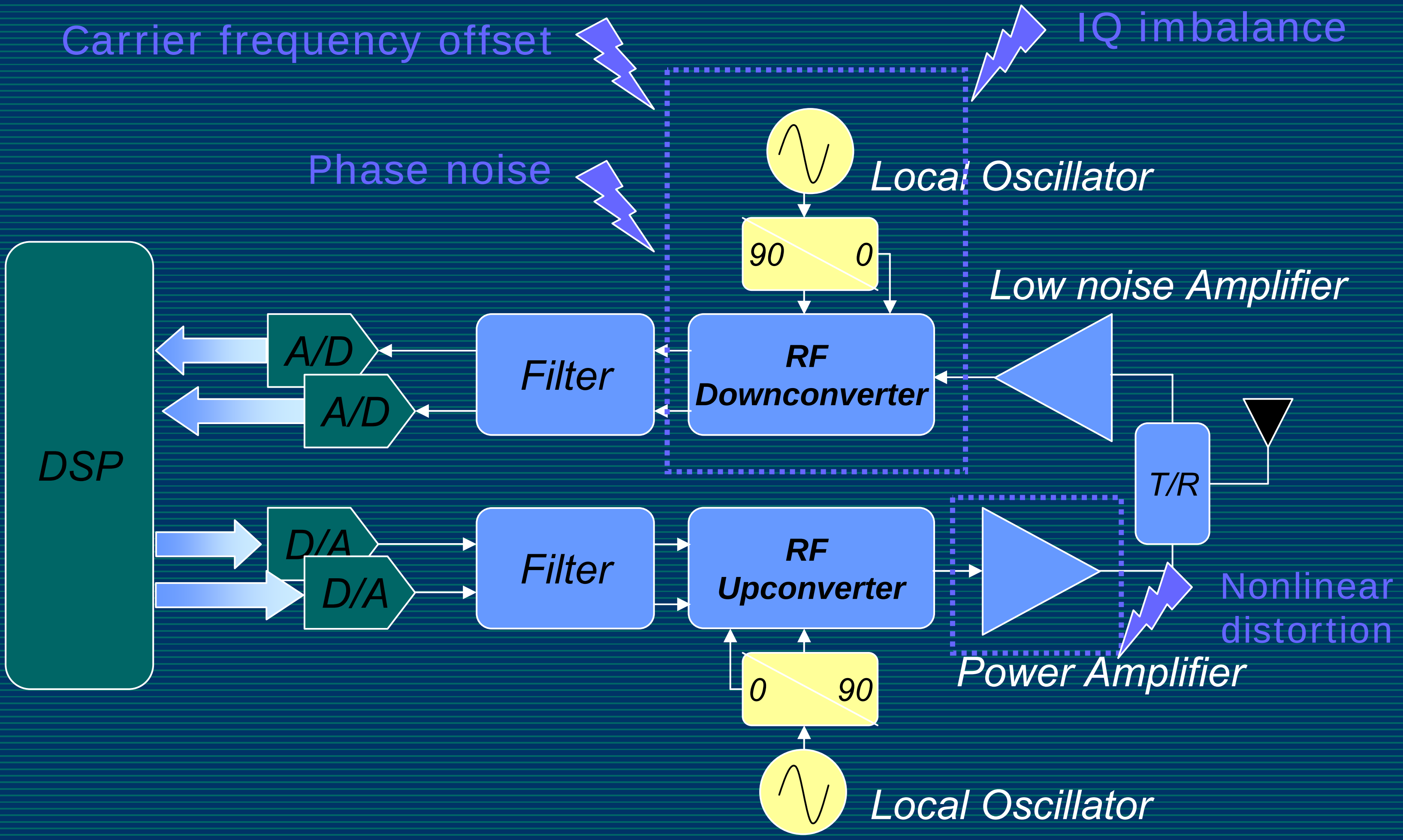
- High PAPR of OFDM signals
  - Nonlinear distortion
  - Low power efficiency
  - Interference
- I/Q imbalance
  - Performance reduction
  - Low-cost implementation?
- Carrier frequency offset (CFO)
  - Performance reduction
- Phase noise



Introduction

- Low-cost analog implementation techniques suffer from several imperfections:
  - Nonlinear response of analog front-end power amplifiers
  - Inaccurate local oscillators
  - Mismatches in the I and Q branches in direct-conversion transceivers
- These impairments can be compensated in digital domain in a cost effective manner

System model



System model

- Transmitter side
  - Nonlinear distortion $x_{pa}(n) = g[x(n)] = K_L x(n) + d(n)$
- Receiver side
  - IQ imbalance $y_{iq}(n) = K_1 y(n) + K_2 y^*(n)$
  - Carrier frequency offset $y_{cfo}(n) = y_{iq}(n) e^{j\Delta_f n}$
  - Phase noise $y_{pn}(n) = y_{cfo}(n) e^{j\phi(n)}$
- Baseband signal after downconversion
  - Time domain

$$y_{bb}(n) = K_1 e^{-j(\Delta_f n+\phi(n))} y(n) + K_2 e^{j(\Delta_f n+\phi(n))} y^*(n) + v(n))$$

System model

- Baseband signal after downconversion
  - Frequency domain

$$\mathbf{Y}_{bb} = K_1\left[\mathbf{QCHX}_{pa} + \boldsymbol{\Upsilon}\right] + K_2\left[\mathbf{QCHX}_{pa} + \boldsymbol{\Upsilon}\right]^{\#}$$

Additive noise

PA output

$X^{\#}(k) = X(-k)^{*}$

Mirror conjugate

H is an $N \times N$ diagonal channel matrix

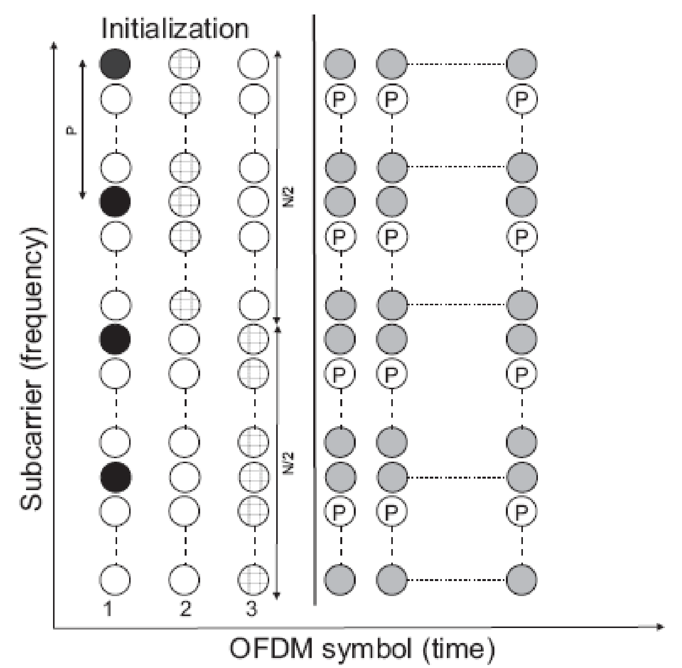
C and **Q** are $N \times N$ non-diagonal matrices which model CFO and phase noise

⇩

-Diagonal elements create common phase error (CPE)
-Nondiagonal elements generate intercarrier interference (ICI)

Sequential compensation

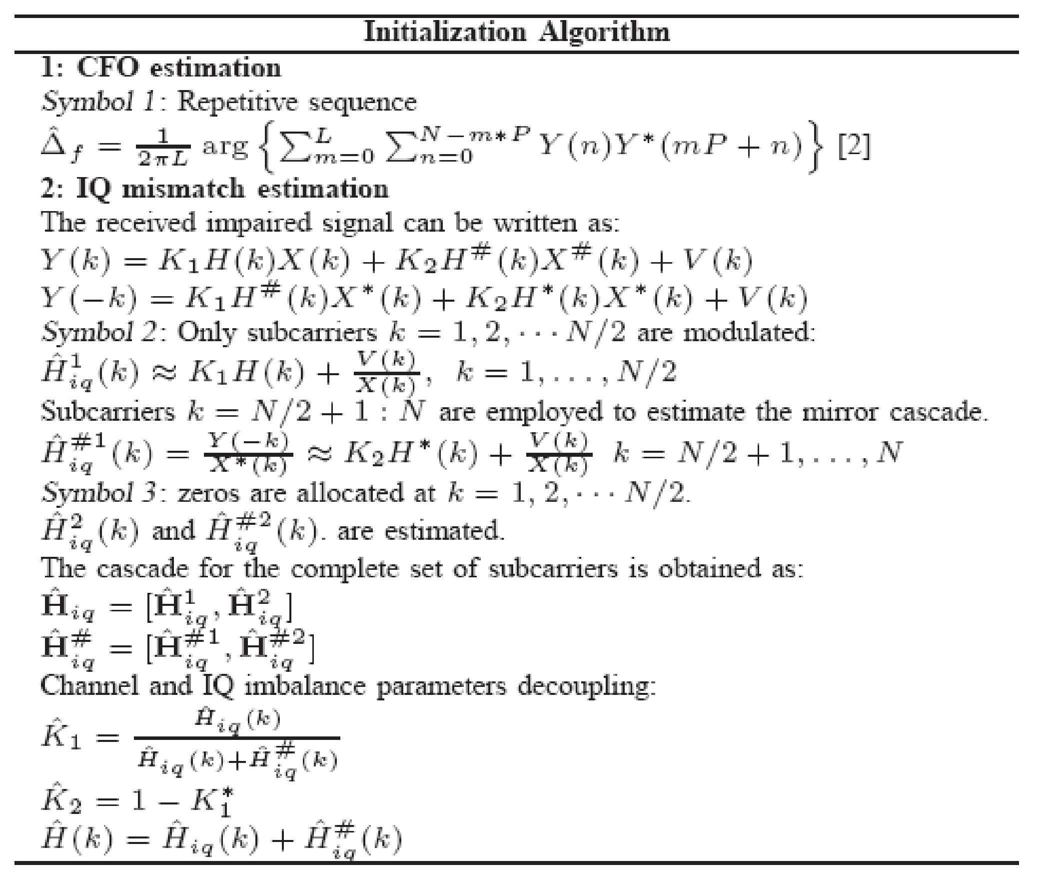
- *Initialization: acquisition of IQ imbalance and CFO parameters*
  - A preamble of three OFDM symbols is employed to estimate parameters for distortion of the original transmitted signal



- Symbol 1 is a repetitive sequence of length *N* consisting of P identical blocks of length L employed for CFO estimation
- IQ imbalance parameters are estimated with the following two symbols
- Frank-Zadoff-Chu (FZC) low PAPR sequence

Sequential compensation

- Initialization algorithm



Initialization Algorithm

1: CFO estimation

Symbol 1: Repetitive sequence

$\hat{\Delta}_f = \frac{1}{2\pi L} \arg \left\{ \sum_{m=0}^{L} \sum_{n=0}^{N-m*P} Y(n) Y^*(mP+n) \right\}$ [2]

2: IQ mismatch estimation

The received impaired signal can be written as:

$Y(k) = K_1 H(k) X(k) + K_2 H^{\#}(k) X^{\#}(k) + V(k)$

$Y(-k) = K_1 H^{\#}(k) X^*(k) + K_2 H^*(k) X^*(k) + V(k)$

Symbol 2: Only subcarriers $k = 1, 2, \cdots N/2$ are modulated:

$\hat{H}_{iq}^{1}(k) \approx K_1 H(k) + \frac{V(k)}{X(k)}, \quad k = 1, \ldots, N/2$

Subcarriers $k = N/2+1 : N$ are employed to estimate the mirror cascade.

$\hat{H}_{iq}^{\#1}(k) = \frac{Y(-k)}{X^*(k)} \approx K_2 H^*(k) + \frac{V(k)}{X(k)} \quad k = N/2+1, \ldots, N$

Symbol 3: zeros are allocated at $k = 1, 2, \cdots N/2$.

$\hat{H}_{iq}^{2}(k)$ and $\hat{H}_{iq}^{\#2}(k)$. are estimated.

The cascade for the complete set of subcarriers is obtained as:

$\hat{\mathbf{H}}_{iq} = [\hat{\mathbf{H}}_{iq}^{1}, \hat{\mathbf{H}}_{iq}^{2}]$

$\hat{\mathbf{H}}_{iq}^{\#} = [\hat{\mathbf{H}}_{iq}^{\#1}, \hat{\mathbf{H}}_{iq}^{\#2}]$

Channel and IQ imbalance parameters decoupling:

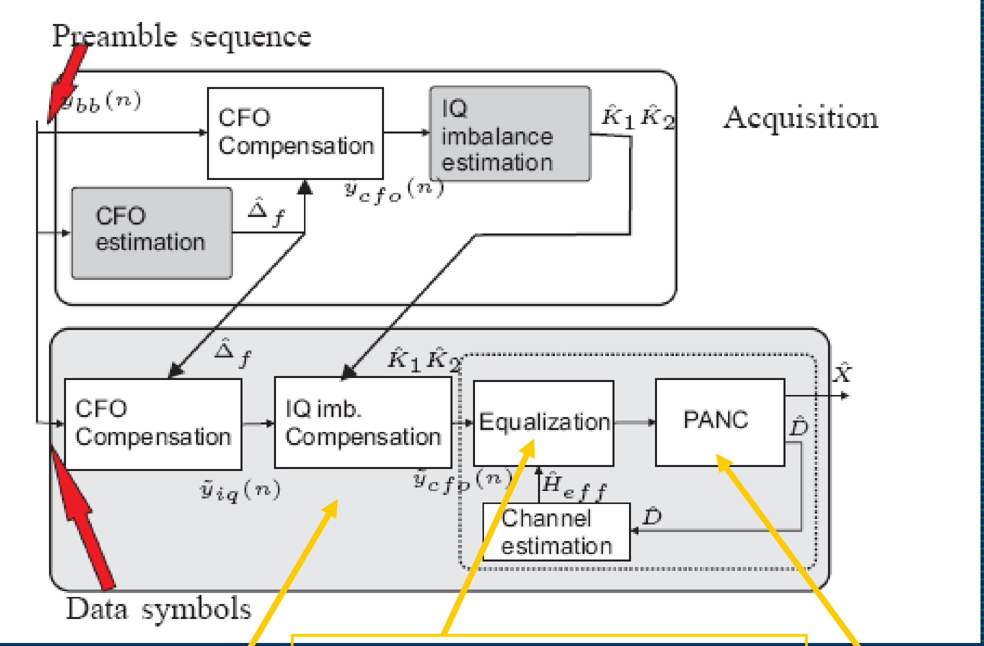
$\hat{K}_1 = \frac{\hat{H}_{iq}(k)}{\hat{H}_{iq}(k) + \hat{H}_{iq}^{\#}(k)}$

$\hat{K}_2 = 1 - K_1^*$

$\hat{H}(k) = \hat{H}_{iq}(k) + \hat{H}_{iq}^{\#}(k)$

Sequential compensation

- *Sequential compensation*



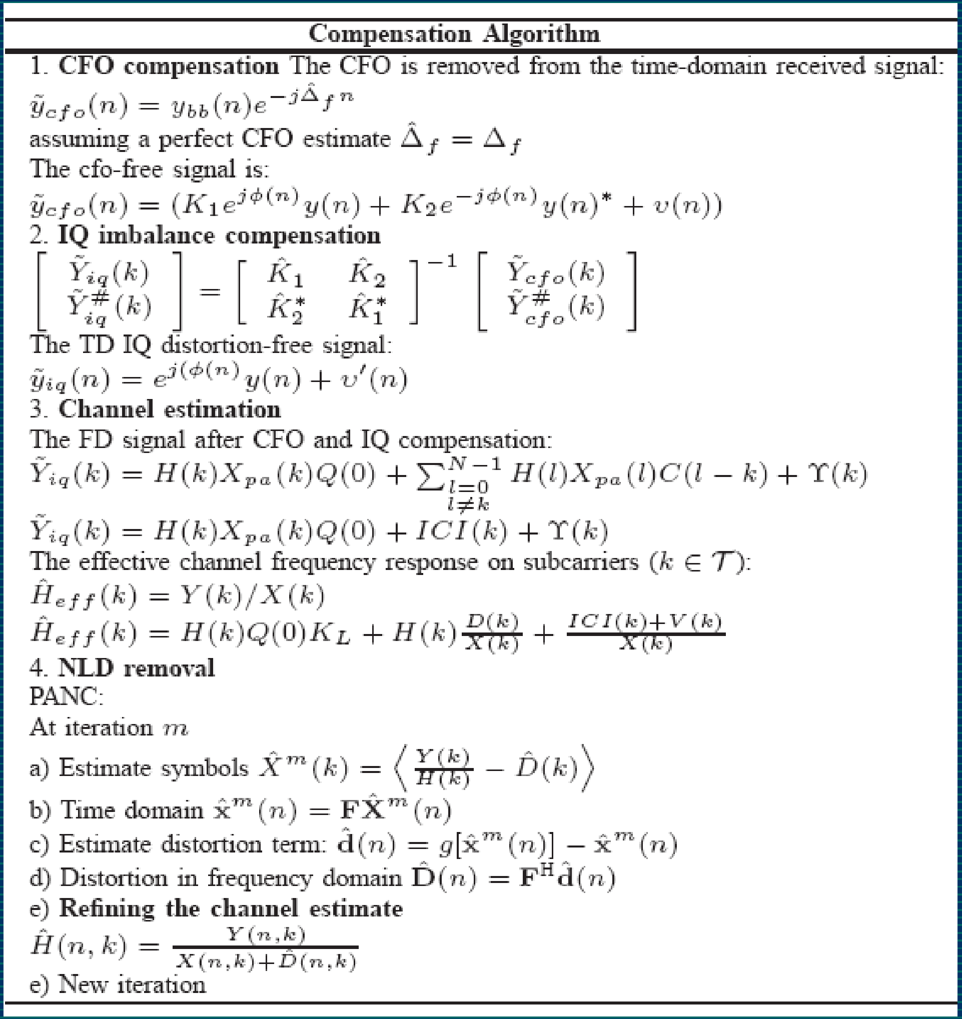
Channel equalization and CPE compensation

IQ mismatch compensation

Nonlinear distortion removal

- •Common phase error (CPE) due to phase noise and residual CFO are included in the effective channel estimate
- •In the equalization process both channel and CPE effects are compensated at the same time
- •The ICI created by PN is considered as an additional noise term which reduces the effective signal to noise ratio
- •A Power Amplifier Nonlinearity Cancellation (PANC) technique is considered for removing the nonlinear distortion effects

Sequential compensation



Compensation Algorithm

1. **CFO compensation** The CFO is removed from the time-domain received signal:

$\tilde{y}_{cfo}(n) = y_{bb}(n)e^{-j\hat{\Delta}_f n}$

assuming a perfect CFO estimate $\hat{\Delta}_f = \Delta_f$

The cfo-free signal is:

$\tilde{y}_{cfo}(n) = (K_1 e^{j\phi(n)} y(n) + K_2 e^{-j\phi(n)} y(n)^* + v(n))$

2. **IQ imbalance compensation**

$$\begin{bmatrix} \tilde{Y}_{iq}(k) \\ \tilde{Y}^{\#}_{iq}(k) \end{bmatrix} = \begin{bmatrix} \hat{K}_1 & \hat{K}_2 \\ \hat{K}_2^* & \hat{K}_1^* \end{bmatrix}^{-1} \begin{bmatrix} \tilde{Y}_{cfo}(k) \\ \tilde{Y}^{\#}_{cfo}(k) \end{bmatrix}$$

The TD IQ distortion-free signal:

$\tilde{y}_{iq}(n) = e^{j(\phi(n)} y(n) + v'(n)$

3. **Channel estimation**

The FD signal after CFO and IQ compensation:

$\tilde{Y}_{iq}(k) = H(k)X_{pa}(k)Q(0) + \sum_{\substack{l=0 \\ l \neq k}}^{N-1} H(l)X_{pa}(l)C(l-k) + \Upsilon(k)$

$\tilde{Y}_{iq}(k) = H(k)X_{pa}(k)Q(0) + ICI(k) + \Upsilon(k)$

The effective channel frequency response on subcarriers ($k \in \mathcal{T}$):

$\hat{H}_{eff}(k) = Y(k)/X(k)$

$\hat{H}_{eff}(k) = H(k)Q(0)K_L + H(k)\frac{D(k)}{X(k)} + \frac{ICI(k)+V(k)}{X(k)}$

4. **NLD removal**

PANC:

At iteration m

a) Estimate symbols $\hat{X}^m(k) = \left\langle \frac{Y(k)}{H(k)} - \hat{D}(k) \right\rangle$

b) Time domain $\hat{\mathbf{x}}^m(n) = \mathbf{F}\hat{\mathbf{X}}^m(n)$

c) Estimate distortion term: $\hat{\mathbf{d}}(n) = g[\hat{\mathbf{x}}^m(n)] - \hat{\mathbf{x}}^m(n)$

d) Distortion in frequency domain $\hat{\mathbf{D}}(n) = \mathbf{F}^{\mathrm{H}}\hat{\mathbf{d}}(n)$

e) **Refining the channel estimate**

$\hat{H}(n,k) = \frac{Y(n,k)}{X(n,k)+\hat{D}(n,k)}$

e) New iteration

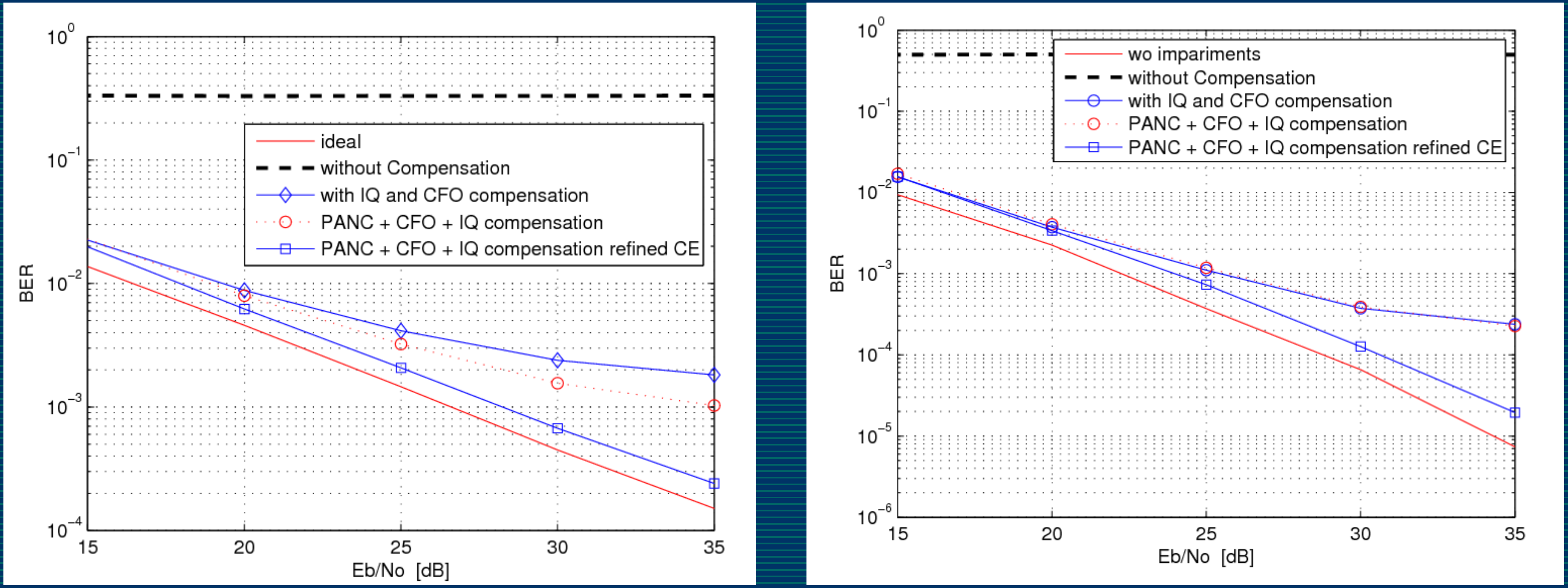
Simulations

☐ Parameters

- OFDM system: N=256 subcarriers with 16-QAM modulation
- Rayleigh fading channel typical urban (TU) scenario
- Mobile speed 40km/h
- Number of pilot subcarriers: 32
- Power amplifier: soft-limiter with clipping level of 1.6
- Normalized CFO, Δf=0.25
- Local oscillator: PLL with an Integrated Phase Noise Power (IPNP) of −32 dBc with loop bandwidth of 1000 Hz and an error floor of −130 dBc
- Receiver IQ imbalance is assumed frequency-independent with a phase and amplitude imbalance of 5 degrees and 5%

Simulations

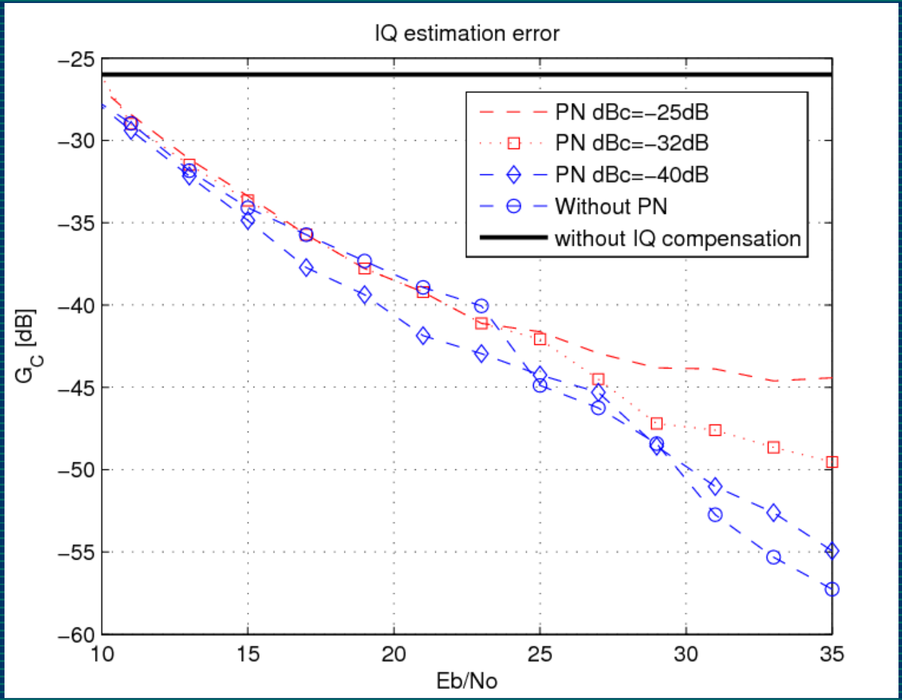
- Bit error rate



BER a) without coding and b) with convolutional coding $R = 1/2$

Simulations

- Normalized image power gain
  - Quantifies the improvement obtained with the IQ imbalance compensation method



$$G_C = \left| \frac{K_2 \hat{K_1}^* - K_1 \hat{K_2}^*}{K_1 \hat{K_1}^* - K_2 \hat{K_2}^*} \right|^2$$

Normalized image power gain with and without compensation vs. Eb/No including phase noise

Conclusions

- The proposed method jointly mitigates the effects of IQ imbalance, phase noise, carrier frequency offset and nonlinear distortion
- Analog-domain compensation is a challenging issue due to cost reasons
- The proposed baseband digital-domain compensation technique is able to dramatically improve the system performance
- The compensation technique can be used to relax the analog front-end specifications to facilitate a cost-efficient implementation
- Compensation techniques need to attack the overall problem: Previous techniques developed for an isolated impairment do not see the big picture