A Survey of Delay and Gain Correction Methods for the Indirect Learning of Digital Predistorters

Harald Enzinger, Karl Freiberger, Gernot Kubin, Christian Vogel

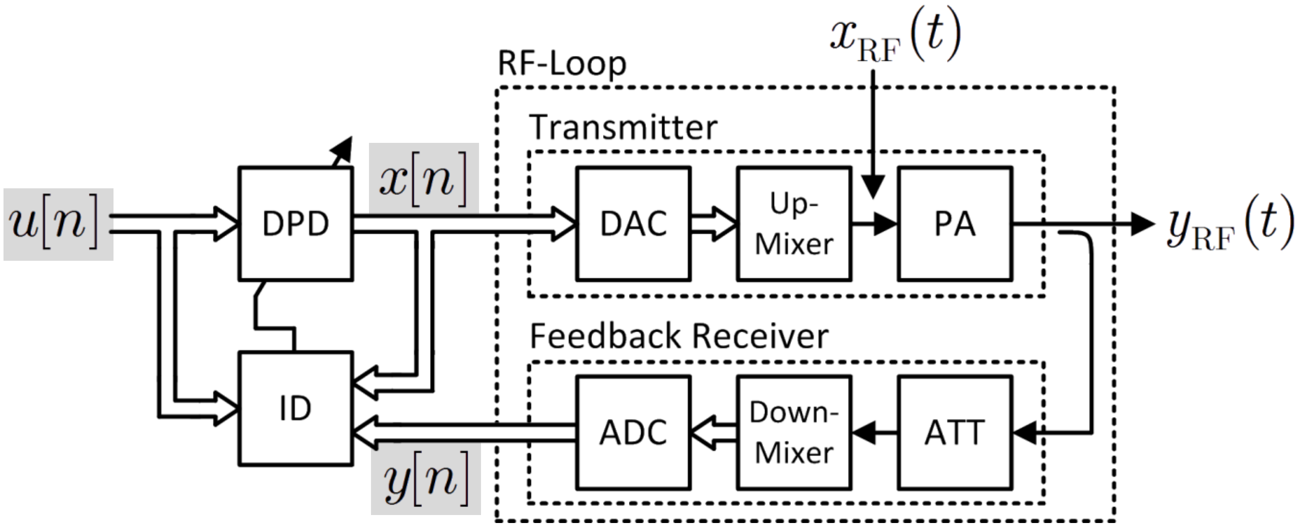
IEEE International Conference on Electronics, Circuits and Systems

Monte Carlo, Monaco

13.12.2016

Digital Predistortion (DPD)

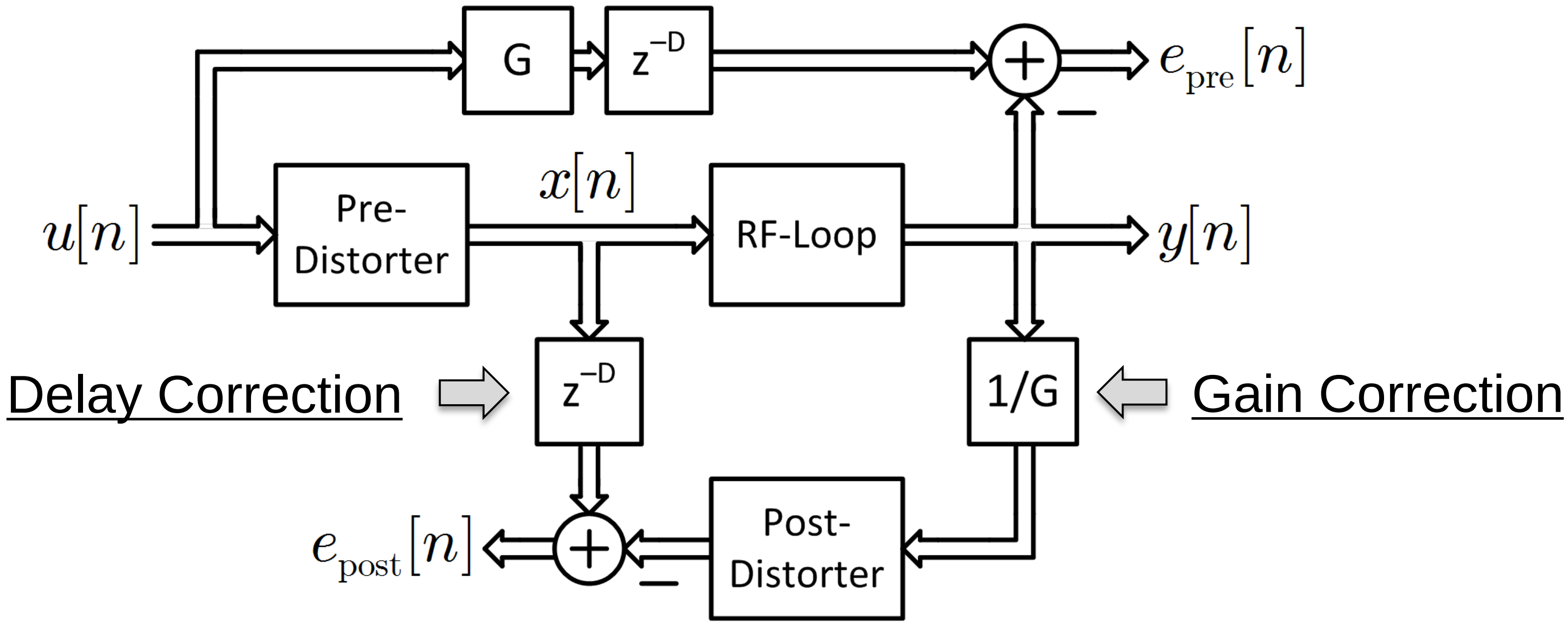
- Digital Enhancement of Wireless Transmitters



- Identification (ID)
  - Based on inversion: Identify $x[n] \mapsto y[n]$ and invert the system.
  - Direct learning: Adaptation of DPD such that $y[n] = u[n]$.
  - Indirect learning: Identify $y[n] \mapsto x[n]$ and use the result as DPD.

Indirect Learning Architecture (ILA)

- Learn the post-inverse and use it as pre-inverse

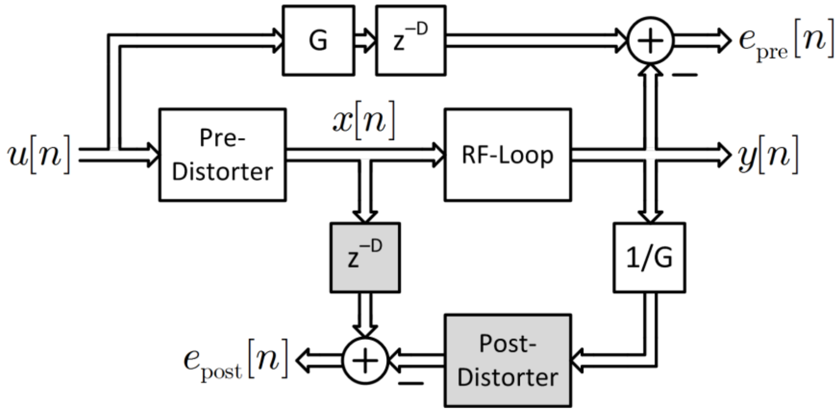


Requirements for the Success of ILA

(R1)

The postdistorter sufficiently minimizes its error signal.

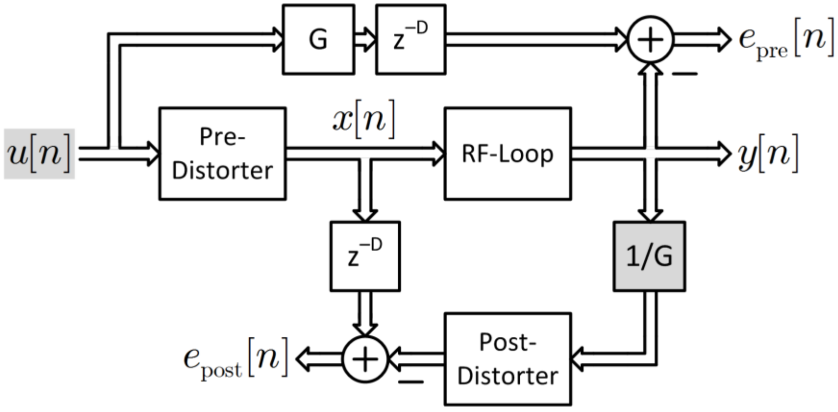
⇨ Model
⇨ Delay-correction



(R2)

The predistorter operates within the region identified by the postdistorter.

⇨ Signal
⇨ Gain-correction



Delay Correction

- Narrowband systems ↔ memoryless models
  - Sensitive to loop delay error
    - High oversampling ratio
    - Fractional delay correction
- Wideband systems ↔ models with memory
  - Insensitive to loop delay error, if causal & within memory-depth
    - Underestimate for forward-modeling
    - Overestimate for inverse-modeling

Methods for Delay Estimation

- Objective function must be insensitive to
  - Noise
  - Distortion
  - Complex scaling
- Real-valued objective functions
  - Cross-covariance of magnitudes
  - Cross-correlation of differential magnitudes
  - Distance of local extrema of phase characteristic
- Complex-valued objective functions
  - Complex cross-correlation between signals

Complex Cross-Correlation

$$r_{xy}[m] = \sum_{n=0}^{N-1} x^*[n-m]\, y[n] \quad \Big| \quad x[n] \text{ and } y[n] \text{ are defined for } 0 \leq n \leq N-1$$

- Linear cross-correlation
  - Zero-padding of signals

    $r_{xy}[m]$ is non-zero for

    $-(N-1) \leq m \leq +(N-1)$
- Circular cross-correlation
  - Periodic extension of signals

    $r_{xy}[m]$ is uniquely defined for

    $0 \leq m \leq +(N-1)$
- Further considerations with respect to the definition
  - Direction of shift

    m represents the delay of $y[n]$ with respect to $x[n]$
  - Conjugation of signal

    choice may be motivated by the technique for fast computation

Computation of Cross-Correlation

- On-Chip Implementation
  - Synchronization, small delay, non-periodic signals
  - Direct computation of linear cross-correlation
- Lab-based measurements
  - Use periodic input signal
  - Acquire one or two periods of output signal
  - FFT-based computation of circular cross-correlation

$$\boldsymbol{r_{xy}} = \mathrm{IFFT}\left\{(\mathrm{FFT}\{\boldsymbol{x}\})^* \circ \mathrm{FFT}\{\boldsymbol{y}\}\right\}$$

$$\boldsymbol{x} = [\ x[0]\ ,\ x[1]\ ,\ \dots\ ,\ x[N-1]\ ]^{\mathrm{T}}$$
$$\boldsymbol{y} = [\ y[0]\ ,\ y[1]\ ,\ \dots\ ,\ y[N-1]\ ]^{\mathrm{T}}$$
$$\boldsymbol{r_{xy}} = [\ r_{xy}[0]\ ,\ r_{xy}[1]\ ,\ \dots\ ,\ r_{xy}[N-1]\ ]^{\mathrm{T}}$$

Frequency domain ↔ Time domain
Multiplication ↔ Convolution
Conjugation ↔ Conjugation + time-reversal

Integer and Fractional Delay Estimation

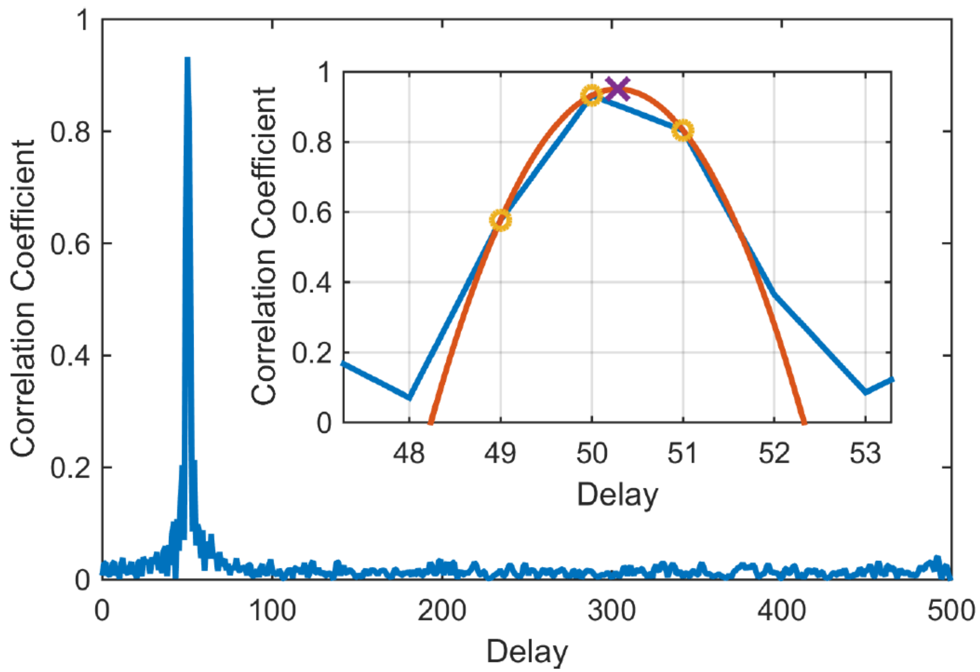
- Integer delay
  - Maximum magnitude

$$D_{\text{int}} = \arg\max_m \left| r_{xy}[m] \right|$$

- Fractional delay
  - Parabolic interpolation

$$c_i = \left| r_{xy}[D_{\text{int}} + i] \right|$$

$$D_{\text{frac}} = \frac{c_{-1} - c_{+1}}{2\left(c_{-1} - 2c_0 + c_{+1}\right)}$$



Correlation Coefficient:

$$\rho_{xy}[m] = \frac{r_{xy}[m]}{\sqrt{(\boldsymbol{x}^{\mathrm{H}}\boldsymbol{x})(\boldsymbol{y}^{\mathrm{H}}\boldsymbol{y})}}$$

Integer and Fractional Delay Correction

- Integer delay
  - Shift either input or output signal
- Fractional delay
  - On-chip implementation
    - Farrow filter, efficient technique for interpolation (linear, cubic)
  - Lab-based measurements
    - Sinc-interpolation implemented in frequency domain

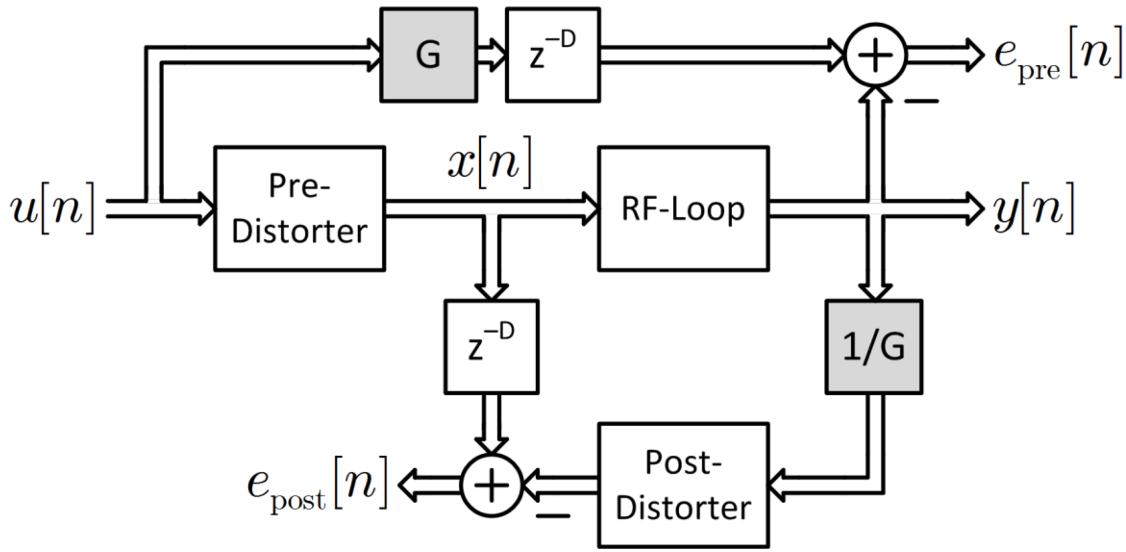
$$\boldsymbol{X} = \mathrm{FFTSHIFT}\{\mathrm{FFT}\{\boldsymbol{x}\}\}$$

$$\boldsymbol{X}_{\mathrm{delay}} = \boldsymbol{X} \circ e^{-j\boldsymbol{\omega}D} \qquad \boldsymbol{\omega} = \frac{2\pi}{N}\left[-\left\lfloor\frac{N}{2}\right\rfloor, -\left\lfloor\frac{N}{2}\right\rfloor + 1, \ldots, \left\lceil\frac{N}{2}\right\rceil - 1\right]^{\mathrm{T}}$$

$$\boldsymbol{x}_{\mathrm{delay}} = \mathrm{IFFT}\{\mathrm{IFFTSHIFT}\{\boldsymbol{X}_{\mathrm{delay}}\}\}$$

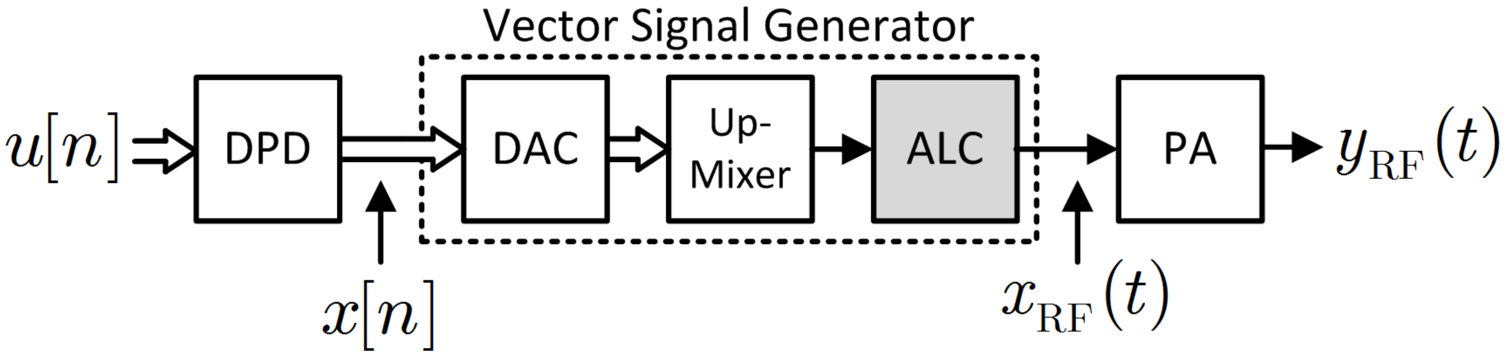
Gain Correction

- Considerations for gain normalization
  - Normalization gain ⬄ Target gain of linearized system
  - Too high gain will lead to clipping (DAC)



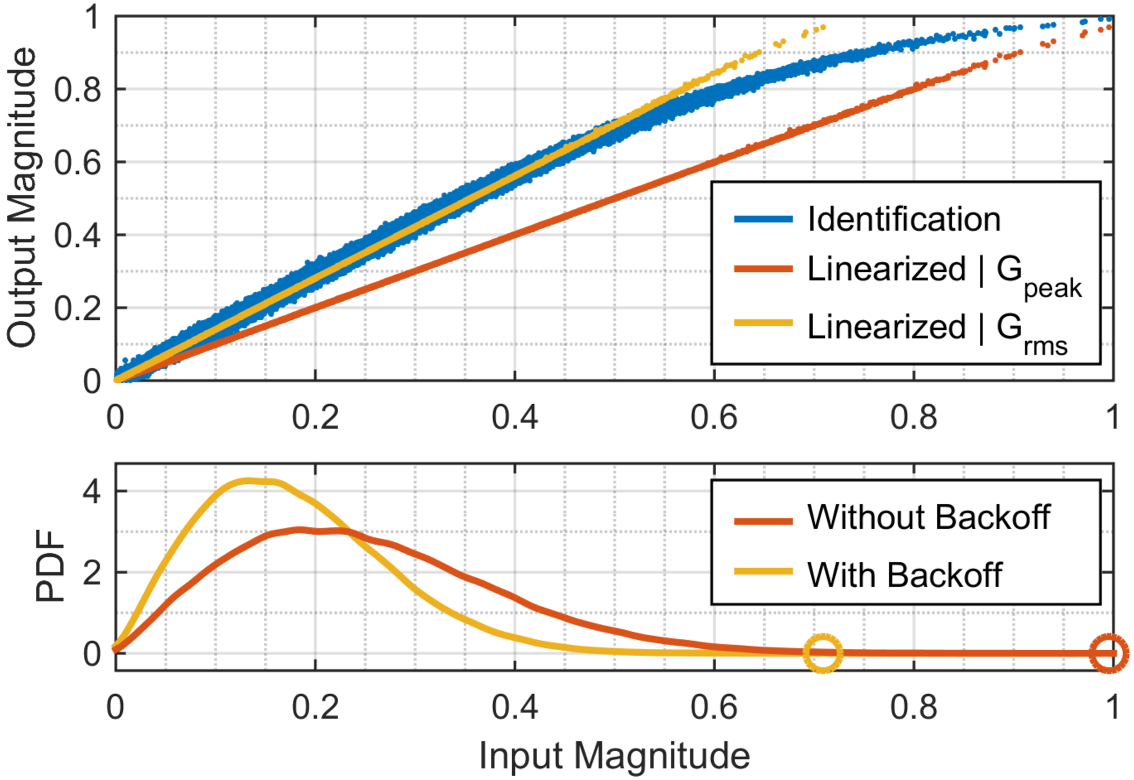
Automatic Level Control (ALC)

- ALC controls output power of vector signal generator
- ALC changes gain depending on signal statistics
- DPD changes signal statistics
- Different gain between identification and evaluation



Turn off ALC!

Methods for Gain Correction

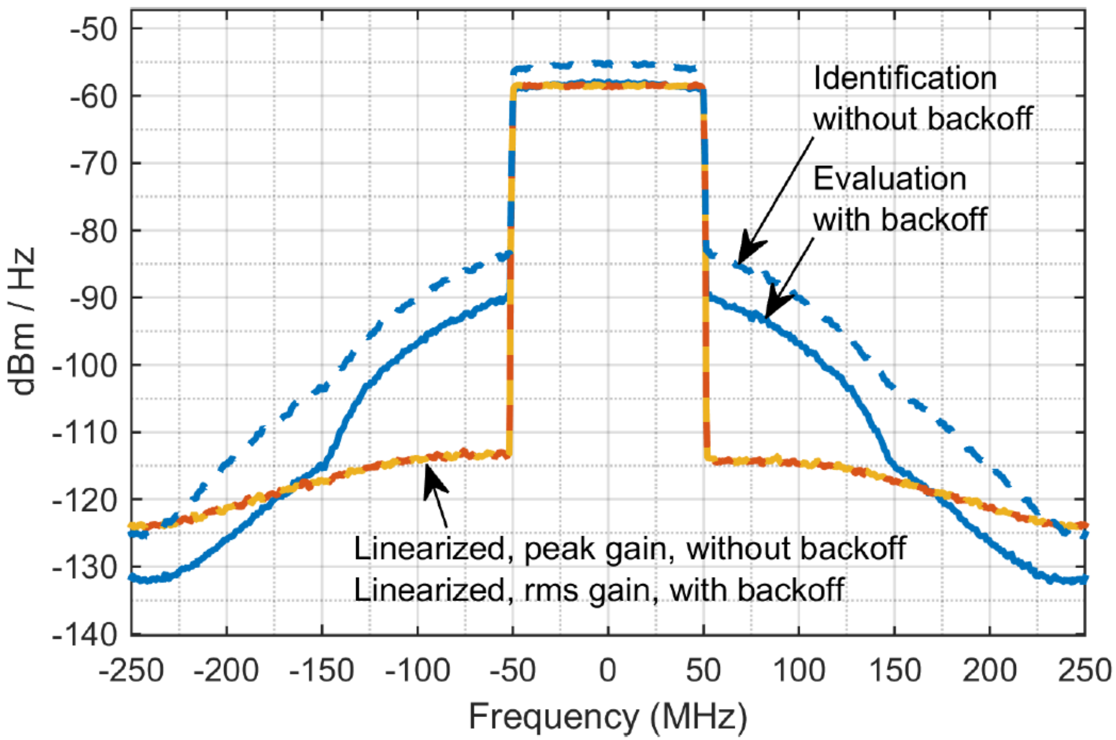


Both methods are equivalent if the required backoff is considered.

- **Peak Gain**
  - $G_{\text{peak}} = \frac{\max |\boldsymbol{y}|}{\max |\boldsymbol{x}|}$
  - Use fullscale without clipping
  - Reduces gain
- **RMS Gain**
  - $G_{\text{rms}} = \frac{\text{rms}\{\boldsymbol{y}\}}{\text{rms}\{\boldsymbol{x}\}}$
  - Keeps gain
  - Requires backoff to avoid clipping

Example for Gain Correction

- Identification from signal without backoff
- Comparison of gain correction methods



The reduction of output power and the required backoff can be calculated by

$$G_{\text{backoff}} = \frac{\text{crestfactor}\{\boldsymbol{y}\}}{\text{crestfactor}\{\boldsymbol{x}\}}$$

where $\boldsymbol{x}$ and $\boldsymbol{y}$ are the input and output signal vectors during identification.

Conclusions

- Two requirements for the success of ILA
  - Postdistorter performance ↔ Delay correction
  - Predistorter operation point ↔ Gain correction
- Delay correction
  - Complex cross-correlation
  - Integer and fractional delay estimation and correction
- Gain correction
  - Peak gain and RMS gain
  - DPD reduces the output power
  - Performance must be compared at the same output power!