# RF Distortion Analysis for OFDM WLAN (part I)

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# Outline

- Amplifier Nonlinearity
- Pre-distortion Techniques
- OFDM and PAPR
- Conclusions

# Next . . .

- **Amplifier Nonlinearity**
- Pre-distortion Techniques
- OFDM and PAPR
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# Amplifier Non-Linearity

- Amplifier non-linearity leads to
  - Harmonic Distortion
  - Intermodulation Distortion / Spectral Regrowth
  - Cross Modulation
  - SNR Degradation
  - Constellation Deformation

# Harmonic Distortion

- Harmonics distortion comes because of the amplifier non-linear transfer characteristics

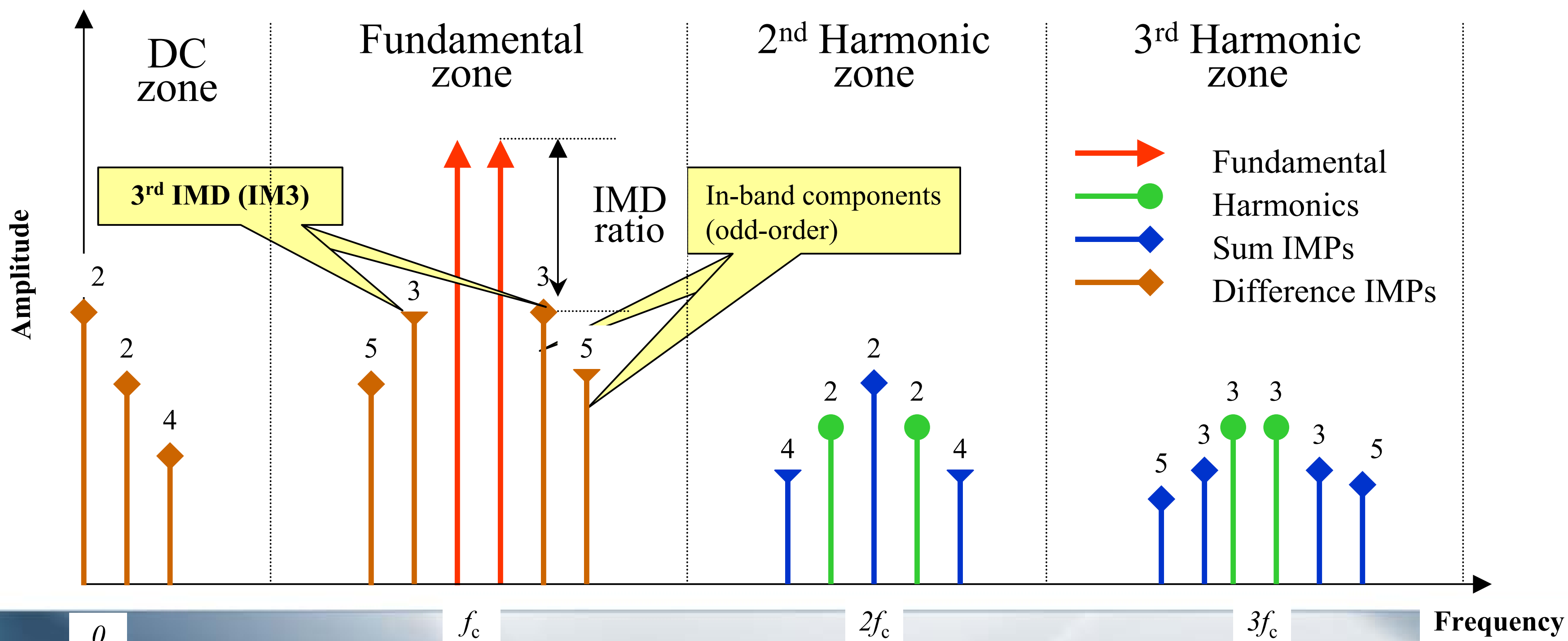
$$v_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + a_4 v_i^4 + \dots$$

  - Every nonlinear term ($n > 1$) generates a new harmonic component at $nf_1$ and $nf_2$

- Harmonics can be filtered out without degrading the system performance, since they are far away from the fundamental frequency

# Intermodulation Distortion (1/2)

- Intermodulation Distortion (IMD) is a result of amplifier nonlinear terms ($n > 1$)
  - generates Intermodulation products (IMP) at $f_{im} = m f_1 - n f_2$
  - Distortion order = $n + m$



# Intermodulation Distortion (2/2)

- IMD is a serious problem in RF systems, especially the third-order IMD (IM3)
  - At $2f_2 - f_1$ and $2f_1 - f_2$
- IM3 is the strongest and the most closest to the fundamental frequency components
- IMD products appear regularly on either side of each carrier
- Odd-order products introduce in-band distortion
- Even-order products introduce out-of-band distortion

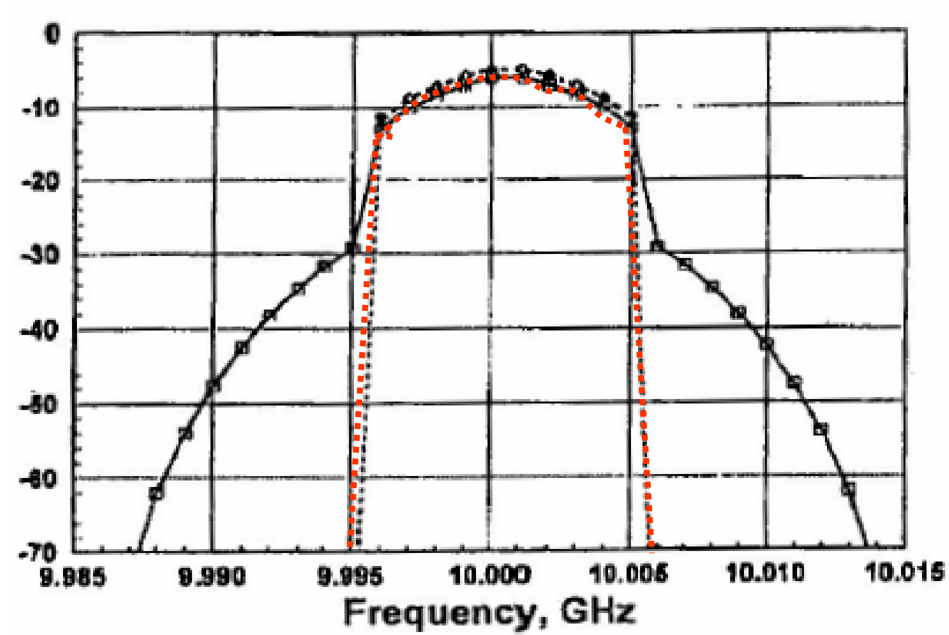
# Cross Modulation

- The crossmodulation comes as a result of the amplifier nonlinearity
  - For the input $V_{in} = V_1 \cos(2\pi f_{c_1} t) + V_2 \left(1 + m\left(t\right)\right) \cos(2\pi f_{c_2} t)$
  - The 3rd order term is $V_o = \frac{3}{2} a_3 V_1 V_2^2 \left(1 + 2m\left(t\right) + m^3\left(t\right)\right) \cos(2\pi f_{c_1} t)$
  - New modulation term at $f_{c1}$

# Spectral Regrowth

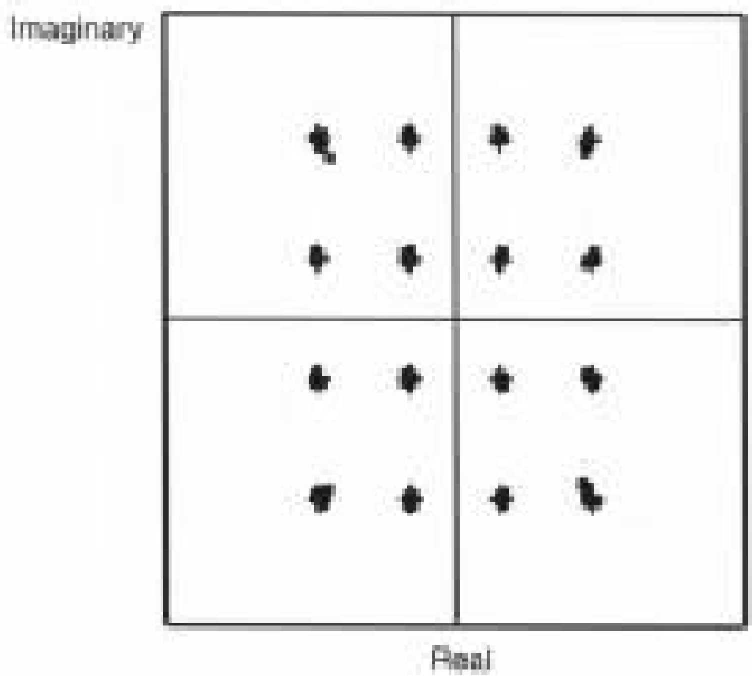
- Also called “Adjacent Channel Interference”

- IM3 energy leaks to the adjacent channels
- ACLR (Adjacent Channel Leakage Ratio)

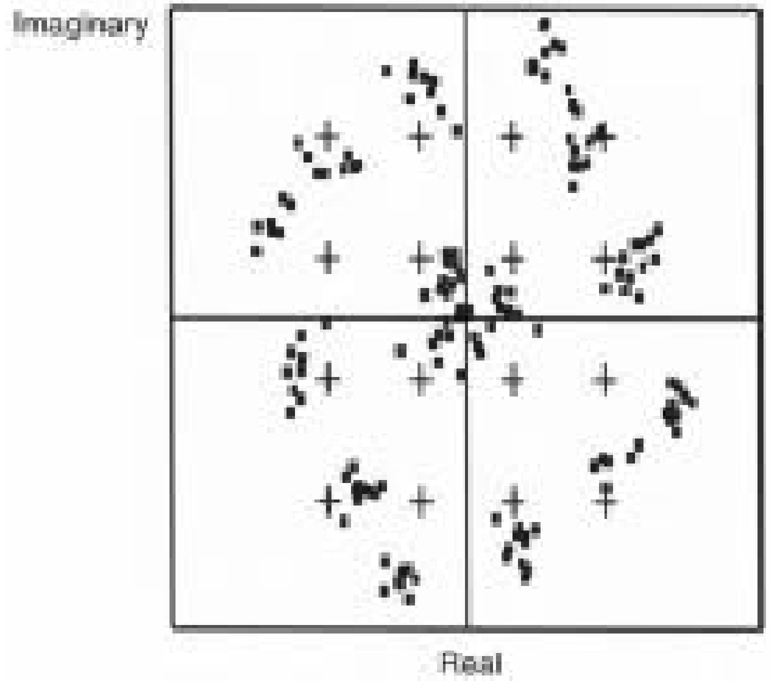


# Constellation Deformation

- 16-QAM signal




Input signal



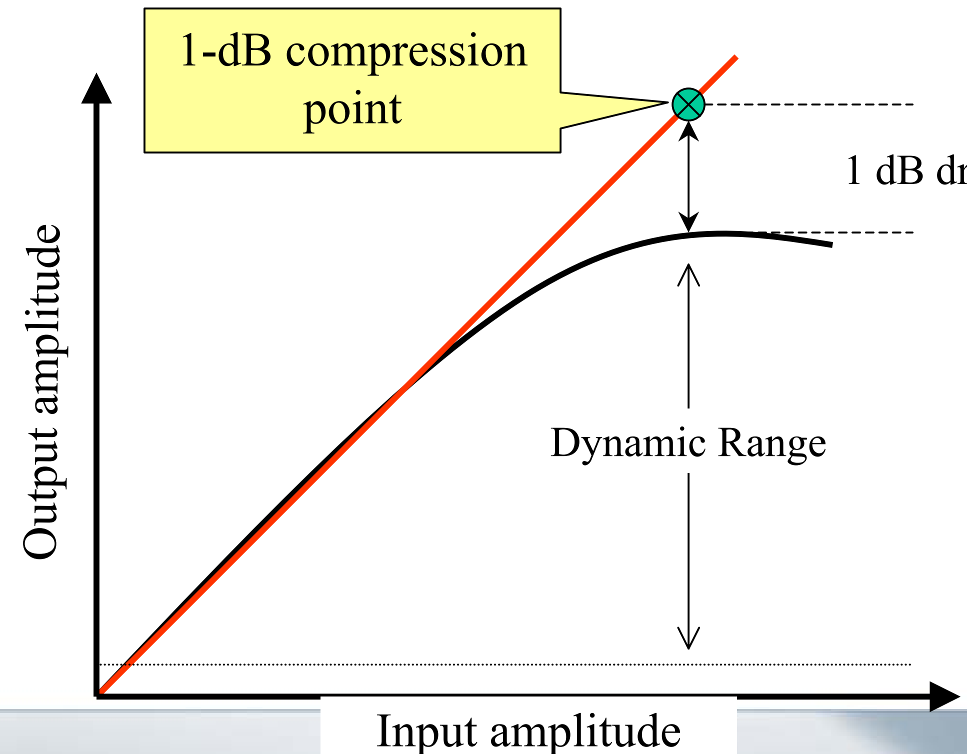

Output signal

# Measuring Nonlinearity

- Most common measures of nonlinearity
  - 1-dB compression point
  - Intercept points
  - AM/AM and AM/PM conversion

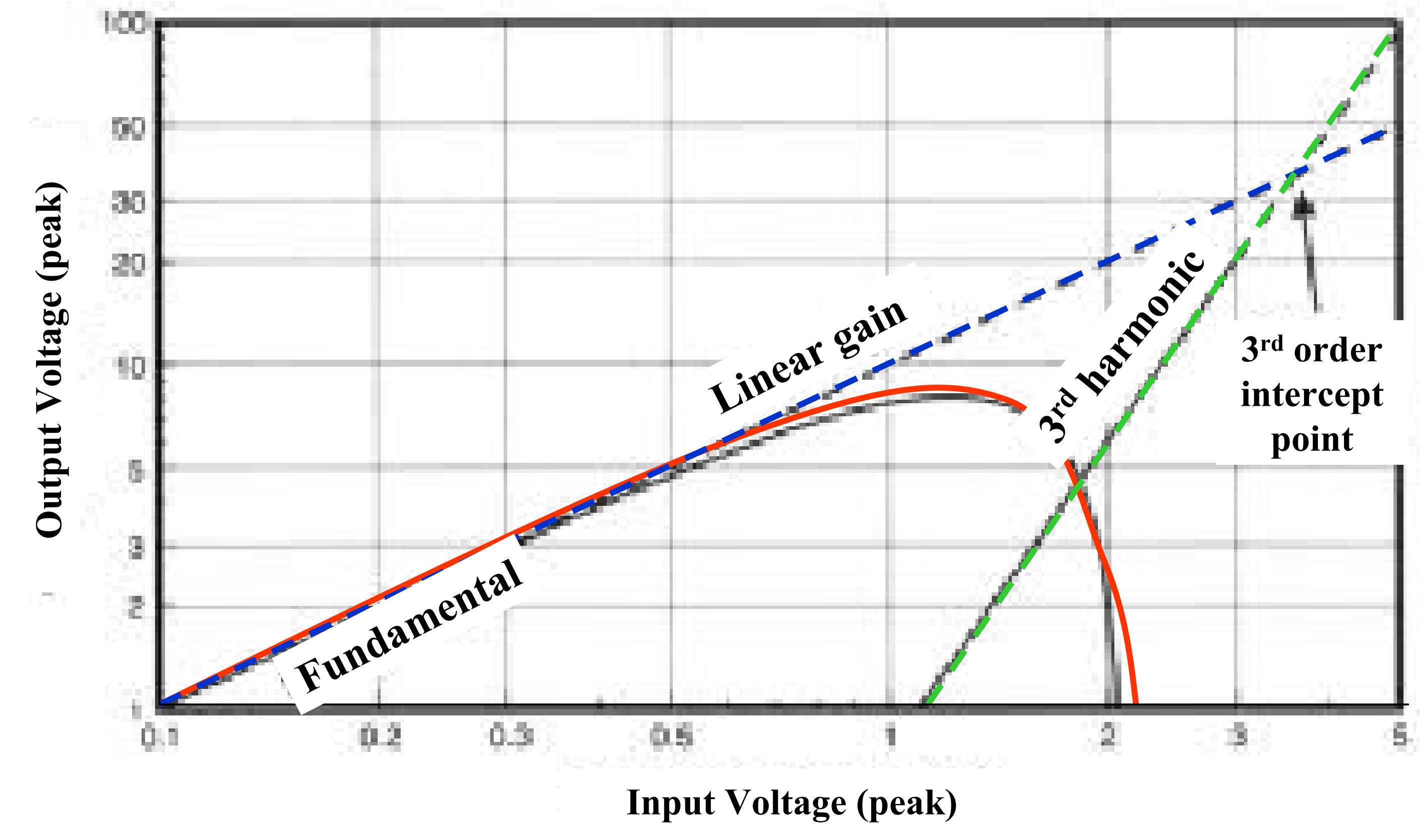
# 1-dB Compression Point

- The point where the output signal gain has dropped by 1dB from the ideal linear characteristics



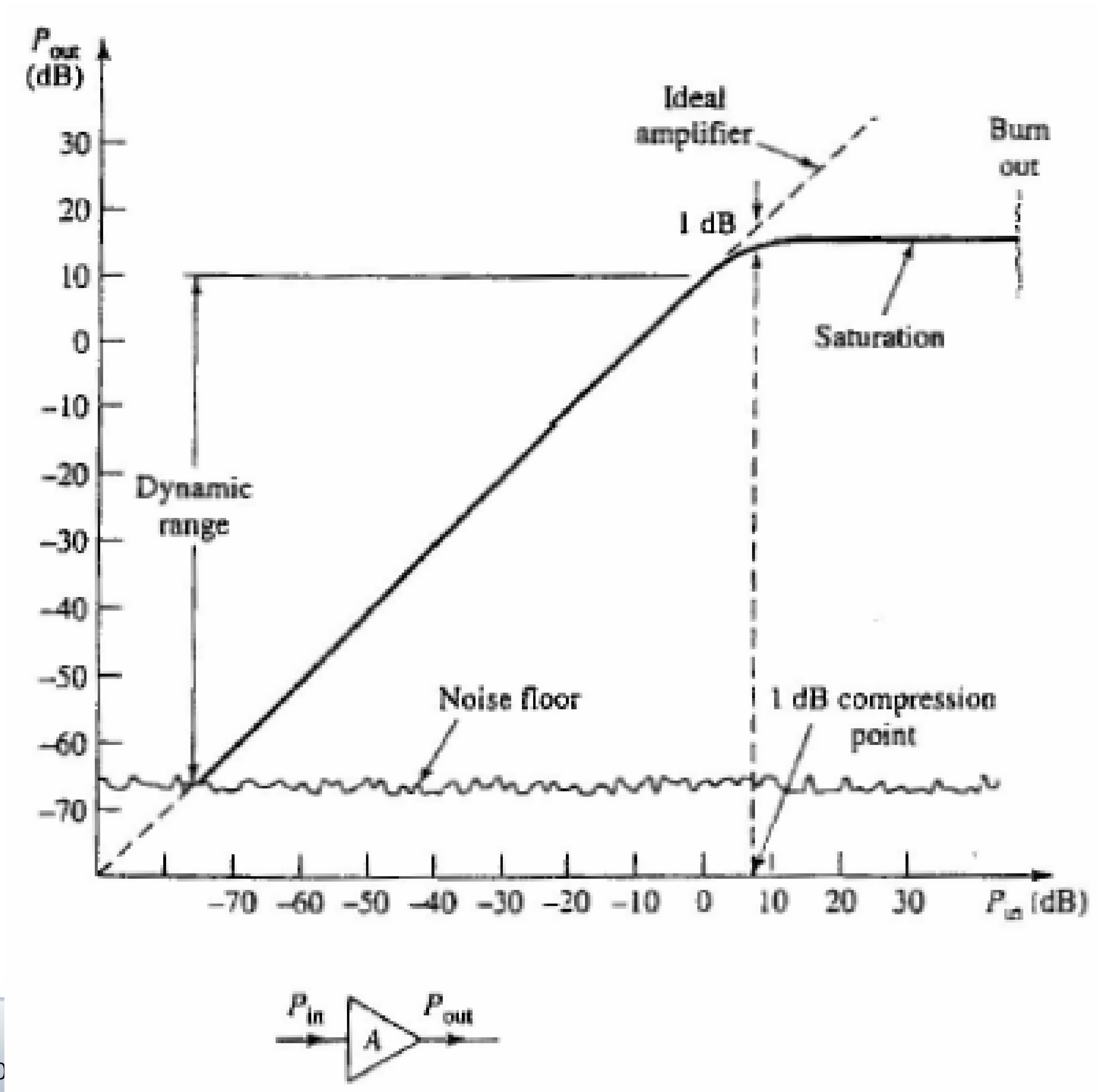
# 3rd Order Intercept Point (IIP3)

- The interception point between the  the extrapolated linear fundamental component and 3rd distortion product



# Amplifier Dynamic Range

- Noise floor
  - $GkT_eB$



# Distortion in Power Amplifiers

- There are two reasons for power amplifiers distortion
  - Distortion due to the amplifier nonlinear characteristics
    - Small signal distortion
  - Distortion due to the amplifier saturation
    - Large signal distortion
- The impact of the large-signal-distortion is more sever than that of small-signal-distortion

# Amplifier Back-Off

- Input Back-Off (IBO)

$$IBO = 10\log\left(\frac{P_{sat,in}}{P_{avg,in}}\right)$$

- Output Back-Off (OBO)

$$OBO = 10\log\left(\frac{P_{sat,out}}{P_{avg,out}}\right)$$

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# OFDM Problems

- There are some obstacles when using OFDM
  - High sensitivity to the frequency errors
  - Intercarrier Interference (ICI) between the subcarriers
  - OFDM signal exhibits very high Peak to Average Power Ratio (PAPR)

# PAPR of OFDM Signals

- The complex envelope of the OFDM signal, over T second interval is given by

$$S(t) = A_c \sum_{n=0}^{N-1} w_n \varphi_n(t), \qquad 0 > t > T$$

Where

$A_c$ is the carrier amplitude, and

$w_n$ is the data vector

And the orthogonal carriers are

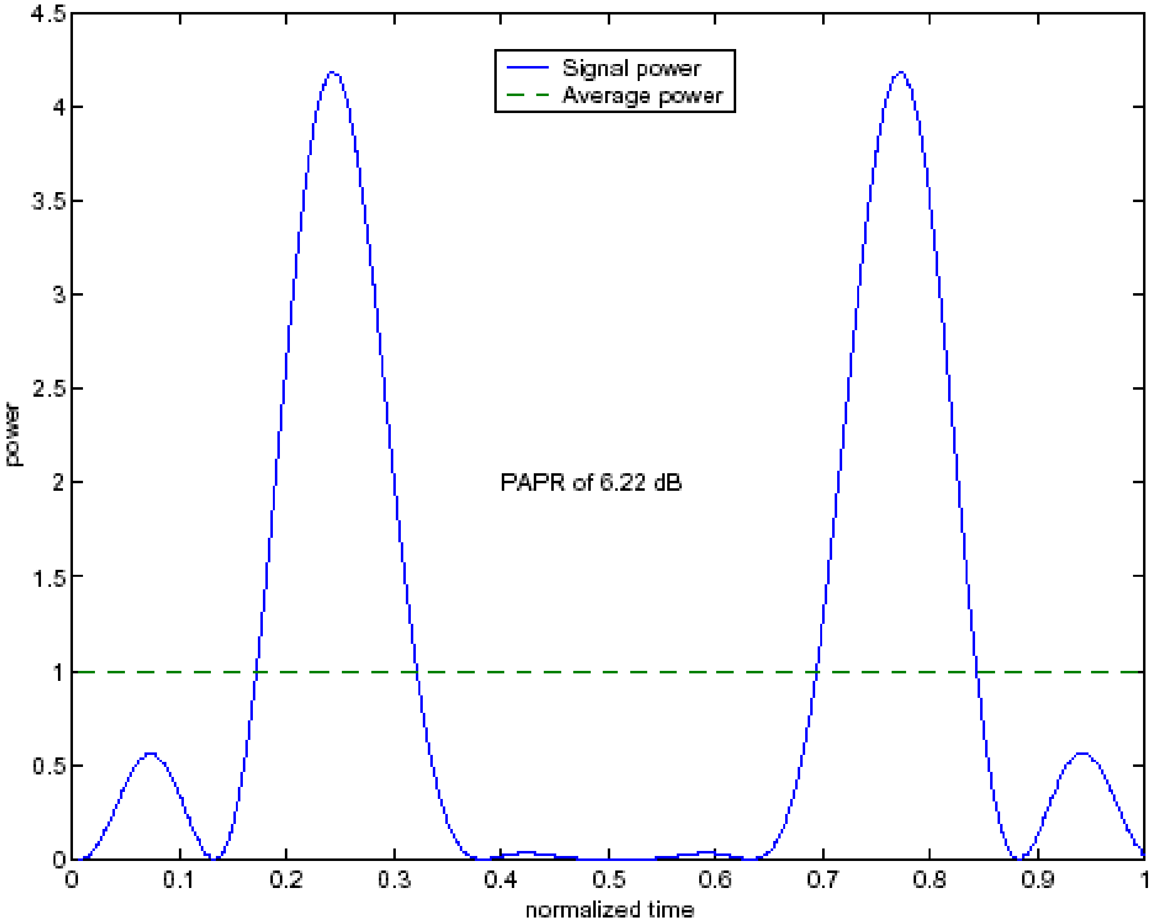
$$\varphi_n(t) = e^{j2\pi f_n t}$$

where

$$f_n(t) = \frac{1}{T}\left(n - \frac{N-1}{2}\right)$$

# PAPR Definition

- The PAPR is defined as $PAPR\left(S(t)\right) = \dfrac{\max_t \left|S(t)\right|^2}{E_s\left[\dfrac{1}{NT}\displaystyle\int_0^{NT} \left|S(t)\right|^2 dt\right]}$



# Quantifying PAPR

- As N becomes larger, the imaginary and real parts of *S(t)* becomes Gaussian distributed (central limit theory)
  - The amplitude of PAPR has a Rayleigh distribution, with zero mean and variance N times of one complex sinusoid
- Assuming mutually uncorrelated symbols, the CDF of PAPR per OFDM symbol is given by

$$\Pr\{PAPR > \gamma\} = \left(1 - \left(1 - e^{\gamma}\right)^{N}\right)$$

# PAPR Properties

- From the pervious two slides, we can conclude the following PAPR properties
  - PAPR results from the superposition of large number of subcarriers
  - The PAPR follows the Rayleigh distribution
  - The large peaks do not occur very often

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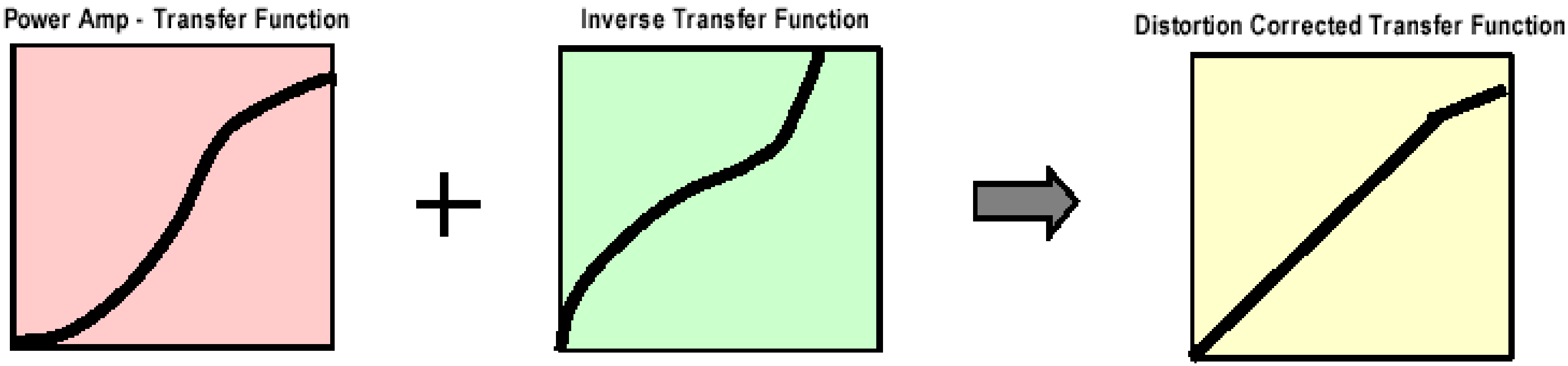
# Predistortion Techniques

- Attempts to compensate for the nonlinear distortions by modifying the input signal characteristics
  - These modifications can be either non-adaptive or adaptive



# Amplitude Clipping

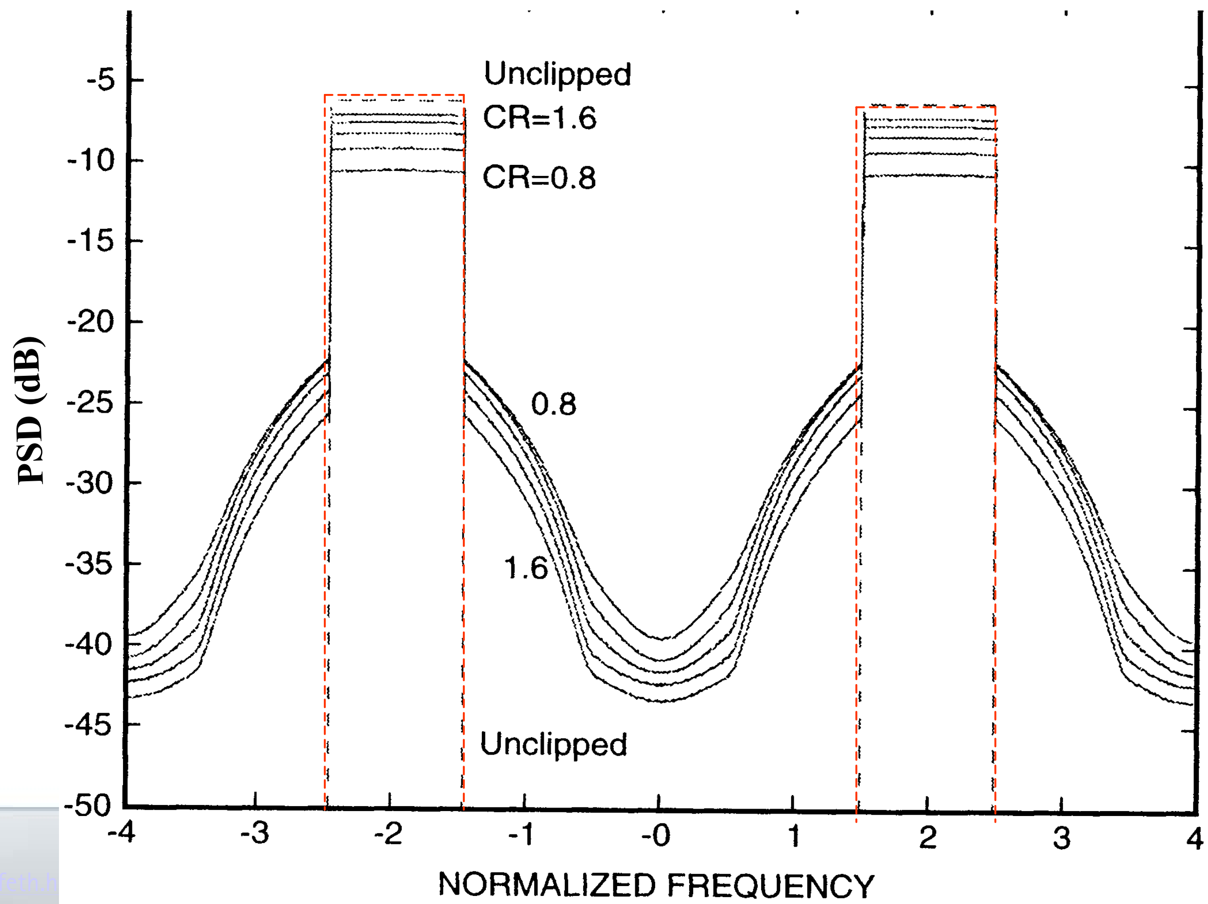
- Limits the peak envelope of the input signal to a predefined value

$$L(x) = \begin{cases} x, |x| \le A \\ Ae^{j\arg(x)}, |x| > A \end{cases}$$

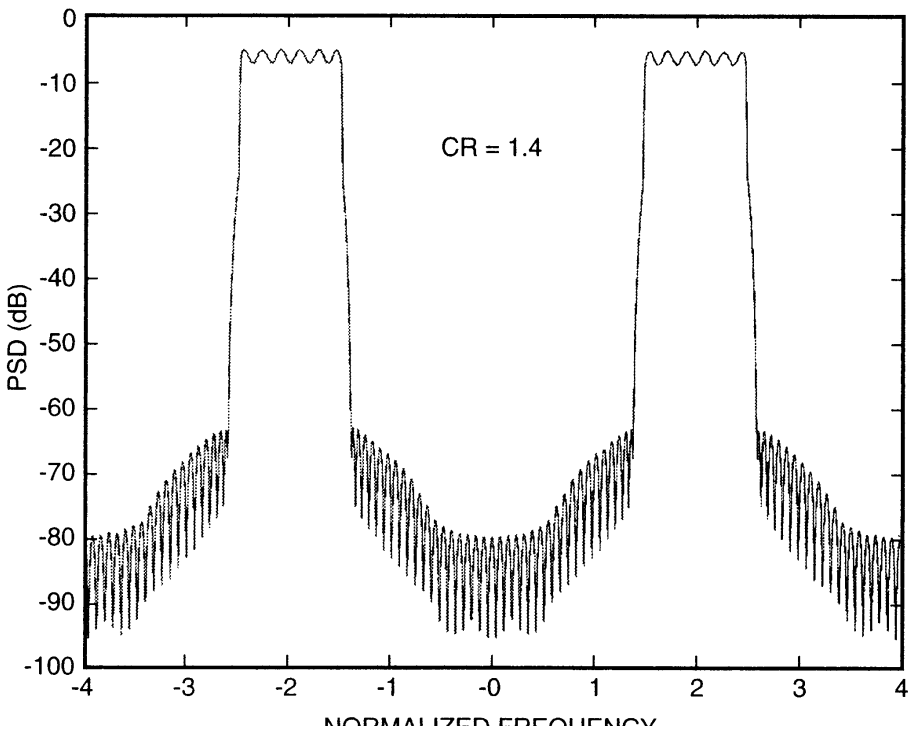
- The amplitude clipping introduces additional distortion, which can be viewed as a *clipping noise*
  - In-band noise for Nyquist sampled signals
  - Out-of-band noise for oversampled signals

# Clipping Ratio

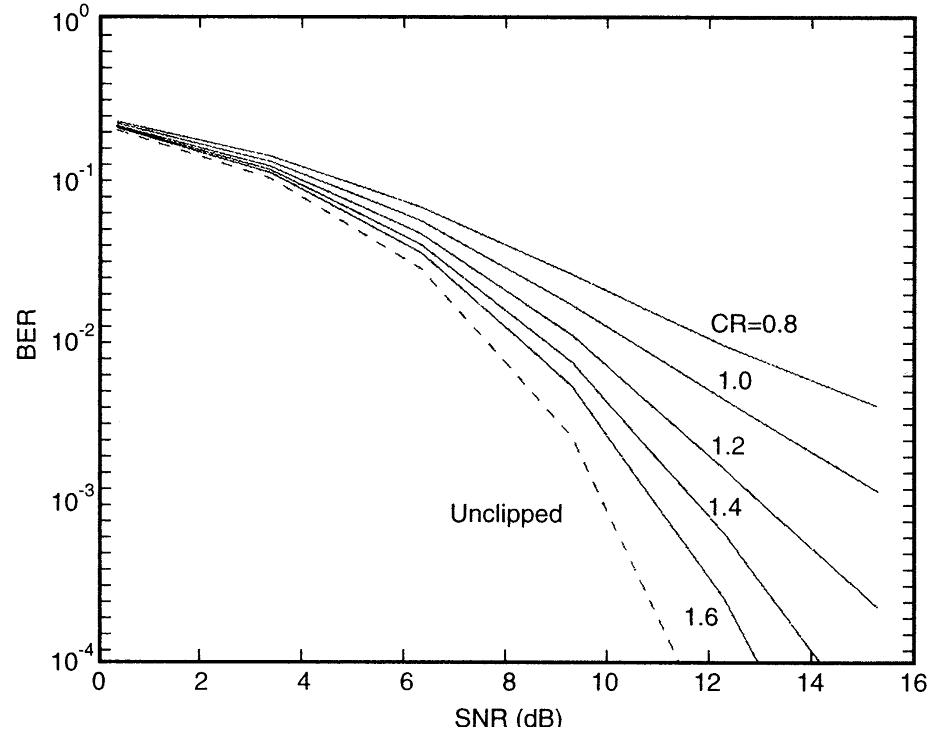
- Clipping Ratio (CR)
  - The ratio of peak value (A) to the RMS value of the OFDM signal



# Clipping Noise




**Clipped and Filtered OFDM signals**



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# Conclusions

- Clipping is the simplest and most common non-adaptive predistortion technique
- Although clipping helps limits the peak amplitude of the input signal, it also introduces an additional noise source called clipping noise
- Clipping noise can greatly degrade the BER performance of the system

# *Thank You!*

# References


- J. Heiskala and J. Terry, “*OFDM Wireless LAN: A Theoretical and Practical Guide*”, SAM Publishing, 2001
- Peter B. Kenington, “*High Linearity RF Amplifier Design*”, Artech House, 2002

# Exercise

- Clipping is one method to overcome the PAPR in OFDM. List three other methods, and give a two lines description for each.

Hint.

There are around 9 popular PAPR reduction methods.

You may google the internet with “PAPR Reduction”