# How does Peak-to-Average Ratio affect the On-Air Performance of Single-Carrier and Multi-Carrier Waveforms

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# Presentation Overview

- Presentation Overview
- Peak-to-Average Ratio (PAR)
- Power Complementary Cumulative Density Function (Power CCDF)
- Single-Carrier Waveforms
- Multi-Carrier Waveforms
- PAR effects on Power Amplifiers
- Conclusions

# Peak-to-Average Ratio (PAR)

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- Peak-to-Average Ratio
  - Peak envelope power of waveform divided by the average power
- Source of PAR
  - Single-Carrier CPM – None (i.e. 0 dB PAR)
  - Single-carrier MPSK
    - Filtering to reduce spectral occupancy
  - Single-carrier MQAM
    - Peak power to average power of constellation and filtering to reduce spectral occupancy
  - OFDM
    - Addition of tones in time-domain and filtering

# Power CCDF

- Power CCDF
  - Compute the Probability Density Function (PDF) of the instantaneous power of a waveform (normalized by average power of waveform and converted to dB)
  - Compute Cumulative Density Function (CDF)
  - Take Complement (i.e. CCDF = 1-CDF)
- A Power CCDF curve shows how much time a signal spends at or above a given power level (relative to the average power of waveform)
- Standard Peak-to-Average (PAR) of a waveform is the largest value Power CCDF function will attain

# Single-Carrier Waveforms

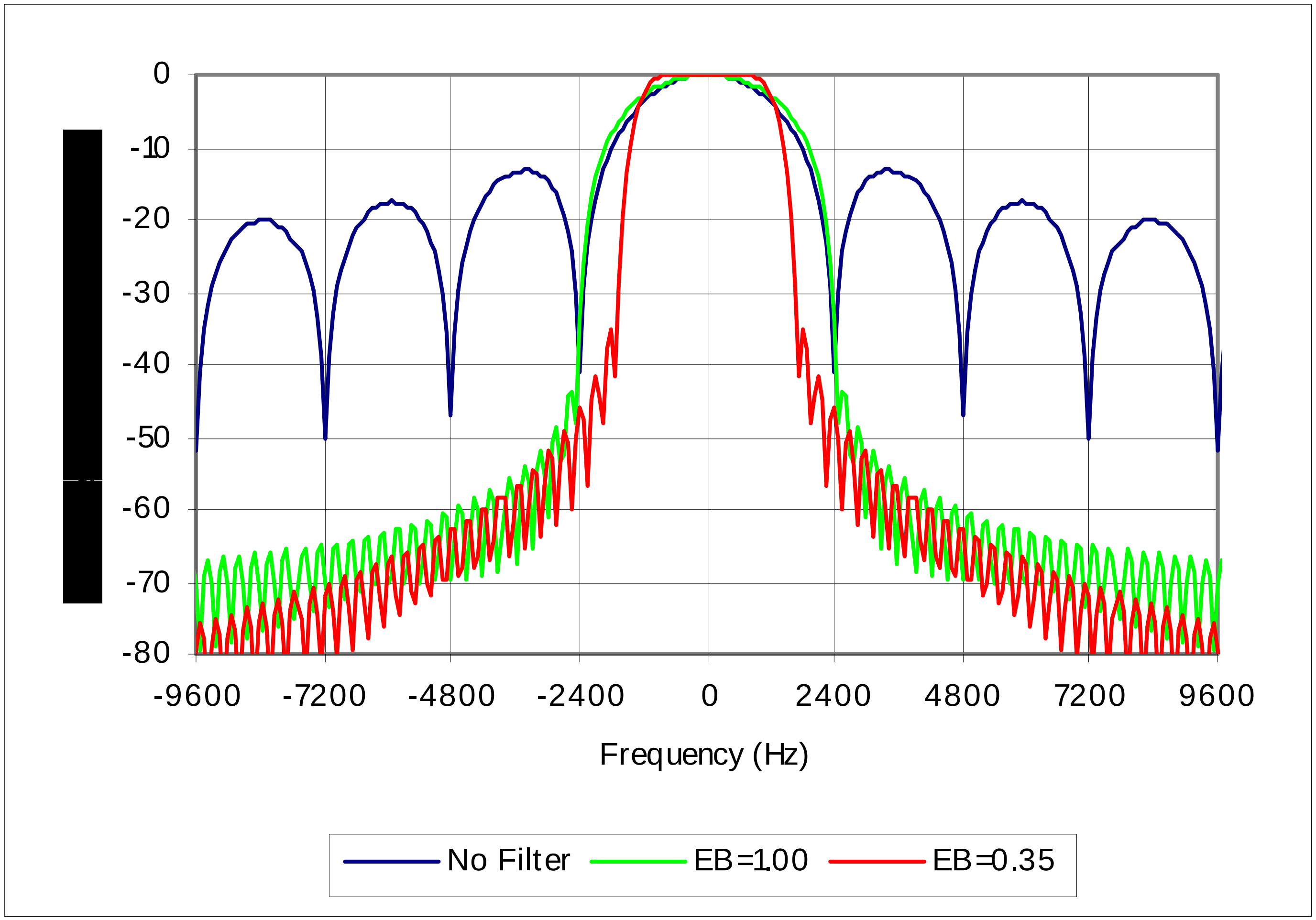
- Continuous Phase Modulation (CPM)
  - 0 dB PAR
  - Does not require time-domain filtering to constrain spectral occupancy. Filtering done in phase domain
- MPSK and MQAM
  - MPSK with no filtering, 0 dB PAR but fairly wide bandwidth
  - Filtering required to reduce spectral occupancy

# Single-Carrier Waveforms

- Most common family of filter shapes is Square-Root Raised Cosine (SRRC)
  - Zero Inter-Symbol Interference (ISI) during detection on AWGN channel
  - Excess Bandwidth (EB) parameter controls bandwidth
    - EB = 0.0 bandwidth approximately equal to symbol rate
    - EB = 1.0 bandwidth approximately equal to twice the symbol rate
  - PAR increases as bandwidth is decreased

# *Single-Carrier Waveforms*

## MPSK Spectral Properties

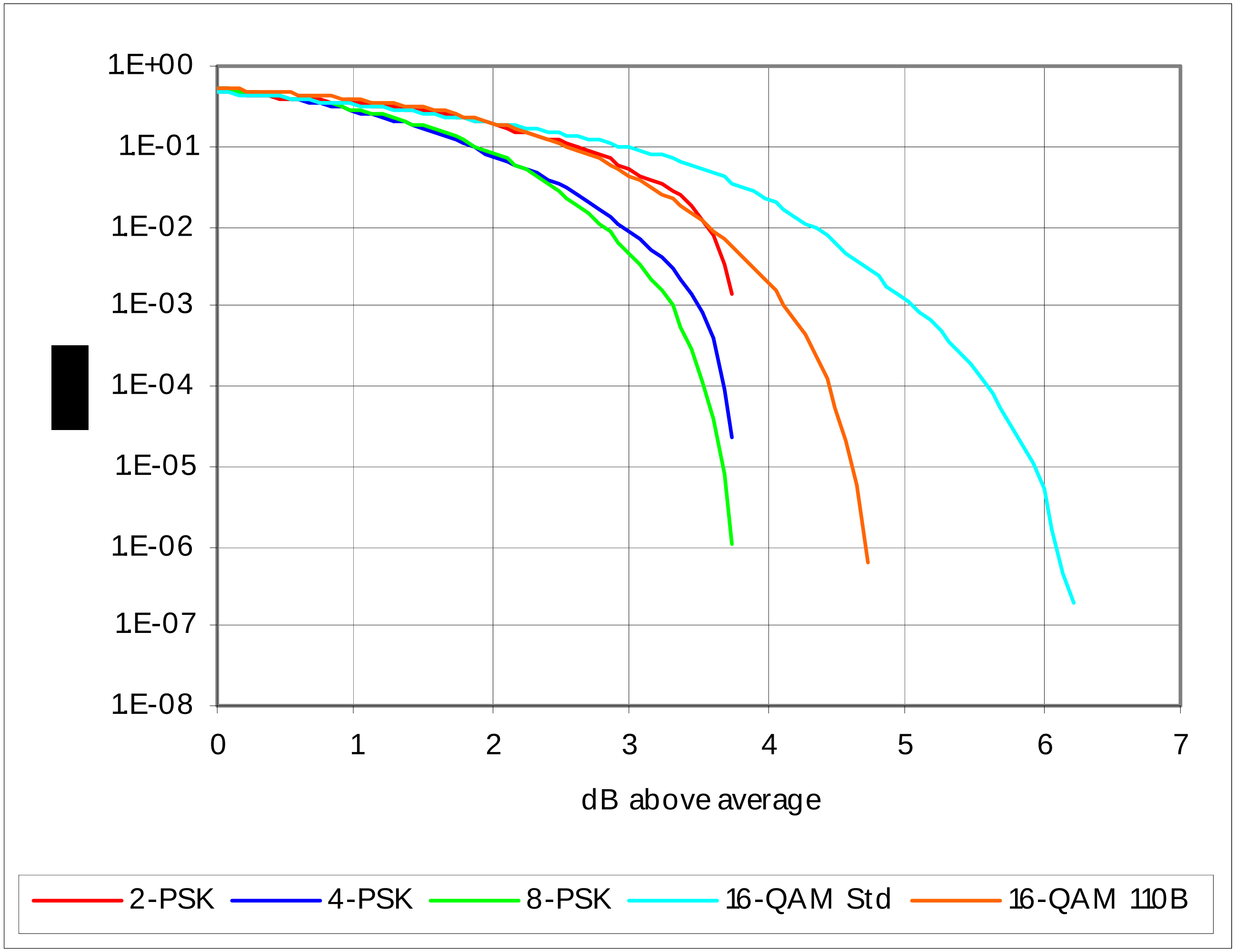


# SRRC PAR and Bandwidth for MPSK
# (129-tap filter, 16 samples per symbol)

| EB | PAR (dB) | 99% Power Bandwidth | 99.9% Power Bandwidth |
|---|---|---|---|
| 0.10 | 7.0 | 1.031250 | 1.093750 |
| 0.20 | 5.5 | 1.078125 | 1.179688 |
| 0.35 | 3.9 | 1.156250 | 1.281250 |
| 0.50 | 3.3 | 1.265625 | 1.398438 |
| 1.00 | 3.6 | 1.637500 | 1.828125 |

# *Single-Carrier Waveforms*

## Power CCDF of Single-Carrier Waveforms



# Multi-Carrier Waveforms

- Orthogonal Frequency Division Multiplexing (OFDM)
  – Dominant source of PAR is addition of tones in time-domain
    - Worst case PAR = 10*log10(N)
      – where N is the number of tones
    - Typical PAR for N > 20 is between 9-14 dB
  – Filtering to reduce spectral occupancy
    - Small effect on PAR

# Multi-Carrier Waveforms

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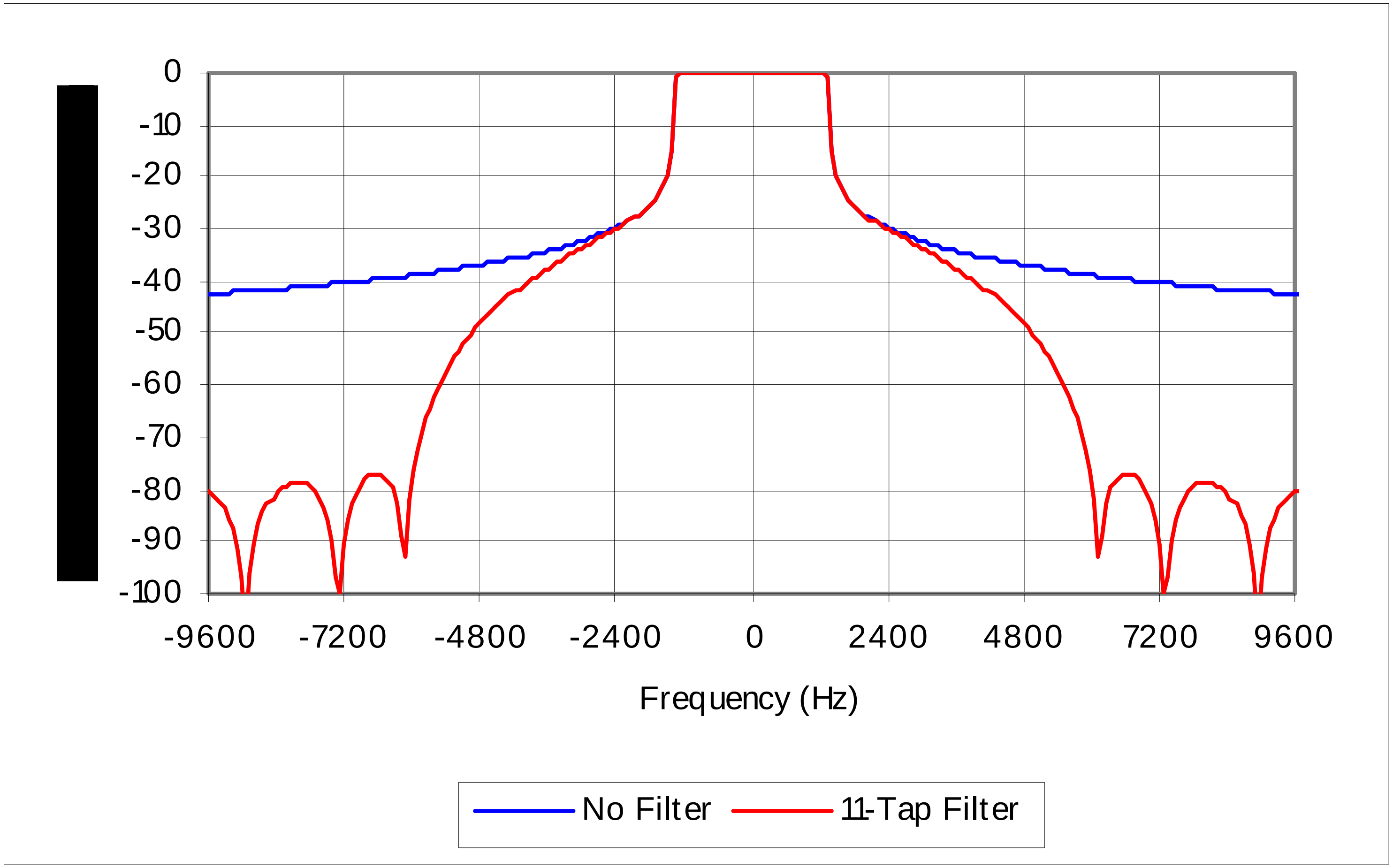
## Example Spectral Occupancy of OFDM



# Multi-Carrier Waveforms

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- Clipping typically used to reduce PAR
  - Other techniques exist but most usually require more MIPS and transmission of information to receiver
- Clipping distorts OFDM signal and limits RX SNR

| Clip Level (dB) | SNR (dB) |
|---|---|
| 11.7 | 58.3 |
| 7.0 | 30.6 |
| 6.0 | 25.2 |
| 5.0 | 21.4 |
| 4.0 | 17.6 |

# Multi-Carrier Waveforms

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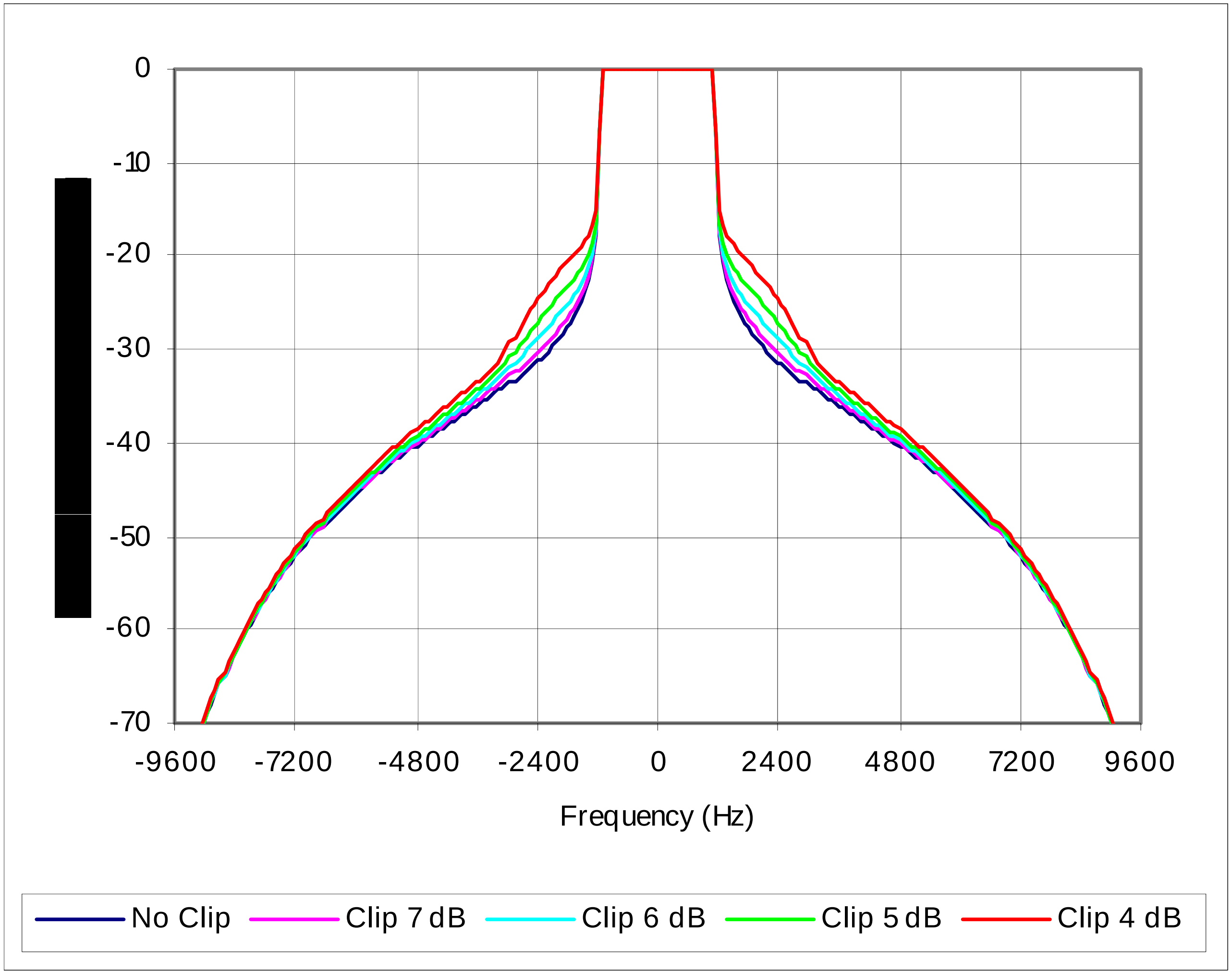
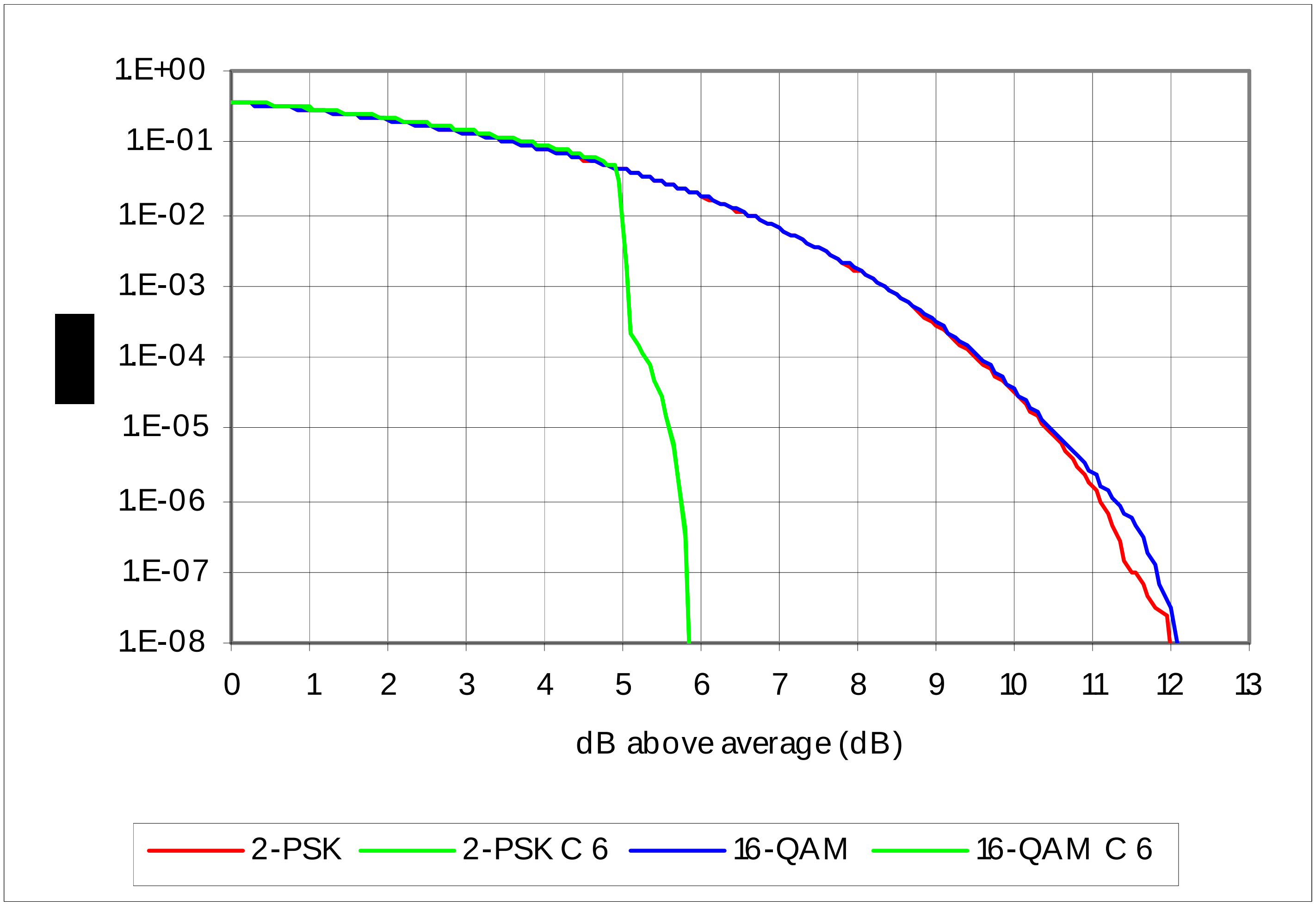
## Effects of Clipping on OFDM Spectrum



# Multi-Carrier Waveforms

Power CCDF of 59-Tone OFDM Waveform



# PAR effects on Power Amplifiers

- Power Amplifiers (PAs) convert low-power Radio Frequency (RF) signals into high-power RF signals
- Most wireless communication systems employ power amplifiers in order to increase the operating range of the system
- However, this conversion process can have some undesired effects on the underlying physical layer waveforms that are used for communicating

# PAR effects on Power Amplifiers

- PA backoff (BO) required  to avoid operating in non-linear region of PA
  - Reduces average transmit power of waveform
- PA Distortion effects similar to clipping
  - Increase in spectral occupancy
  - Distortion reduces RX SNR

# PAR effects on Power Amplifiers

Average Transmitted Power and Receive SNR for 110B Waveforms (RF-5000)
(125 Watt Peak)

| | 2400S | 39T 2400S | 9600S |
|---|---|---|---|
| ATP | 82 Watts | 37 Watts | 43 Watts (60 Watts) |
| RX SNR | 29 dB | 27 dB | 28 dB (23 dB) |

Average Transmitted Power and Receive SNR for 110B Waveforms (RF-5800H)
(20 Watt Peak)

| | 2400S | 39T 2400S | 9600S |
|---|---|---|---|
| ATP | 10 Watts | 6 Watts | 8 Watts |
| RX SNR | 30 dB | 21 dB | 30 dB |

## RAPP Model for PA

$$V_{out} = \frac{V_{in}}{\left(1 + \left(\frac{|V_{in}|}{V_{sat}}\right)^{2p}\right)^{\frac{1}{2p}}}$$

$$P_{sat} = |V_{sat}|^2$$

P usually between 2-4. This presentation will use P=2

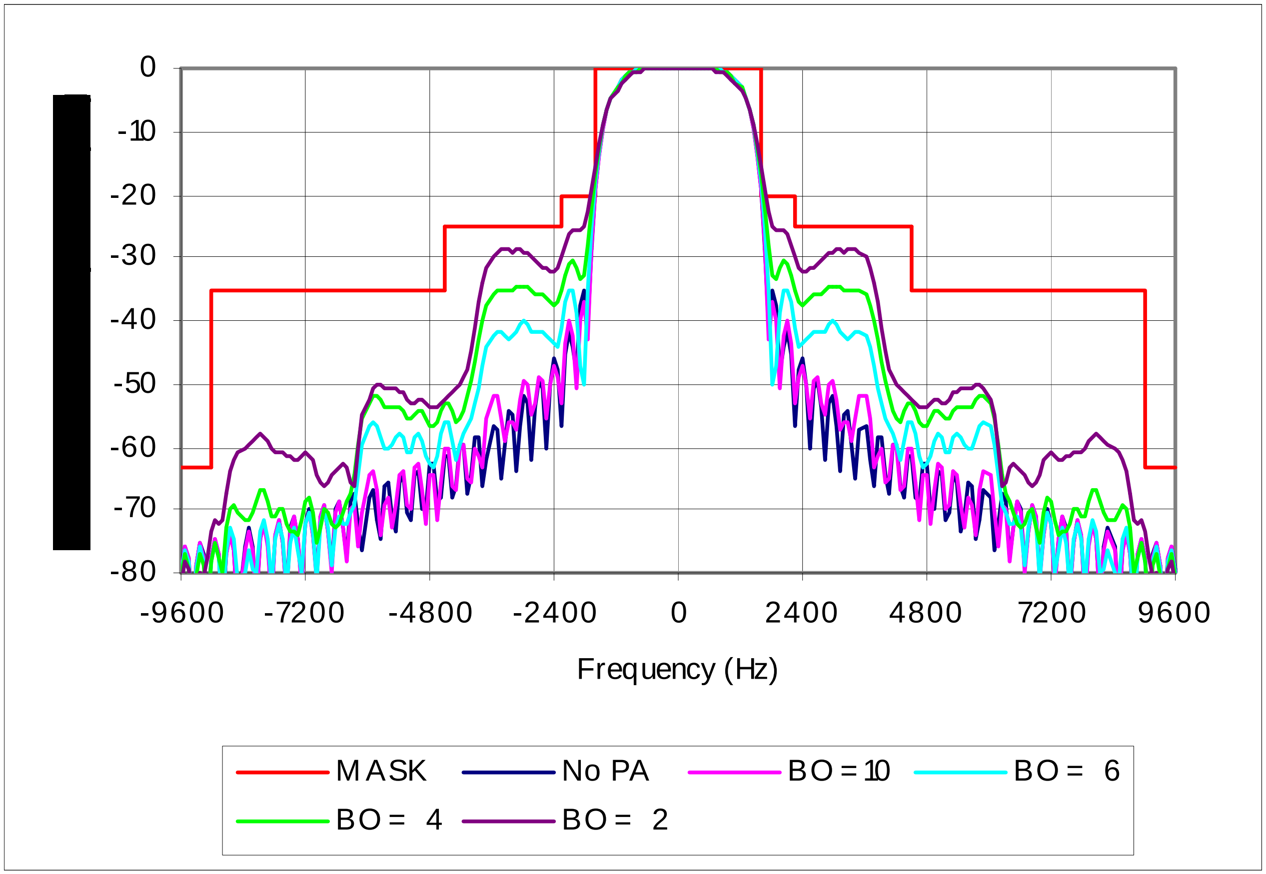
## Generic model for a PA

$$V_{out} = \sum_{i=0}^{N-1} a_i V_{in}^i$$

$$\Delta\theta_{out} = \sum_{i=0}^{N-1} b_i V_{in}^i$$

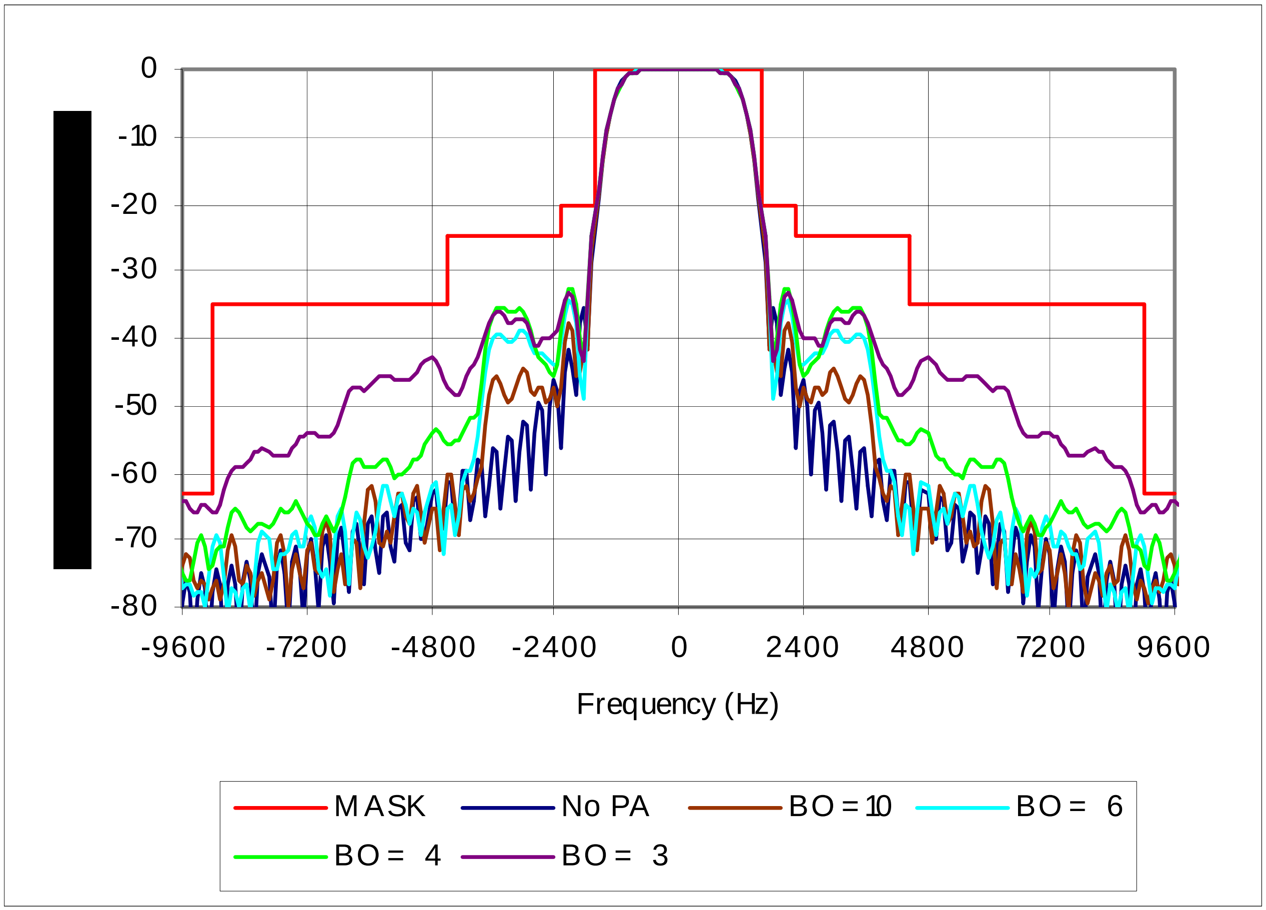
# PAR effects on Power Amplifiers

SC 2-PSK Transmit Spectra for Rapp Model



# PAR effects on Power Amplifiers

## SC 2-PSK Transmit Spectra for Actual PA (RF) Model



# PAR effects on Power Amplifiers

| Modulation | BO (dB) | Rapp SNR (dB) | RF SNR (dB) |
|---|---|---|---|
| 2-PSK | 10 | 36.0 | 35.8 |
| | 6 | 34.8 | 35.1 |
| | 4 | 32.0 | 34.8 |
| | 2 | 28.4 | 17.5 |
| 4-PSK | 10 | 36.0 | 35.8 |
| | 6 | 35.3 | 35.3 |
| | 4 | 33.4 | 34.8 |
| | 2 | 30.0 | 26.5 |
| 8-PSK | 10 | 36.0 | 35.9 |
| | 6 | 35.4 | 35.4 |
| | 4 | 33.5 | 34.7 |
| | 2 | 30.1 | 30.1 |

# SC 16-QAM Receive SNR

| Modulation | BO (dB) | Rapp SNR (dB) | RF SNR (dB) |
|---|---|---|---|
| 16-QAM | 4 | 27.7 | 28.6 |
| | 2 | 23.4 | 0.6 |
| 16-QAM (110B) | 10 | 36.0 | 35.6 |
| | 6 | 34.5 | 34.2 |
| | 4 | 31.3 | 33.4 |
| | 2 | 27.1 | 12.8 |

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- The original OFDM waveform used in this study consisted of 73 tones instead of 59 tones. When the spectral mask was first applied to the 73-tone waveform, it was found that a clip level of 6 dB caused the spectral mask to be violated in the –20 dB range. After a quick literature search on the Internet, it was found that most OFDM waveform designs only fill 70-75% of the allocated bandwidth with tones and the rest of the bandwidth is used as a guard band. The clipping results definitely confirmed why the guard band is necessary.

# PAR effects on Power Amplifiers

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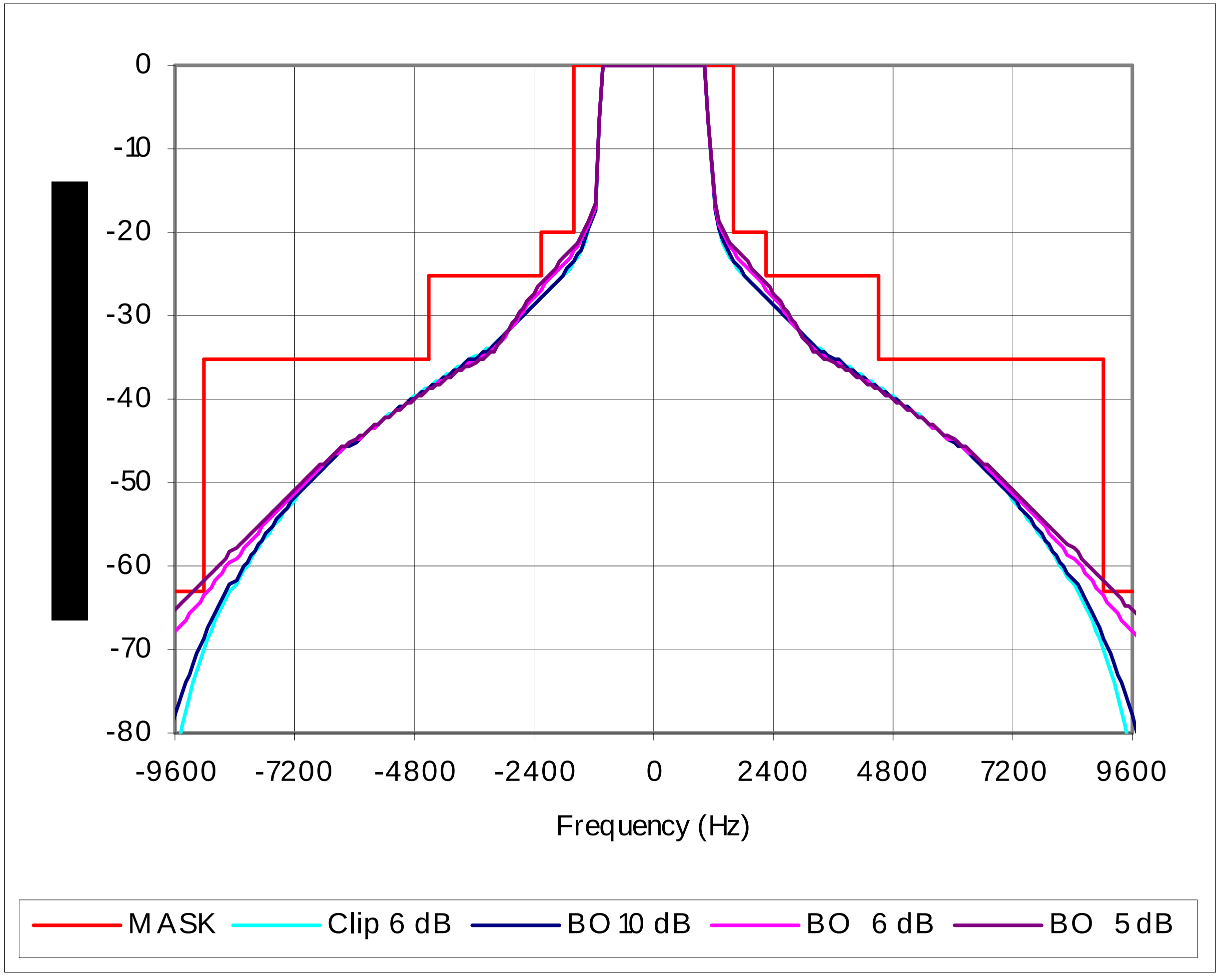
## 59-tone OFDM Transmit Spectra for Rapp Model



# PAR effects on Power Amplifiers

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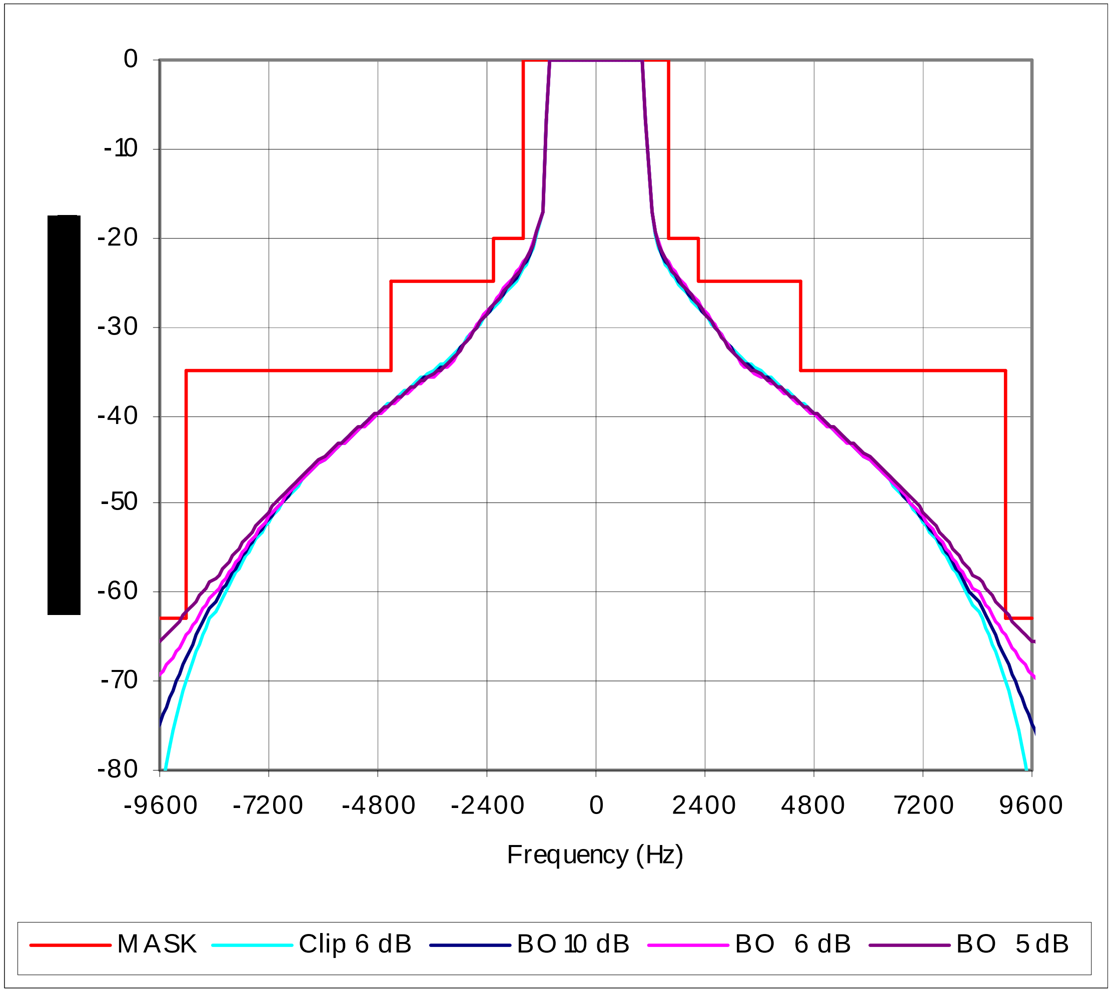
## 59-tone OFDM Transmit Spectra for Actual PA (RF) Model



# 59-tone 2-PSK OFDM Receive SNR

| | BO (dB) | Rapp SNR (dB) | RF SNR (dB) |
|---|---|---|---|
| 2-PSK | 10 | 24.6 | 24.1 |
| | 6 | 22.0 | 23.0 |
| | 5 | 20.9 | 22.6 |

## Clip level 6 dB – Maximum RX SNR = 25.2 dB

# Conclusions

- PAR of waveforms can have a significant impact on On-air performance
- PAR, clipping and PA should be considered when designing waveforms to meet specific spectral masks
- PAR and PA effects are
  - Reduction in average transmit power
  - Spectral re-growth
  - Distortion of waveform reducing RX SNR