IEEE

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Paper 18-4:
Practical Considerations for Application-Specific Time Interleaved ADCs

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Tue
29 Sep 2015


I Feel the Need……

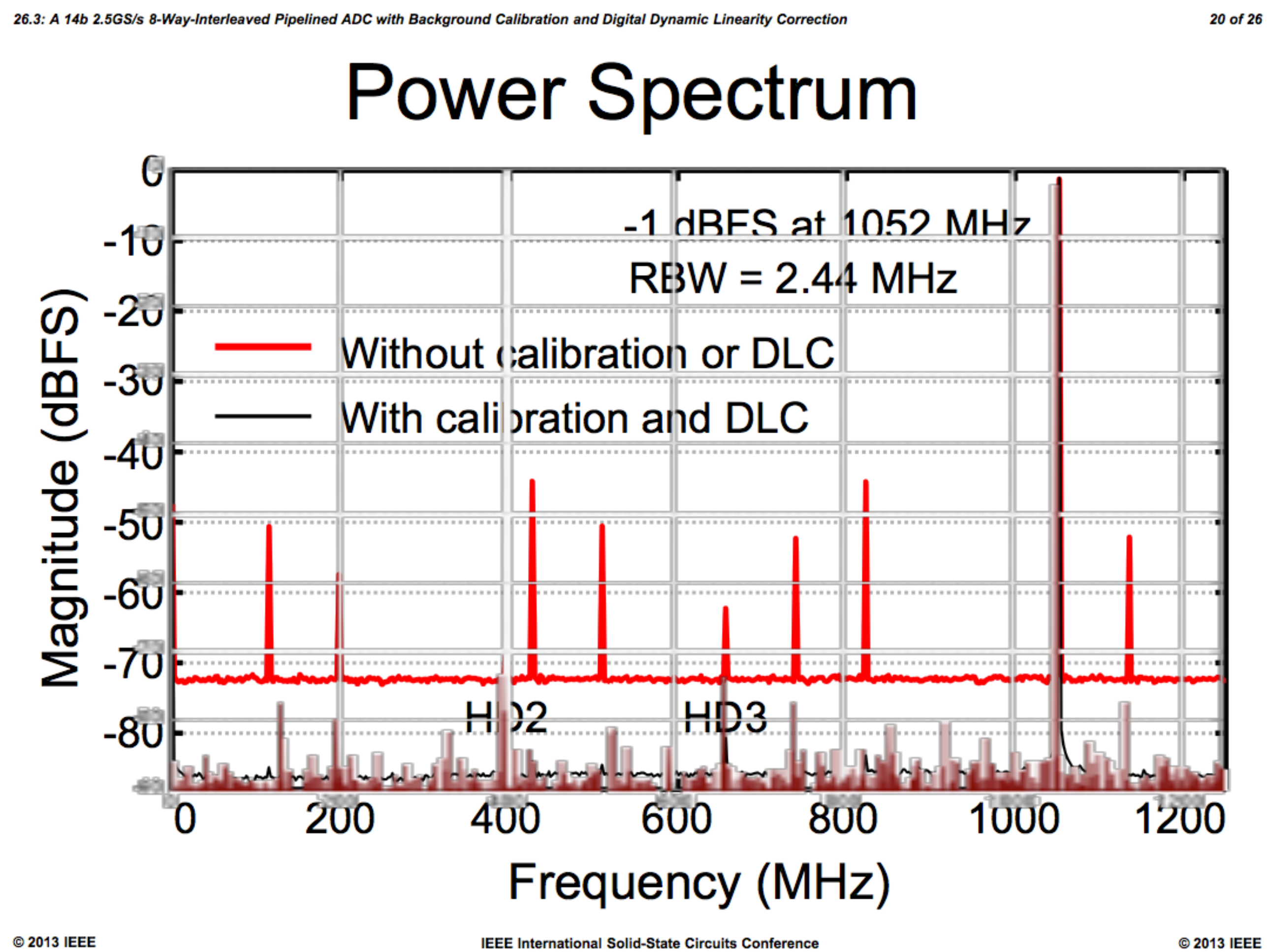
Time-Interleaved ADC Overview

- We Have a Problem
- We Have a Solution


Multiple Offerings
for Diverse Tastes


We Serve Soup
Only Soup

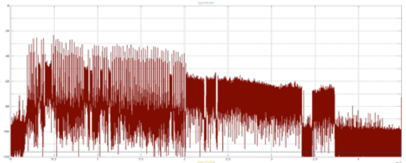
Agilent Spectrum: Fin=1052-MHz



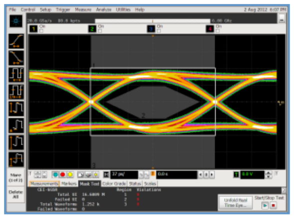
Applications for High-Speed ADCs

1) Test & Measure: Frequency Domain & Time Domain

2) Standard Parts: Spectral “Sniffing”, Software-Defined Receiver



3) **Broadband Capture** of Multiple Frequency-Domain Channels
Terrestrial TV, Cable, Satellite



4) Baseband signals
SerDes, Optical, Read-Channels

Requires Generalized Solutions

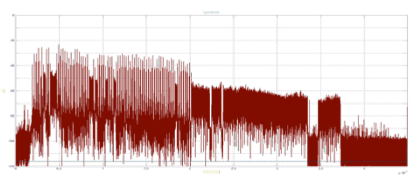
1) Accuracy: No artifacts of calibration or time-interleaving can be tolerated

2) Robust: Don't know what the customer will do
ADC needs to work in all situations

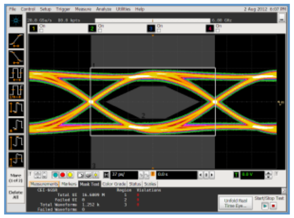
- Varied Requirements
  - Multiple Applications
  - ADCs Need to be "General Purpose"
  - No Assumptions about Input Signal

Dedicated SoC: Specific Solutions

- Dedicated Requirements
  - One application
  - ADCs is "Special Purpose"
  - Input signal is known
    - Can be used in the calibration process



3) **Dynamic Range:** Nearly all of what is captured will be thrown out when looking at one specific narrowband channel



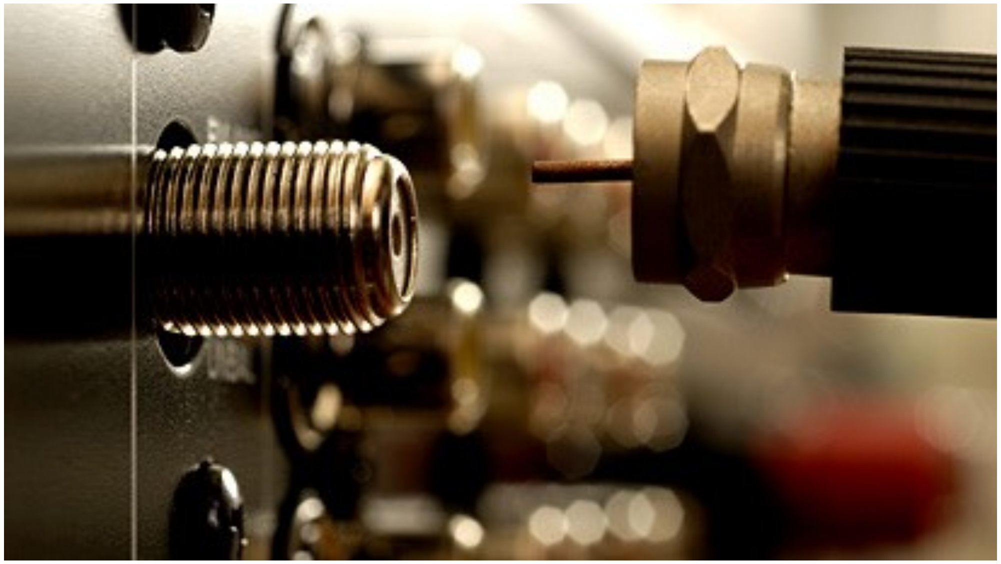
4) Fast, Simple and Low-Power Processing the entire signal. SNR and linearity are typically not as critical

Brief Outline

- Frequency Domain Channels– Cable and Satellite
  - Specification for various error sources
- Baseband Signals – Optical & SerDes
  - Impact of errors on the system
- Architectural Considerations for Specific Applications

Broadband Example

Cable TV

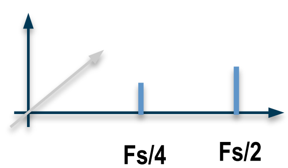


Satellite TV

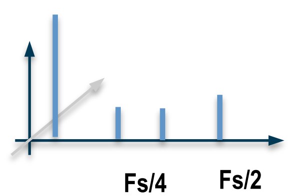
Time Interleaved ADCs

- Time Interleaving of ADCs
  - Necessary technology for implementing high-speed multi-gigasample data converters
  - Mitigate effects of gain, offset and skew mismatches between interleaved ADC's (errors can be frequency dependent)

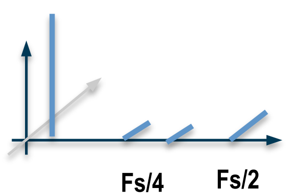
Offsets
Fixed pattern errors

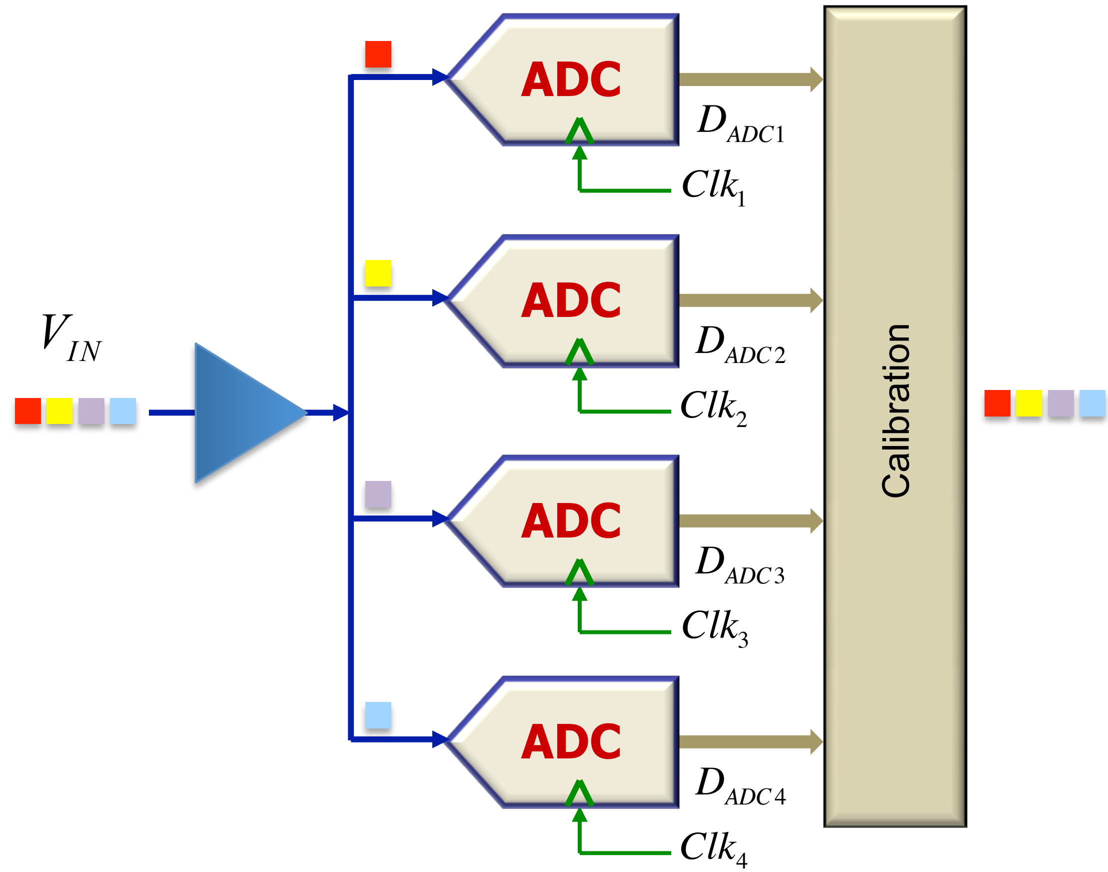


Gain
Amplitude modulation (nF_s/N ± sigal in-phase)

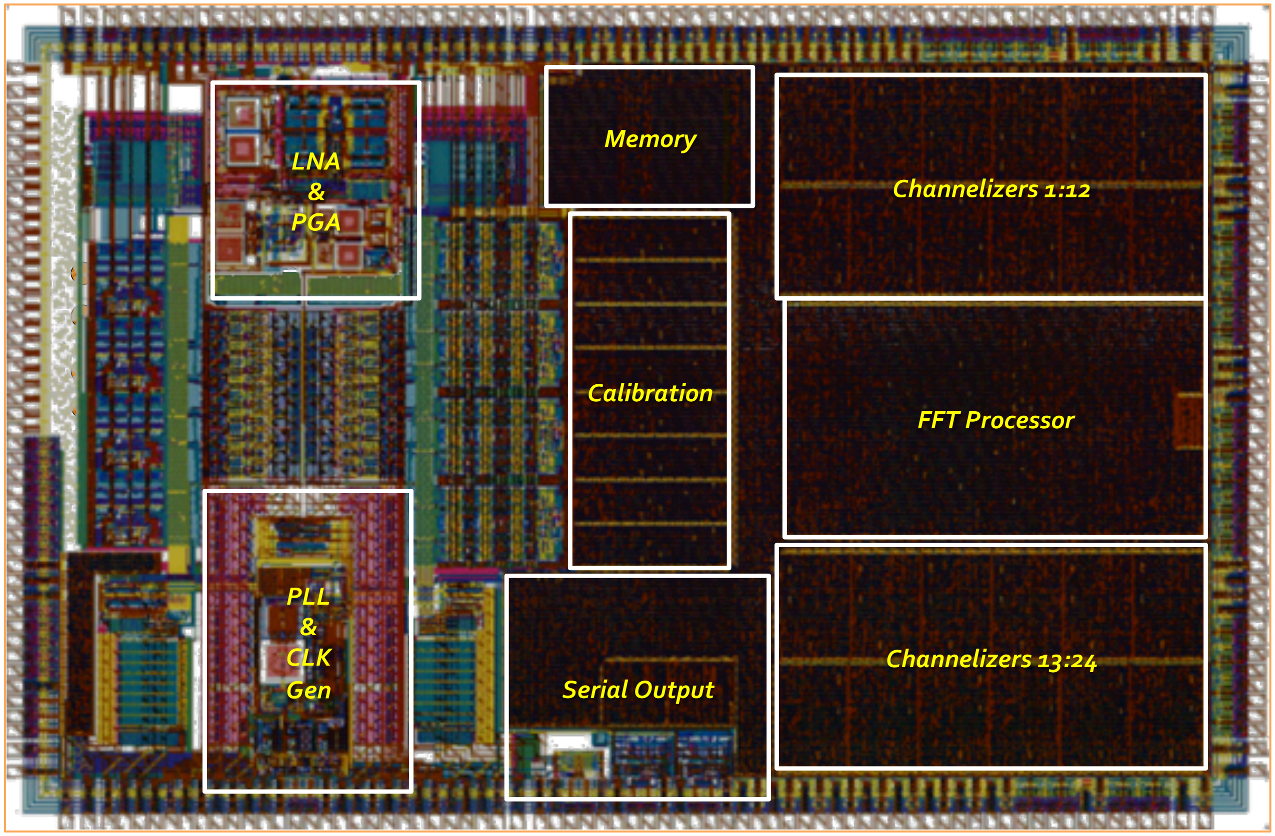


Time-Skew
Phase modulation (nF_s/N ± signal in quadrature)



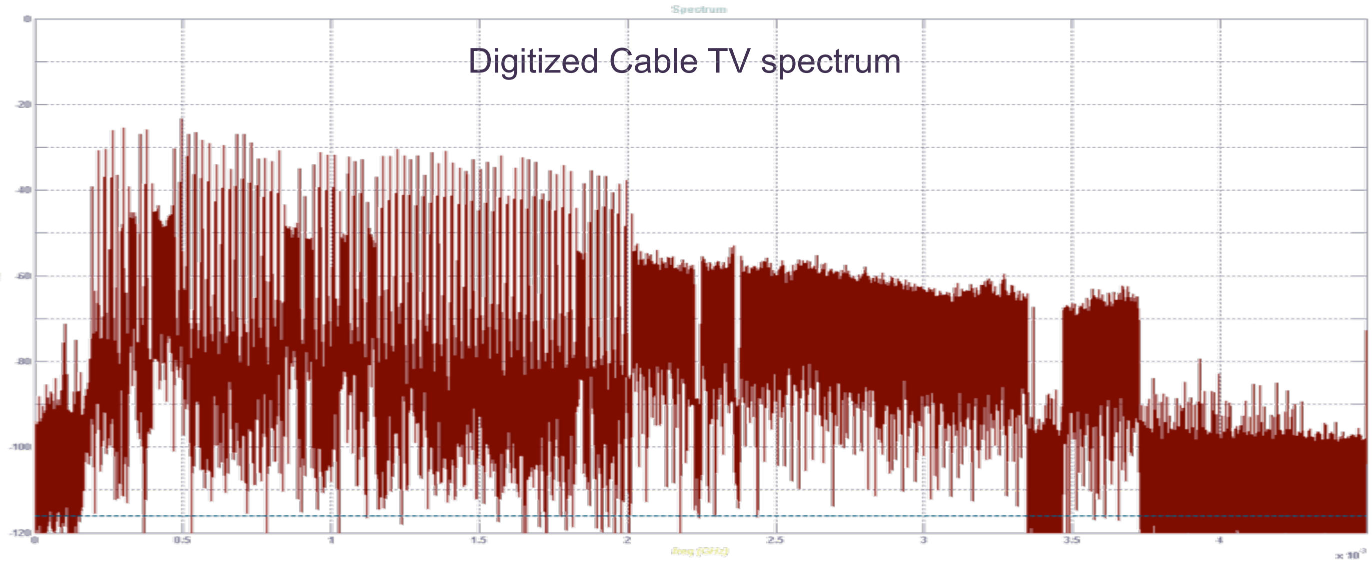


Chip Implementation

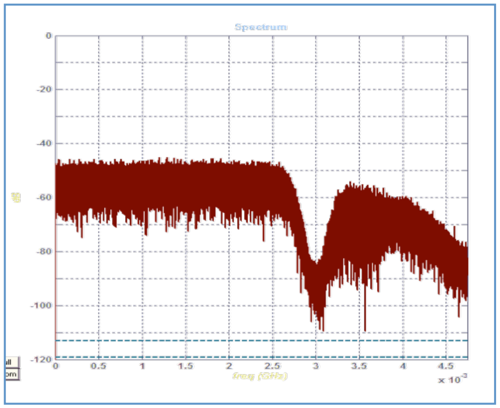


- Equivalent to
  - LNA + 24 Tuners + 24 Baseband ADCs

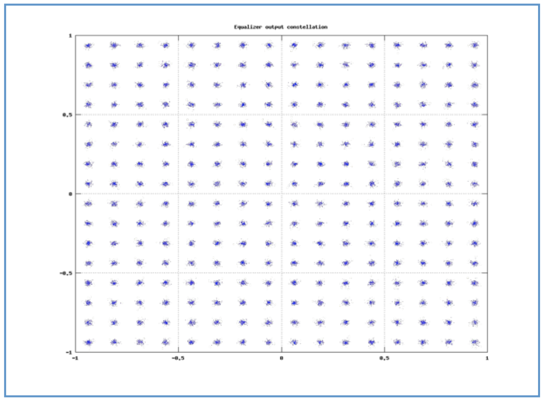
Cable TV Captured Spectrum



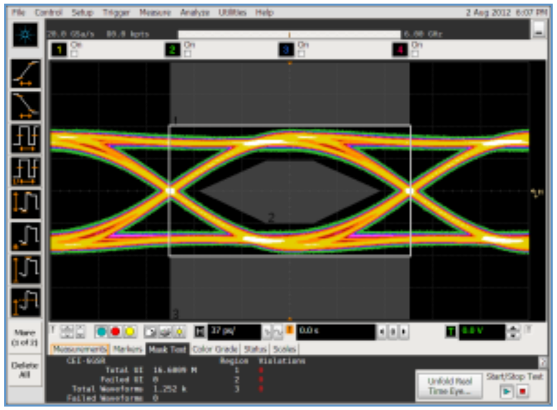
Single Channel Spectrum



256 QAM Received Constellation



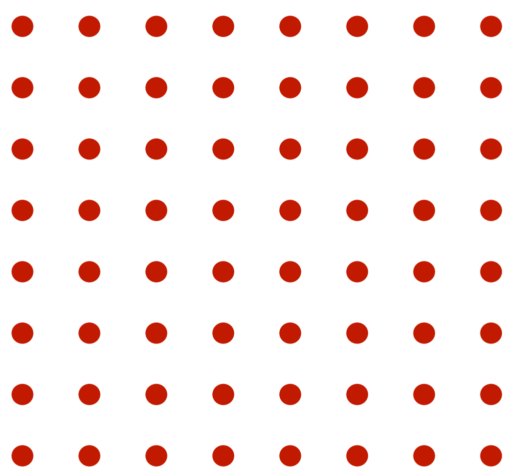
5.4 Gb/s Serdes Interface



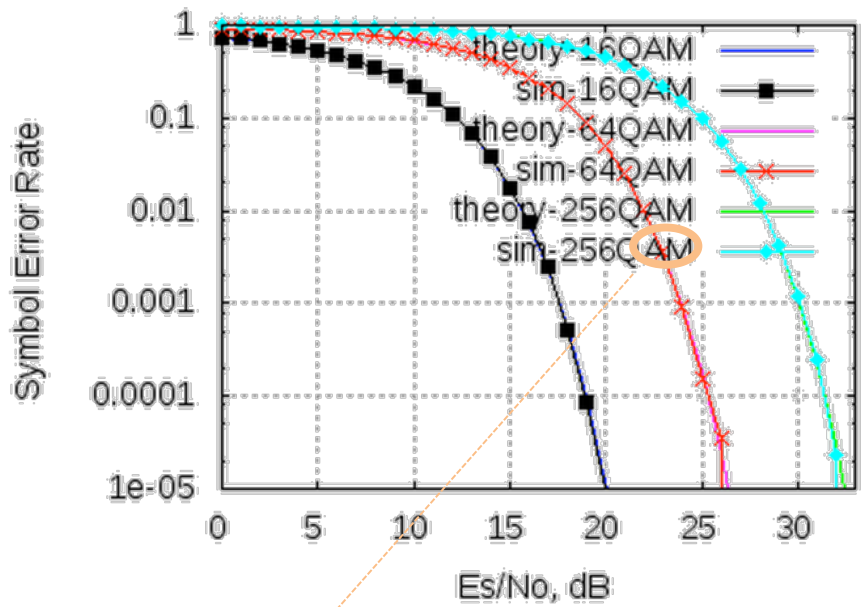

Not Cable
Not Satellite
[redacted]
Confidential
Make up an
Example Spec

64 QAM Hypothetical Channel

64 QAM
Square Constellation



QAM 16 / 64 / 356
Symbol Error Probability Curve



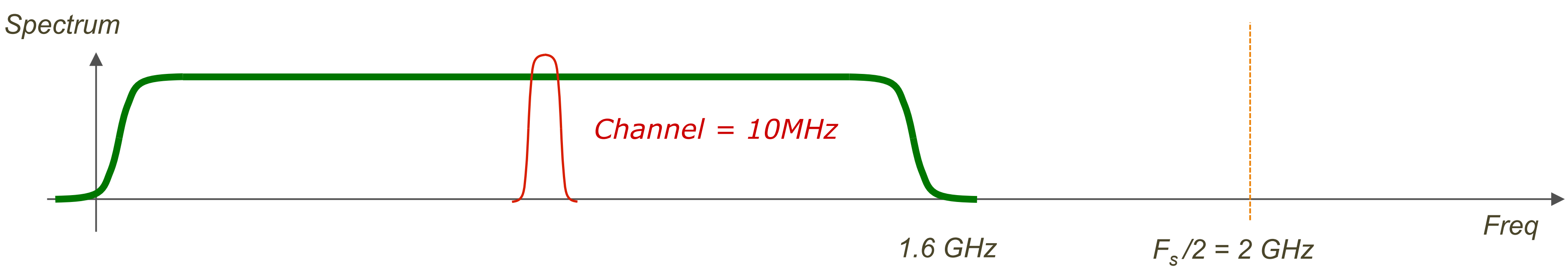
Raw BER (before coding) 1/300

SNR

$$k_{\mathrm{snr}} = 22\mathrm{dB}$$

http://www.dsplog.com/2012/01/01/symbol-error-rate-16qam-64qam-256qam/

Multiple QAM Channels: Fs=4GS/s



Assume a 1600-MHz spectrum with approximately 160 10-MHz channels
Sampled by a 4-GHz time-interleaved ADC

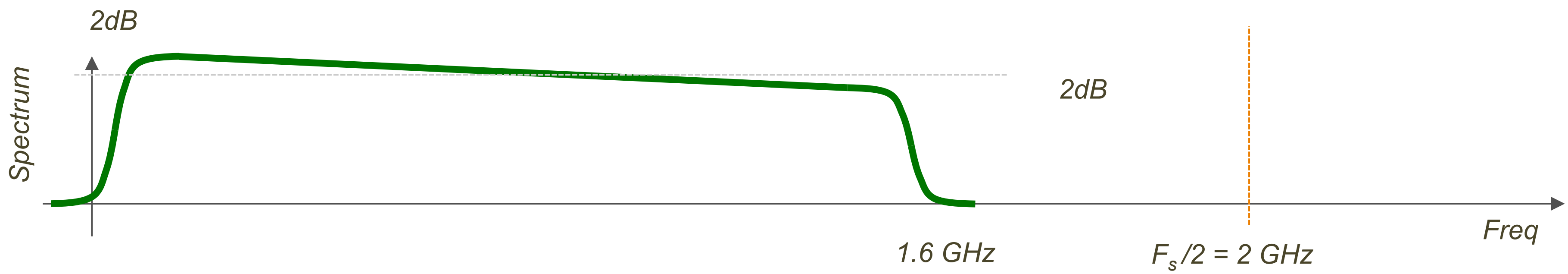
Oversampling Ratio

$$g_{\text{ovsamp}} = \frac{2}{1.6}$$

Oversampling Gain

$$g_{\text{os}} = 10\log\left(\frac{5}{4}\right) = 0.97 \sim 1\text{dB} = 0.16\text{bits}$$

Tilt (Uncompensated)



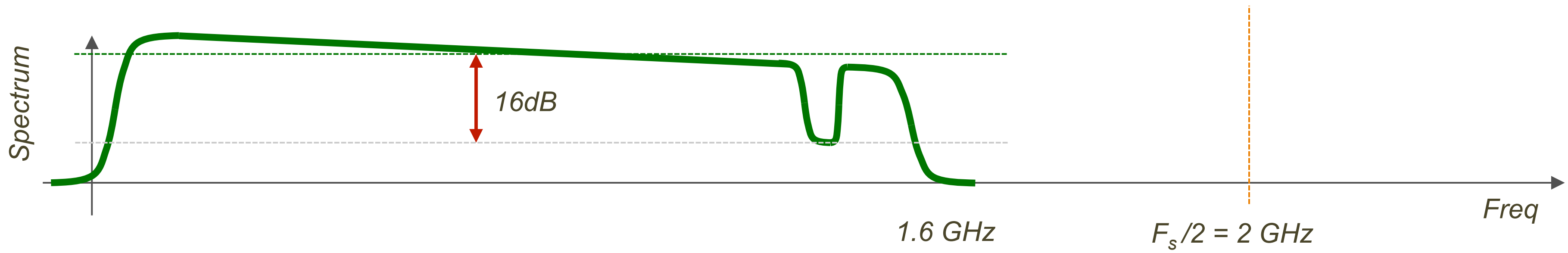
Total "Tilt" of 4-dB is left uncompensated by any analog Equalizers at the front-end.

- ❑ **AGC normalized to average power**
- ❑ **Lower frequencies are 2-dB better**
- ❑ **Higher frequencies are 2-dB worse**

Tilt

$$k_{\text{tilt}} = 2\text{dB}$$

Weak Channel



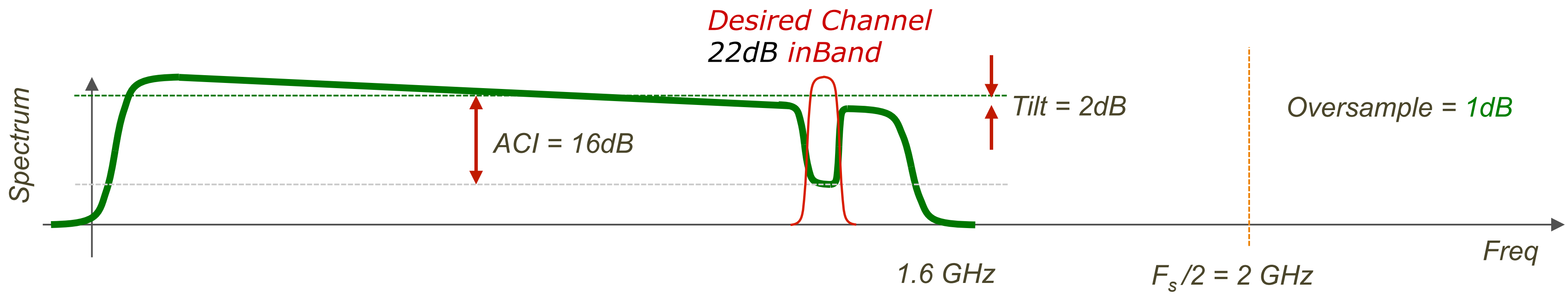
Weakest Channel is lower then average power

- ❑ **Sometimes called ACI (Adjacent Channel Interference)**
- ❑ **Can occur where the tilt is the worst**

ACI

$$k_{\text{aci}} = 16\text{dB}$$

SNR Requirement



SNR $k_{\text{snr}} = 22\text{dB}$

ACI $k_{\text{aci}} = 16\text{dB}$

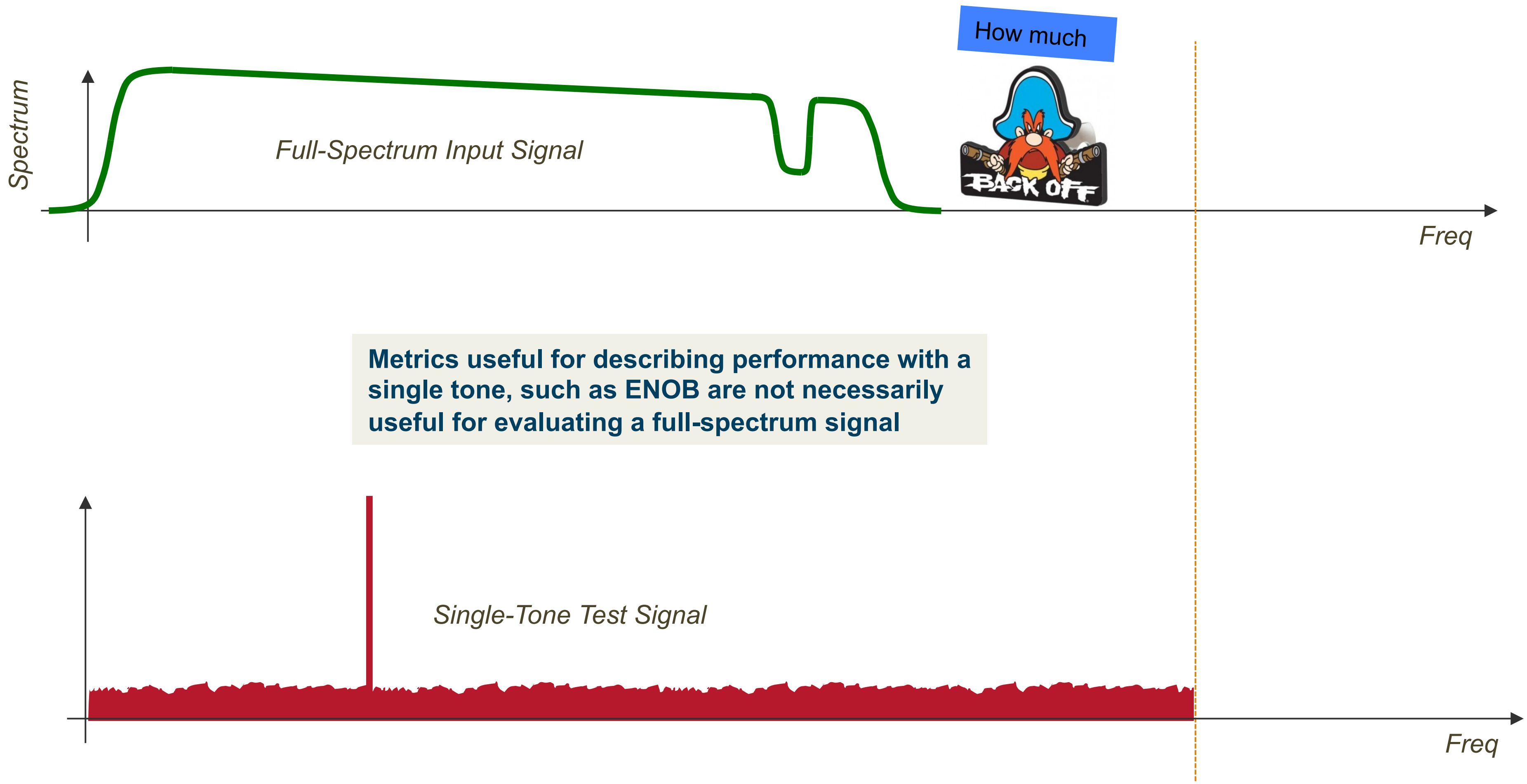
Tilt $k_{\text{tilt}} = 2\text{dB}$

Oversampling $g_{\text{os}} = 10\log\left(\frac{5}{4}\right) = 0.97 \sim 1\text{dB} = 0.16\text{bits}$

SNR Relative to average full-spectral power

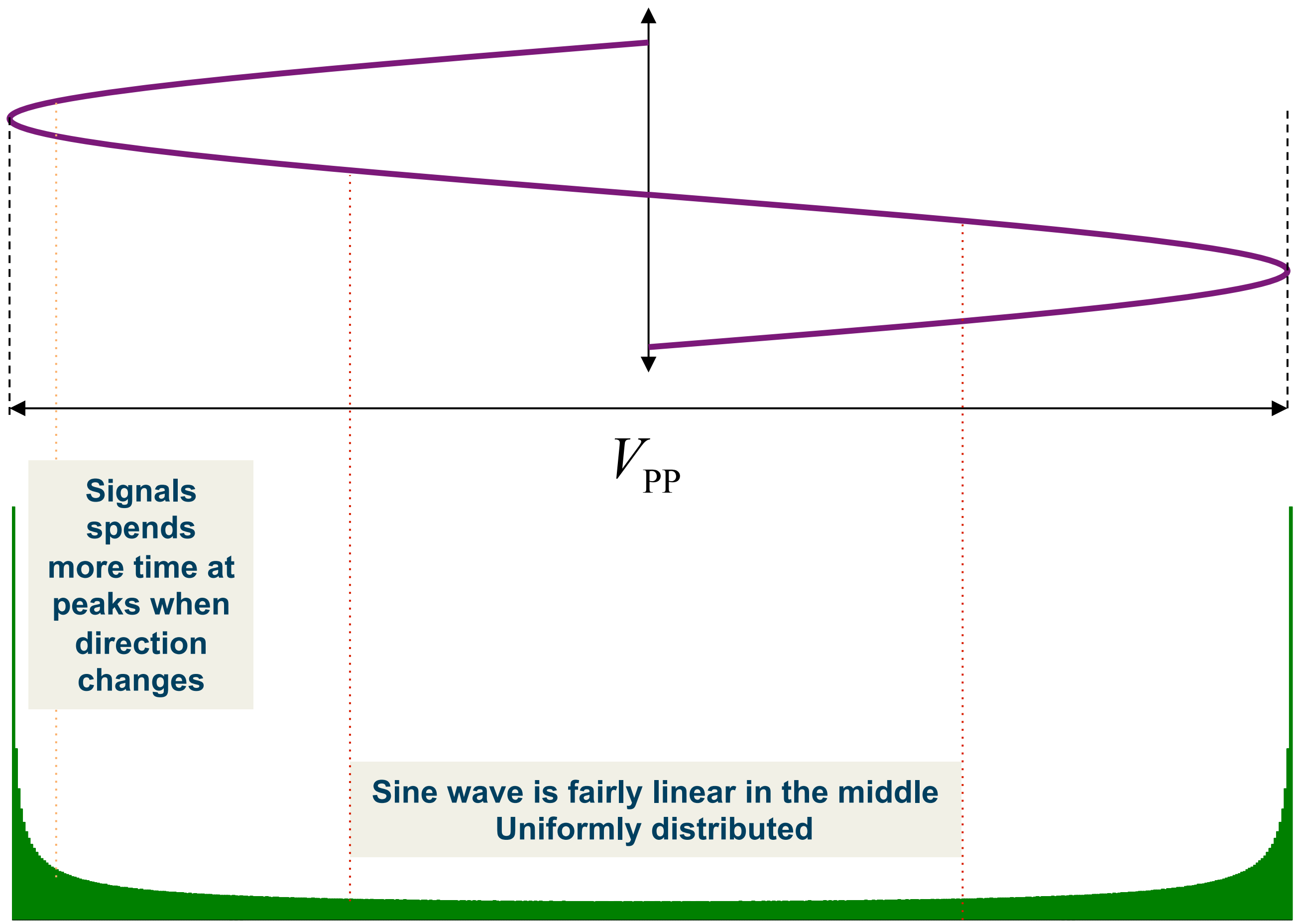
$$\boxed{\text{SNR}_{\text{loaded}} = k_{\text{snr}} + k_{\text{aci}} + k_{\text{tilt}} - g_{\text{ovsamp}} = 39\text{dB}}$$

In-Band SNR vs. ADC with Tone

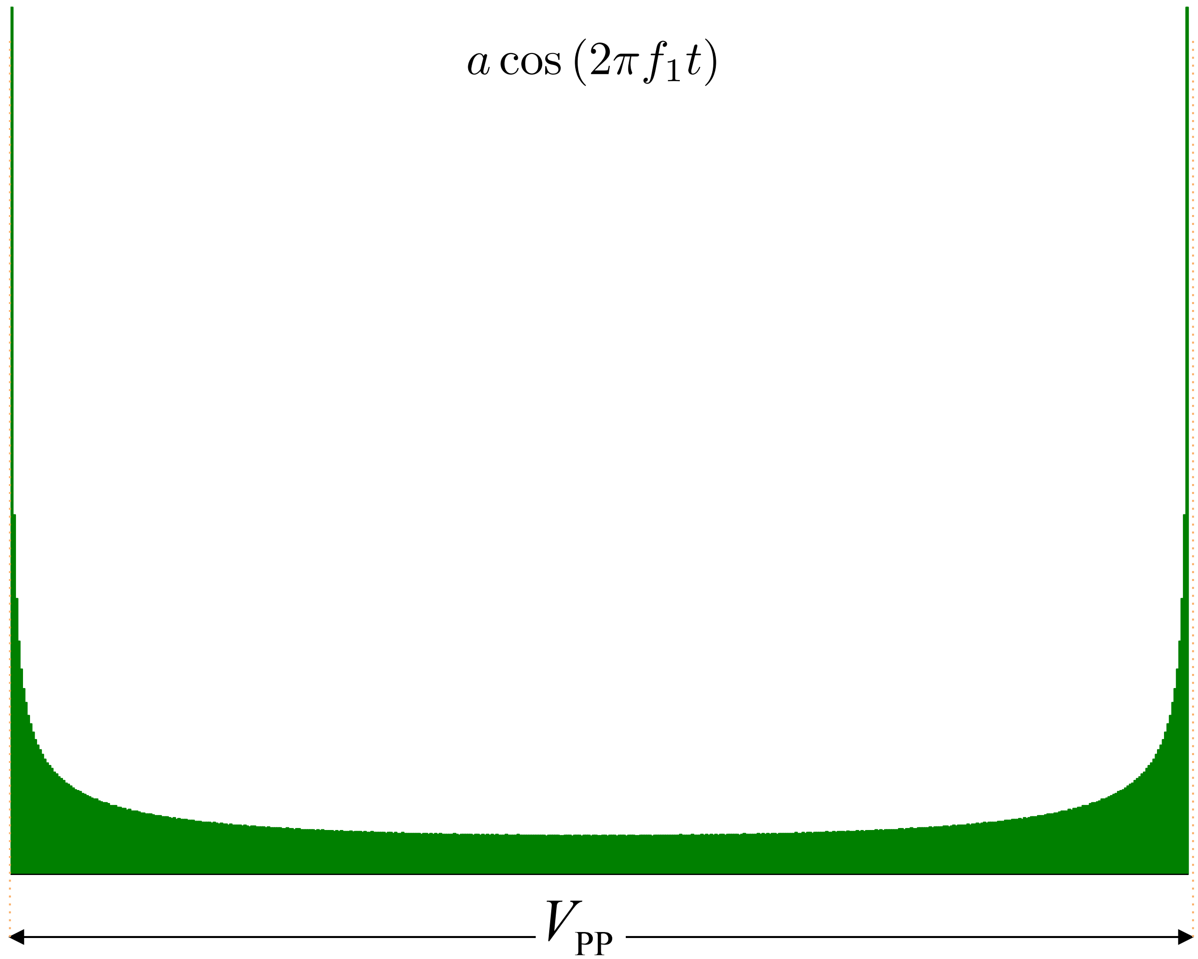


Metrics useful for describing performance with a single tone, such as ENOB are not necessarily useful for evaluating a full-spectrum signal

Probability Density: Sine wave



Probability Density a Sine wave

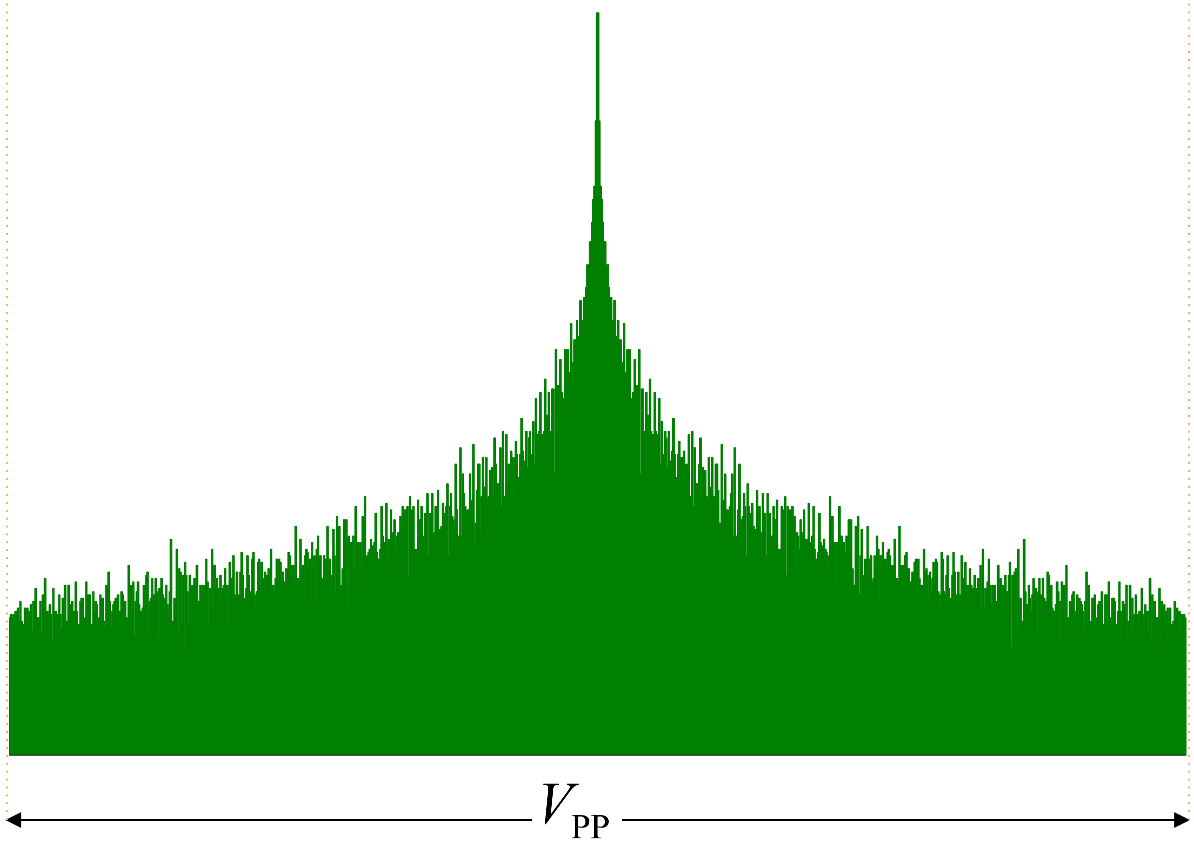


1

Sine wave

Probability Density Sine waves

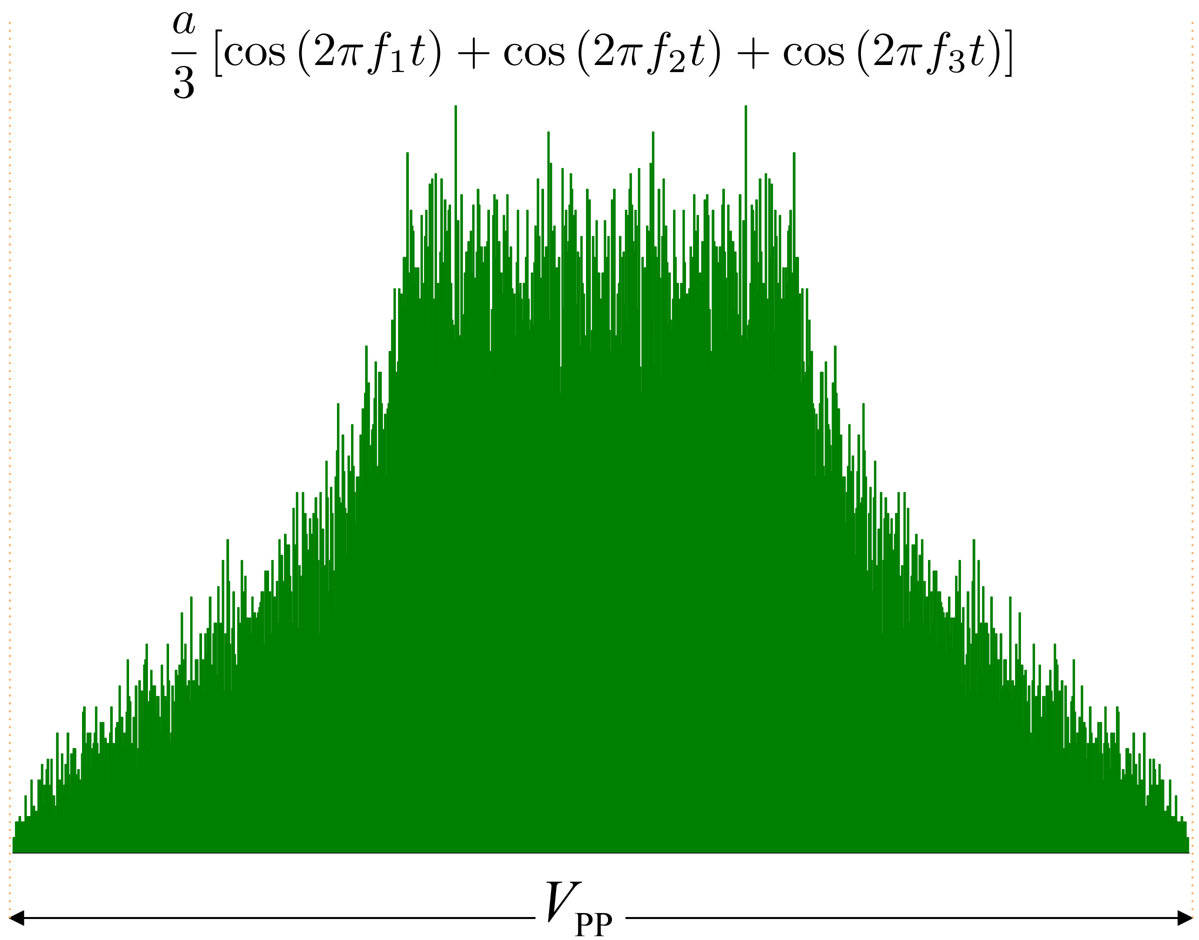
$$\frac{a}{2}\left[\cos\left(2\pi f_1 t\right)+\cos\left(2\pi f_2 t\right)\right]$$



2

Sine waves

Probability Density Sine waves

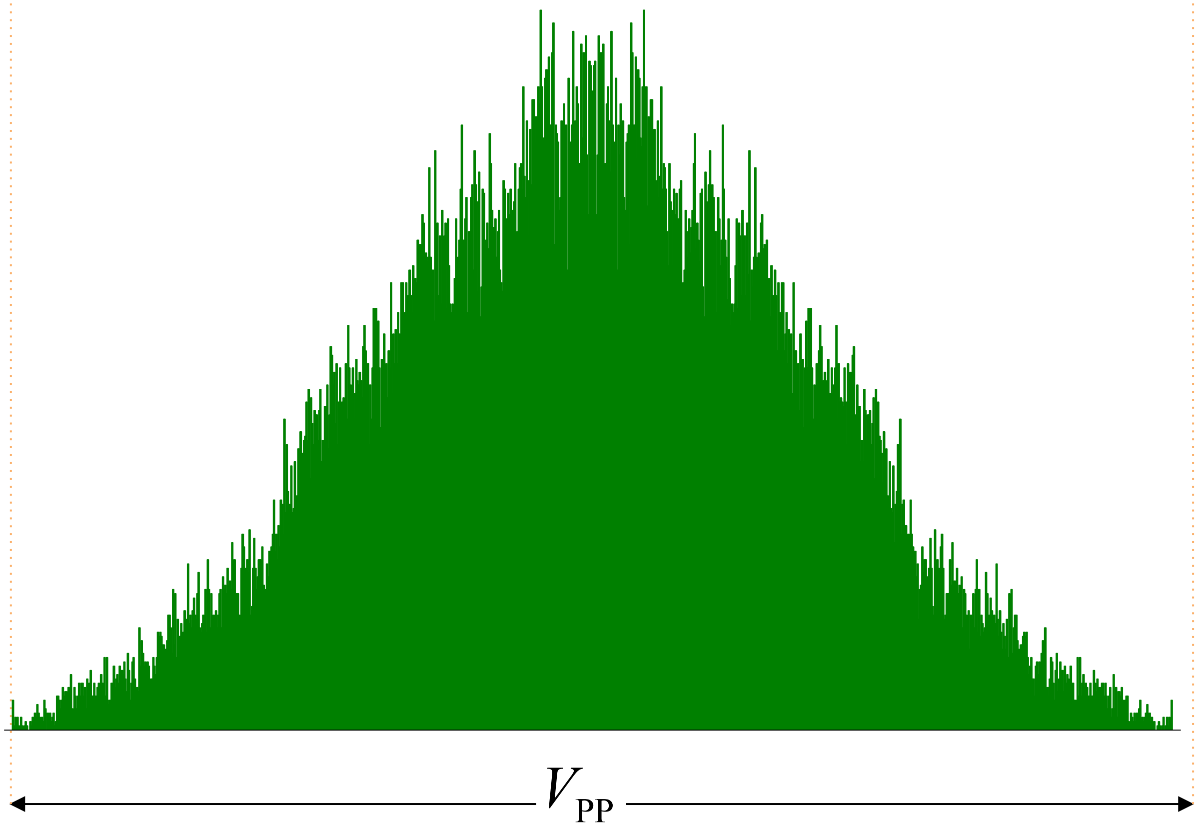


3

Sine waves

Probability Density Sine waves

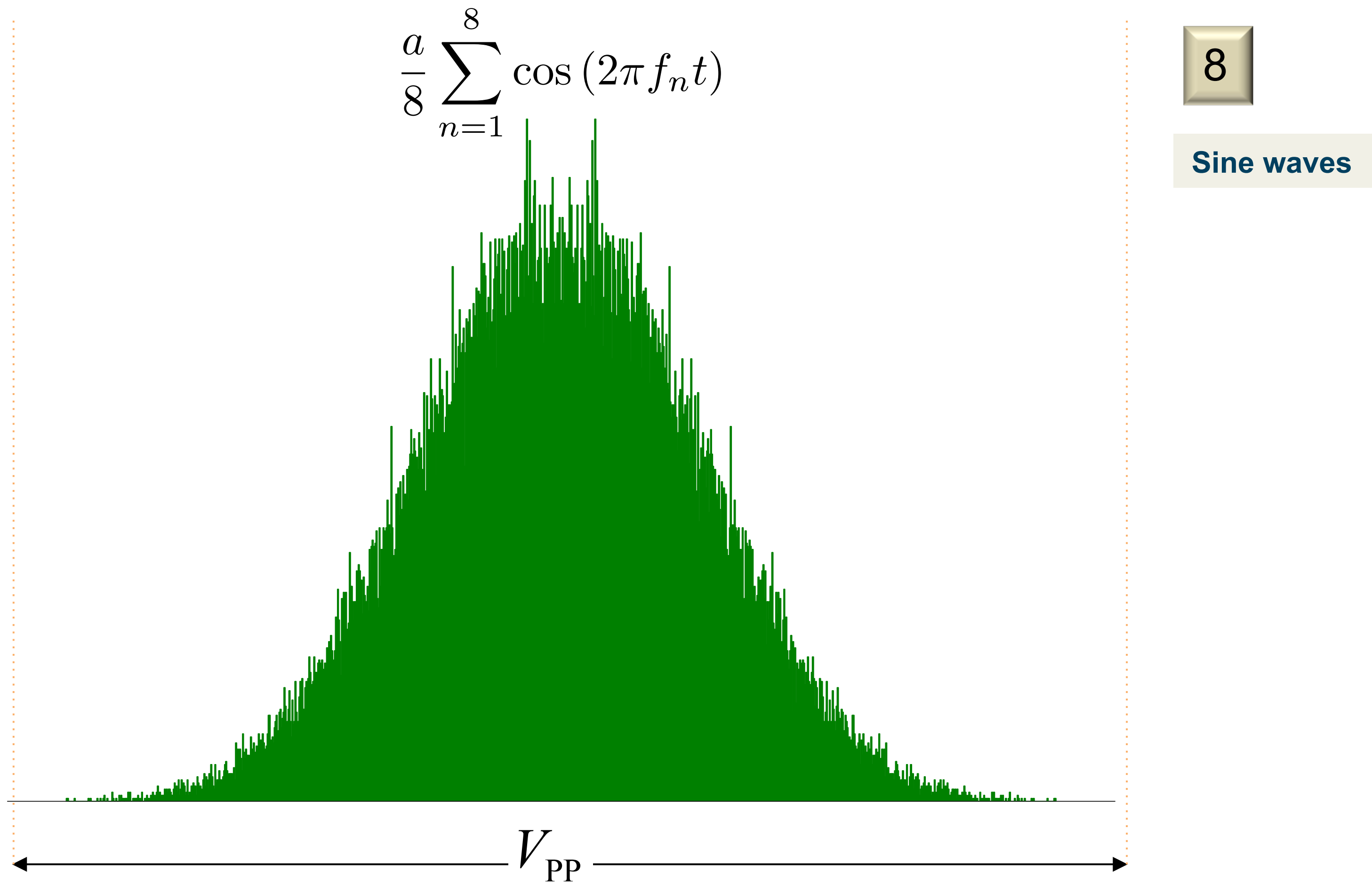
$$\frac{a}{4}\left[\cos\left(2\pi f_1 t\right)+\cos\left(2\pi f_2 t\right)+\cos\left(2\pi f_3 t\right)+\cos\left(2\pi f_4 t\right)\right]$$



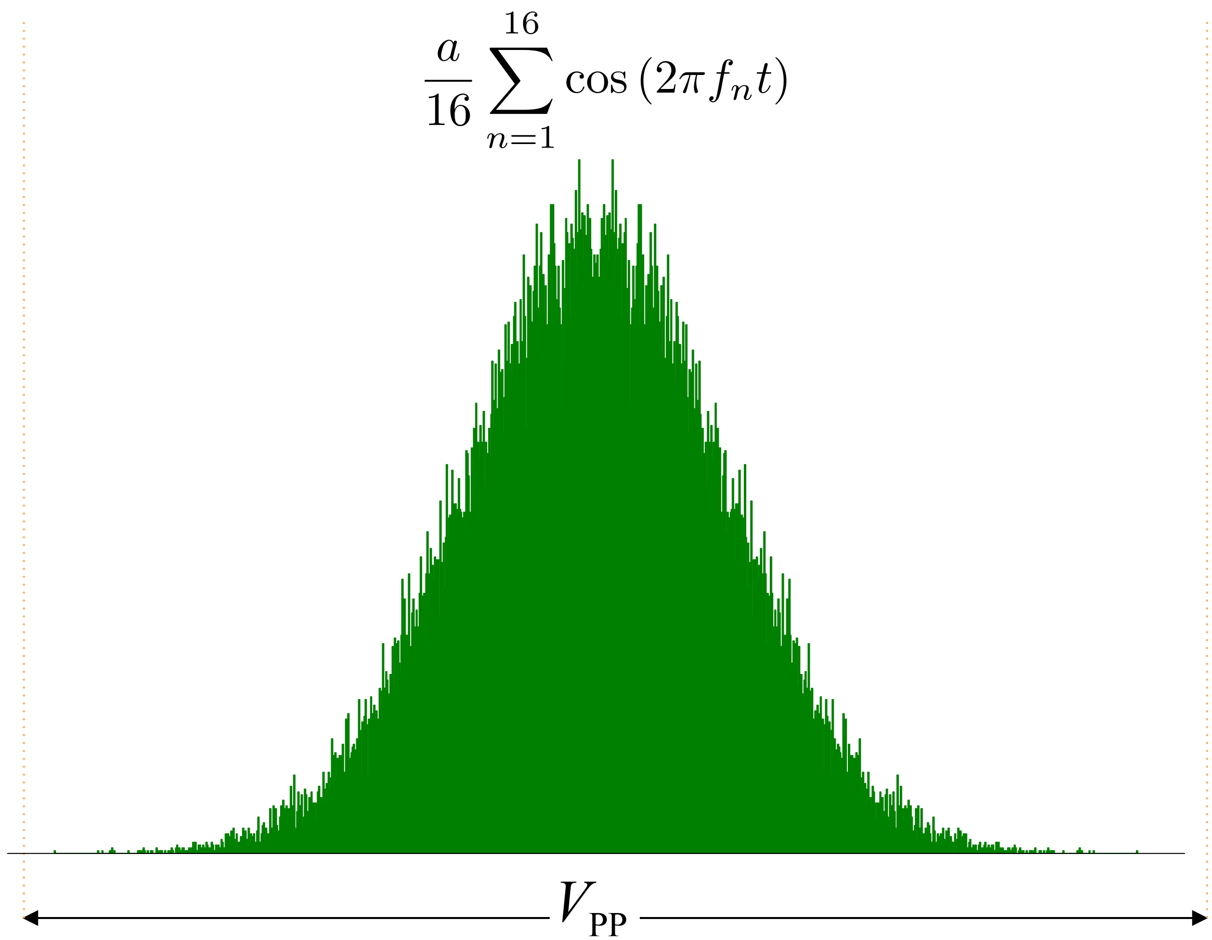
4

Sine waves

Probability Density Sine waves



Probability Density Sine waves

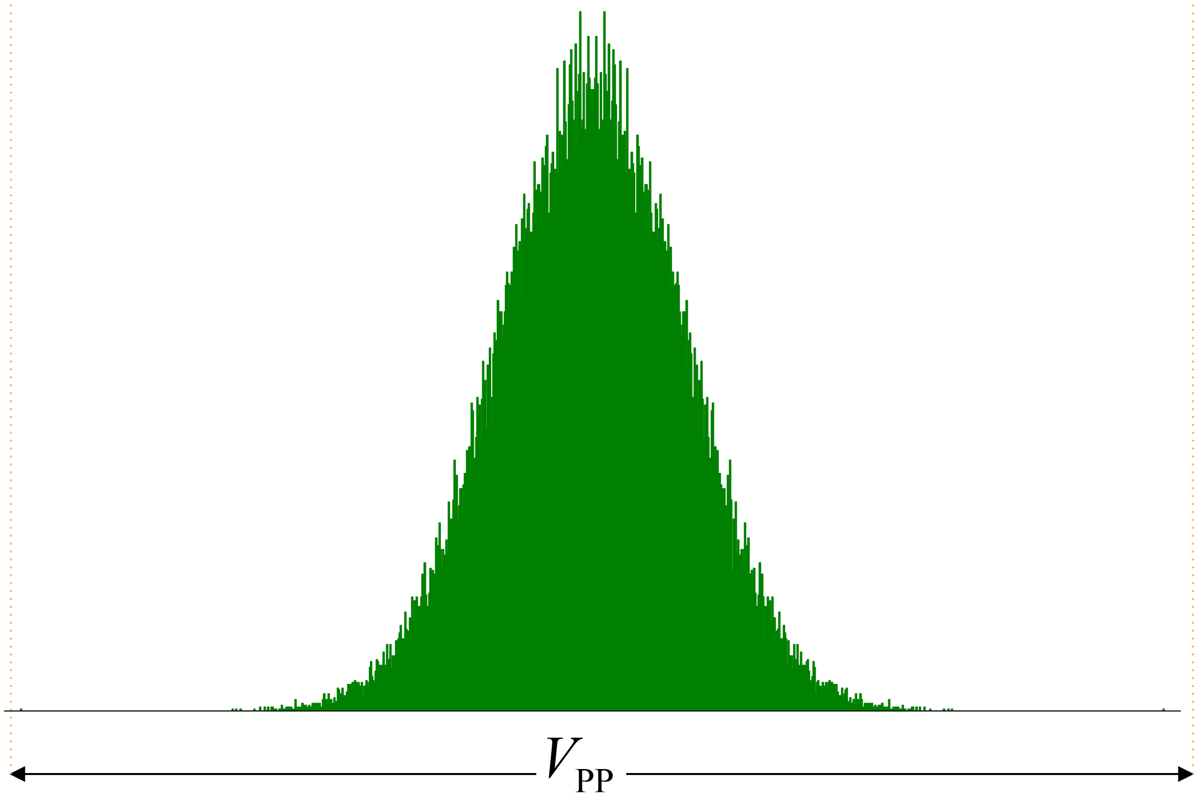


16

Sine waves

Probability Density Sine waves

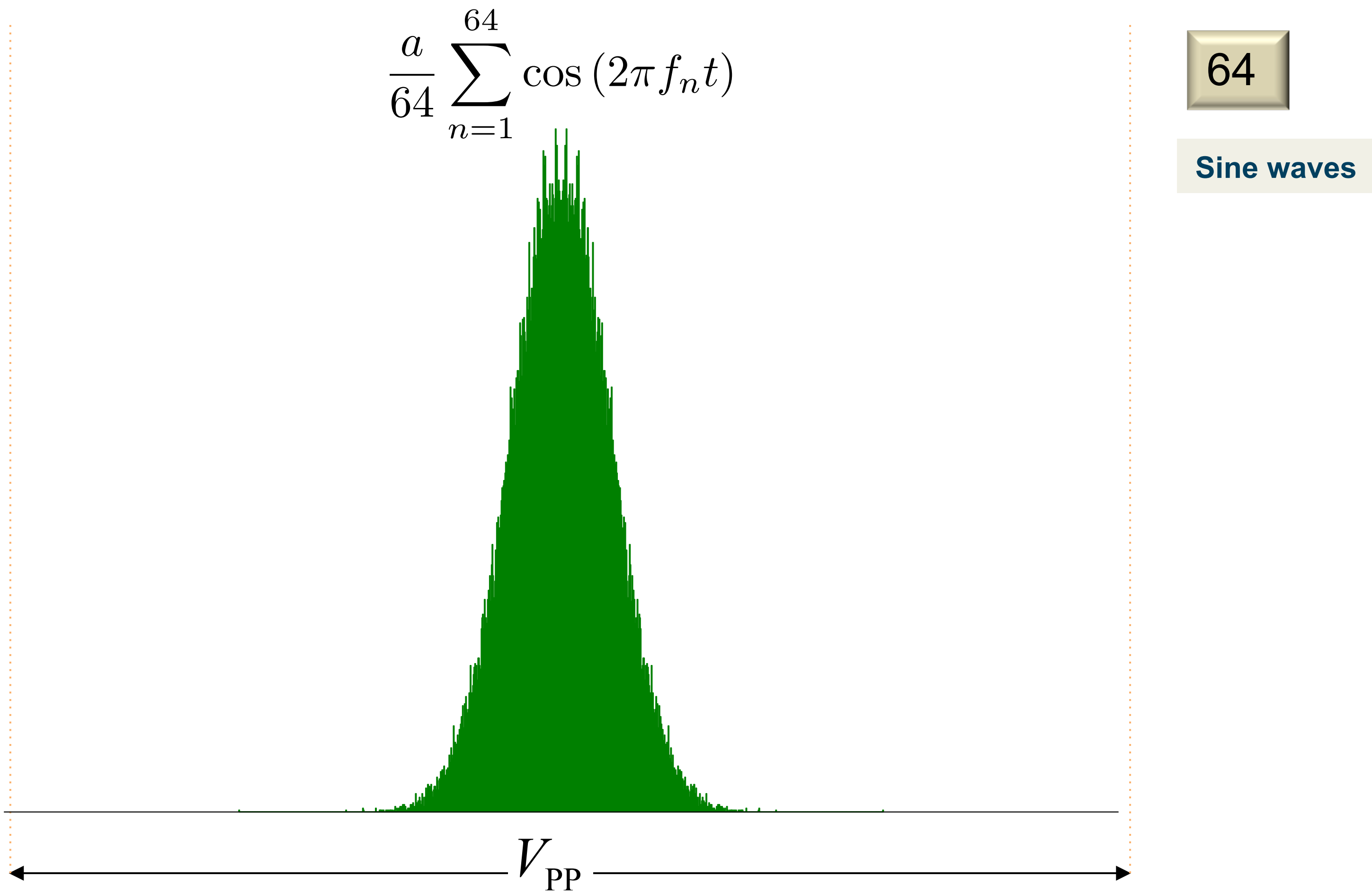
$$\frac{a}{32}\sum_{n=1}^{32}\cos\left(2\pi f_n t\right)$$



32

Sine waves

Probability Density Sine waves

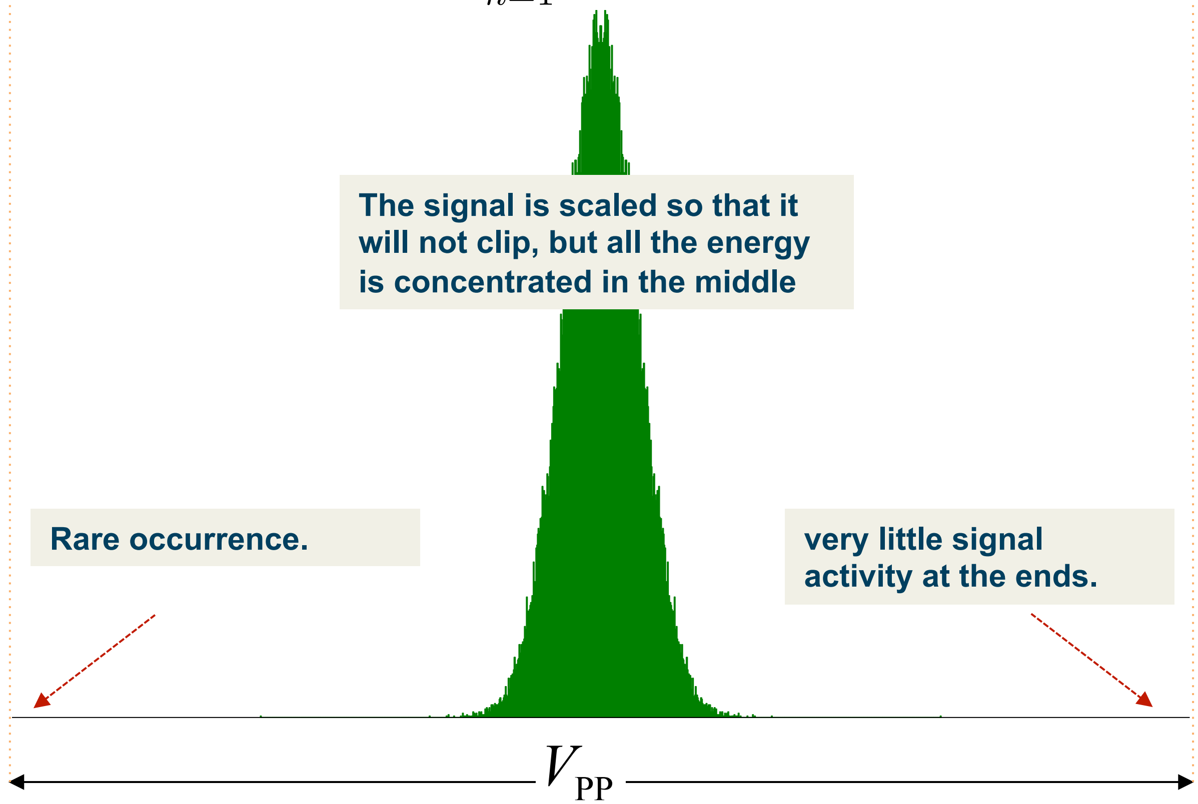


Probability Density Sine waves

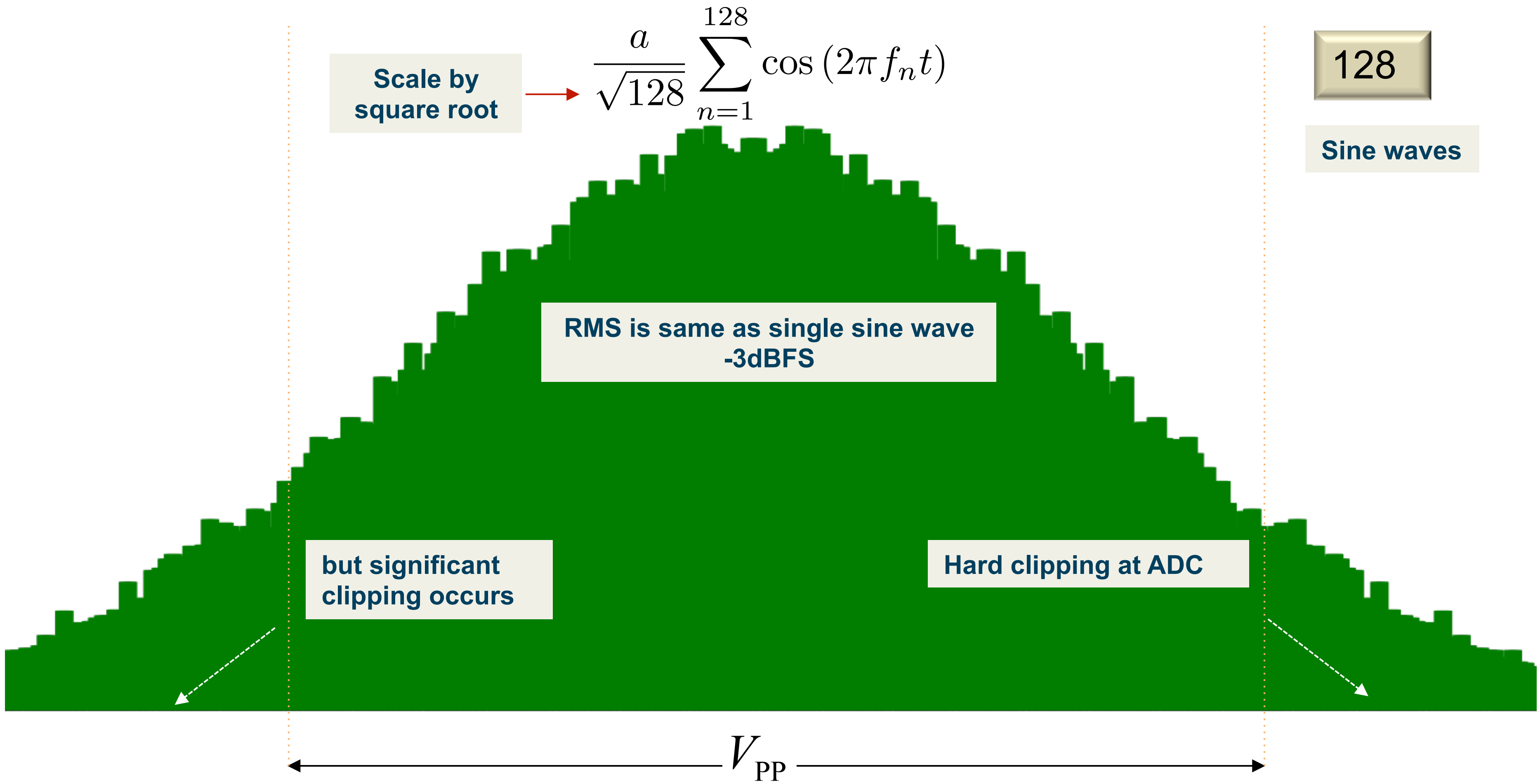
128

Sine waves

$$\frac{a}{128}\sum_{n=1}^{128}\cos\left(2\pi f_n t\right)$$



Probability Density Sine waves



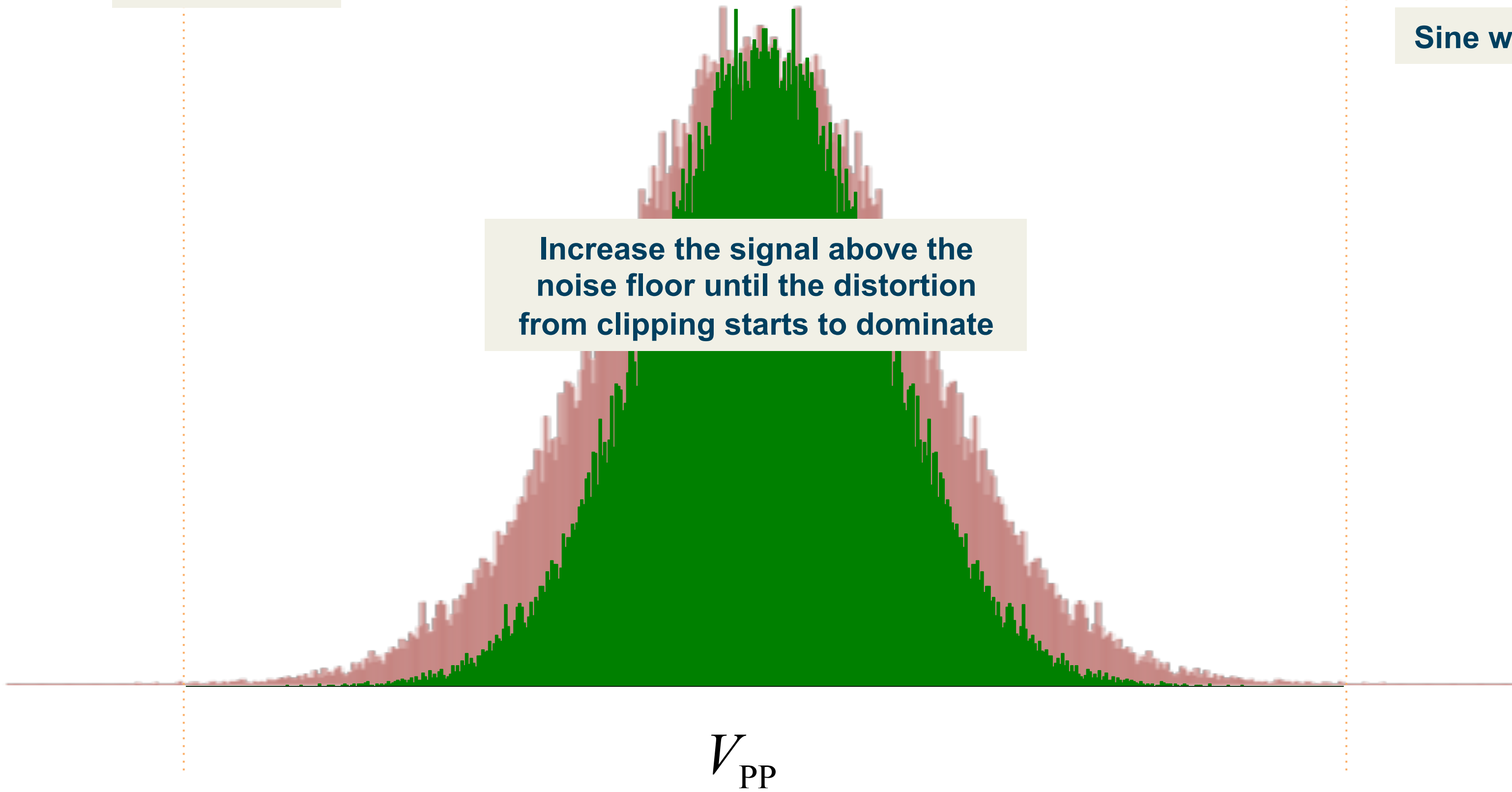
Optimal Backoff for Peak SNR

wrt Sine wave

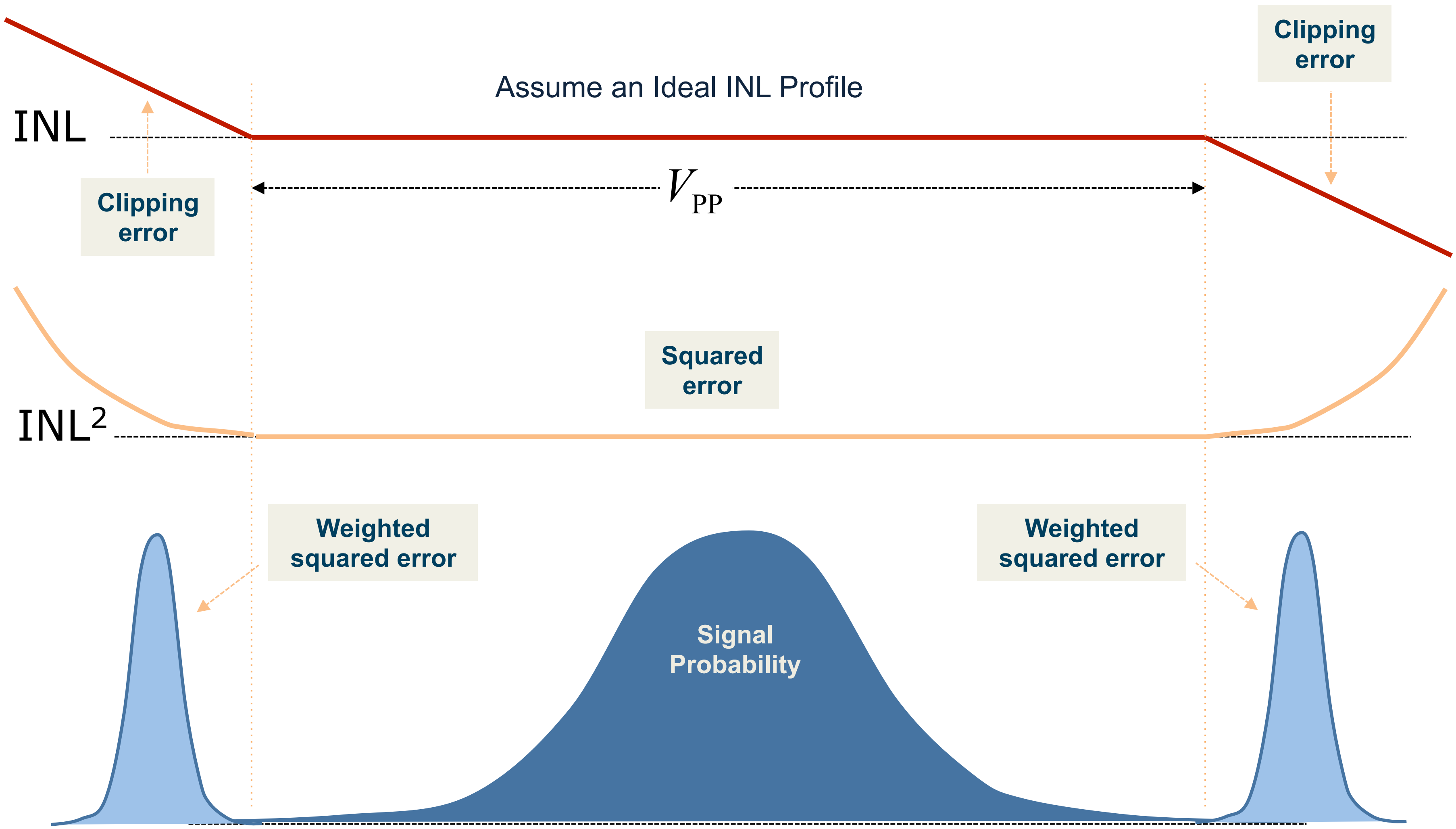
$$\frac{1}{k_{\text{backoff}}} \cdot \frac{a}{\sqrt{128}} \sum_{n=1}^{128} \cos\left(2\pi f_n t\right)$$

128

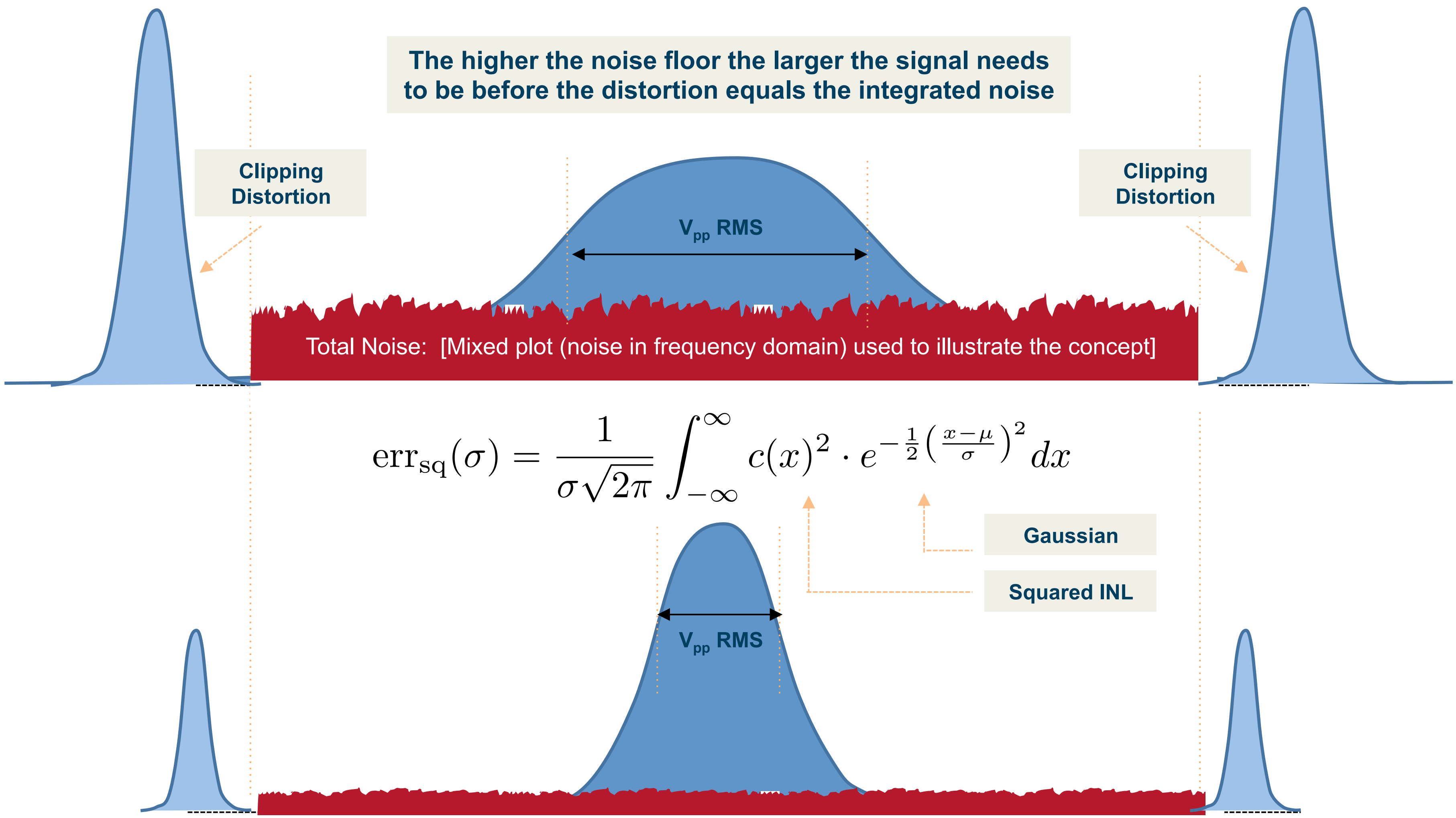
Sine waves



Optimizing Backoff

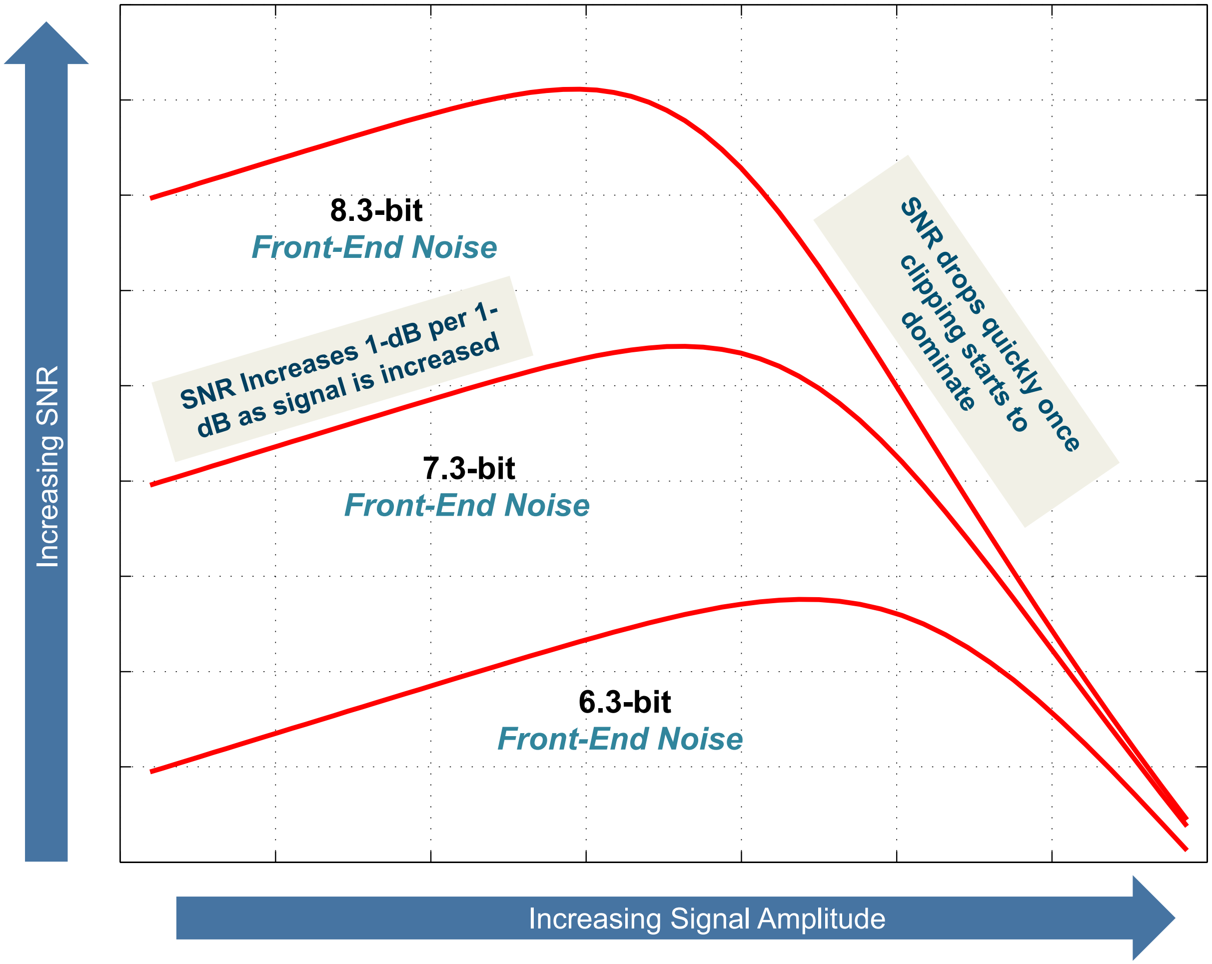


Optimizing Backoff



$$\mathrm{err}_{\mathrm{sq}}(\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\infty} c(x)^2 \cdot e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$

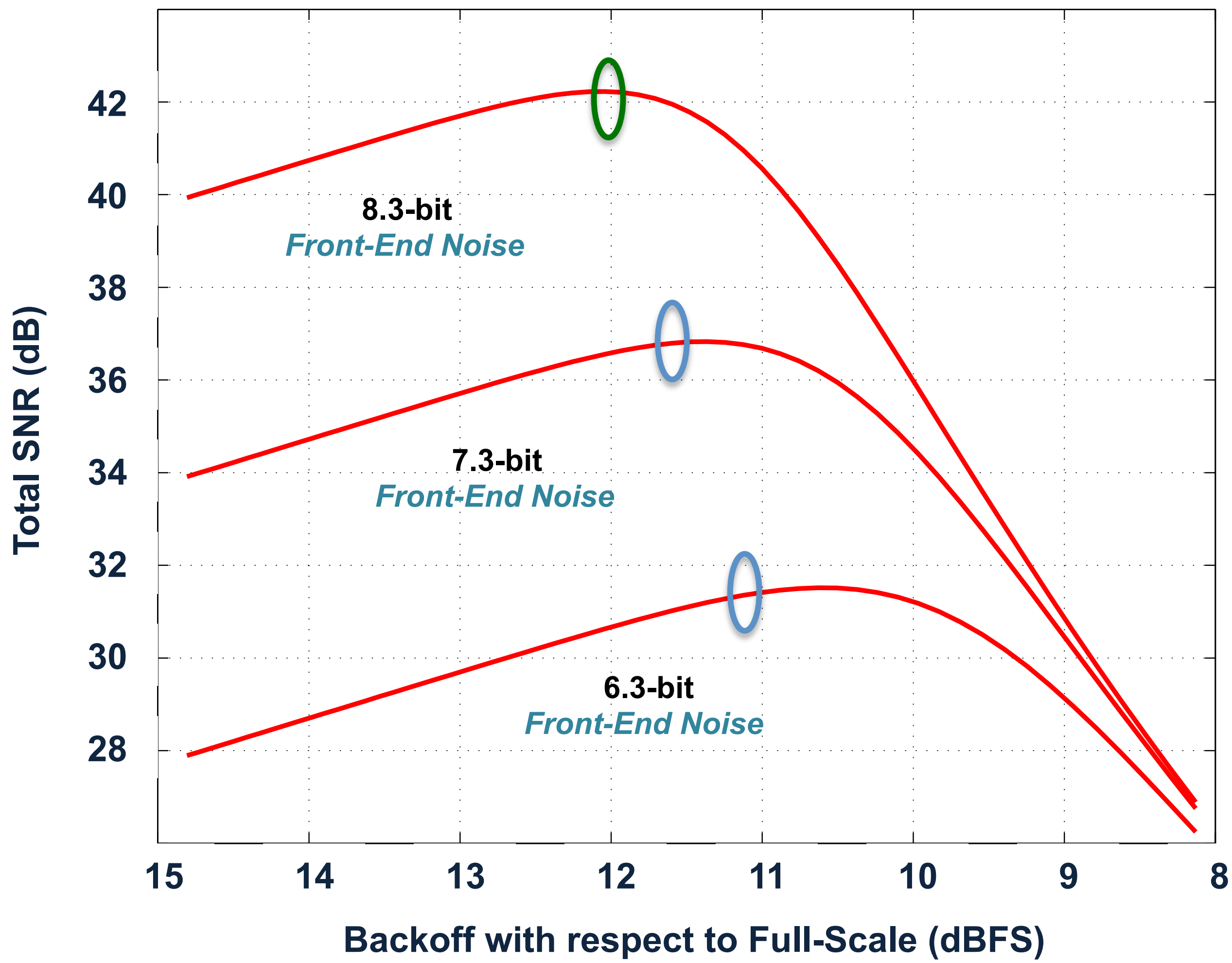
Optimizing Backoff



SNR Increases
as single increases

Optimal signal strength depends on additive noise level

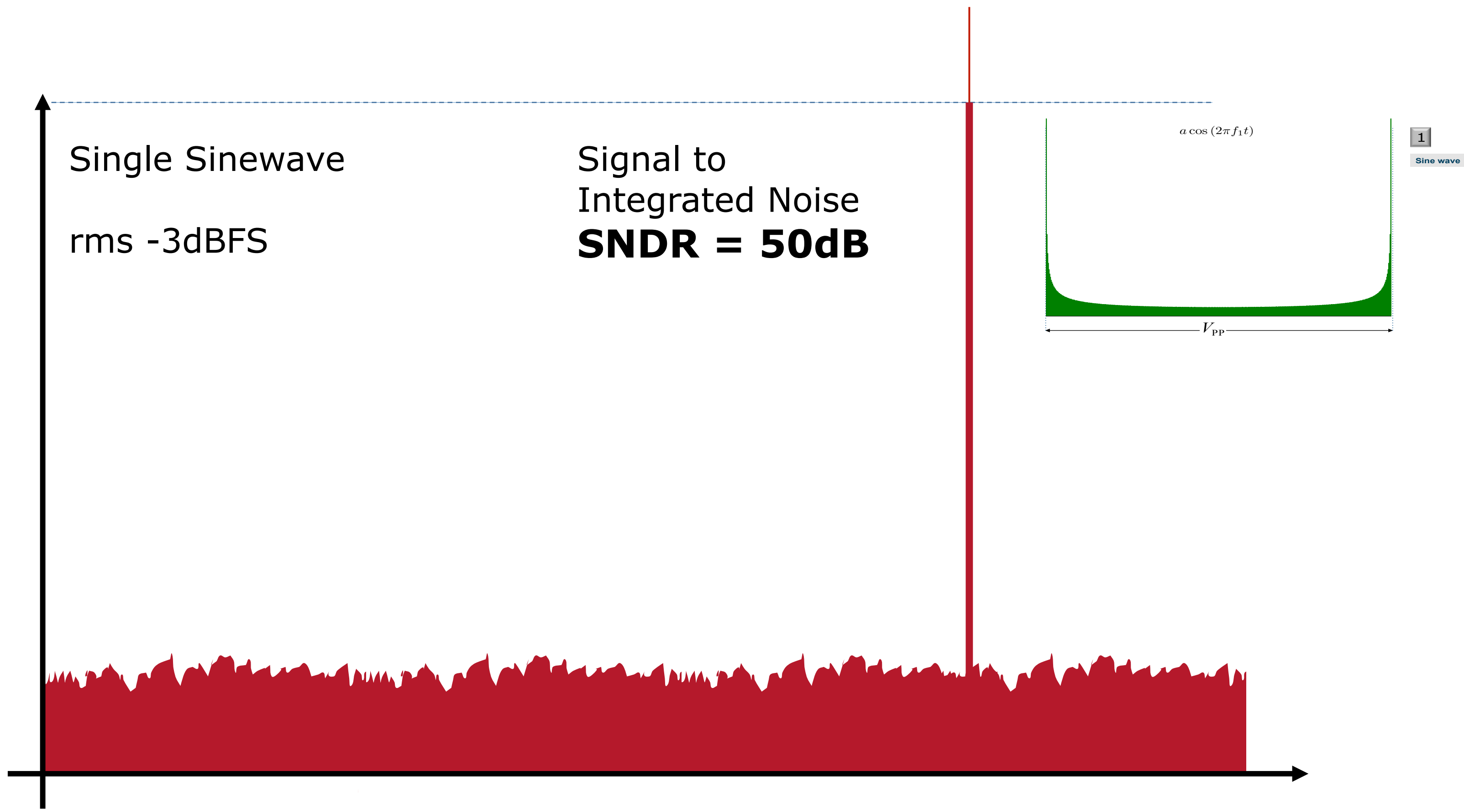
Optimizing Backoff



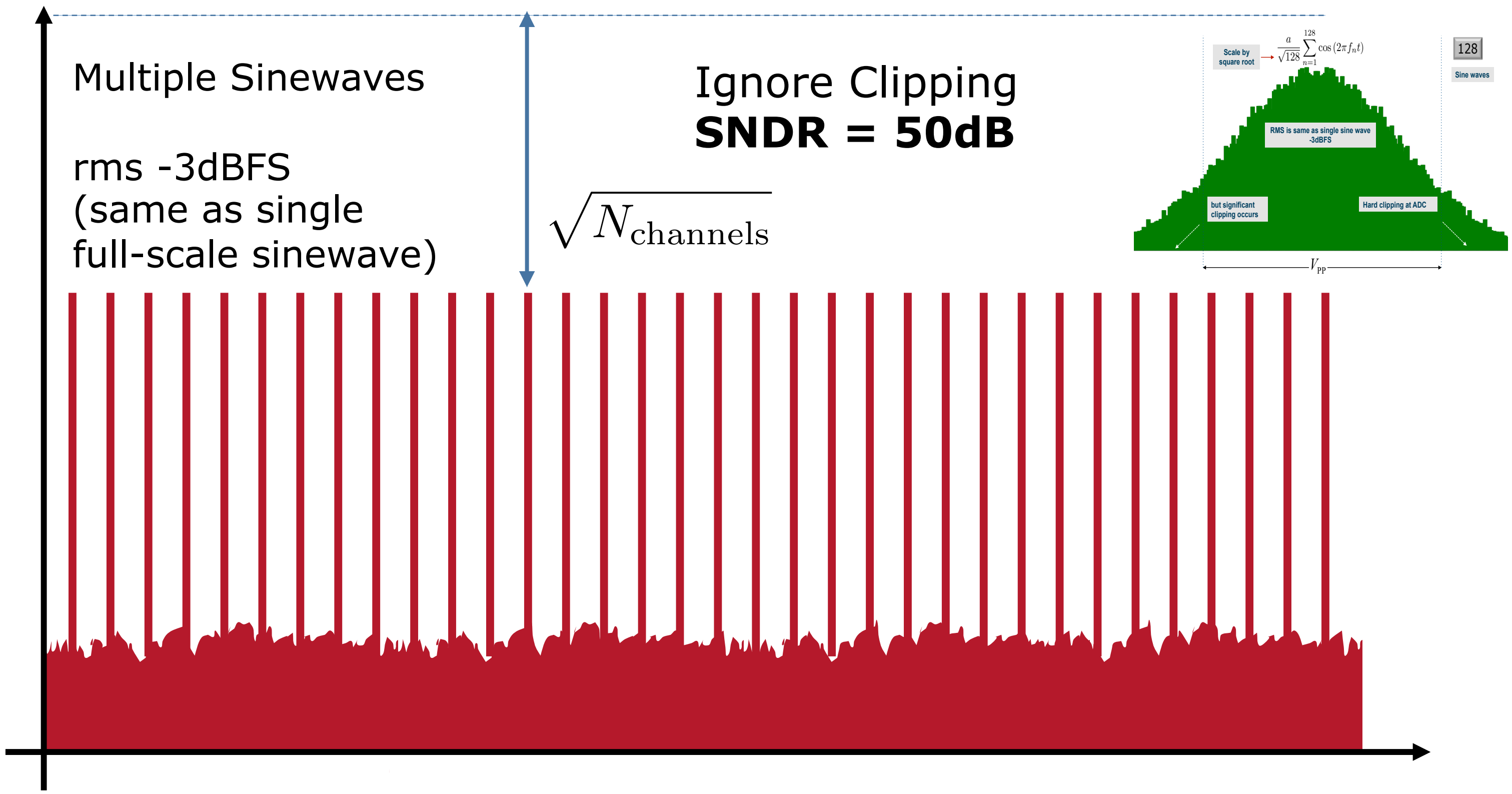
Optimal Loading
~ 12-dBFS backoff
(9-dB wrt sine wave)
For 8.3 bits of Noise

(assumes all channels flat (no ACI) and no processing gain)

Consider Single Tone at -3dBFS

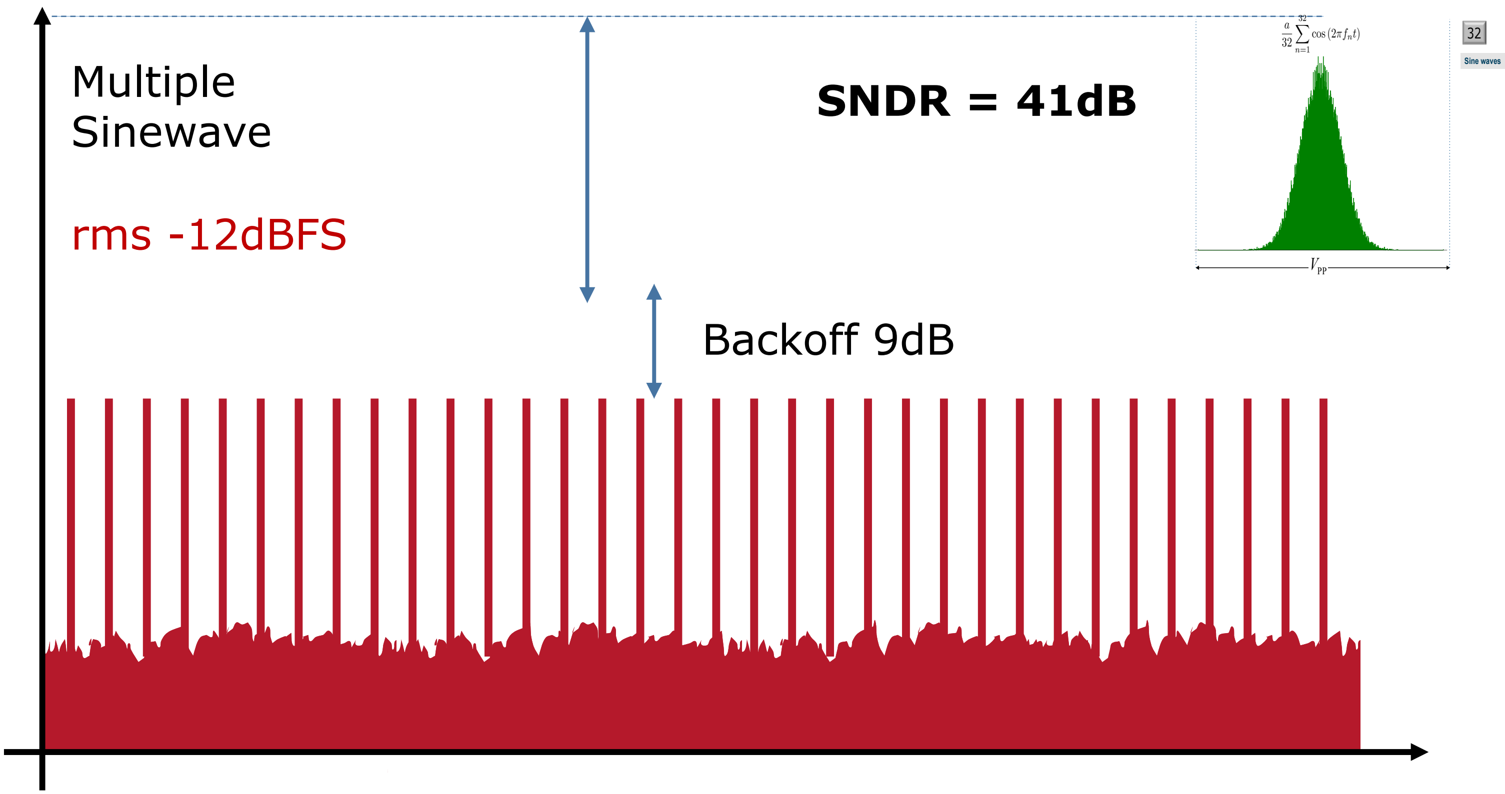


Consider Multi-Tone at -3dBFS



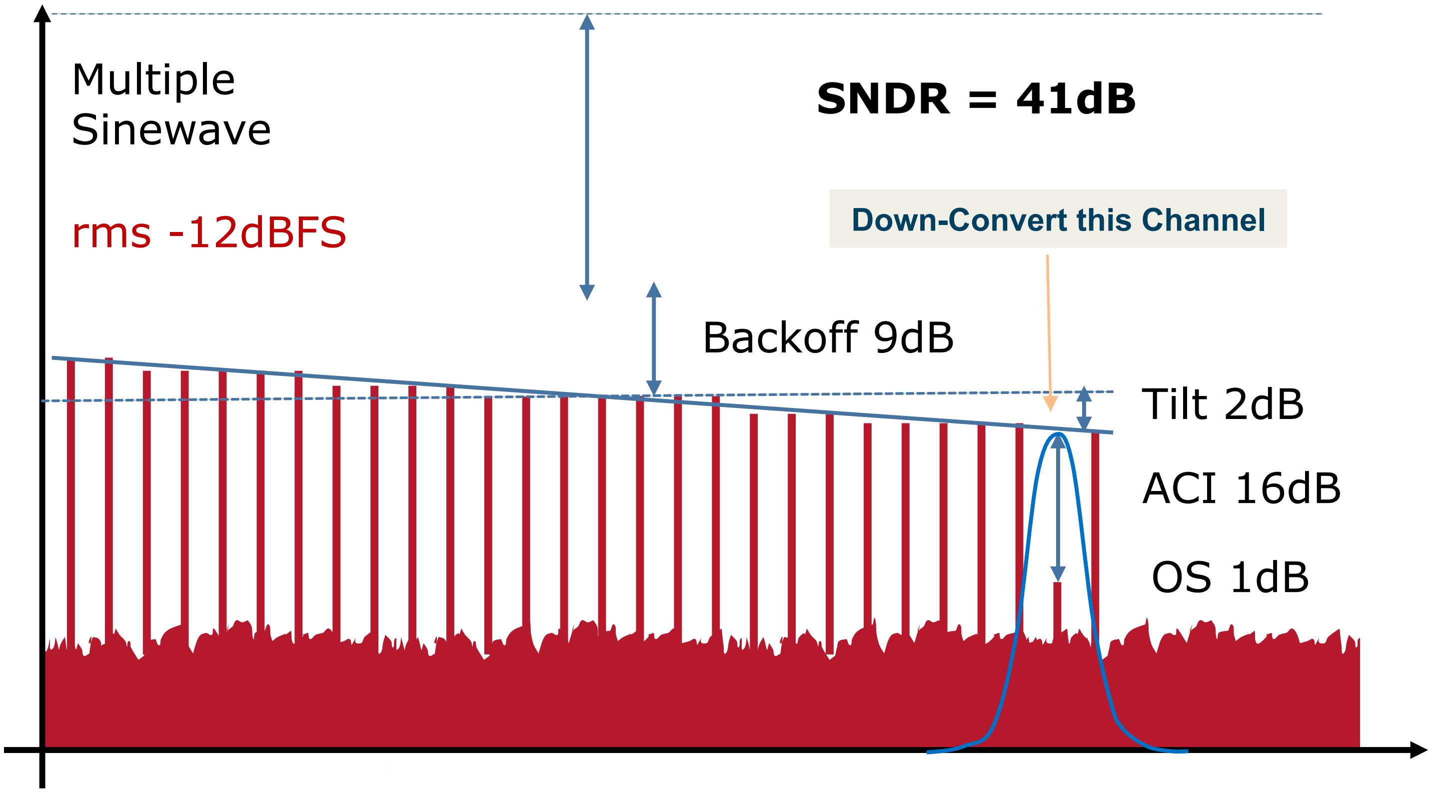
Since ADC is “Ideal” and input RMS level stays the same, SNDR is still 50dB

Recall Multi-Tone at -3dBFS



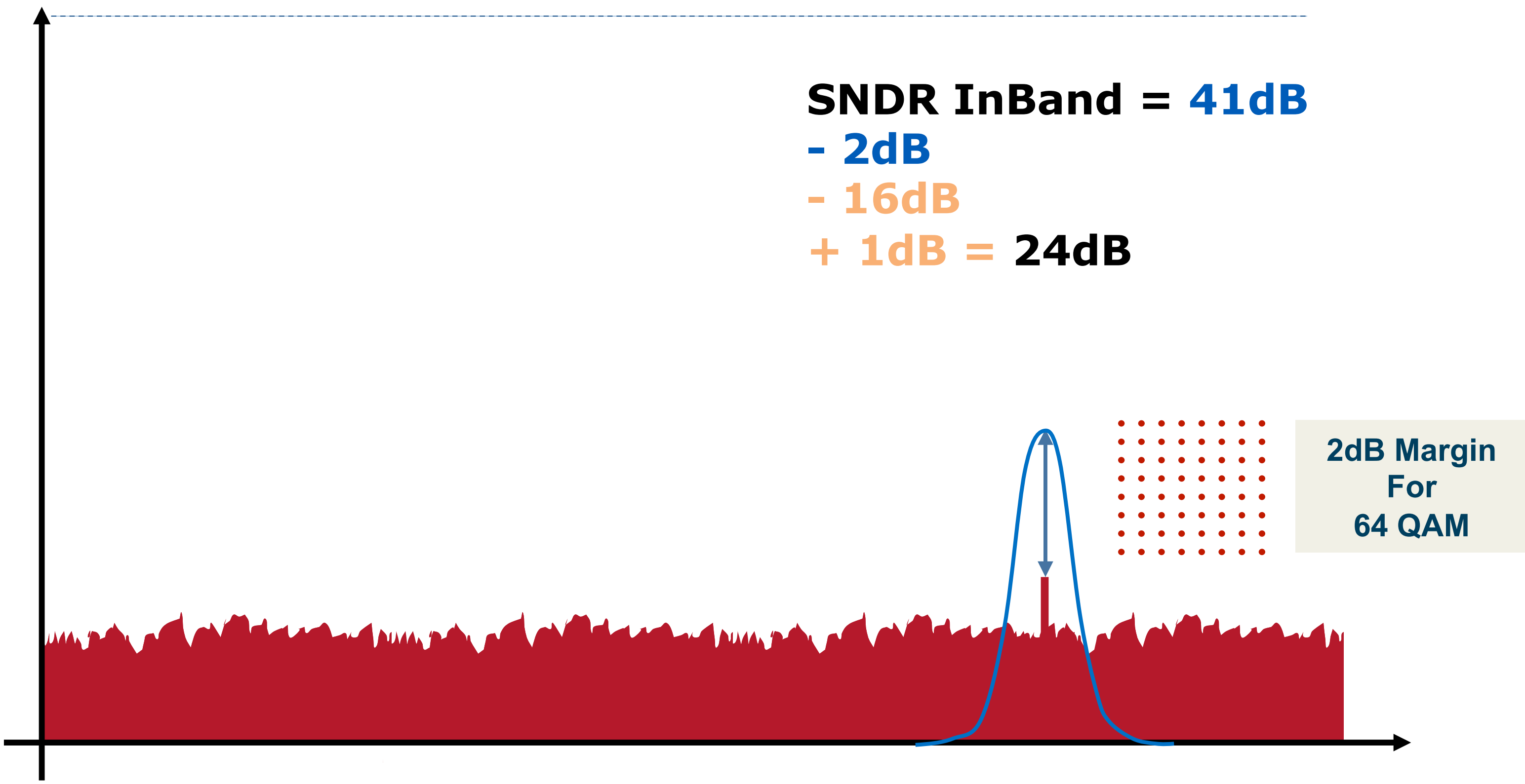
Drop the Signal by 9-dB, SNDR drops to 41-dB

Recall Multi-Tone at -3dBFS



Drop the Signal by 9-dB, SNDR drops to 41-dB

Down-Converted Channel

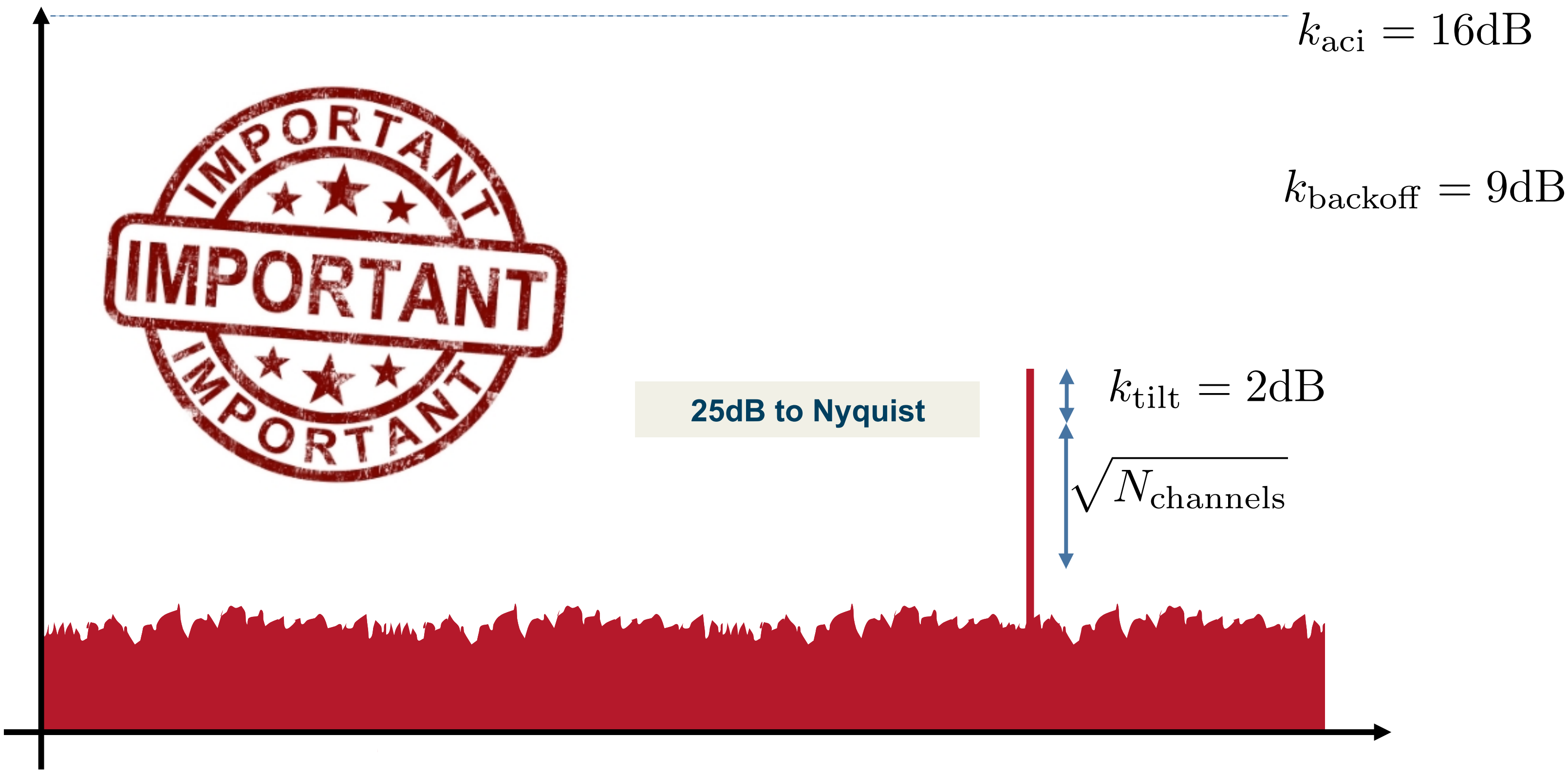


Drop the Signal by 9-dB, SNDR drops to 41-dB

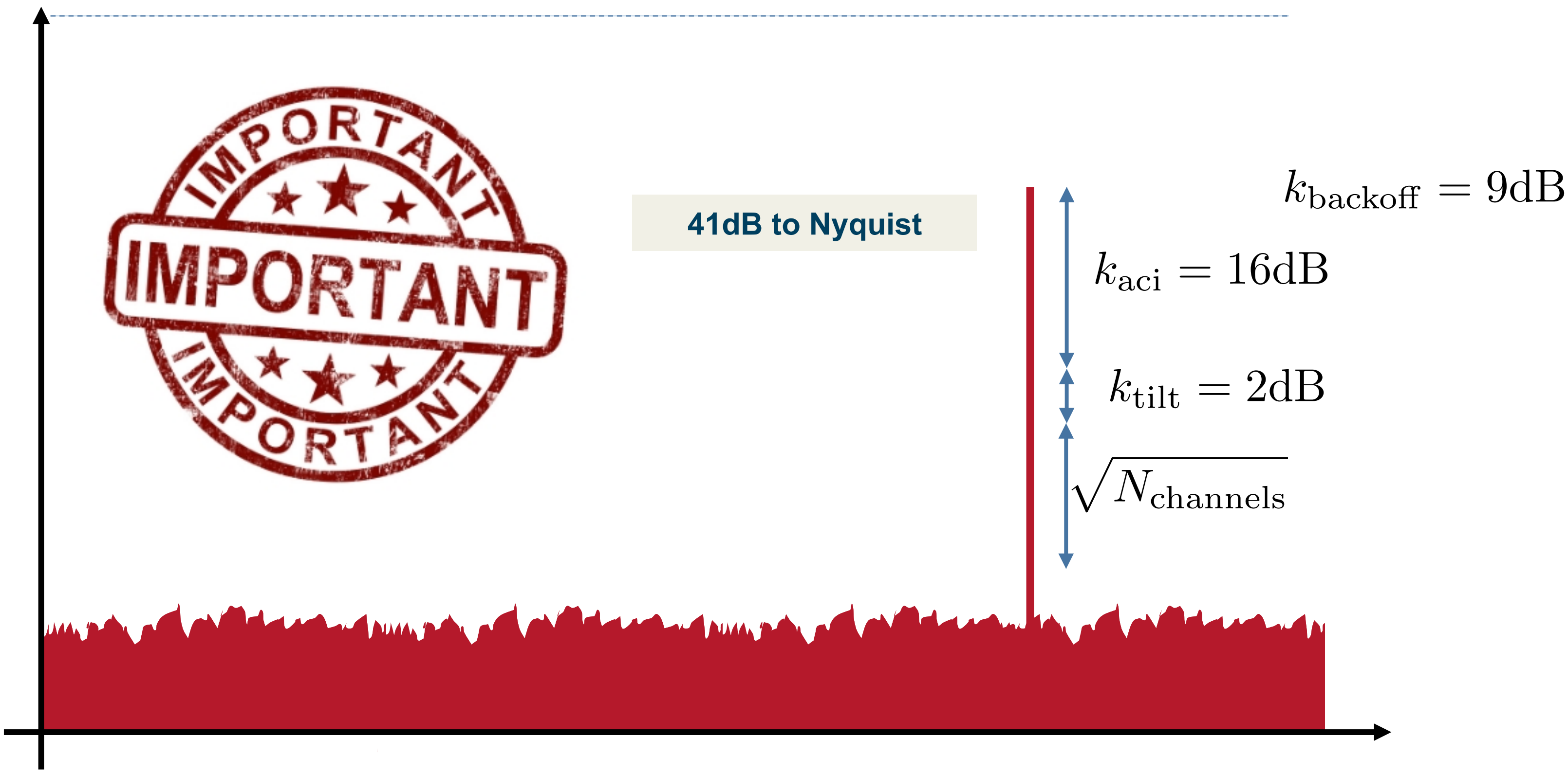
Most Important Slide in Talk

Most Important Slide in Talk

Most Important Slide in Talk

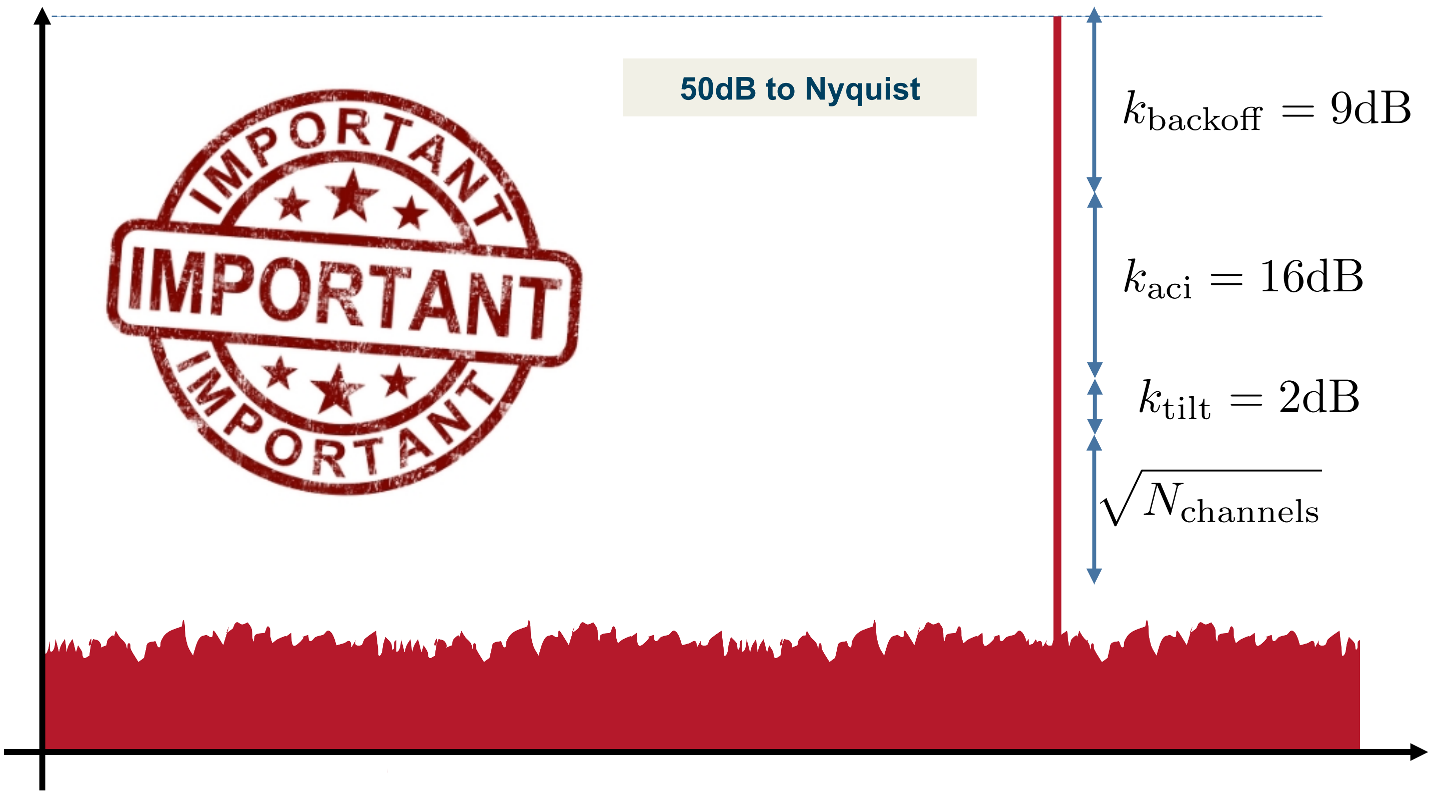


Most Important Slide in Talk



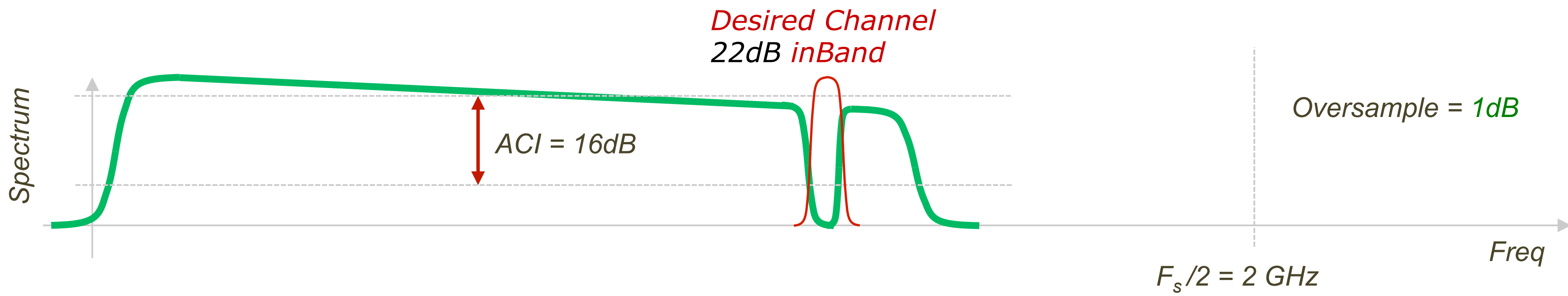
Most Important Slide in Talk

False Conclusion: ENOB of 50dB is Needed




I TAKE THE SPECIFICATIONS FROM THE CUSTOMERS
AND I BRING THEM DOWN TO THE ADC ENGINEERS
INITECH

Actual Requirement

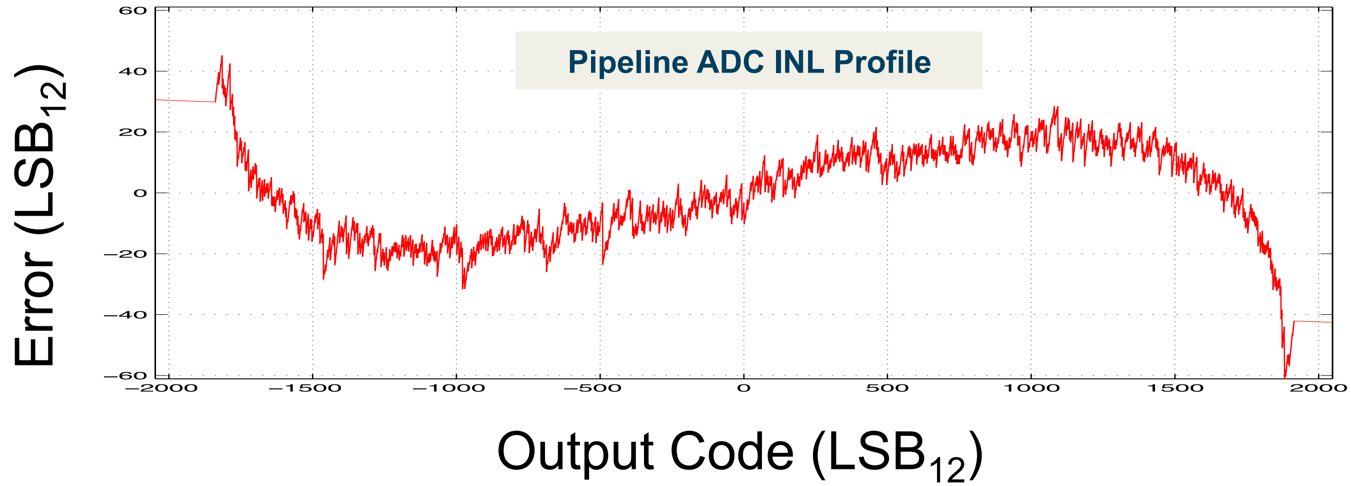


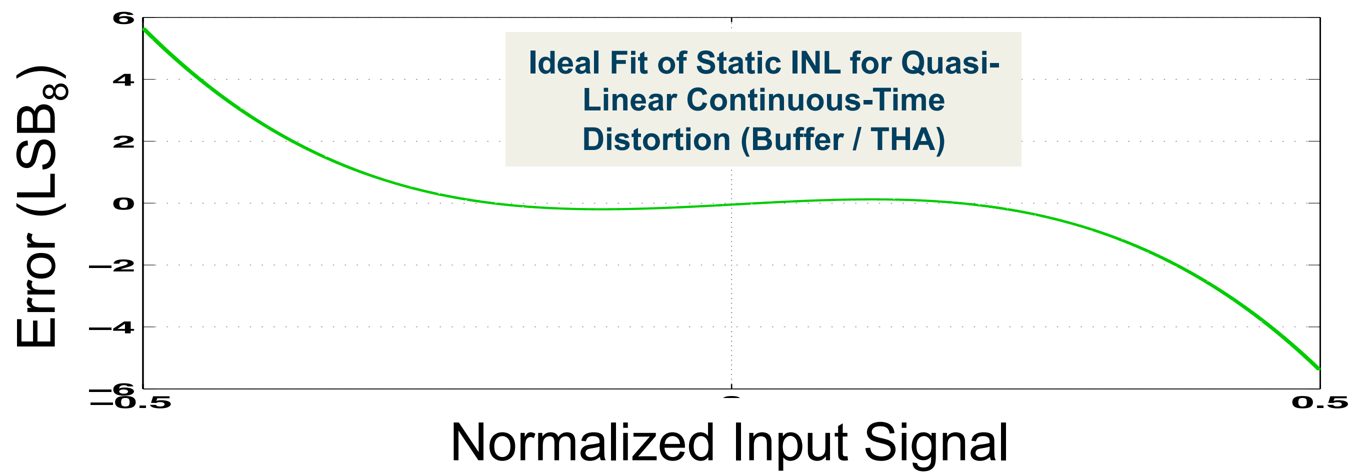
Remove Any Channel
- ❑ Measure the Noise plus inter-modulated in-band errors
- ❑ Compare the noise to a missing channel equal to the average power – tilt – ACI + oversample

Test Signal Have
- ❑ Proper amplitude
- ❑ Proper Amplitude Probability Density
- ❑ Proper Frequency Content

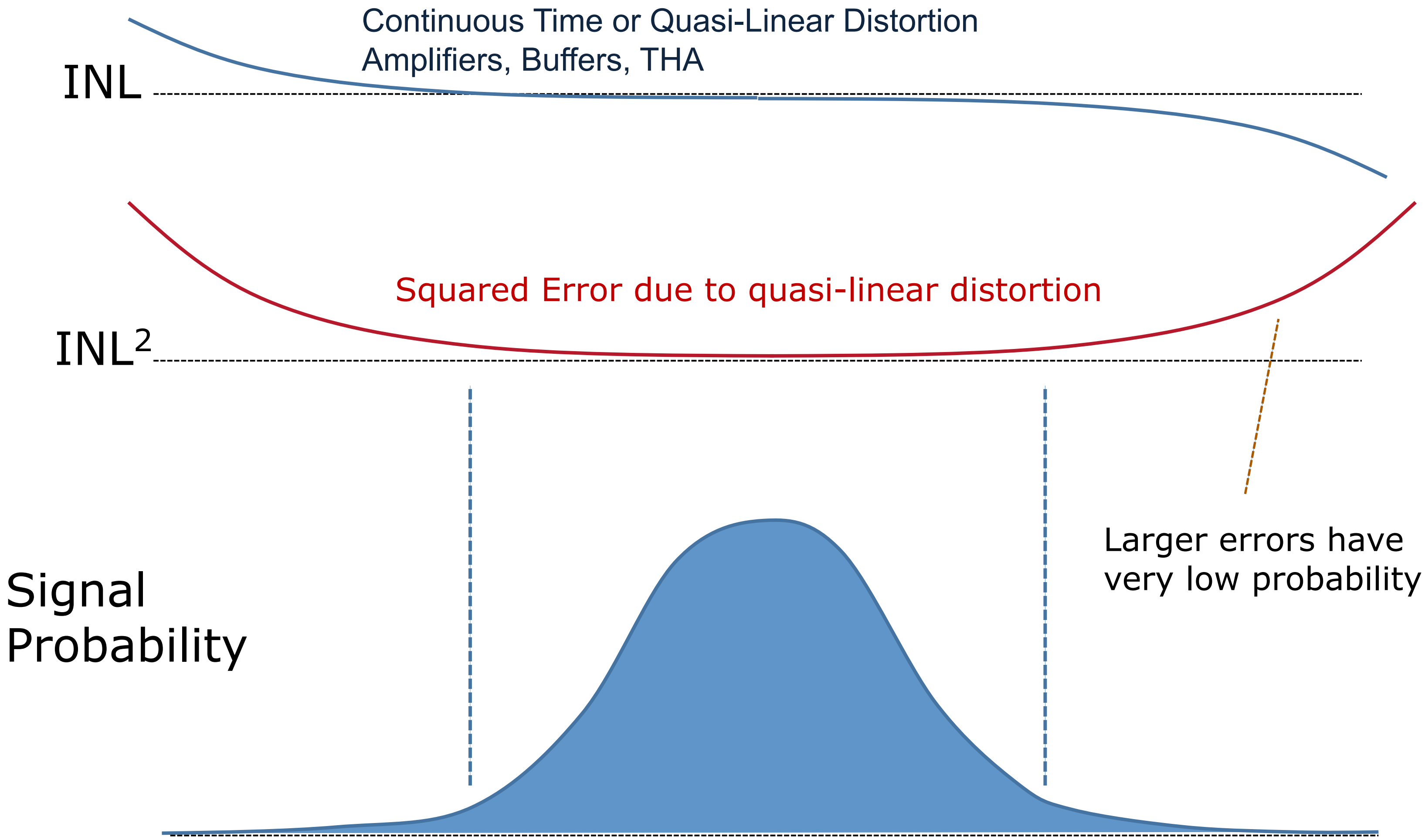
No Spurs
- ❑ Note that nothing creates a "spur" unless it is a clock feed through
- ❑ Spurs are an artifact of testing with sinewave

Static Distortion Requirements

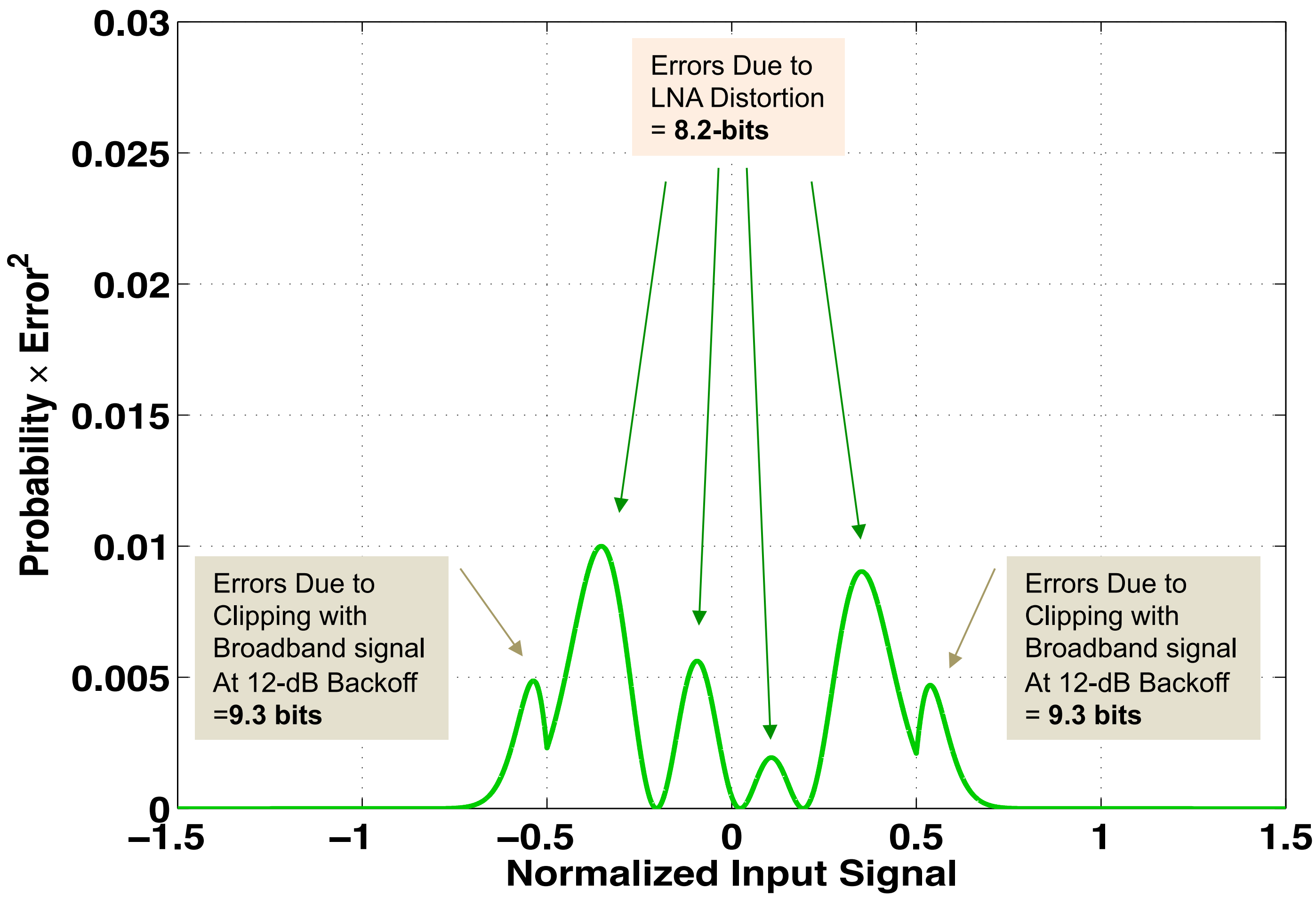




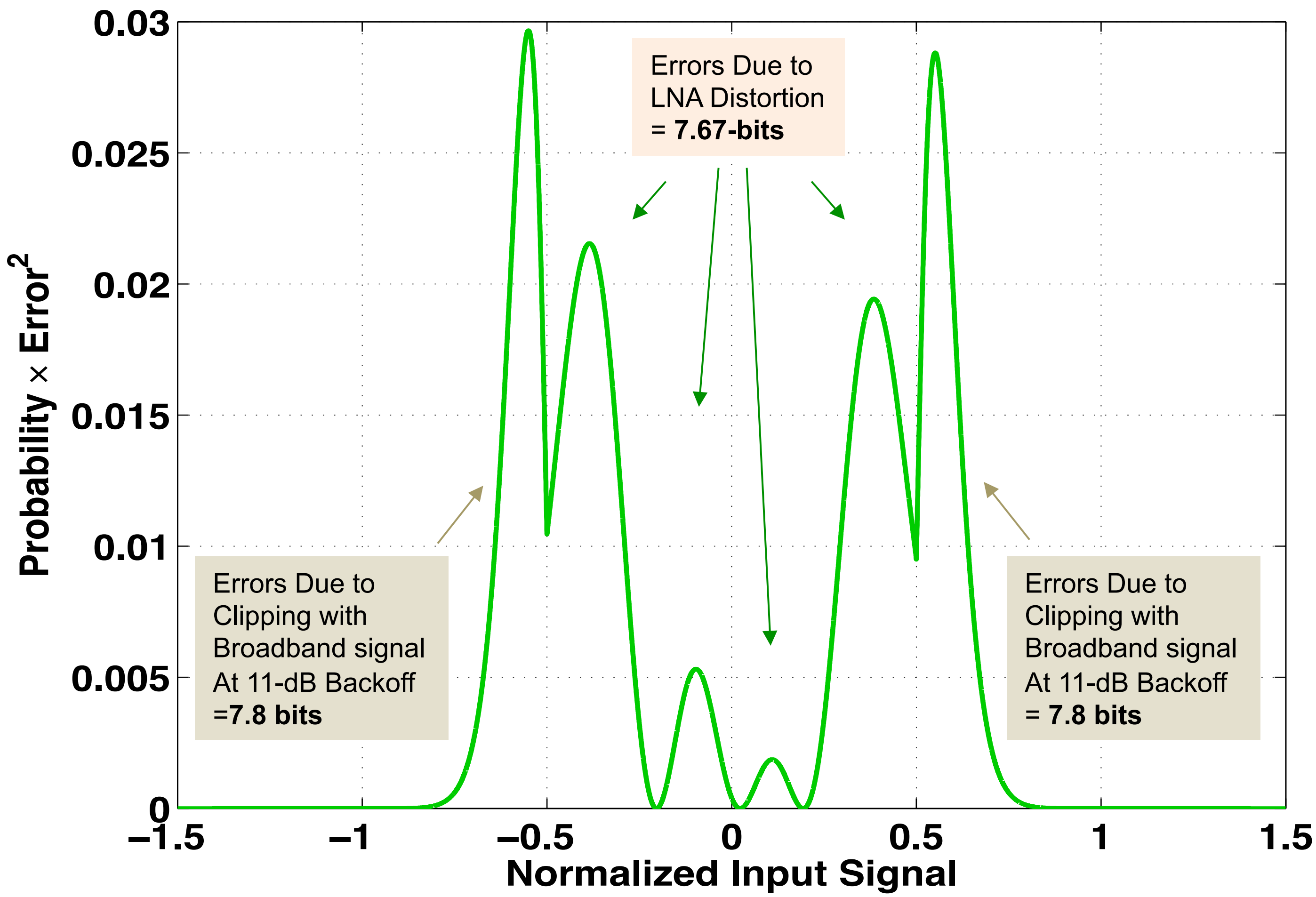
Distortion Treated Like Clipping



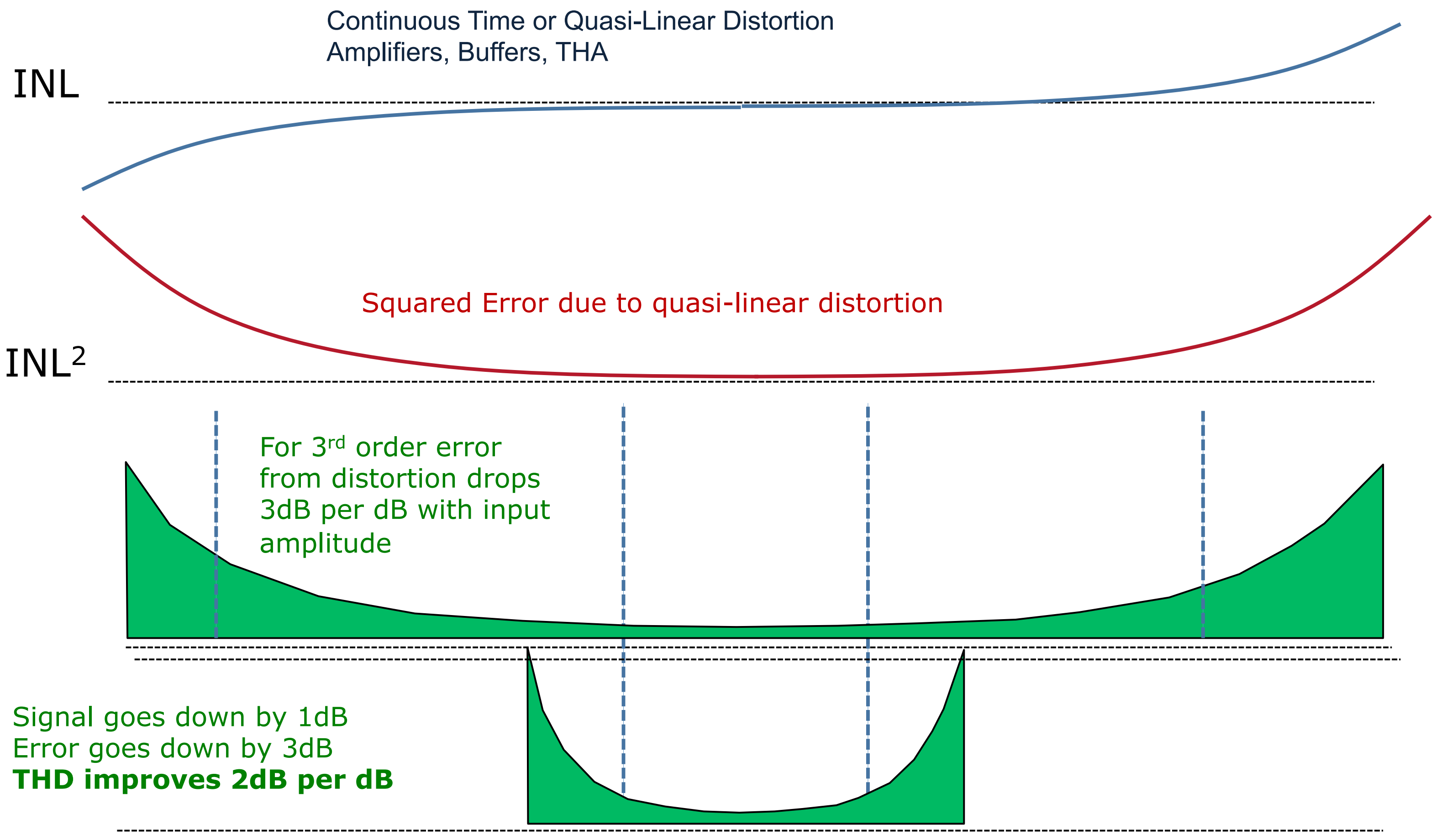
Distortion Error 12-dBFS Backoff



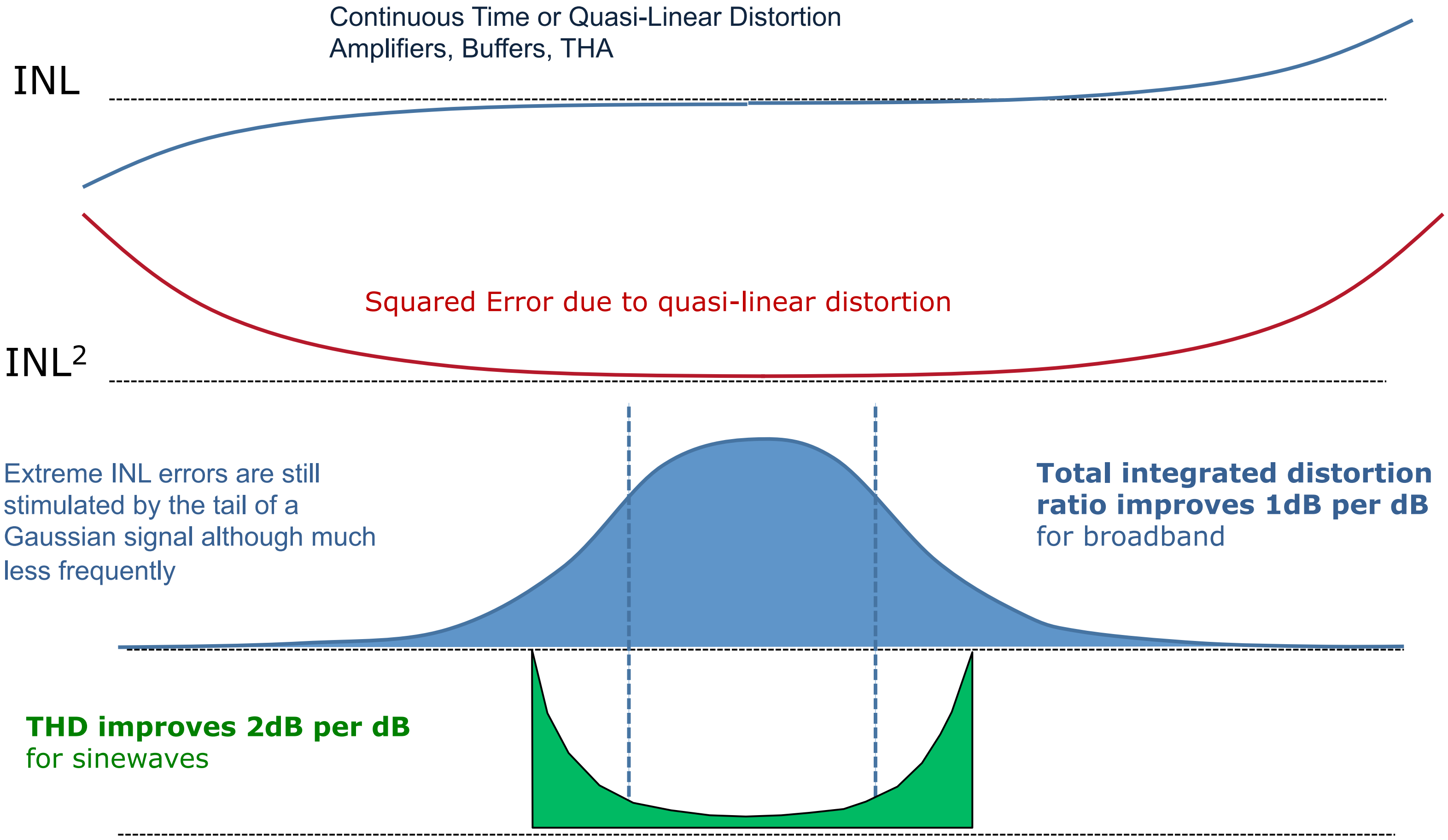
Distortion Error 11-dBFS Backoff



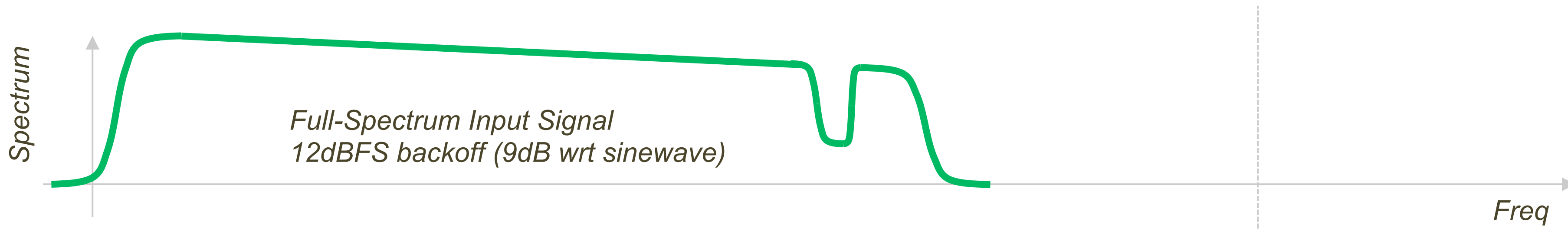
THD vs. Amplitude



THD Scaling with Backoff

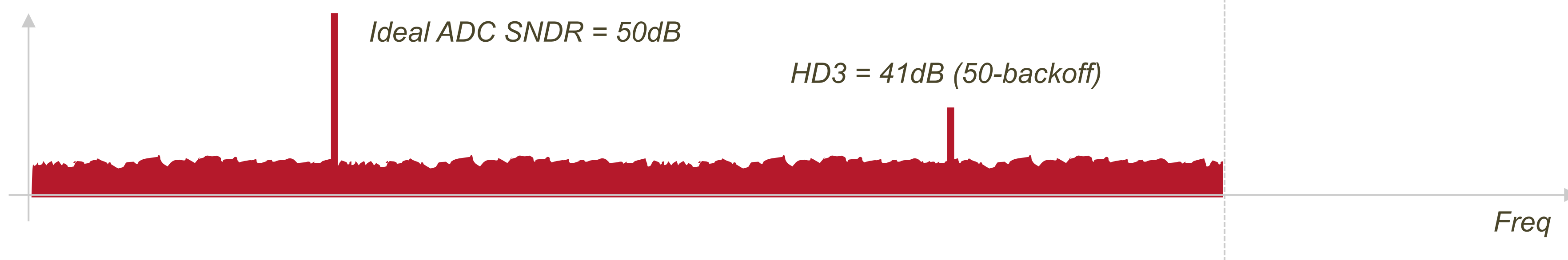


What THD is Needed?



Rule of Thumb (found from simulations) is 1dB per dB

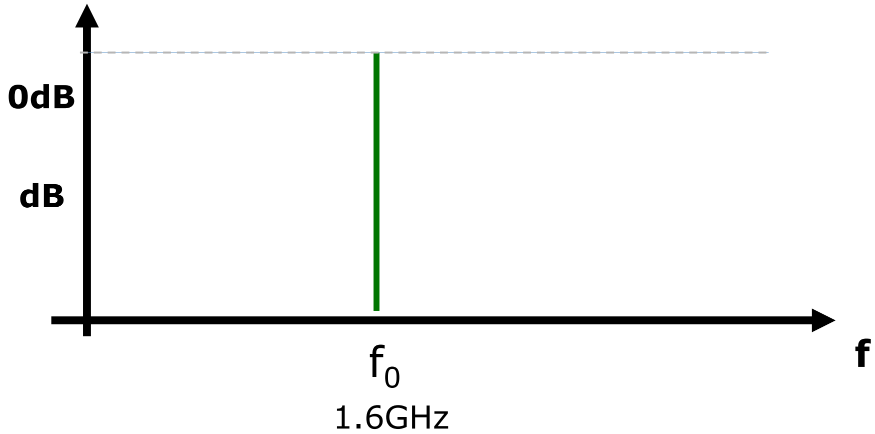
Relief on HD_3 from required noise-floor is approximately equal to the backoff relative to a full-scale sinewave (9dB)



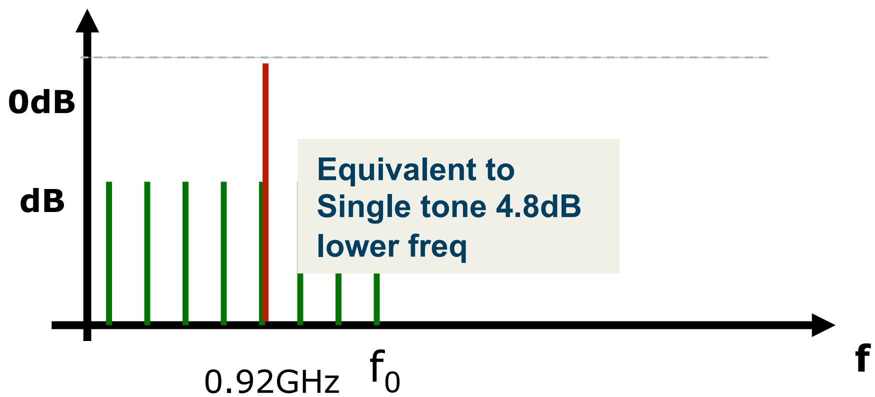

14:54
40
MetLife
Did you Catch That?
41dB! Not 50dB
That's
HUGE!

Timing Requirements

Summary of Next Few Slides

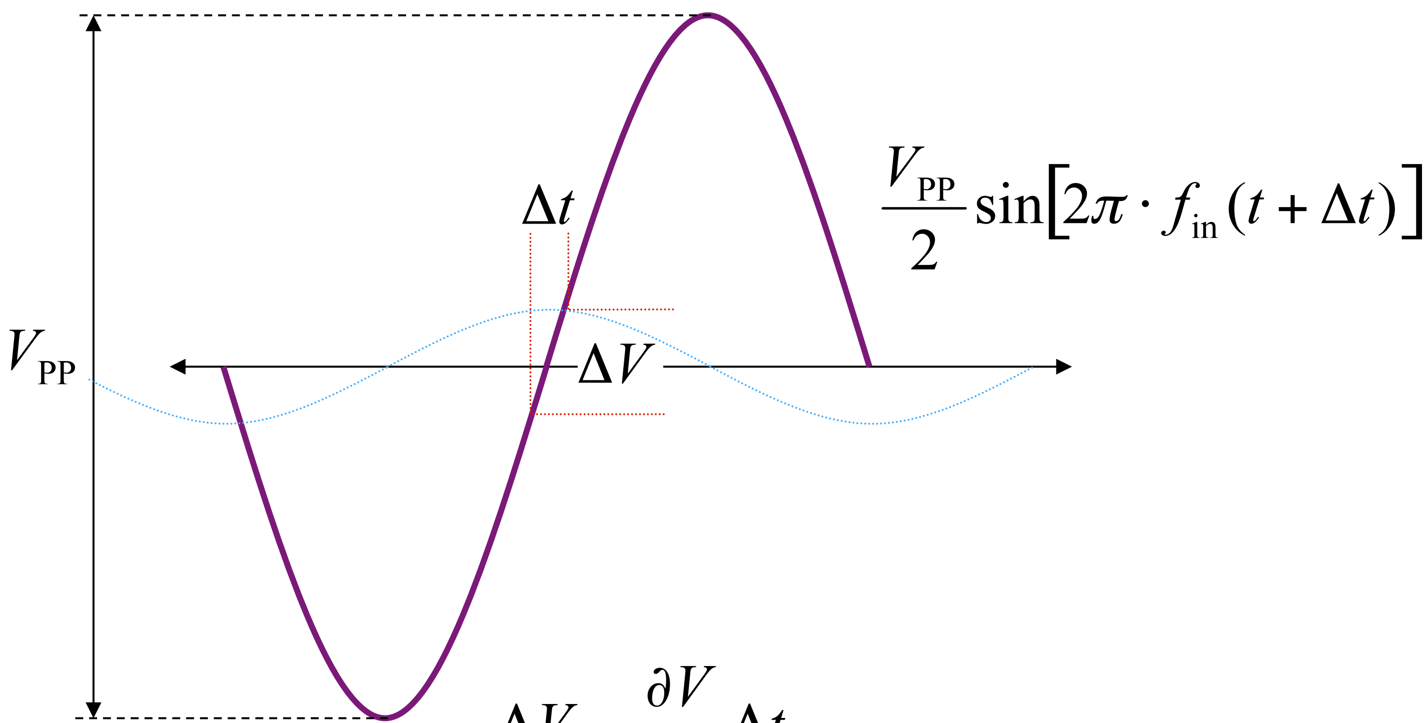


$$\frac{1}{SNR} = 2\pi f_{\text{in}} \Delta t_{rms}$$



$$\frac{SNR_{Multi-Tone}}{SNR_{Nyquist}} = \sqrt{3}$$

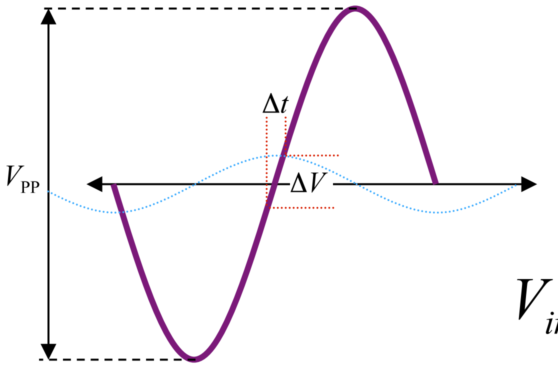
Jitter-Induced Error in Sine Wave



$$\Delta V = \frac{\partial V}{\partial t}\Delta t$$

$$\boxed{\Delta V(t) = \Delta t\left(\pi f_{in}\right)\cdot V_{PP}\cos[2\pi f_{in} t]}$$

Expression for SNR

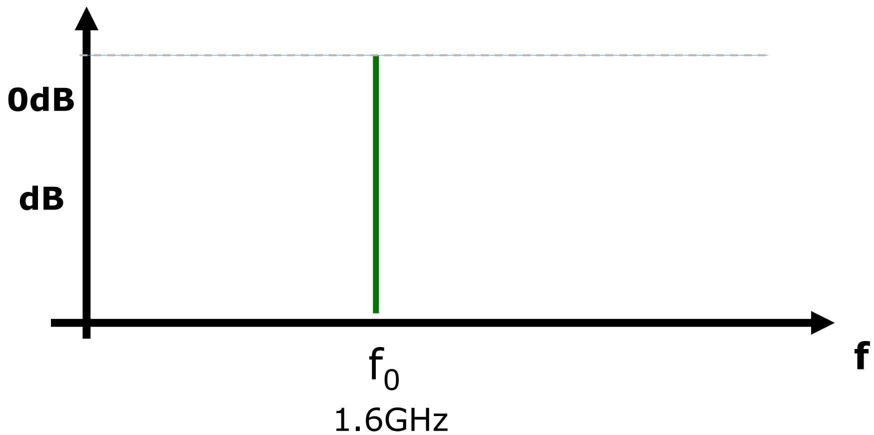


$$V_{inrms} = \sqrt{avg\left[\left(\frac{V_{PP}}{2}\sin\left[2\pi \cdot f_{in}(t+\Delta t)\right]\right)^2\right]} = \frac{V_{PP}}{2\sqrt{2}}$$

$$\Delta V_{rms} = \Delta t_{rms}(\pi f_{in}) \cdot V_{PP} \cdot \sqrt{avg\left(\cos^2[2\pi f_{in} t]\right)} = 2\pi f_{in} \Delta t_{rms} \frac{V_{PP}}{2\sqrt{2}}$$

$$\boxed{\frac{\Delta V_{rms}}{V_{inrms}} = \frac{1}{SNR} = 2\pi f_{in} \Delta t_{rms}}$$

Jitter Example: Fin=1.6GHz

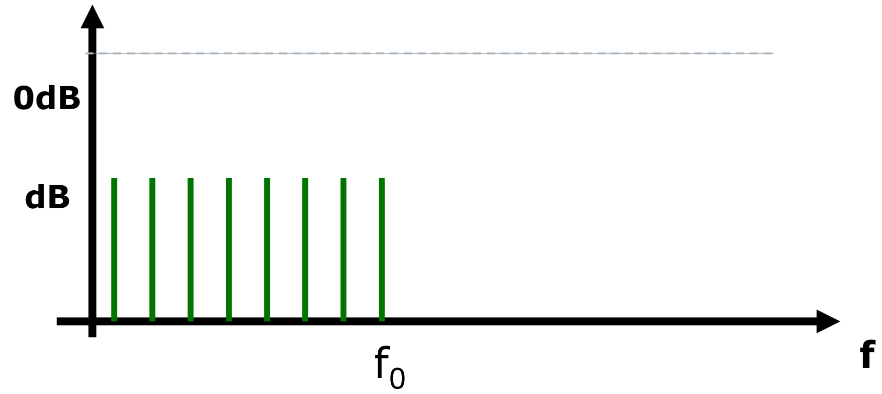


Input Signal $$\frac{V_{PP}}{2}\sin\left[2\pi\cdot 1.6GHz\cdot(t+\Delta t)\right]$$

$$SNR = \frac{1}{2\pi\cdot 1.6GHz\cdot 1000\,fs} = 99 = 39.9dB = 6.34bits$$

Where $$\Delta t_{rms} = 1000\,fs$$

Jitter Analysis for Multi-Tone



Input Signal

$$\frac{aV_{PP}}{2}\sin\left[2\pi\cdot f_1\cdot(t+\Delta t)\right]+\frac{aV_{PP}}{2}\sin\left[2\pi\cdot f_2\cdot(t+\Delta t)\right]+$$

$$\frac{aV_{PP}}{2}\sin\left[2\pi\cdot f_3\cdot(t+\Delta t)\right]+\frac{aV_{PP}}{2}\sin\left[2\pi\cdot f_4\cdot(t+\Delta t)\right]+\ \cdots$$

Error

$$\Delta V(t)=a\Delta t\pi V_{PP}[f_1\cos[2\pi f_1 t]+f_2\cos[2\pi f_2 t]+$$

$$f_3\cos[2\pi f_3 t]+f_4\cos[2\pi f_4 t]+\ \cdots$$

Jitter Analysis for Multi-Tone (2)

Error Squared

$$\Delta V^2(t) = \left[a\Delta t\pi V_{PP}\right]^2 \Big[f_1^{\,2}\cos^2[2\pi f_1 t] + f_2^{\,2}\cos^2[2\pi f_2 t] + f_3^{\,2}\cos^2[2\pi f_3 t] + f_4^{\,2}\cos^2[2\pi f_4 t] + \cdots \text{ Cross Terms } \cdots \Big]$$

Average Error Squared

$$avg\left(\Delta V^2(t)\right) = \left[a\Delta t\pi V_{PP}\right]^2 \left[\frac{f_1^{\,2}}{2} + \frac{f_2^{\,2}}{2} + \frac{f_3^{\,2}}{2} + \frac{f_4^{\,2}}{2} + \cdots \cancel{\text{Cross Terms}} \cdots \right]$$

RMS Error

$$\Delta V_{rms} = \left[\frac{a\pi V_{PP}}{\sqrt{2}}\right] \Delta t_{rms} \sqrt{f_1^{\,2} + f_2^{\,2} + f_3^{\,2} + f_4^{\,2} + \cdots}$$

Jitter Analysis for Multi-Tone (3)

RMS Signal $$V_{inrms} = \frac{aV_{PP}\sqrt{N_t}}{2\sqrt{2}}$$ Where N_t = # of tones

SNR $$\frac{\Delta V_{rms}}{V_{inrms}} = \frac{1}{SNR} = 2\pi \Delta t_{rms} \sqrt{\frac{f_1^{\ 2} + f_2^{\ 2} + f_3^{\ 2} + f_4^{\ 2} + \ \cdots}{N_t}}$$

$$f_n \equiv \frac{nf_{in}}{N_t}$$ for N_t tones equally spaced from DC to f_{in}

SNR $$\frac{\Delta V_{rms}}{V_{inrms}} = \frac{1}{SNR} = 2\pi f_{\text{in}} \Delta t_{rms} \sqrt{\frac{1}{N_t}\left(\frac{1^2}{N_t^{\ 2}} + \frac{2^2}{N_t^{\ 2}} + \frac{3^2}{N_t^{\ 2}} + \frac{4^2}{N_t^{\ 2}} + \ \cdots\right)}$$

Jitter Analysis for Multi-Tone (4)

SNR

$$\frac{V_{inrms}}{\Delta V_{rms}} = \frac{1}{SNR} = 2\pi f_{\text{in}} \Delta t_{rms} \sqrt{\frac{1}{N_t} \sum_{1}^{N_t} \frac{n^2}{N_t^{\ 2}}}$$

SNR

$$\frac{V_{inrms}}{\Delta V_{rms}} = \frac{1}{SNR} = 2\pi f_{\text{in}} \Delta t_{rms} \sqrt{\frac{1}{N_t} \frac{N_t (N_t + 1)(N_t + 1/2)}{3N_t^{\ 2}}}$$

SNR Ratio

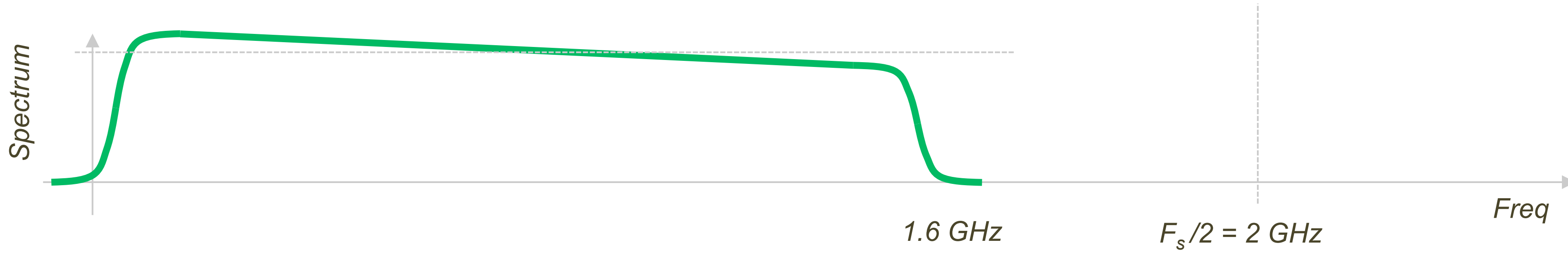
$$\frac{SNR_{Multi-Tone}}{SNR_{Nyquist}} = \sqrt{\frac{3}{\left(1 + \frac{1}{N_t}\right)\left(1 + \frac{1}{2N_t}\right)}} \approx \sqrt{3}$$

For N_t large

$$\boxed{\frac{SNR_{Multi-Tone}}{SNR_{Nyquist}} = \sqrt{3}}$$

4.8-dB improvement vs. single tone
0.8 effective bits increase

Time Skew Requirement for 39dB

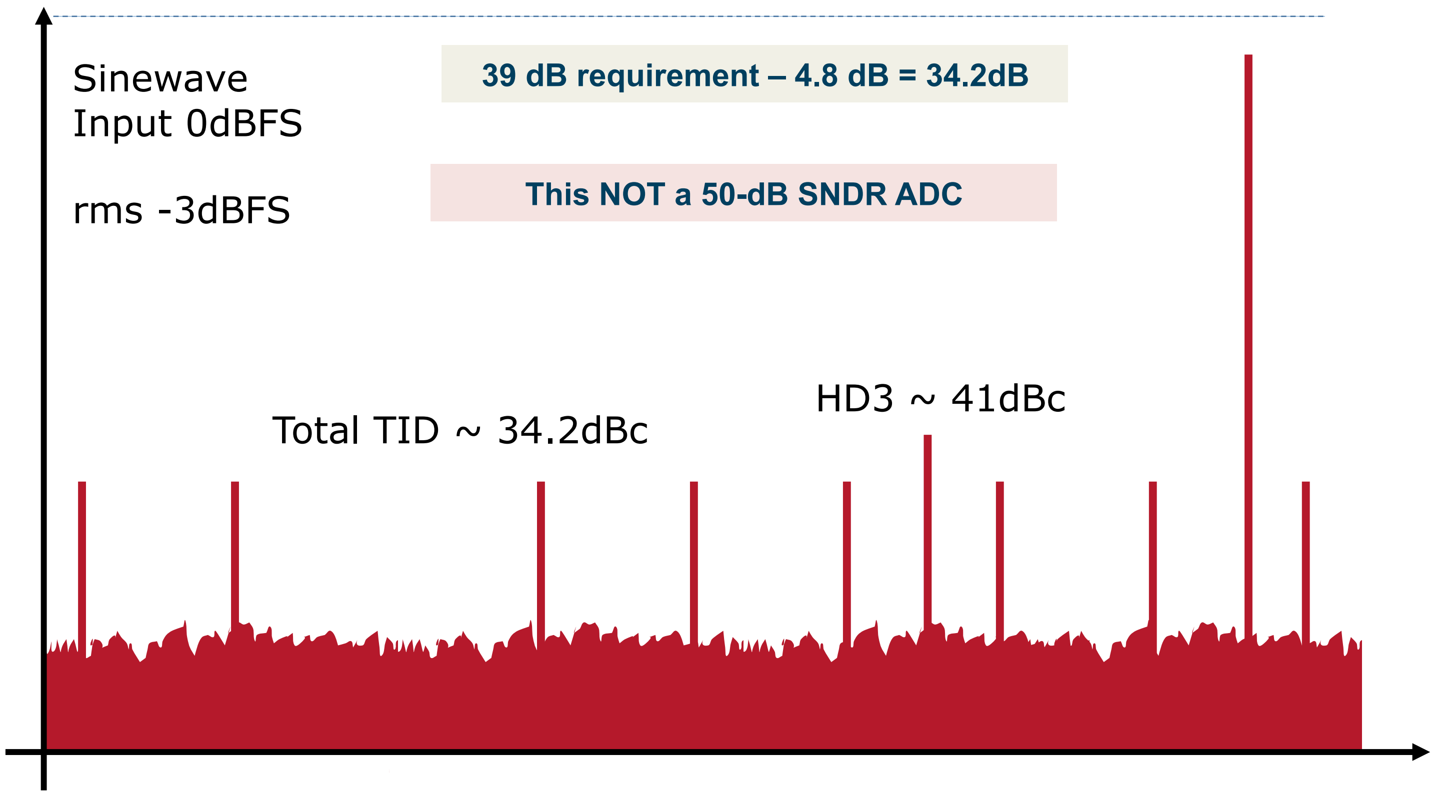


$$\Delta t_{rms-1tone} = \frac{1}{SNR \cdot 2\pi f_{\text{in}}} = \frac{1}{39dB \cdot 2\pi \cdot 1.6\text{GHz}} = 1.1\text{ps}$$

$$\boxed{\Delta t_{rms-broadband} = \sqrt{3}\left(\Delta t_{rms-1tone}\right) = 1.9\text{ps}}$$

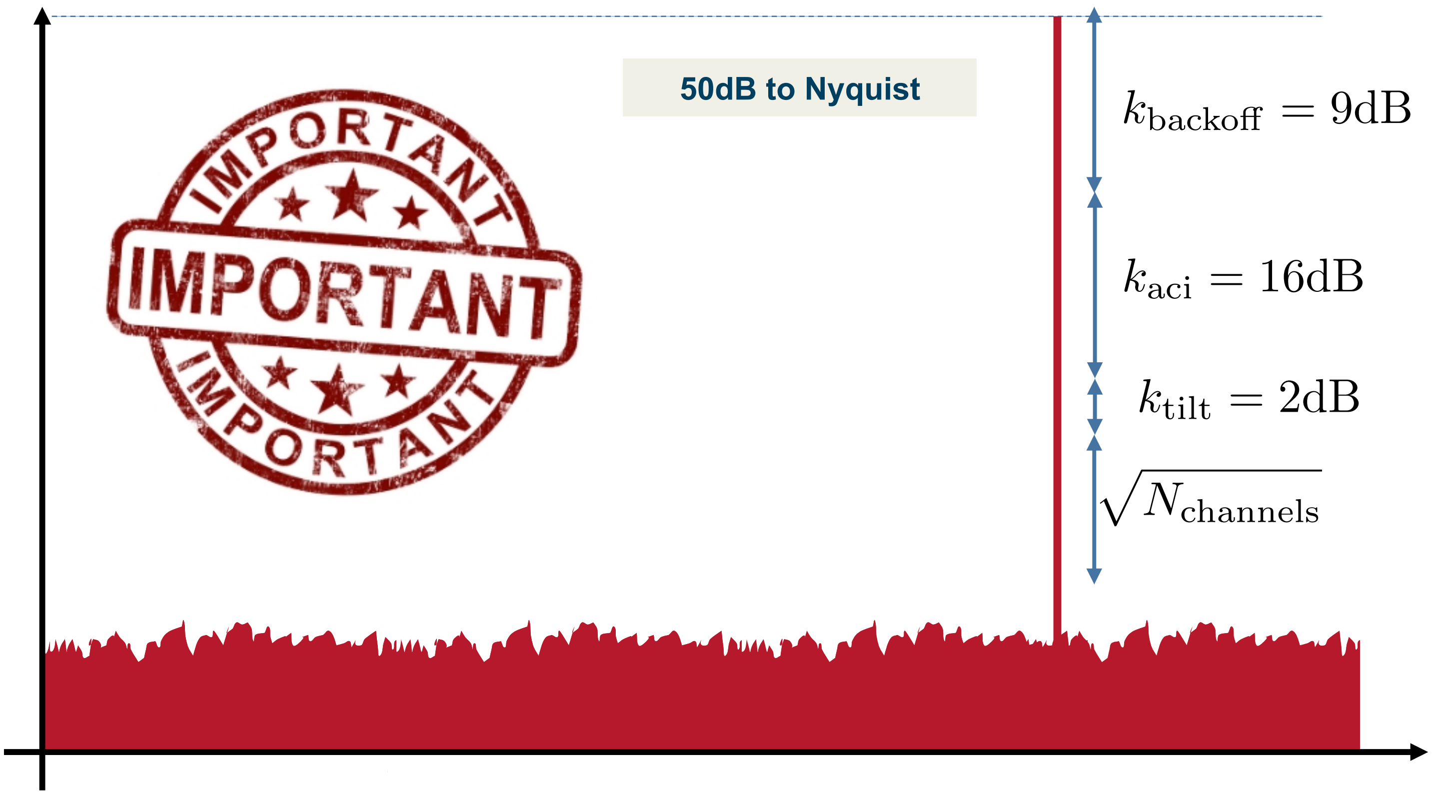
Time Skew Relaxed by Backoff

This is all the better the ADC needs to be

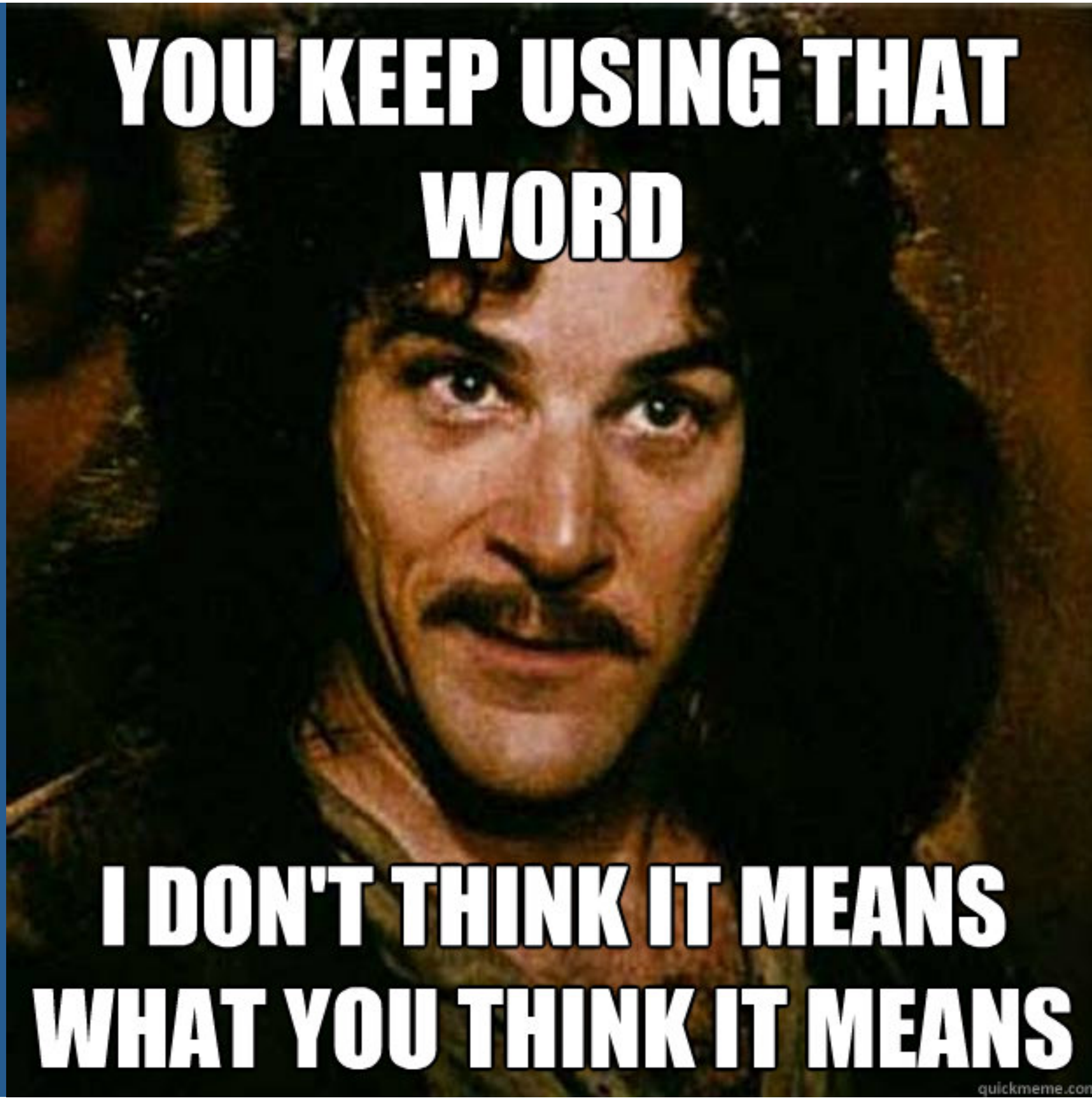


Don’t Do It, If You Don’t Need It

ENOB of 50dB is usually what is specified



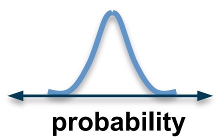
ENOB?


YOU KEEP USING THAT WORD
I DON'T THINK IT MEANS WHAT YOU THINK IT MEANS
quickmeme.com

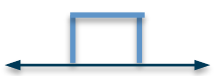
Additive vs. Multiplicative Errors

Errors

Noise
Random Gaussian
Physical Limitation

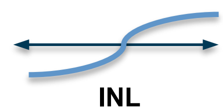


Quantization
Uniform distribution
Correlated with signal Looks Gaussian after filtering several samples



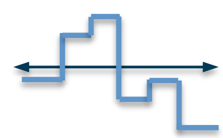
Distortion

Smooth
Quasi-linear reduces with amplitude



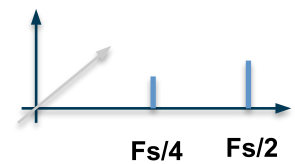
Radix errors
Discrete Jumps

Cap Mismatch
(DAC non-uniformity)
Discrete Jumps

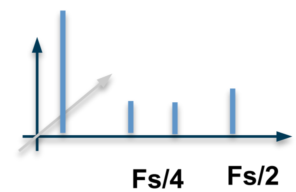


Time Interleaving

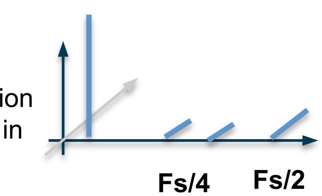
Offsets
Fixed pattern errors



Gain
Amplitude modulation
(nF_s/N ± sigal in-phase)

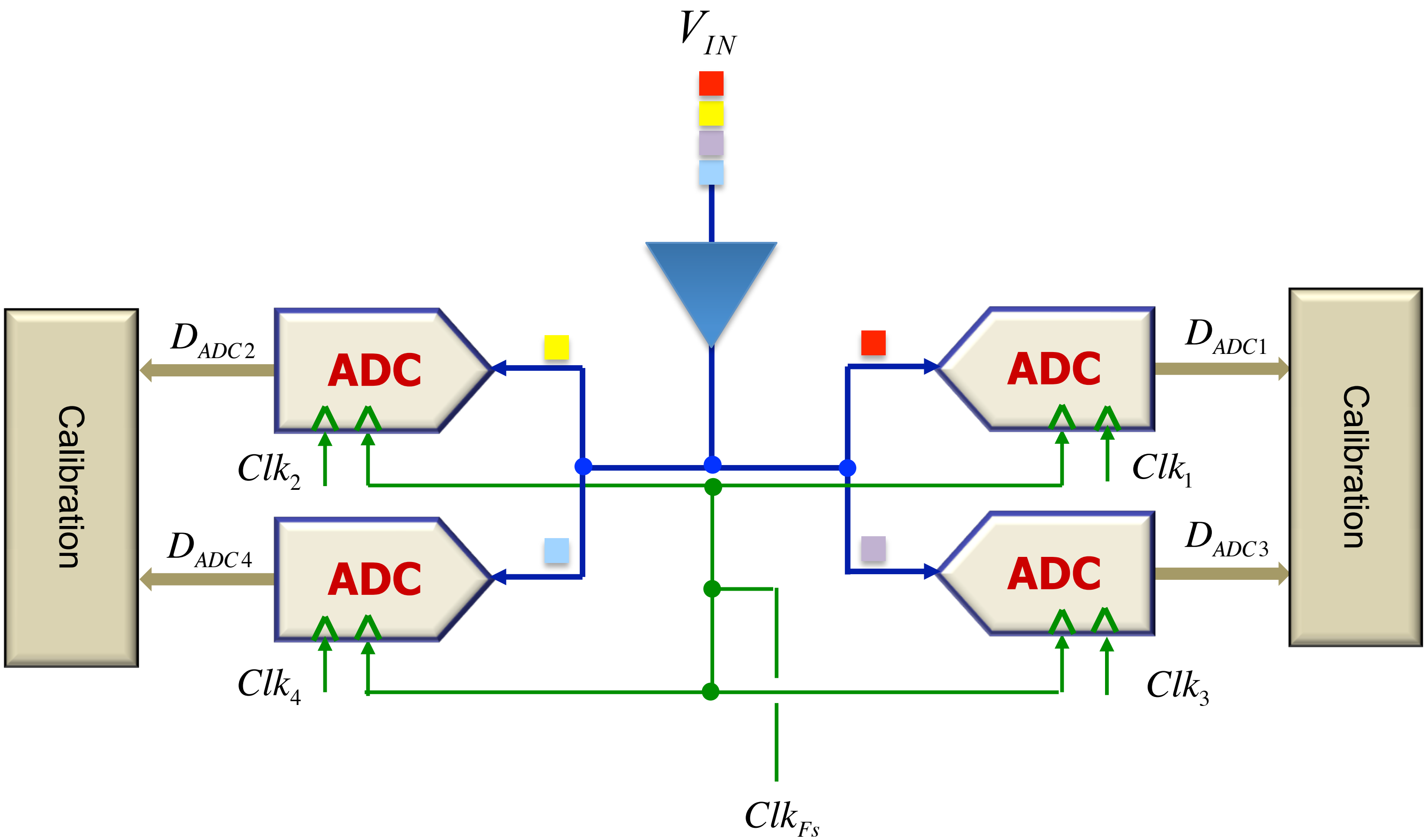


Time-Skew
Phase modulation
(nF_s/N ± signal in quadrature)



Recommended Architecture

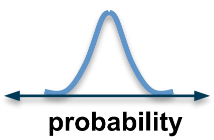
Time Interleaved ADCs



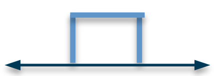
Design Guidelines

Errors

Noise
8-bits. Lowest power to meet goals

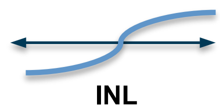


Quantization
9-10 bits. Quantization should should be well below the noise floor



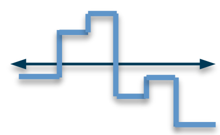
Distortion

Smooth
44dB HD3 gives 3-dB of margin. Make it “fast” so bandwidth effects are irrelevant



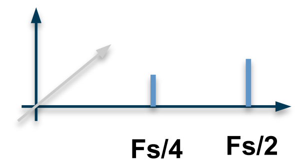
Radix errors
Calibrate for radix Errors in background or use large enough Loop gain in MDAC

Cap Mismatch
Calibrate at start or Factory calibration

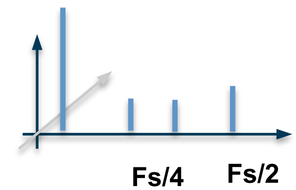


Time Interleaving

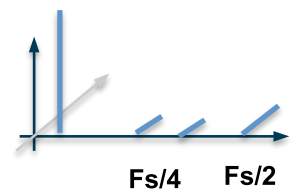
Offsets
Statistical, post Fix, 13-14bit resolution



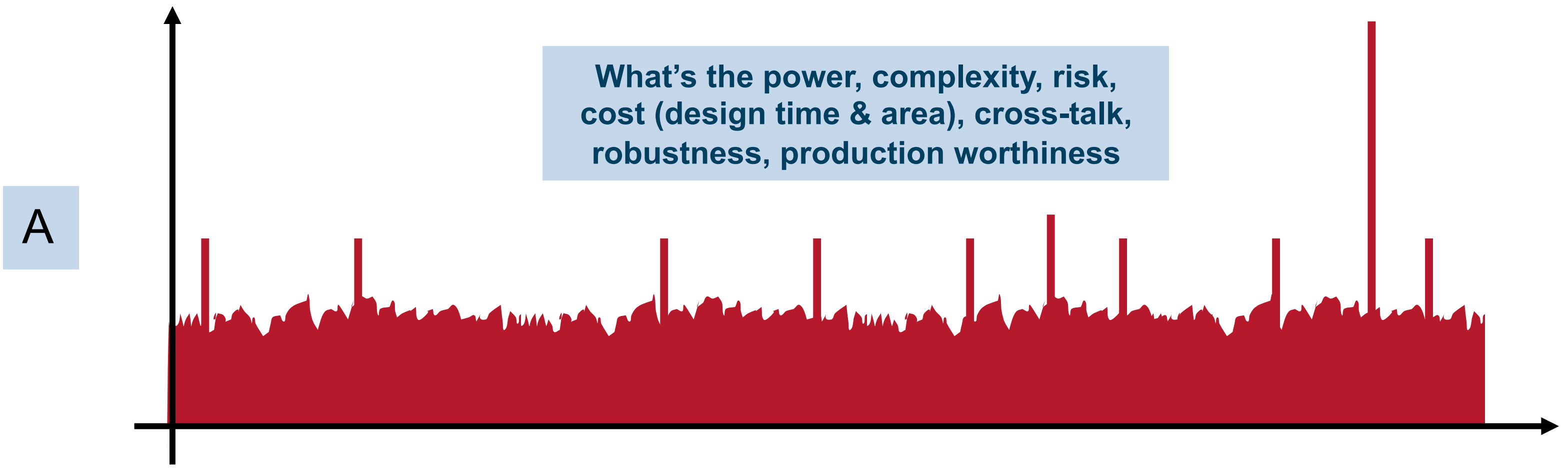
Gain
Statistical, post Fix with 50dB accuracy

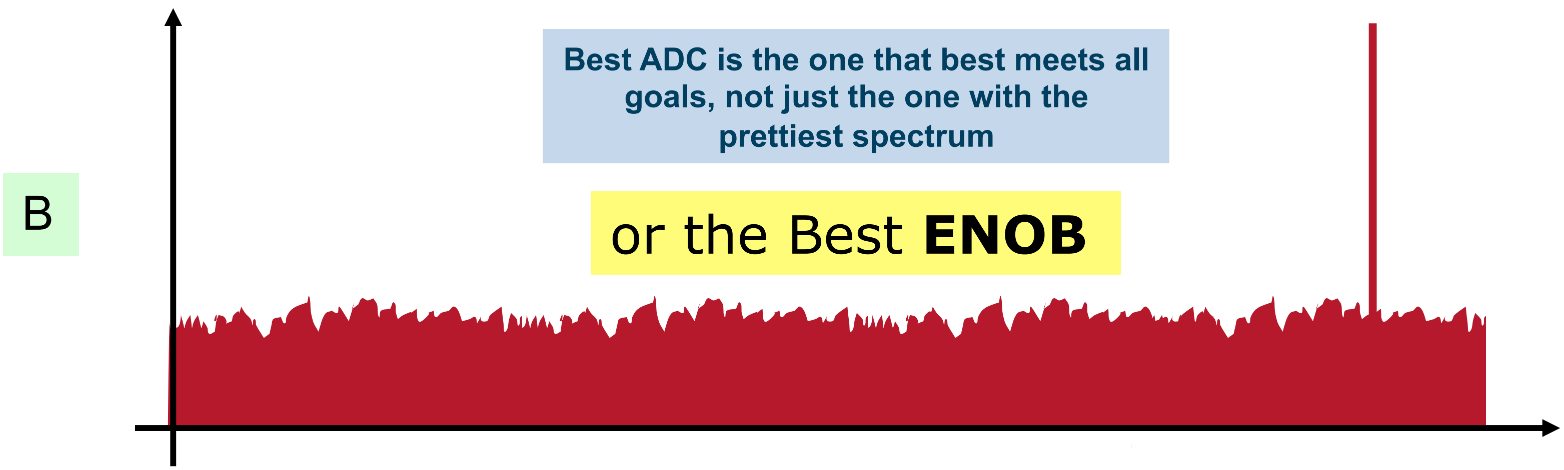


Time-Skew
Match by design with on-time cal at start or factory cal



Which ADC is "Better?"

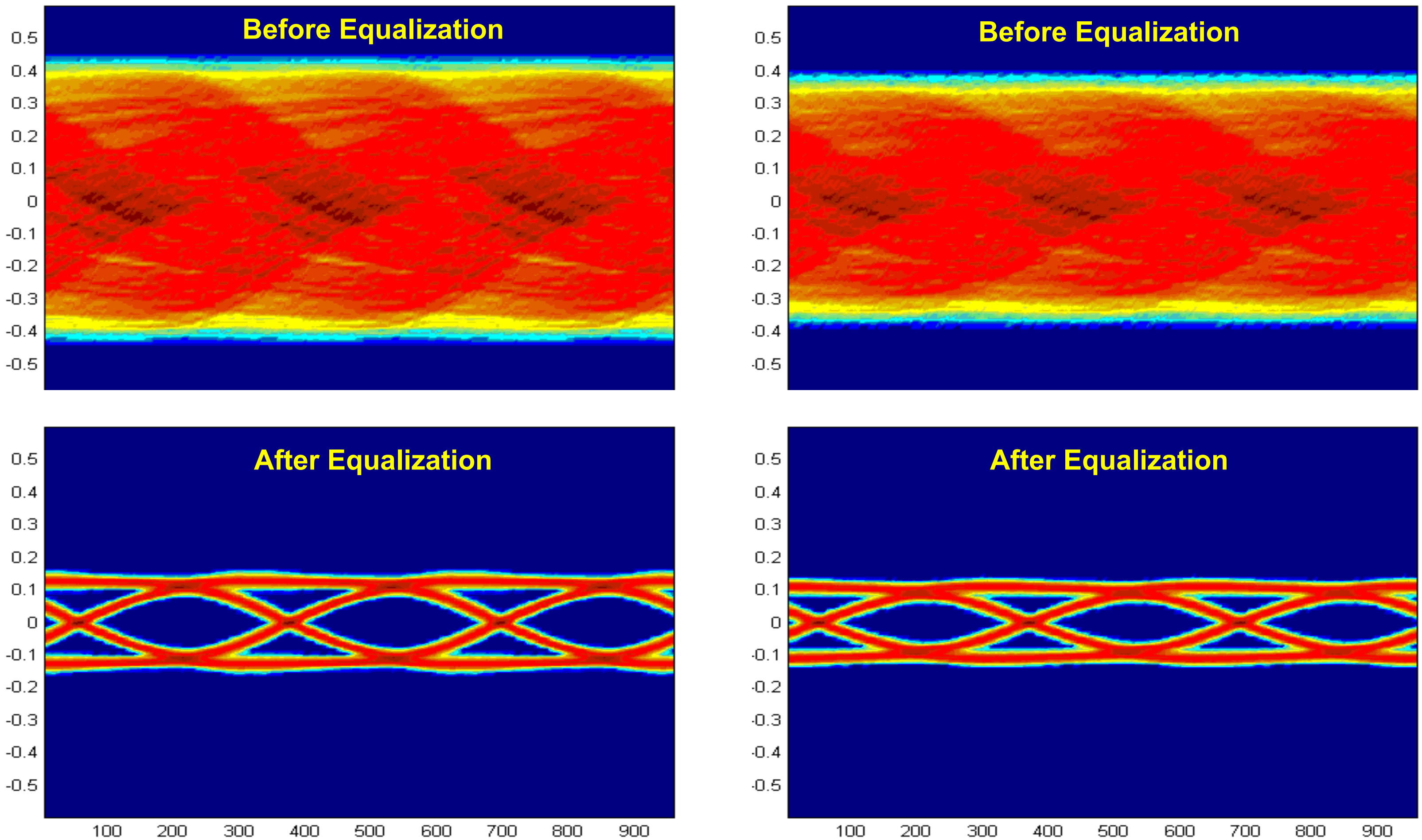




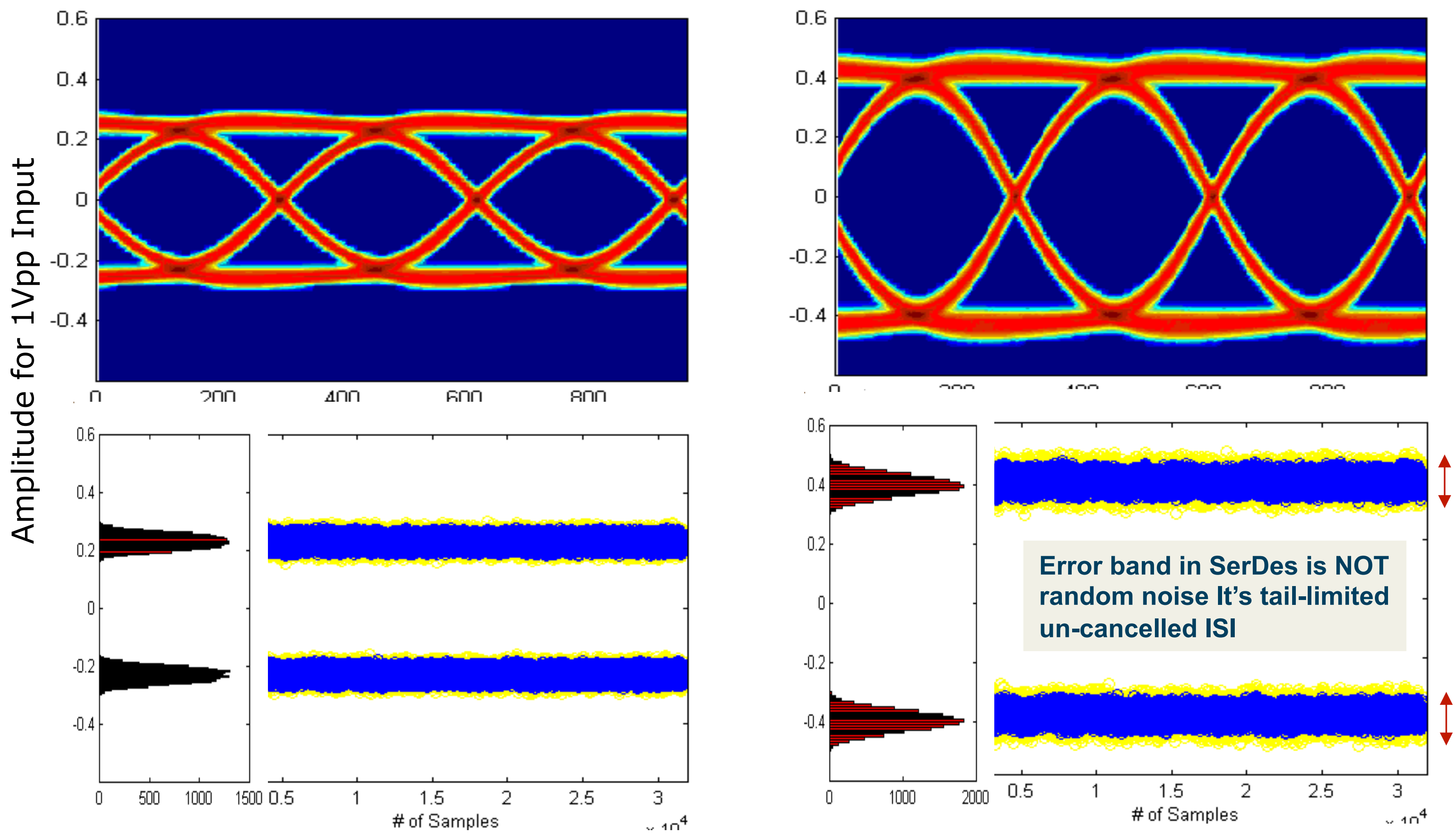

Say "ENOB" Again
I Dare You
© 1994 Miramax Films. All rights reserved

Baseband Signals

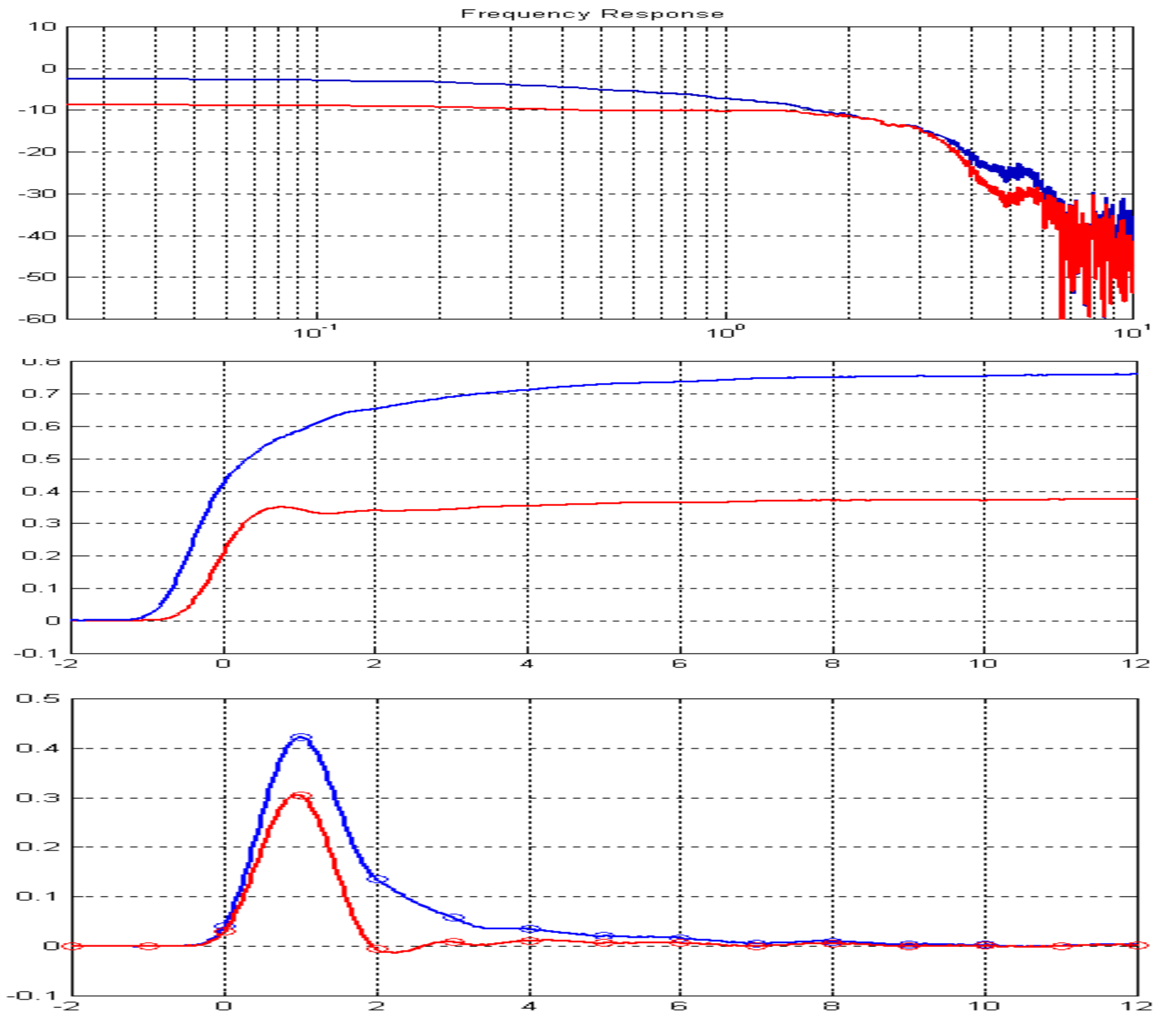
Two Baseband Channels with ISI



NRZ Signals at Slicer



Optical: Time-Domain System

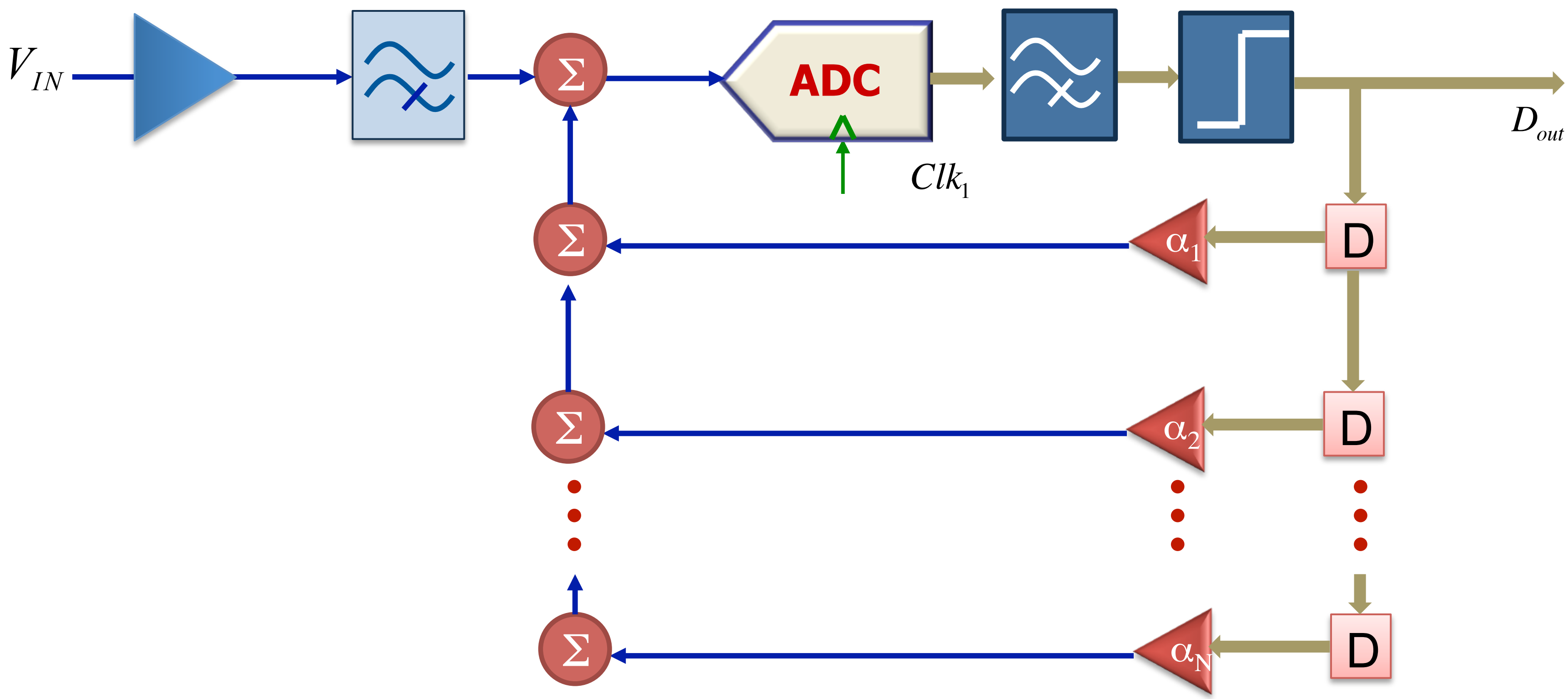


Can view Equalization in terms of "equalizing' each frequency component across the band of interest

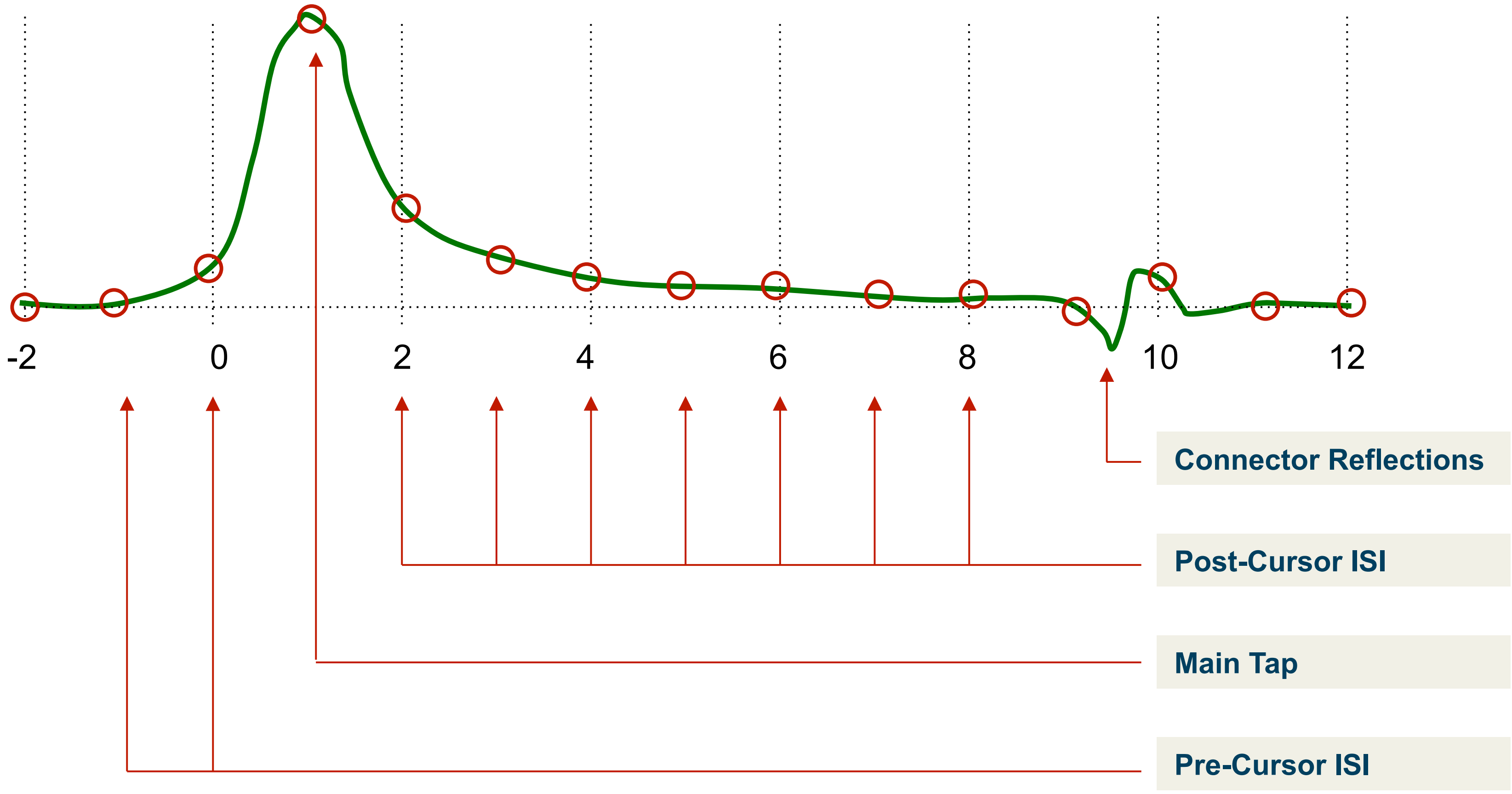
Can view Equalization as a flattening of the step response to remove the slow-settling tail

Best viewed as removing all ISI components of the pulse response

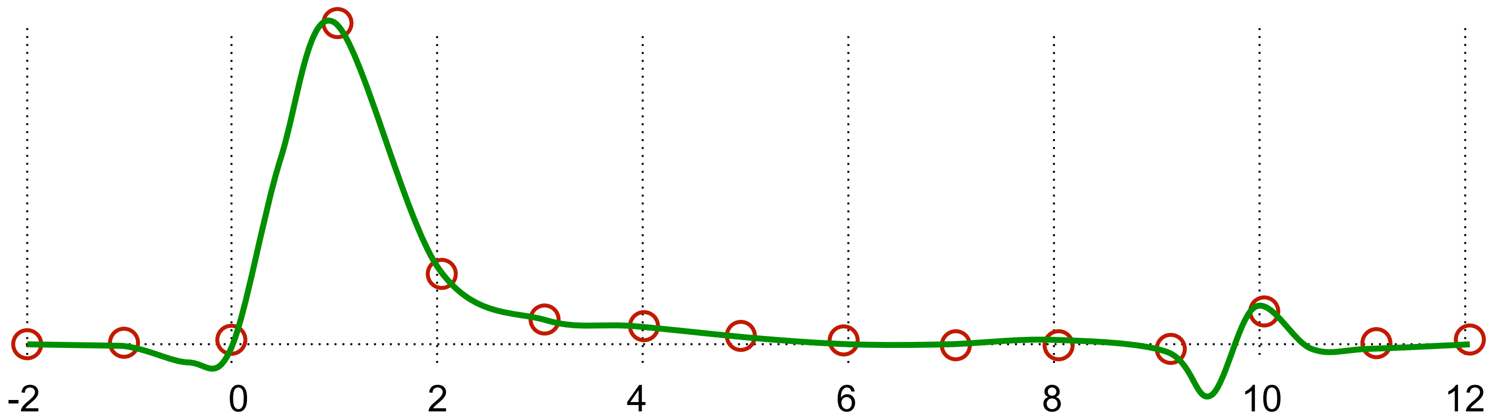
Time Interleaved ADCs

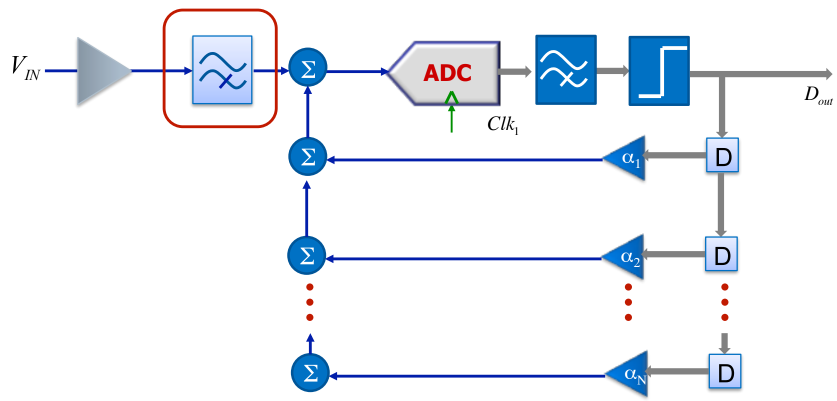


Pulse Response



Analog High-Pass: Pulse-Slimming





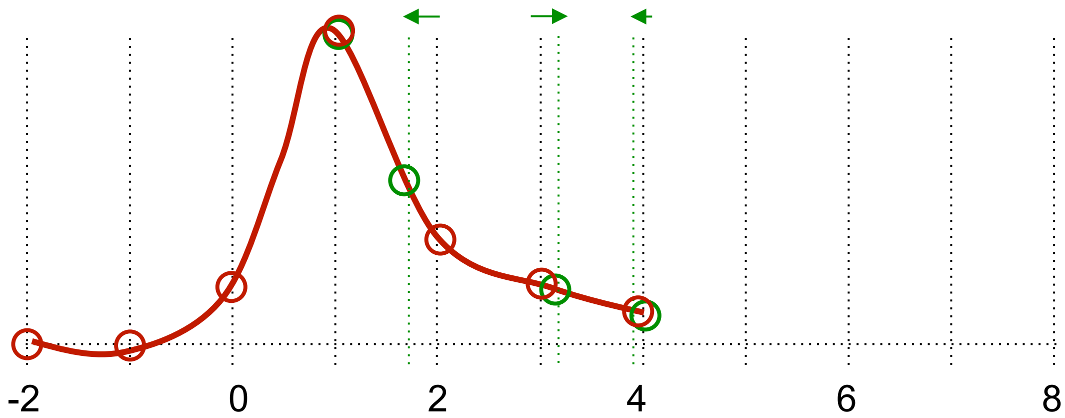
Remove Pre-Cursor ISI

Reduce Post-Cursor ISI

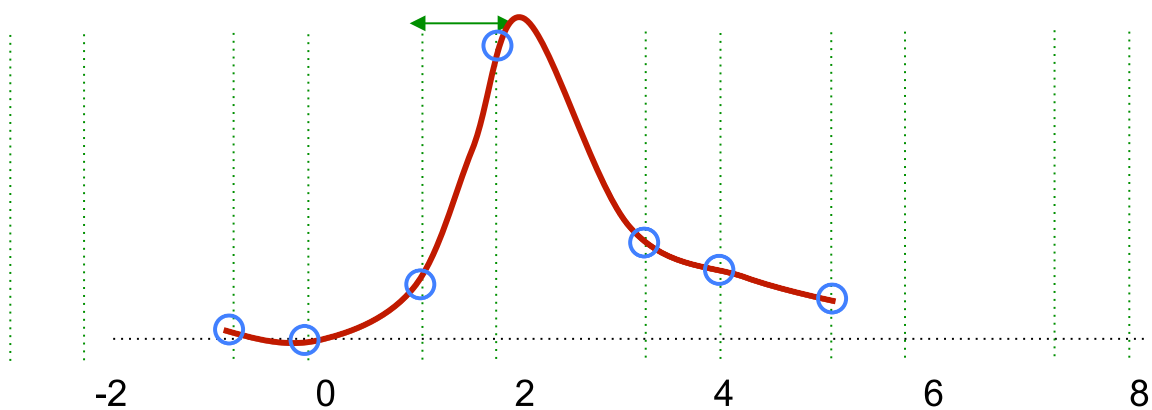
Reduce # of DFE Taps needed

Increases high-frequency noise

Time Skew Errors: 4x Interleave

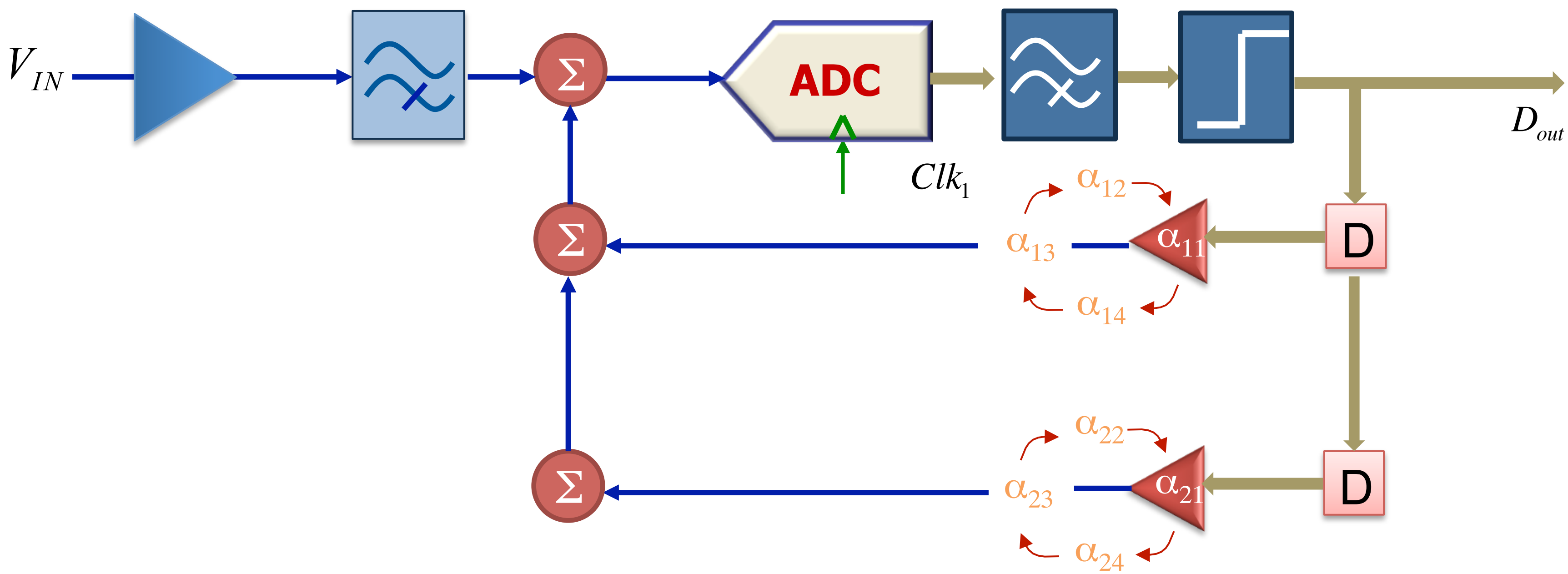


Time Skew Errors



Pulse shift 1-UI
Equalizer coefficients are different due to non-uniform sampling

Time Interleaved DFE



Don't bother correcting the ADC. Signal is KNOWN!
Use knowledge to adapt equalizer on a per-slice basis


So….
What IS the "Best" Architecture
for a Time-Interleaved ADC