وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

Analog Integrated Systems Design

Lecture 05
Data Converters Specifications (2)

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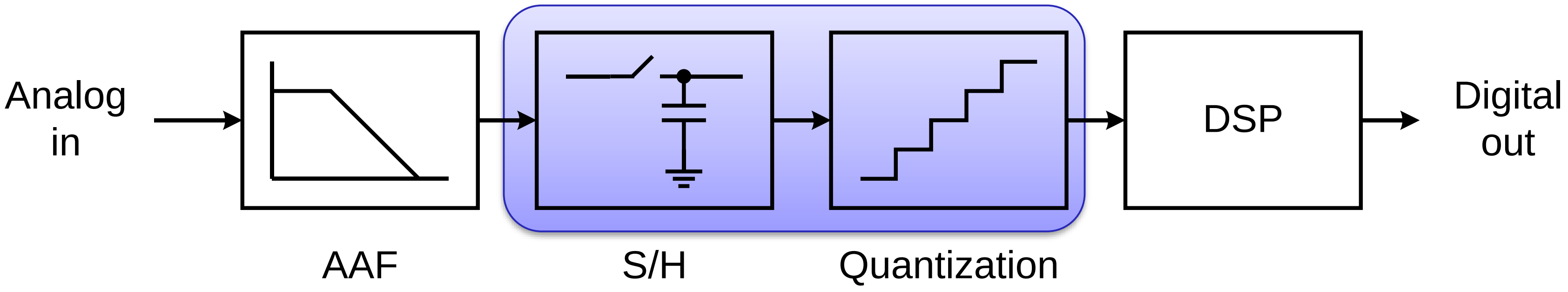
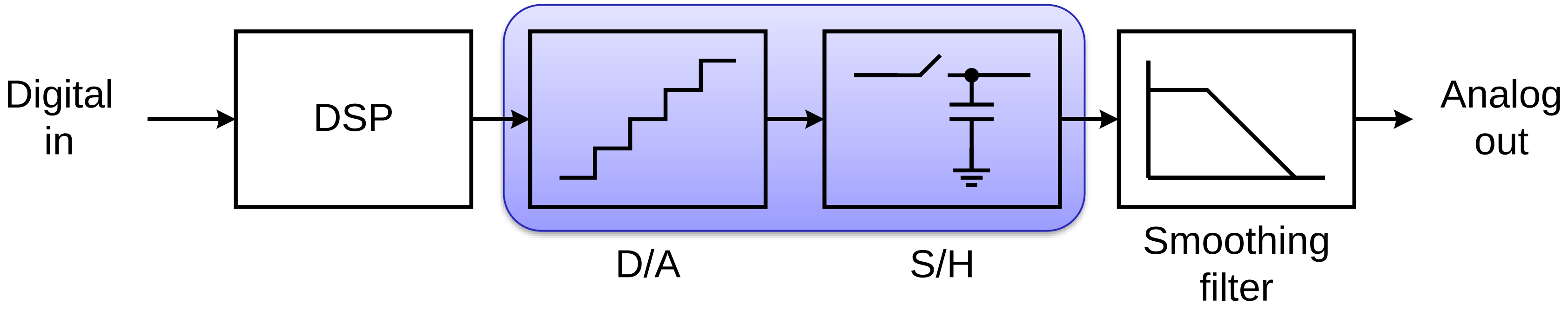
ADC and DAC

- ADC



- DAC



Static (DC) Specifications

- Offset Error
- Gain Error
- Monotonicity
- Linearity
  - Differential Non-Linearity (DNL)
  - Integral Non-Linearity (INL)

Dynamic (AC) Specifications

- Signal-to-quantization noise ratio
- Signal-to-noise ratio (SNR)
- Total harmonic distortion (THD)
- Signal-to-noise-and-distortion ratio (SINAD or SNDR or THD+N)
- Spurious free dynamic range (SFDR)
- Effective no. of bits (ENOB)

Signal-to-Quantization Noise Ratio

$$SQNR = 10\log\left(\frac{Signal\ Power}{Quantization\ Power}\right) = 20\log\left(\frac{V_{sigrms}}{V_{Qnrms}}\right)$$

$$Signal\ Power = \frac{\left(\frac{2^N V_{LSB}}{2}\right)^2}{2} = \frac{2^{2N} V_{LSB}^2}{8}$$

$$Quantization\ Power = \frac{V_{LSB}^2}{12}$$

$$SQNR = 10\log\left(\frac{Signal\ Power}{Quantization\ Power}\right) = 10\log\left(\frac{3}{2}2^{2N}\right)$$

$$\boldsymbol{SQNR = 6.02 \times N + 1.76\ \ [dB]}$$

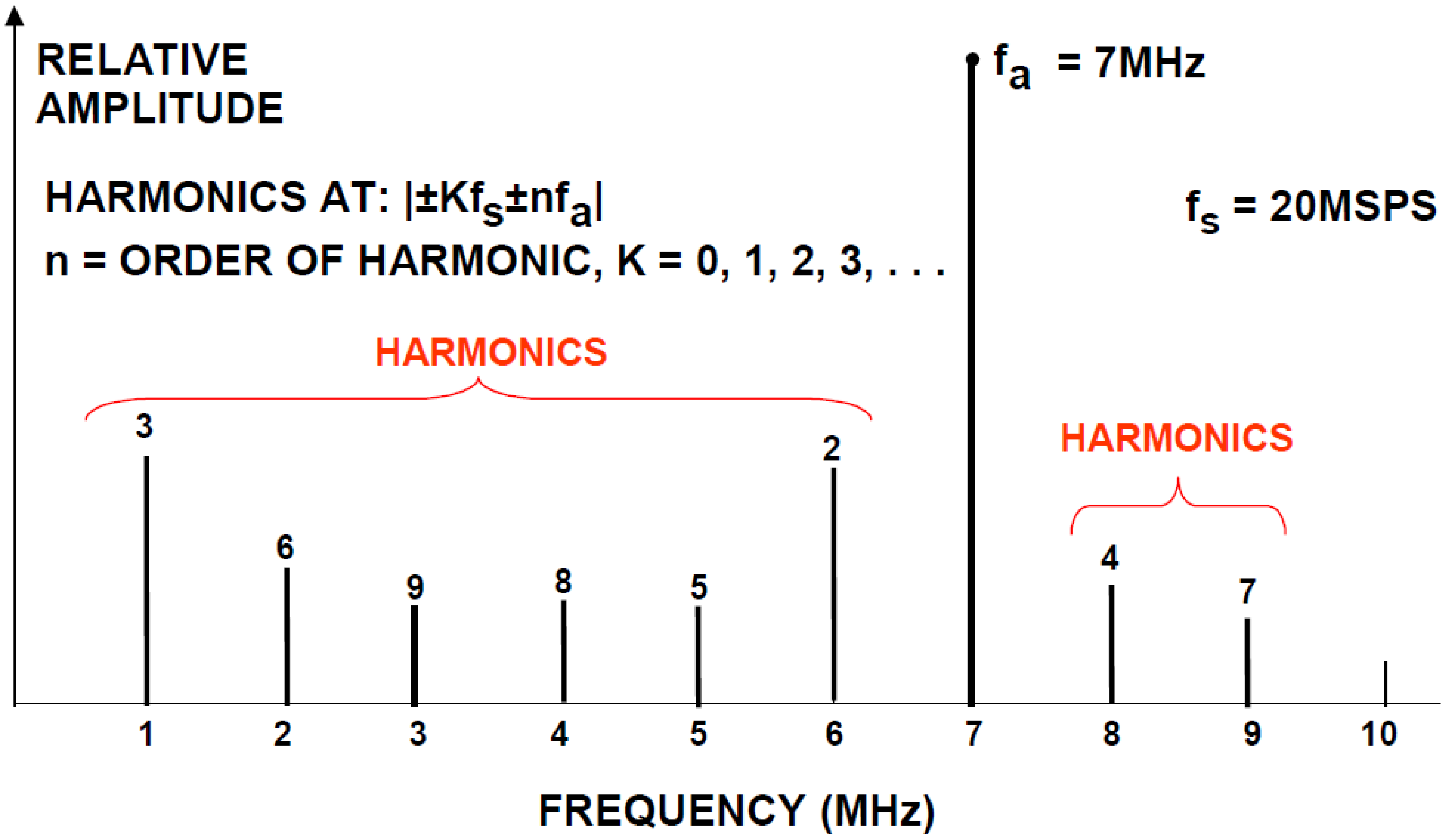
Oversampling/Processing Gain

- Quantization power is uniformly spread from 0 to $f_s/2$.
- If only part of the spectrum is useful, some quantization power can be filtered out (digital filtering).
- Select a bandwidth (BW) out of the available spectrum (0 to $f_s/2$):

$$SQNR = 10\log\left(\frac{Signal\ Power}{Quantization\ Power \times \frac{BW}{f_s/2}}\right)$$

$$SQNR = 6.02 \times N + 1.76 + \boldsymbol{10\log\left(\frac{f_s/2}{BW}\right)}$$

Harmonic Distortion



[W. Kester, 2005]

SNR, SINAD (SNDR), and ENOB

- **SNR (Signal-to-Noise Ratio, or Signal-to-Noise Ratio Without Harmonics:**
  - **The ratio of the rms signal amplitude to the mean value of the root-sum-squares (RSS) of all other spectral components, excluding the first 5 harmonics and DC**

- **SINAD (Signal-to-Noise-and-Distortion Ratio):**
  - **The ratio of the rms signal amplitude to the mean value of the root-sum-squares (RSS) of all other spectral components, including harmonics, but excluding DC.**

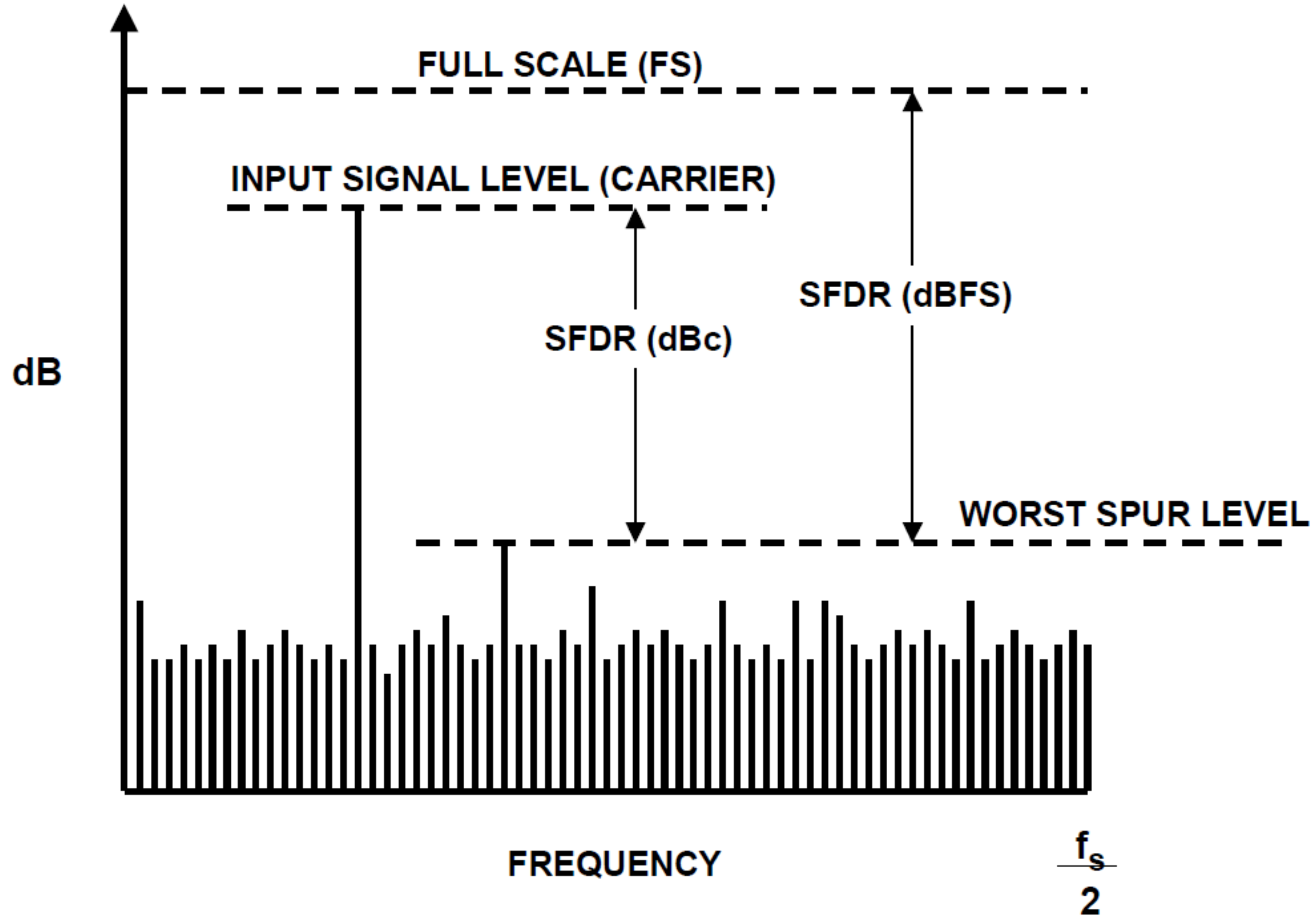
- **ENOB (Effective Number of Bits):**

$$\text{ENOB} = \frac{\text{SINAD} - 1.76\text{dB}}{6.02}$$

[W. Kester, 2005]

Spurious Free Dynamic Range (SFDR)

- SFDR is the ratio of the rms signal amplitude to the rms value of the peak spurious spectral component over the bandwidth of interest



[W. Kester, 2005]

Summary of Signal Quality Definitions

- Signal-to-noise ratio

$$SNR = 10\log\left(\frac{Signal\ Power}{Random\ Noise\ Power}\right)$$

- Total harmonic distortion

$$THD = 10\log\left(\frac{P_{distortion}}{P_{signal}}\right) = 20\log\left(\frac{V_{distortion}}{V_{signal}}\right)$$

- Signal-to-noise-and-distortion ratio (SNDR or SINAD or THD+N)

$$SNDR = SINAD = 10\log\left(\frac{Signal\ Power}{Power\ of\ all\ unwanted\ signals}\right)$$

- Spurious free dynamic range (SFDR) (spurious signal = unwanted)

$$SFDR(dBc) = 10\log\left(\frac{Signal\ Power}{Power\ of\ highest\ spurious\ signal}\right)$$

Effective Number of Bits (ENOB)

$$SQNR = 1.76 + 6.02 \times N$$

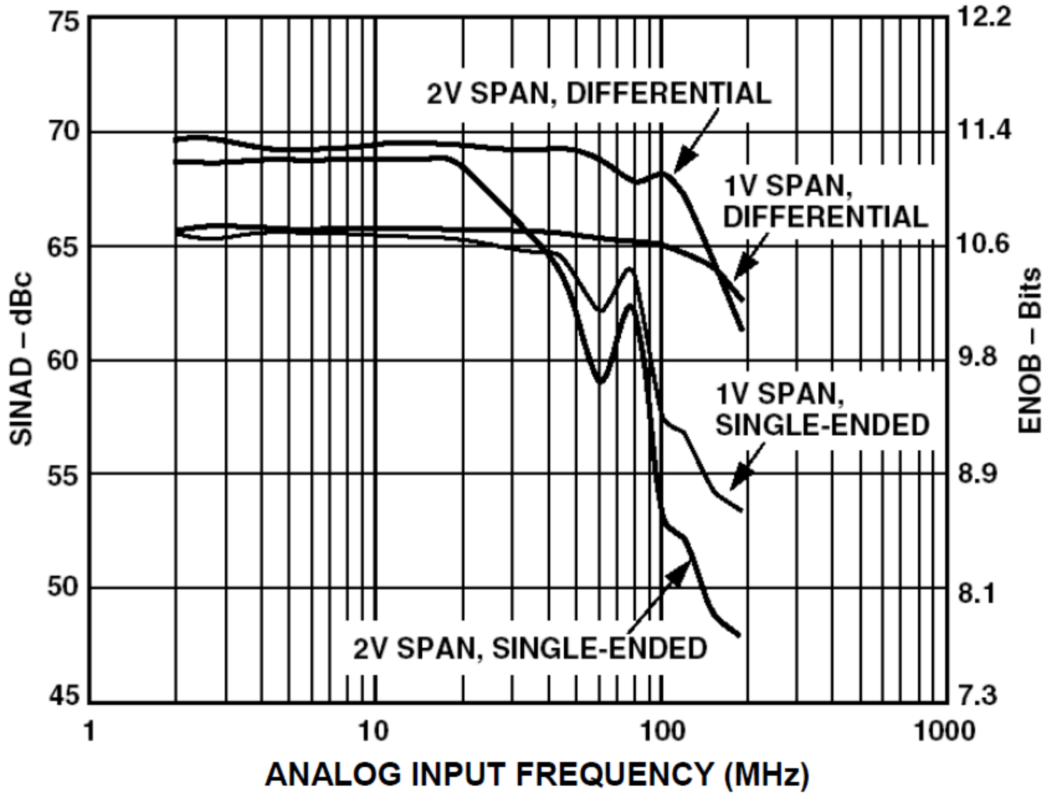
$$SNDR = SINAD = 10\log\left(\frac{Signal\ Power}{Power\ of\ all\ unwanted\ signals}\right)$$

$$ENOB = \frac{SNDR - 1.76}{6.02}$$

- A good 8-bit ADC will have ENOB around 7.5-bit (0.5-bit loss).
- A good 12-bit ADC will have ENOB around 11-bit (1-bit loss).
- For high frequency, undersampling ADCs, and high-resolution ADCs, the ENOB loss can be much higher (may be > 4-bit)

SINAD/ENOB Example

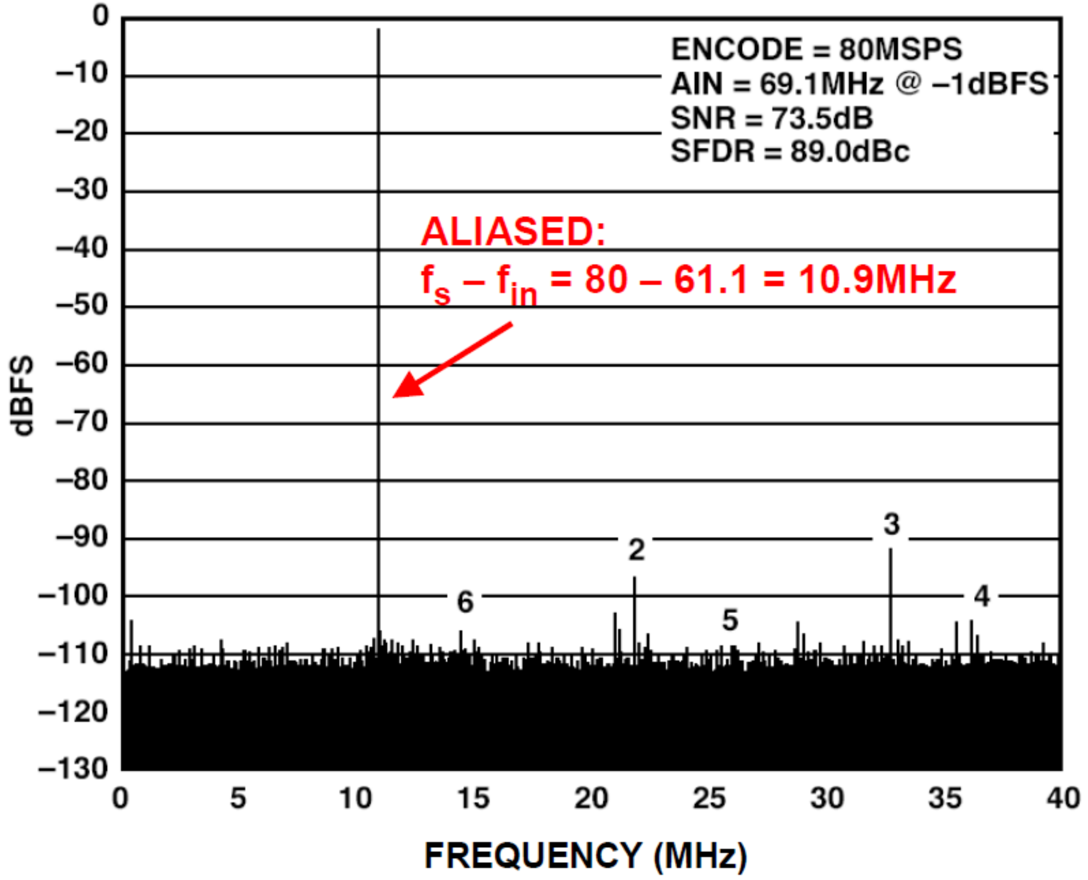
- AD9226 12-bit, 65-MSPS ADC SINAD and ENOB
  - SINAD/ENOB degrades as frequency increases
  - 2V better than 1V (ideally by 6 dB, but limited by distortion)
  - Differential better than SE at high frequency



[W. Kester, 2005]

SFDR Example

- AD6645 14-bit, 80 MSPS ADC SFDR for 69.1 MHz Input
  - SFDR can be improved by injecting a small out-of-band dither signal—at the expense of a slight degradation in SNR.



[W. Kester, 2005]

ADCs Figures-of-Merit

- Different ADCs have different resolution, speed, power consumption, etc.
- How to compare them together?
  - Use a “normalized” figure-of-merit (FoM) to compare the most important specs “combined together”
    1. Resolution: ENOB or SNR
    2. Speed: BW or f_s
    3. Power consumption

Speed vs Power

- Assume we want to double the speed of a thermal noise limited circuit.
  - This means GBW must be doubled.
  - If the capacitance (noise) is constant, this means G_m must be doubled.
    - Current is doubled as well.
    - Power consumption is doubled.

- Conclusion: Power consumption is proportional to speed (bandwidth or f_s)
  - The ratio $\frac{f_s}{Power}$ tends to be constant.
  - This can be a good FoM (for a constant SNR).

ENOB vs Power

- Assume we want to increase the ENOB of a thermal noise limited design by 1-bit.
  - $2^{ENOB} = \frac{V_{REF}}{LSB} = \frac{V_{REF}}{\sqrt{kT/\text{C}}} \rightarrow 2^{ENOB+1} = 2 \times \frac{V_{REF}}{\sqrt{kT/\text{C}}} = \frac{V_{REF}}{\sqrt{kT/4\text{C}}}$
  - The capacitance is quadrupled.
  - To maintain same speed (GBW), G_m must be quadrupled.
    - Current is quadrupled as well.
    - Power consumption is quadrupled.

- Conclusion: Adding one more bit means quadrupling the power.
  - The ratio $\frac{Power}{2^{ENOB}}$ does not seem to be a good FoM.
  - But it is the most widely used ADCs FoM in the literature!

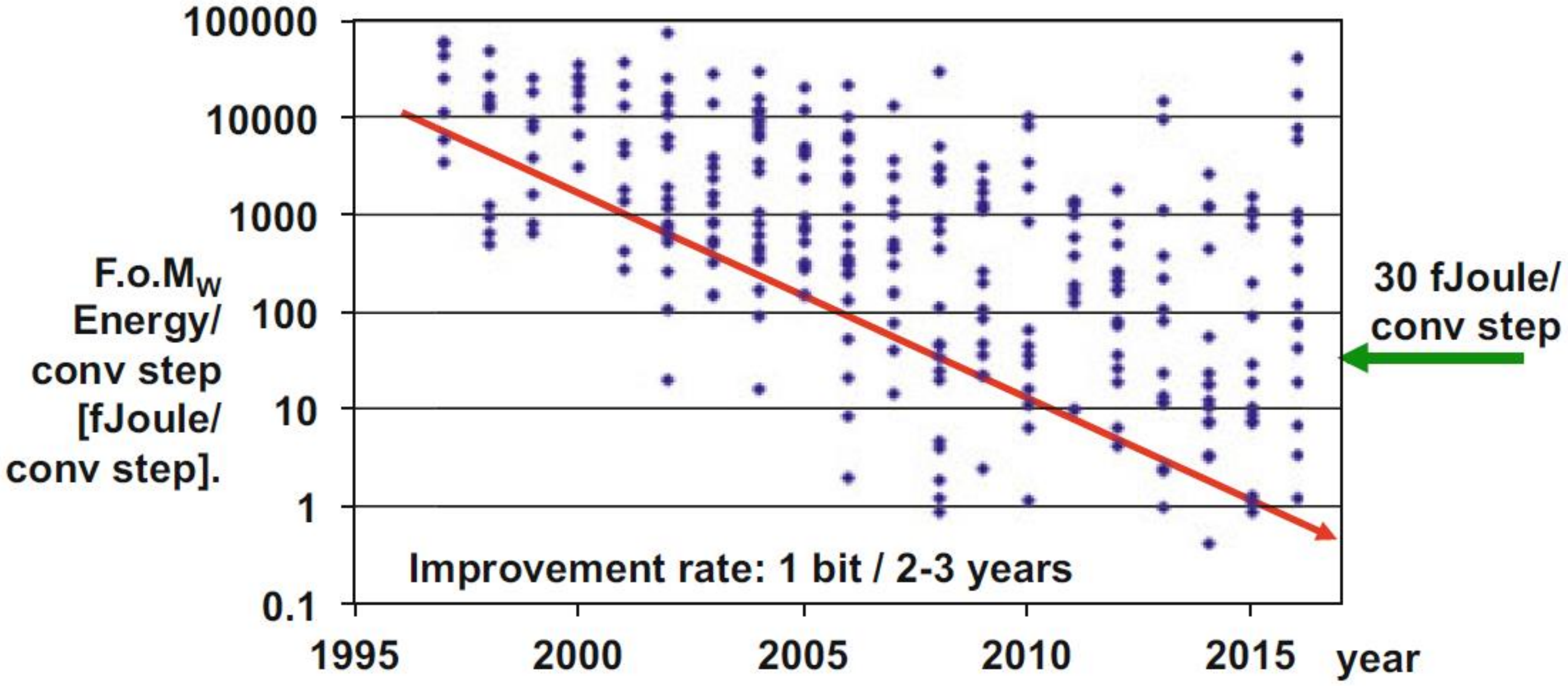
Walden Figure-of-Merit ($\boldsymbol{FoM_W}$)

$$FoM_W = \frac{P_{ADC}}{2^{ENOB} \times f_s}$$

- Empirical formula, but fits well with practical ADCs.
  - Not all ADCs are thermal noise limited.
- Better used to compare ADCs of same resolution.
- Unit of FoM_W is fJ/conversion-step
  - State-of-the-art in the industry is around 100 fJ/step
  - State-of-the-art in the academia is less than 1 fJ/step
  - Note that for FoM_W, the lower the better.

Walden Figure-of-Merit (FoM_W)

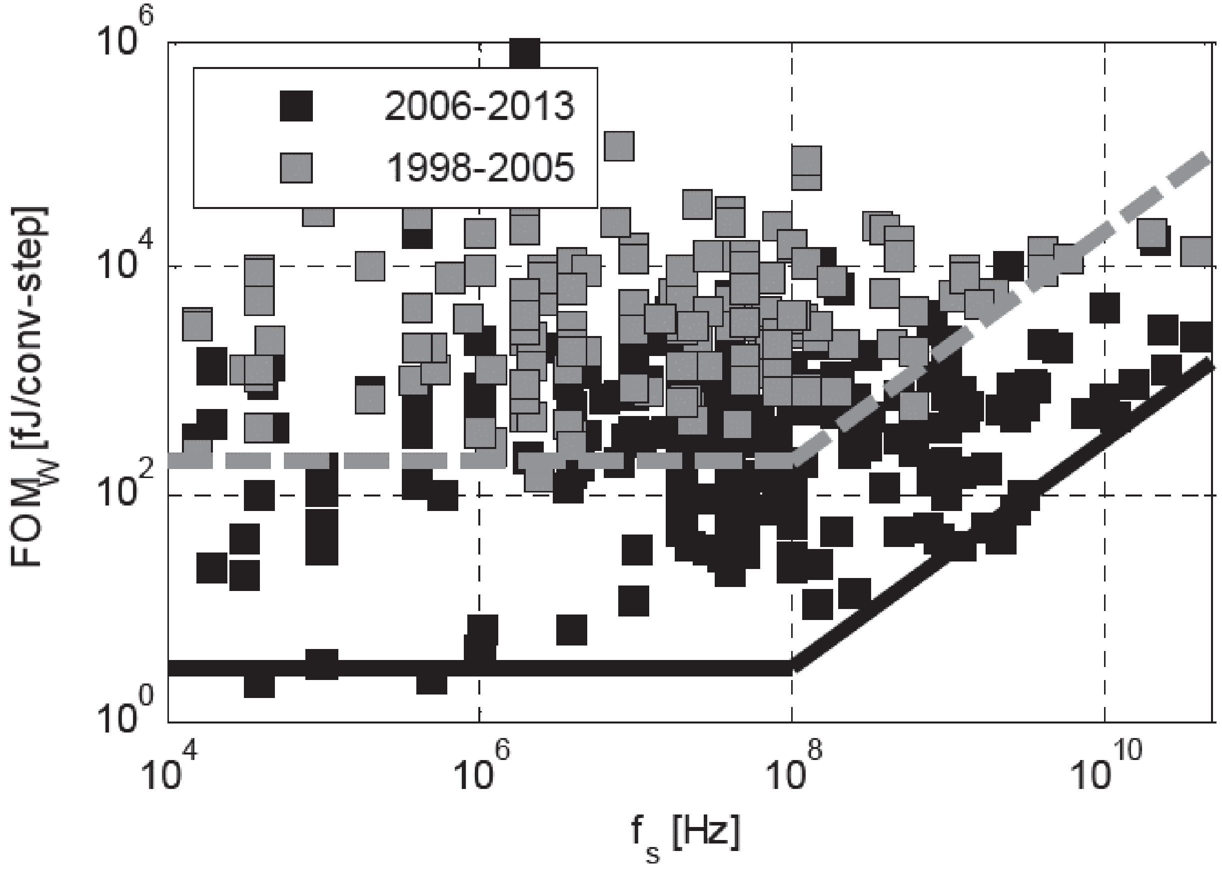
- ISSCC papers from 1997 to 2016.
  - State-of-the-art ADCs have FoM better than 1fJ/Step!



[M. Pelgrom, 2017]

Walden Figure-of-Merit (FoM_W)

- ISSCC and VLSI Symp. papers from 1998 to 2013.
  - Clear trend towards better energy efficiency
  - State-of-the-art ADCs have FoM better than 1fJ/Step

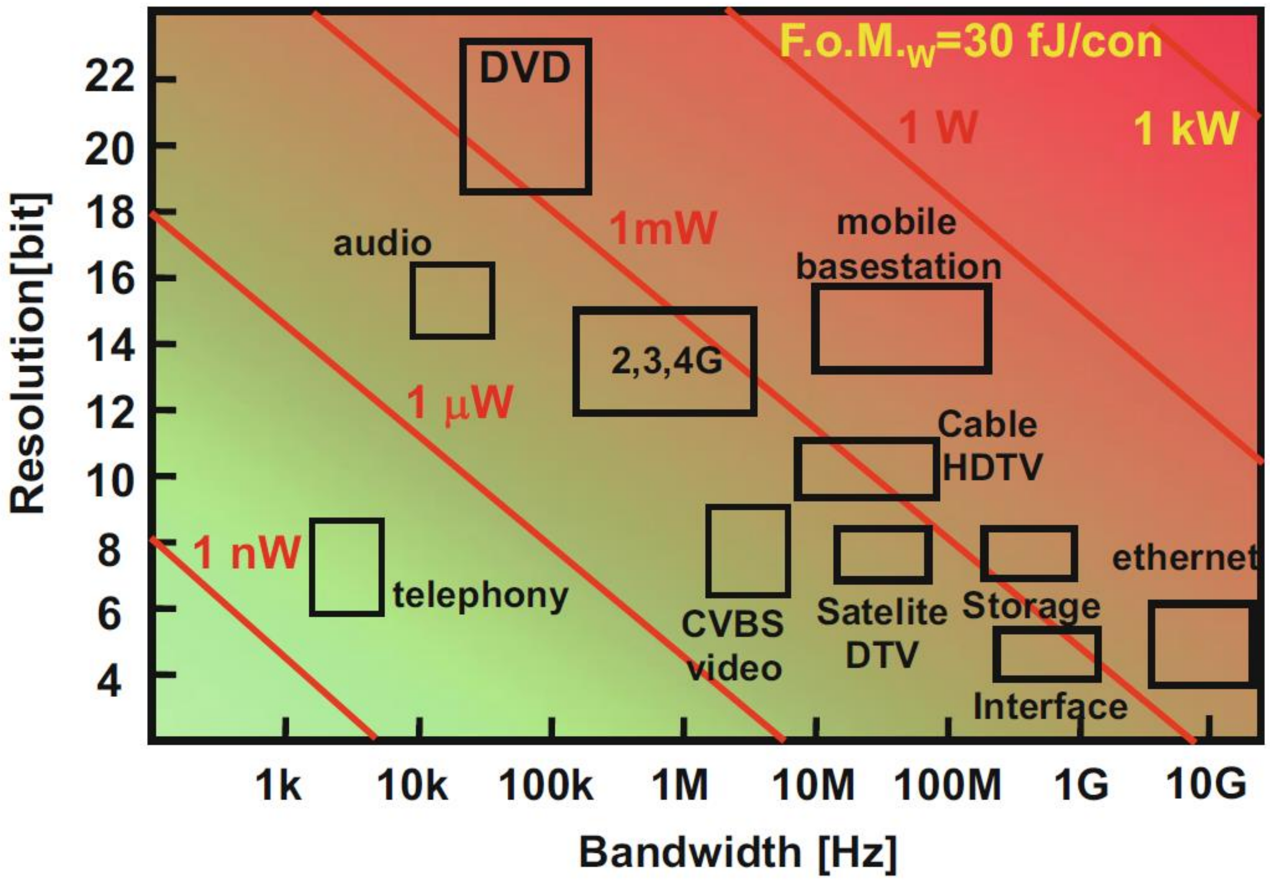


[Murmann, 2013]

Power Consumption Estimation

- FoM_W can be used to get a quick estimate of power consumption
  - Ex: Assume the ADC has $FoM_W = \frac{P_{ADC}}{2^{ENOB} \times f_s} \sim 30fJ/Step$.

$$P_{ADC} \sim 30fJ/Step \times 2^{ENOB} \times f_s$$



[M. Pelgrom, 2017]

SNR vs Power

- Assume we want to increase the ENOB of a thermal noise limited design by 1-bit (SNR increased by 6dB → quadrupled).
  - $2^{ENOB} = \frac{V_{REF}}{LSB} = \frac{V_{REF}}{\sqrt{kT/C}} \rightarrow 2^{ENOB+1} = 2 \times \frac{V_{REF}}{\sqrt{kT/C}} = \frac{V_{REF}}{\sqrt{kT/4C}}$
  - The capacitance is quadrupled.
  - To maintain same speed (GBW), G_m must be quadrupled.
    - Current is quadrupled as well.
    - Power consumption is quadrupled.

- Conclusion: Power consumption is proportional to SNR
  - The ratio $\frac{SNR}{Power}$ tends to be constant.
  - This can be a good FoM (for a constant speed).

Schreier Figure-of-Merit ($\boldsymbol{FoM_S}$)

$$FoM_S = 10\log\left(\frac{SNR \times f_s/2}{P_{ADC}}\right) = SNR_{dB} + 10\log\left(\frac{f_s/2}{P_{ADC}}\right)$$

- It can be shown that min ADC power is given by

$$P_{ADC,min} = 16 \times kT \times f_s/2 \times SNR$$

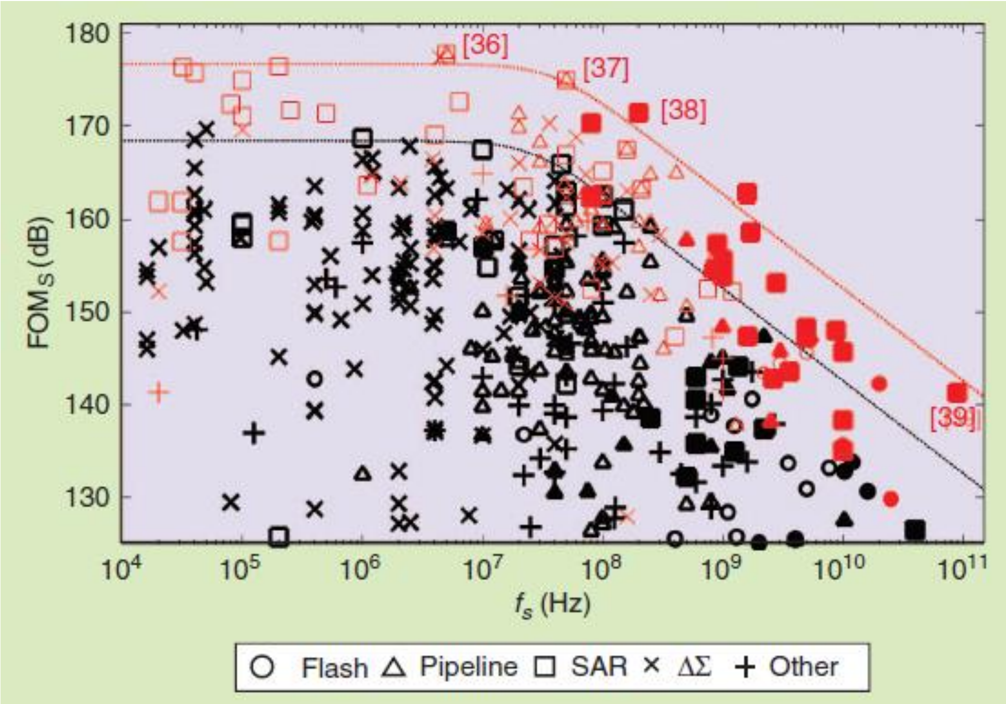
- The theoretical limit on $FoM_{S,max}$ is

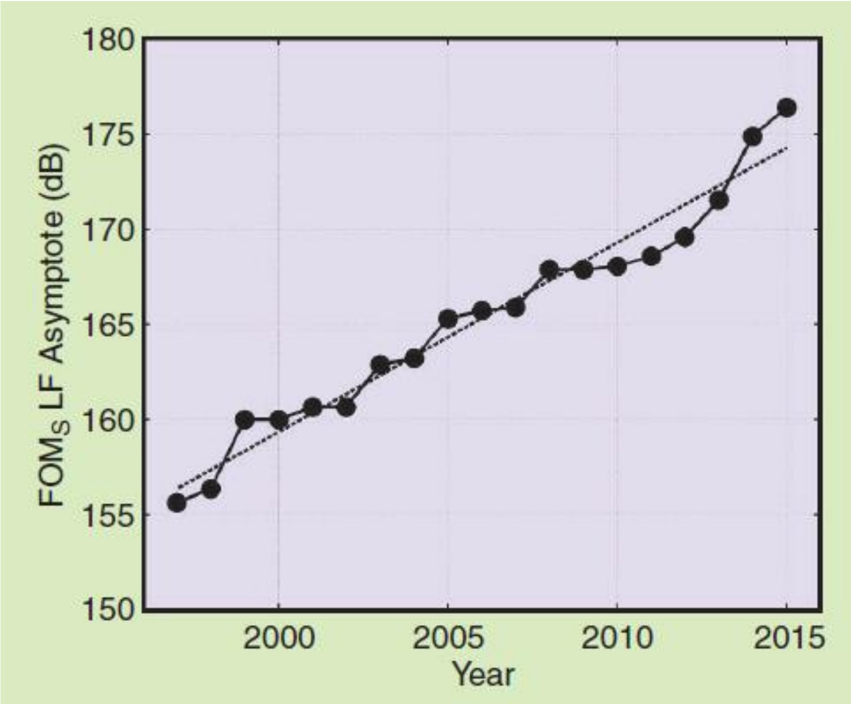
$$FoM_{S,max} = 10\log\frac{1}{16kT} \approx 192\ dB$$

- Schreier FoM best fits thermal noise limited designs.
  - ADCs with high resolution (> 14-bit) and modest speed.
  - Use SNDR (SINAD) instead of SNR to include distortion effects.
- Note that for FoM_S, the higher the better.

Schreier Figure-of-Merit (FoM_S)

- B. Murmann, "**The race for the extra decibel**: a brief review of current ADC performance trajectories." *IEEE Solid-State Circuits Magazine* 7.3 (2015): 58-66.
- ISSCC and VLSI Symp. papers from 1997 to 2015 (**after 2010 in red**)
  - Best practical ADCs are > 10 dB away from the limit.





[B. Murmann, 2015]

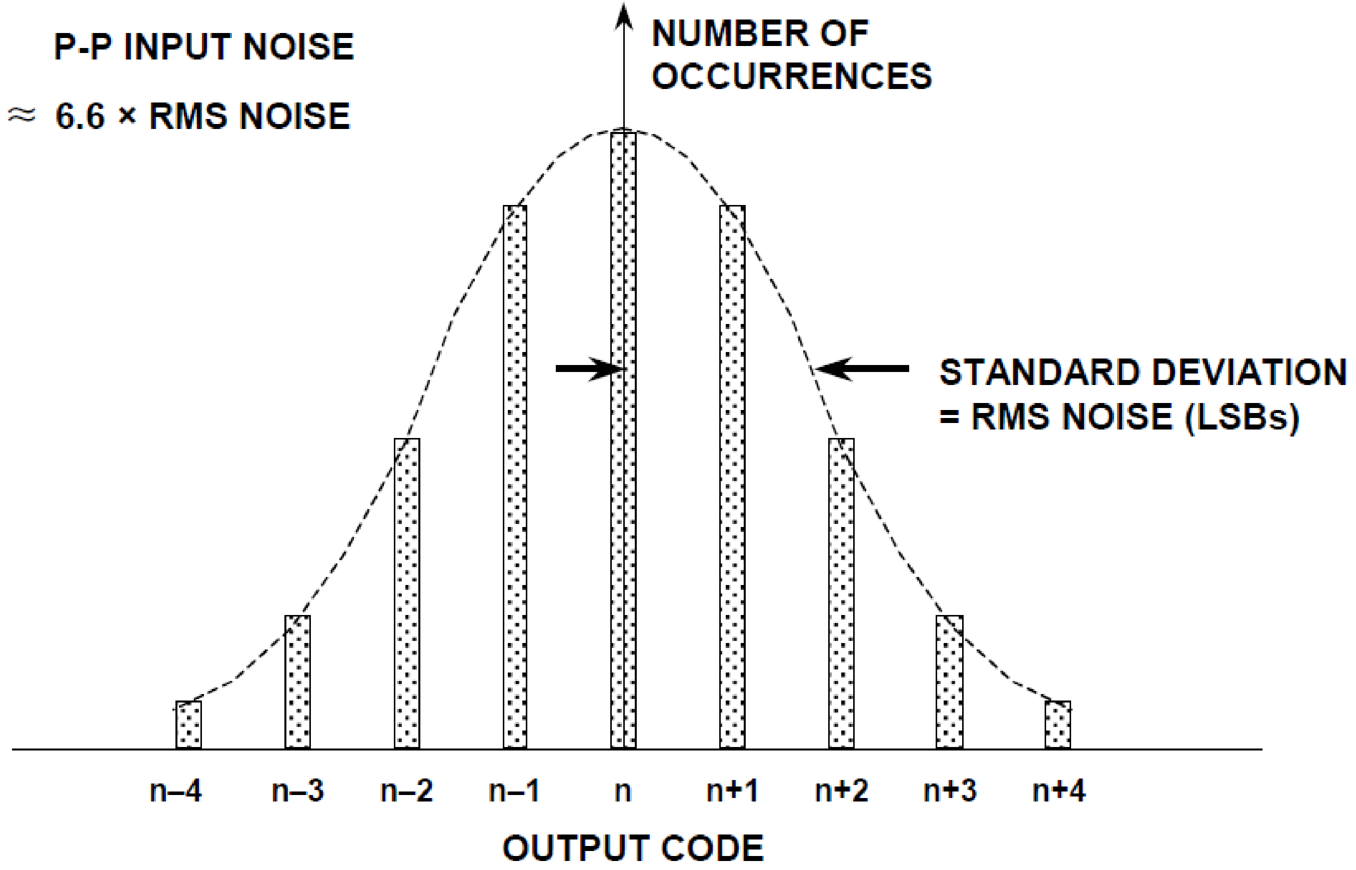
References

- M. Pelgrom, Analog-to-Digital Conversion, Springer, 3rd ed., 2017.
- W. Kester, The Data Conversion Handbook, ADI, Newnes, 2005.
- B. Boser and H. Khorramabadi, EECS 247 (previously EECS 240), Berkeley.
- B. Murmann, EE 315, Stanford.
- Y. Chiu, EECT 7327, UTD.

Thank you!

Equivalent Input Referred Noise

- If the input of the ADC is grounded, the output is a distribution of codes due to noise ➔ Grounded input histogram



[W. Kester, 2005]

Noise-Free and Effective Resolution

- Effective Input Noise $= e_{n\ rms}$
- Peak-to-Peak Input Noise $= 6.6\ e_{n\ rms}$
- Noise-Free Code Resolution $= \log_2 \left[\dfrac{\text{Peak-to-Peak Input Range}}{\text{Peak-to-Peak Input Noise}} \right]$

$$= \log_2 \left[\frac{2^N}{\text{Peak-to-Peak Input Noise (LSBs)}} \right]$$

- "Effective Resolution" $= \log_2 \left[\dfrac{\text{Peak-to-Peak Input Range}}{\text{RMS Input Noise}} \right]$

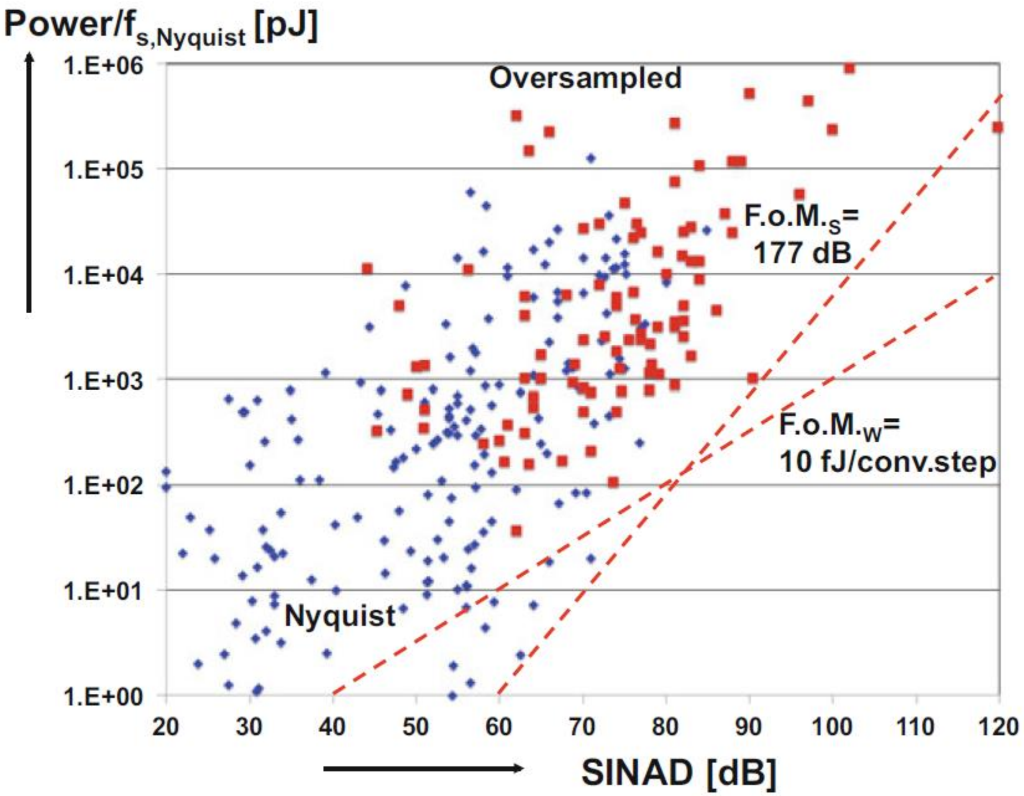
$$= \log_2 \left[\frac{2^N}{\text{RMS Input Noise (LSBs)}} \right]$$

= Noise-Free Code Resolution + 2.7 bits

[W. Kester, 2005]

Nyquist vs Oversampling ADCs

- Nyquist ADCs: $f_s \geq 2 \times BW$
- Oversampling ADCs: $f_s \gg 2 \times BW$
  - Quantization noise reduced by digital filter and noise shaping
  - Very high SNR is possible.



[M. Pelgrom, 2017]