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informatik

Designing Low-Noise Analog Electronics for Time and Frequency Metrology

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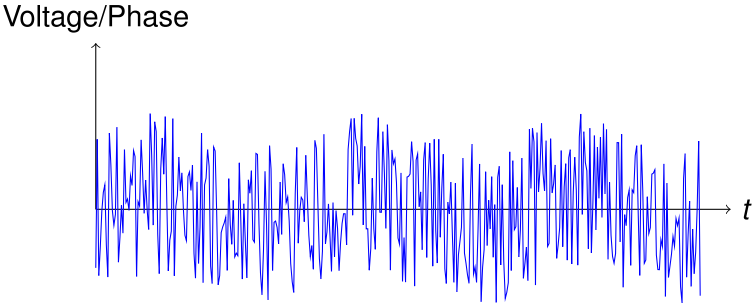
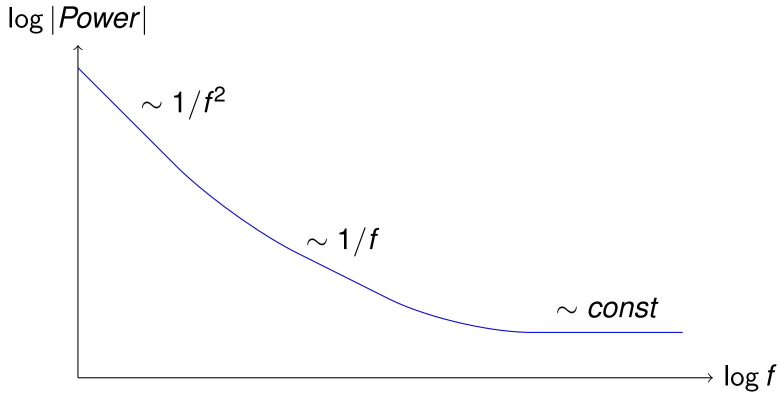
Overview

- Types of noise
- ”Normal” electronics vs metrology electronics
- Design example DMTD
  - Designing multi-stage amplifiers
  - Going digital
- References / Recap

What is Noise?



Noise in Frequency Domain



Types of "Noise"

- White noise
- Flicker noise ($1/f$, $1/f^2$,..)
- Environmental effects
  - Temperature
  - Humidity
  - Barometric pressure
  - EMI / Ground loops
- Aging
  - Relaxation effects
  - Diffusion effects

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- Most systems only limted by white noise
- Other types of noise treated as ”drift”
- Timescales matter

Component Noise - Passives

- Resistor
  - Thermal/white noise ($\sqrt{4kTR}$)
  - Flicker noise insignificant (mostly carbon resistors)
- Capacitor
  - "Noiseless"
  - Mechanical noise
  - ESR
  - Leakage current
- Inductor
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Component Noise - Actives

- Transistor (BJT, JFET, MOSFET)
  - White noise
  - Flicker noise
  - Temperature dependent gain modulation
- Opamp / Amplifier / Comparator
  - Input voltage noise (white and flicker)
  - Input bias current noise (white and flicker)
  - Power supply noise
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Limits of Noise

- Thermal noise power:
  - @ 20 °C: $-174\,\mathrm{dBm}/\sqrt{\mathrm{Hz}}$
  - @ -200 °C: $-180\,\mathrm{dBm}/\sqrt{\mathrm{Hz}}$
  - Power independent of resistance
- Thermal noise voltage:
  - 50 Ω @ 20 °C: $0.9\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$
  - 50 Ω @ -200 °C: $0.45\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$
  - 12.5 Ω @ 20 °C: $0.45\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$
- P-N junction reverse bias current:
  - increases with $\times$ 2 / 9 °C

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Measurement

What doeas measuring mean?

The process of taking an *analog* signal, *processing* it and recording *numerical* (digital) data is called *measuring*.

Measurements in the Past vs Today

The past:

- Digital electronics slow and expensive
- ADCs were slow, noisy and low resolution

$\rightarrow$

- Lots of analog processing
- Late digitalization

Today:

- Digital electronics cheaper than analog
- ADCs fast, low noise and high resolution

$\rightarrow$

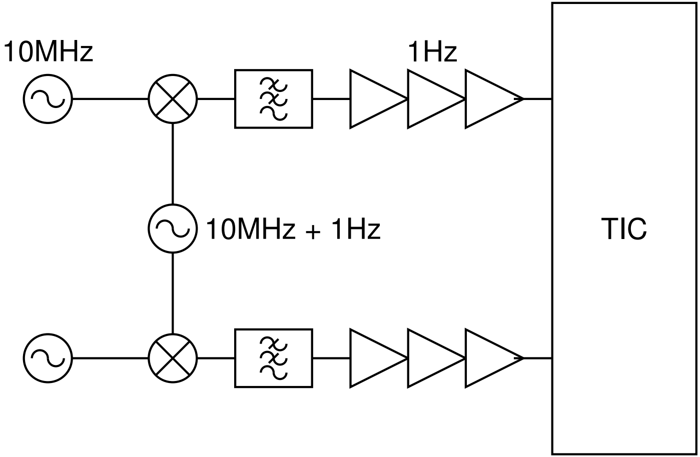
- Little analog processing
- Early digitalization

Digitalize early!

- Bits are cheap
- 32 bits give 182 dB dynamic range
- 64 bits give 385 dB dynamic range

$\rightarrow$ Digital processing can be made ”noiseless”, given enough processing power. DSP and FPGA are cheap.

Mise en Pratique: Le DMTD



[Allan & Daams 1975]

Performance Limits of the DMTD

- TIC: 100 ps
- Time ”amplificiation”: 10^7

$\rightarrow$ 10 as resolution

System will be limited by the input noise and contributions by the mixer and amplifiers.

Performance Limits of the DMTD

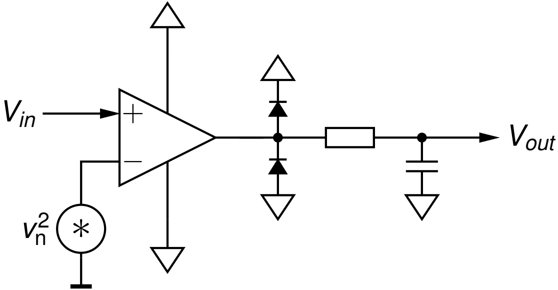
The TIC needs high input slopes: 10 V/µs to 1000 V/µs

$4\,\text{dBm} = 1\,\text{V}_{pp}$ @ $1\,\text{Hz} \rightarrow 3\,\mu\text{V}/\mu\text{s}$

$\rightarrow$ 70 dB to 110 dB gain needed

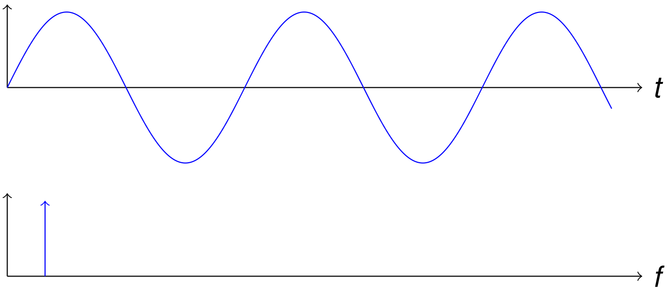
74 dBm = 25 kW

Limiting Amplifier



[Allan & Daams 1975]
[Dick, Kunle, Sydnor 1990]
[Collins 1996]

Limiting Amplifier



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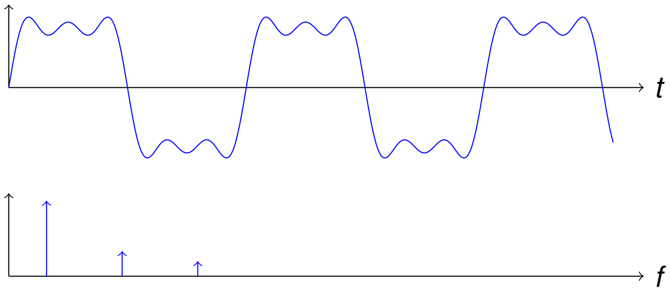

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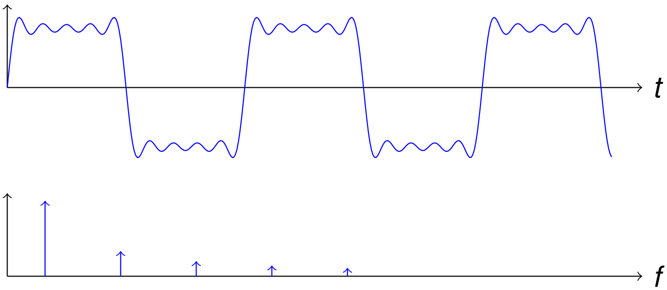

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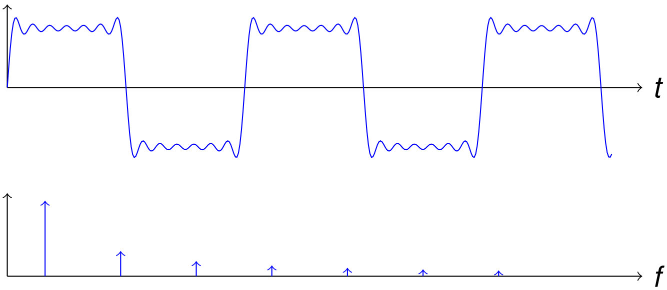
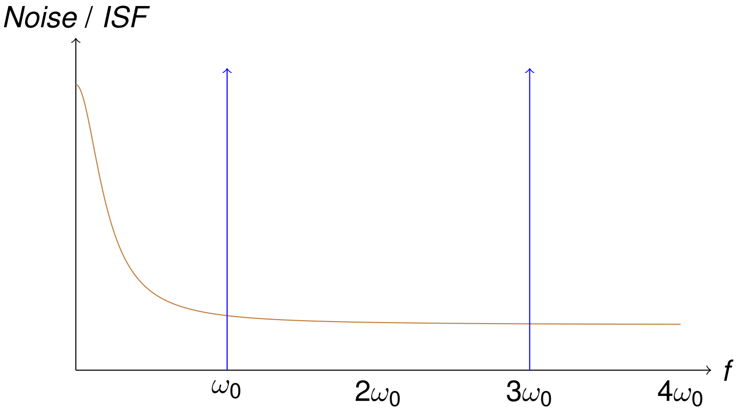


Noise Folding Due to Harmonics



[Hajimir & Lee 1998]
[Kinali 2018 & 2019]

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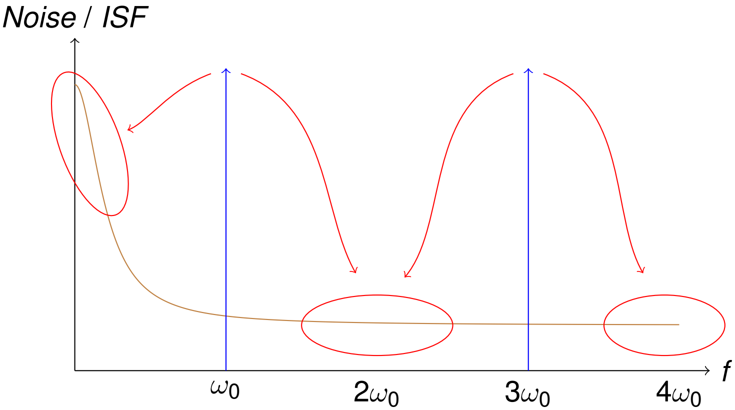

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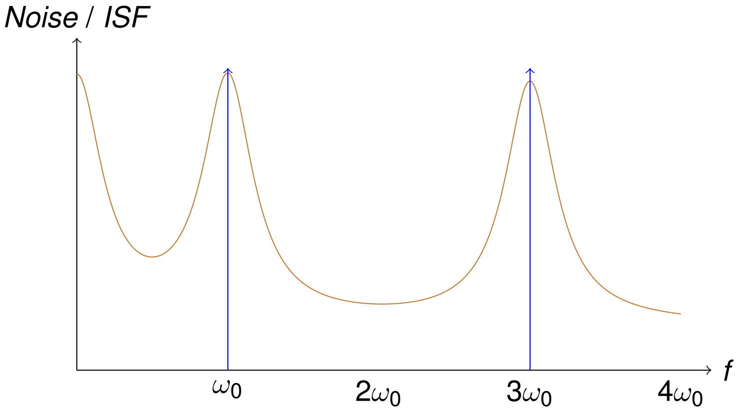

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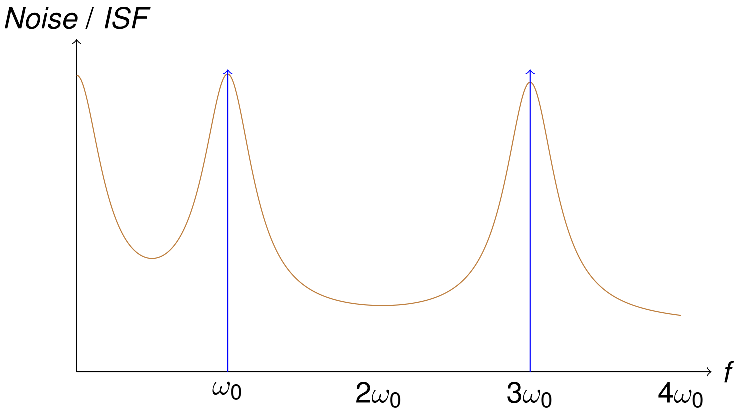
Multistage?



[Kinali 2018 & 2019]

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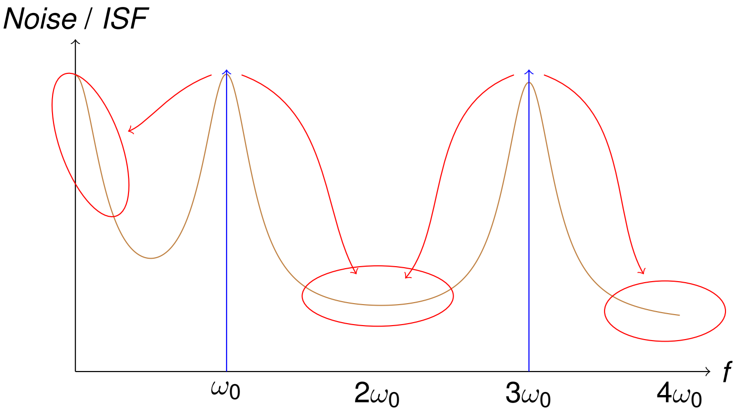
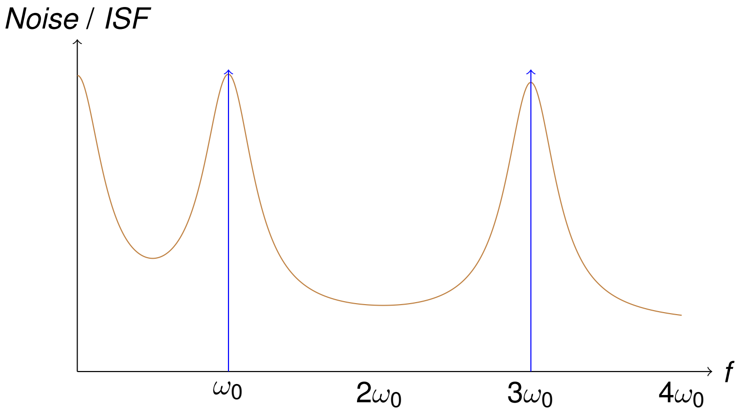


[Kinali 2018 & 2019]

Multistage with duty cycle $\neq$ 50%



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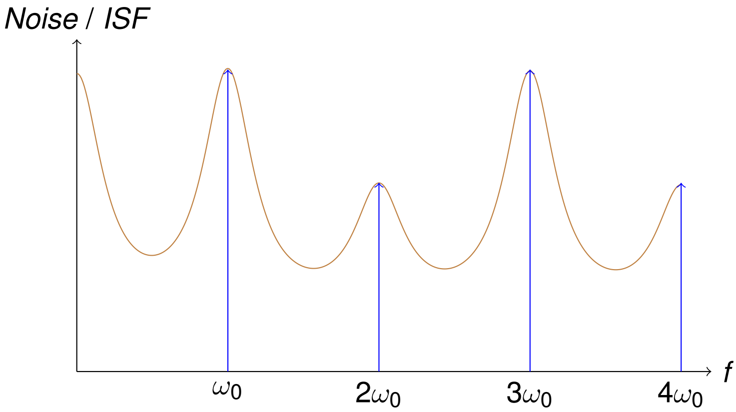

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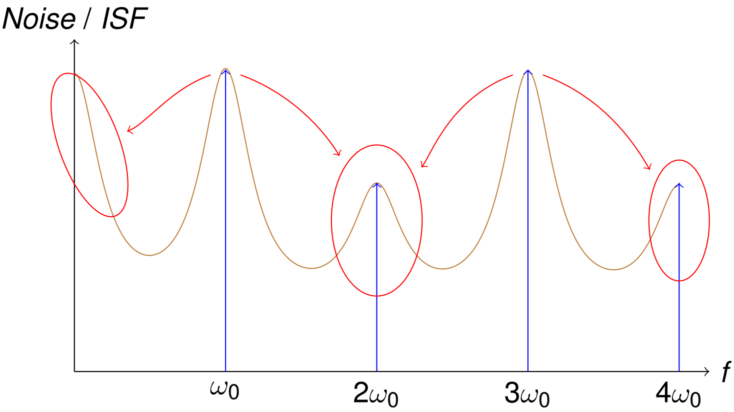


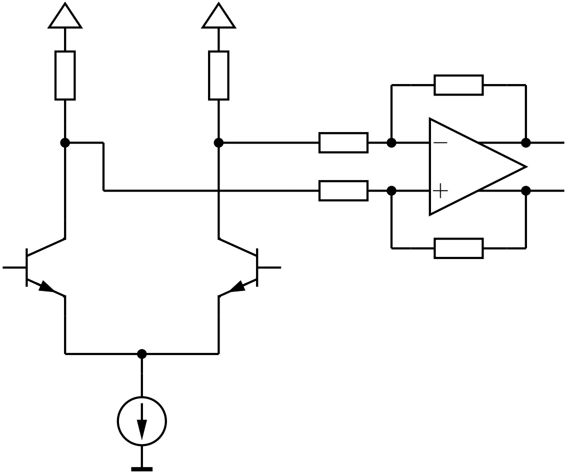
[Kinali 2018 & 2019]

How to Design an Amplifier

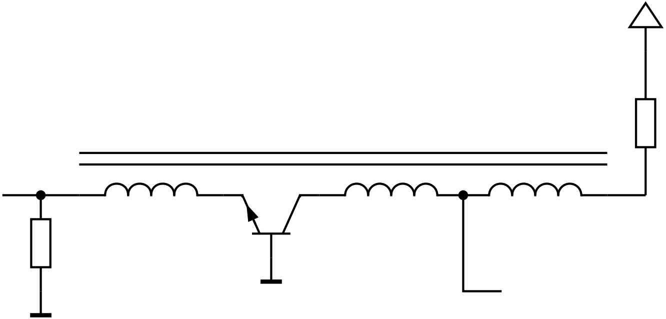
Signal frequency and bandwidth:

- Low frequency:
  - Opamps offer low noise and ease of use
  - Use discrete transistor pre-amp for lower noise
  - Use differential signaling for high power supply rejection
  - Add differential-drift cancelation circuit for second harmonic supression
- High frequency:
  - Opamps are noisy, but might be good enough
  - MMIC amplifiers available with low noise figure
  - Use discrete transistor amplifiers if possible
  - Use push-pull architecture for second harmonic supression

Differential Low Frequency Amplifier



High Frequency Amplifier



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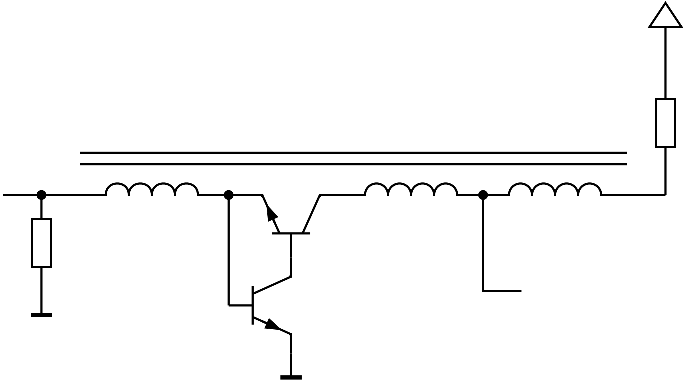
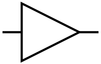


Push-Pull High Frequency Amplifier



Push-Pull High Frequency Amplifier

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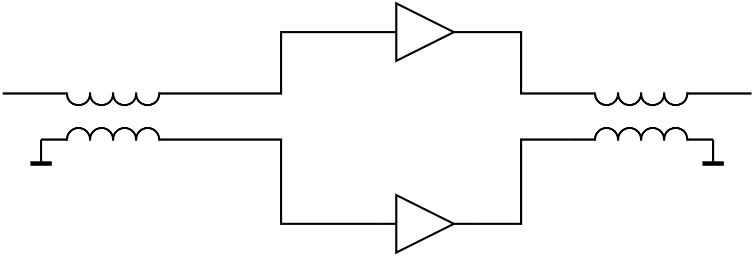
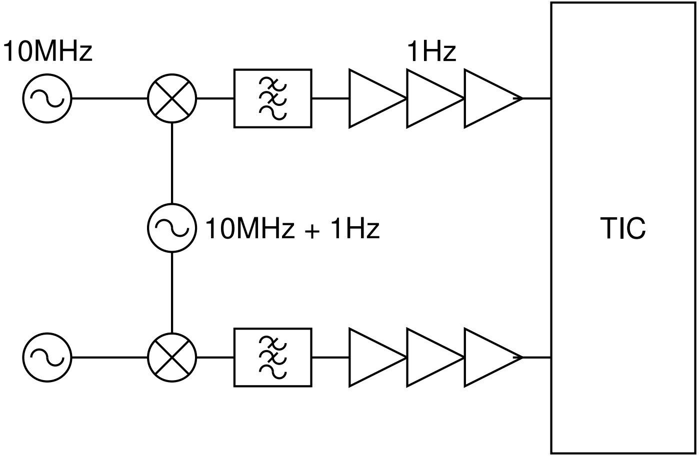


Can We Avoid the Amplifiers?



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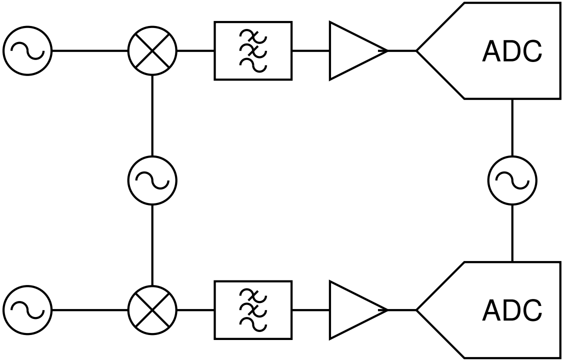
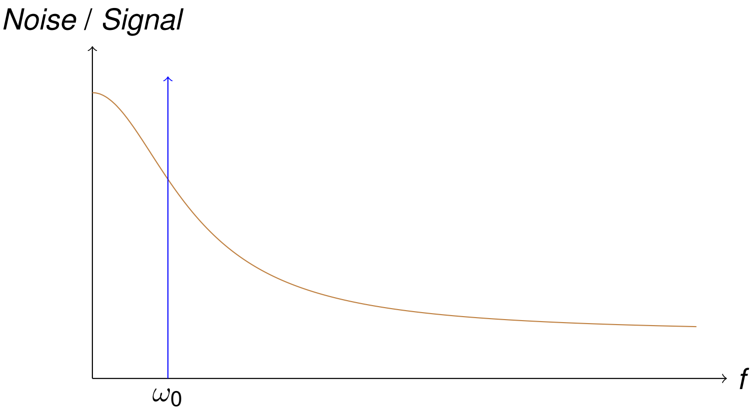


[Uchino & Mochizuki 2004]

Moving Away From Flicker Noise



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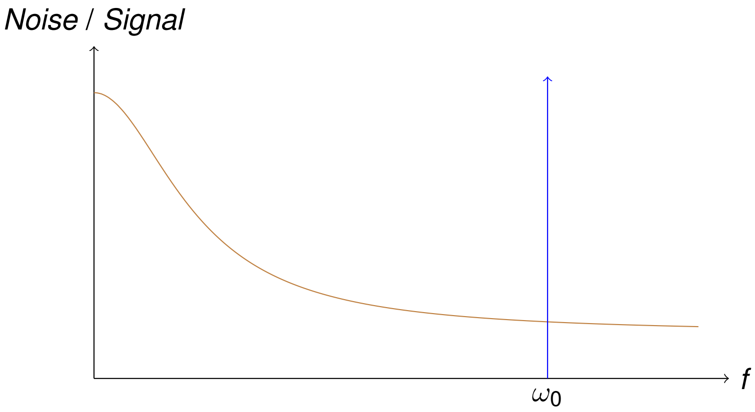
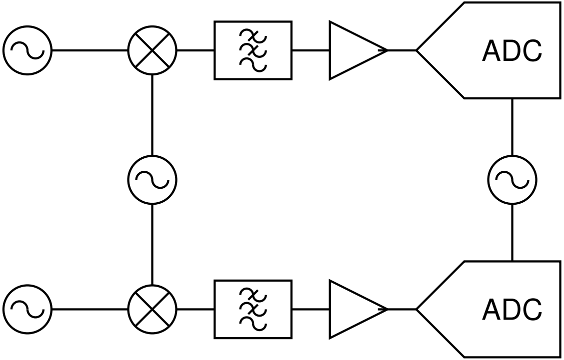


Further Improvements



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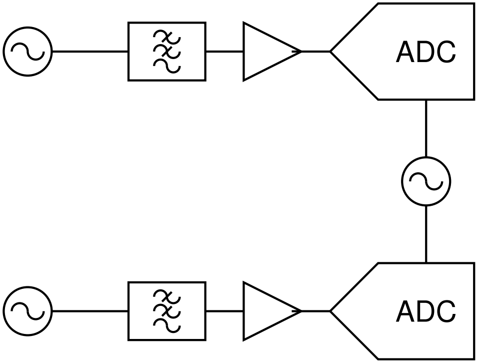

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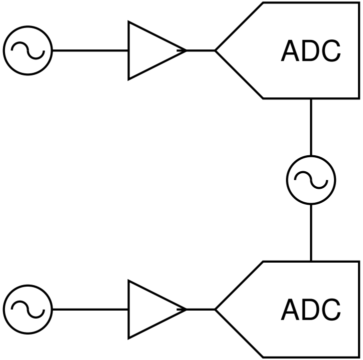


[Mochizuki, Uchino & Morikawa 2007]
[Sherman & Jördens 2016]

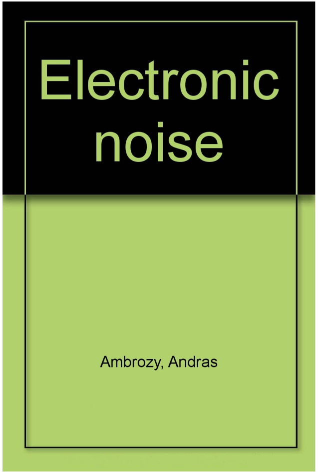
What We Have Seen

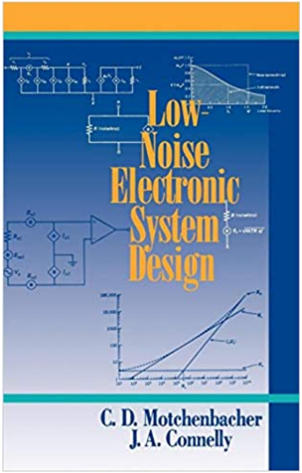
- Digitalization is a powerful tool
- One can incrementally improve a design, given enough leverage to work with
- The right architecture saves you headaches while having better performance

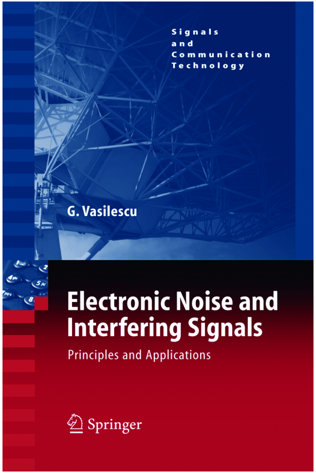
Things We Have Not Talked About

- Power supplies (linear vs switched)
- Digital signal processing and its noise and non-linearities
- How to find the right architecture
- Component selection
- How to estimate the noise performance of the circuit

Further Reading







Further Reading