Tutorial: Analog Signal Processing and Design for Low Noise LLRF Front Ends

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LLRF17, Barcelona, October 2017

Strong overlap from

- Teytelman "Ingredients for Perfect RF Transceiver" LLRF15
- Doolittle: "Error Model and Specification of a LLRF System & System Design Pattern for LLRF Systems" LLRF15

I hope this material adds both context and specifics to that body of knowledge

Outline

- Background and history
- Goals: quantifying noise and disturbance
- Design (systems)
- Worked example
- Technology (components)
- Characterization

History

Electromagnetism *vs.* General Relativity

- First theoretical prediction of electromagnetic waves: Maxwell, 1864
- Experimental confirmation: Hertz, 1887
- First theoretical prediction of gravitational waves: Einstein, 1916
- Experimental confirmation: LIGO, 2015

Oliver Heaviside (1850 - 1925)

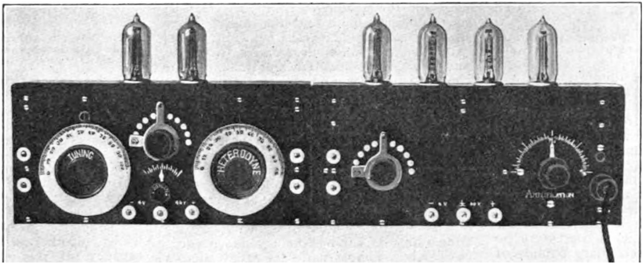
- Discovered/invented transmission lines, 1880
- Re-wrote Maxwell's equations in their currently used form, 1884
- First to use complex numbers to describe AC circuits, 1886
- One of the first to hypothesize gravitational waves, 1893

Superhet

Superheterodyne Receiver

- Invented by U.S. engineer Edwin Armstrong in 1918
- Overcame serious limitations of triode tubes of the day; their gain at 75 kHz IF was much higher than at 2 MHz RF

"Superheterodyne receivers have essentially replaced all previous receiver designs." - Wikipedia

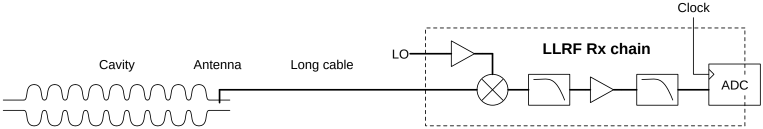


Six tubes: mixer, LO, 3 $\times$ IF amplifier, audio detector

Digital LLRF has taken over!

JLab 1989: analog
SNS 2001: digital
LLRF'01 discussion point: "Is analog still viable? Under what conditions?"

Today's definition of LLRF Front End Receiver
multiple channels sharing LO and ADC clock



Noise and disturbance categorization

- electrical noise
  - white noise
  - $1/f$ noise
- temperature changes
  - day/night and air conditioning on/off cycles
  - turbulent airflow
  - hysteresis and memory effects of long cables
- humidity changes
- atmospheric pressure
- AC power
  - power supply ripple
  - variations in amplitude and frequency
- crosstalk
- vibration of components
  - SRF cavities
  - cables
  - capacitors
  - driven by broadband noise, asynchronous motors, AC transformers

Any effect creating a mismatch between the digital readout and the acceleration vector felt by the beam

Rx channel noise spectra

Additive phase noise power density terms

$1/f^1$	flicker phase noise
$1/f^0$	white phase noise

White noise is well-understood, and is independent of signal level.

1/f noise still has an air of mystery to it, and is proportional to input signal.

Fake $1/f^5$ behavior often seen at the low-frequency end of measurements; blamed on self-heating and/or turbulent airflow. It cannot be sustained as a low-frequency limit. Indication that you should extend measurement to lower frequencies.

Refer to LLRF'15 tutorial for details on integrating $1/f$ and white noise

Distortion

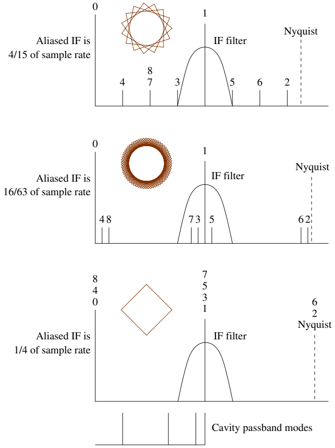
Qualifies as "an effect creating a mismatch between the digital readout and the acceleration vector felt by the beam" but is approximately repeatable, and therefore is usually considered of lower importance than "noise."

Formal power series for the simplest nonlinear element without energy storage:

$$v_{\mathrm{out}} = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \ldots$$

Trigonometry shows effect of applying this to a sine wave.
Second harmonic doesn't corrupt fundamental; third harmonic does

Distortion mitigation: near-IQ sampling



more attractive than dithering

Worked Example

Suppose:

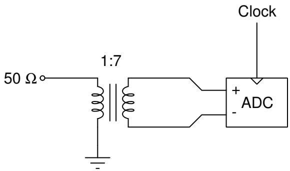
- +30 dBm available from probe
- at least 6 dB loss in cables, attenuators, filters to mixer input
- 7 dB mixer conversion loss
- +34 dBm mixer OIP3
- 2.0 dB amplifier Noise Figure
- 2.0 V p-p ADC input

Question: how much IF gain is appropriate between mixer and ADC?

Worked Example

Attaching to ADC

- Sine wave with 2.0 V p-p has $2.0/\sqrt{8} = 0.7$ V rms
- Switched capacitor input, claimed input resistance 2.6 kΩ
- Match 50 Ω to 2.6 kΩ with 1:7 turns-ratio transformer?
- Power level $0.7^2/2600 = 0.19$ mW → -7.2 dBm

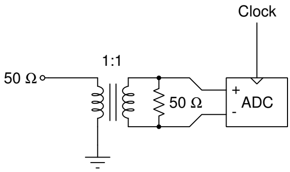


Not recommended
ADCs are designed and characterized with low-impedance drive

Worked Example

Attaching to ADC

- Sine wave with 2.0 V p-p has $2.0/\sqrt{8} = 0.7$ V rms
- Switched capacitor input, claimed input resistance 2.6 kΩ
- Use 1:1 transformer to convert to differential
- Power level $0.7^2/50 = 10.0$ mW $\rightarrow +10.0$ dBm



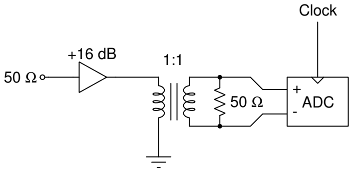
Worked Example

IF amplifier gets up to +17 dBm input full-scale, delivers +10 dBm to ADC.

- Just a 7 dB attenuator, right?

But to get 1% distortion from mixer, output must be -40 dB from OIP3: -6 dBm

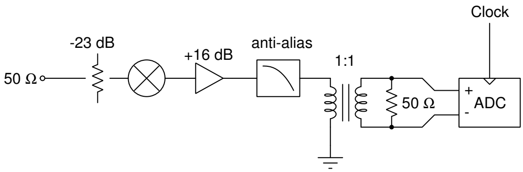
- Requires +16 dB gain



Noise power density at ADC input is thermal noise floor (-173 dBm/Hz) + 2.0 dB Noise Figure relative to -6 dBm full-scale is -165 dBc/Hz

Worked Example

Amplifiers have broad-band noise
Can't afford to let that into the broad-band (e.g., 650 MHz) input of the ADC, or all that noise will alias onto the signal band.
Get signal level right at mixer input, -6 dBm output, 7 dB conversion loss, needs +1 dBm at input, not the +24 dBm available.



System engineering

Sensible design depends on "market" size:

- choices for a run of 3 may be different from a run of 300
- *e.g.*, LCLS-II gun *vs.* LCLS-II L-band

Components

Inductors

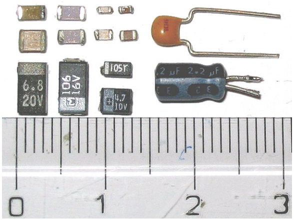
- when you buy an inductor, they also give you a capacitor, resistor, and antenna, for FREE!

Capacitors

- Ceramic capacitors (other than C0G) are piezoelectric microphones
  - Have a pencil and an AC-coupled 'scope handy when testing a board
- Electrolytic capacitors run near their temperature or voltage limit will fail

Resistors

- Power dissipation + temperature coefficient = nonlinearity



Components

power supplies / on-board voltage regulators:

Switcher + filter + LDO

- Disable pulse-skipping on switcher
- Prefer synchronizable switcher
  - A fixed frequency is easier to characterize, and reject in DSP, than a variable frequency
- π-filters separate switcher from LDO, and LDOs from each other
  - LDOs have poor rejection at higher frequencies, e.g., 100 kHz
- Use non-microphonic capacitors for low-noise LDO's reference filter capacitor

Ideally, compute or measure effect of power supply noise on system performance. Also, build and measure prototypes of several on-board voltage regulator designs.

Data sheets

Some engineering can be successfully based on the data sheet:

- White noise and power dissipation are usually nicely documented
- If you're lucky, $1/f$ noise or other close-in noise spectra will be covered

Other things are not:

- Sensitivity to humidity and vibration.

Need your own measurements

- Implied trust that the supply chain delivers consistent parts
- That's a reminder that you need to test more than one prototype

Plea to any component manufacturers hearing or reading this:

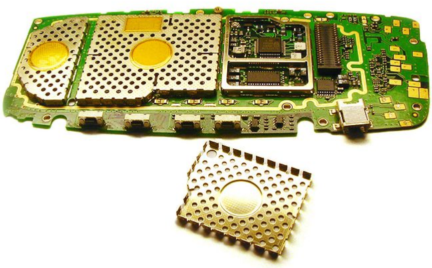
- Please test, and publish as much information as you can about your parts!
- It's awkward when your customers know more about your parts' behavior than you do

Shielding

To addresses crosstalk and "EMI"
proper layout with ground planes already minimizes antenna area

- a ground plane is an easy way to provide a return path for signals between any two points on the board
- the return path is essential, even when a ground plane is not used

many options: clip-on, solder-on, milled aluminum



Characterization

Digitally acquire big buffers (e.g., 2^{18} to 2^{20} points) for analysis - can make do with repeated fills of smaller buffers, with proper averaging

Plan to take a lot of data in an OODA-ish loop:
measure, analyze, diagnose, improve, repeat.
systematically include as much meta-data as you can,
e.g., control register dump

Toolkit should include at least

- digital downconversion
- CIC filter
- buffered data transfer to host
- (windowed) FFT
- cross-correlation

Highly recommended:

The Magic of Cross Correlation in Measurements from DC to Optics, E. Rubiola, 2008

(note that when Rubiola draws a "dual channel FFT analyzer" we can (and should) do the same thing with our ADC + FPGA and a dozen lines of Python or Matlab. The ADC is (correctly) part of the device-under-test.

Possible future work

Evaluate transformer-coupled amplifier

- Not (to my knowledge) tried on LLRF, but looks ideal for driving an ADC with low impedance and low distortion
- *Transformer Feedback Amplifiers: Variations on a Theme*, Chris Trask, 2011

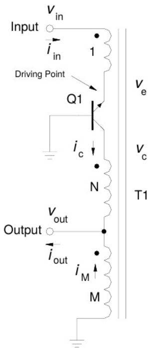


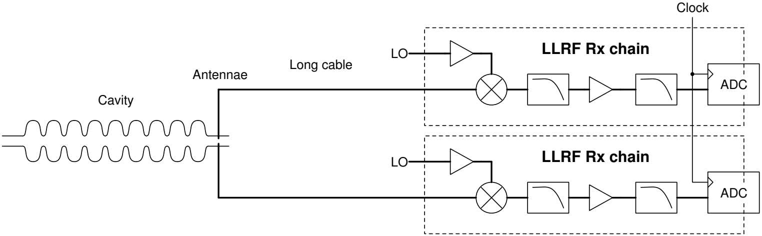
Figure 1 - Basic Norton Transformer Feedback Amplifier

Possible future work

Add a second field probe and cable to each SRF cavity

could have important benefits for

- reliability
- out-of-loop system characterization
- long cable characterization
- maybe even cavity fill-fraction in the cryomodule



(I always get shouted down when I suggest this)

Conclusion

Get the first-order engineering design sensible first

Use components you understand

Prototype and test early and often

Gracias!

Thank You!