LLRF Analog/RF Hardware Fundamentals

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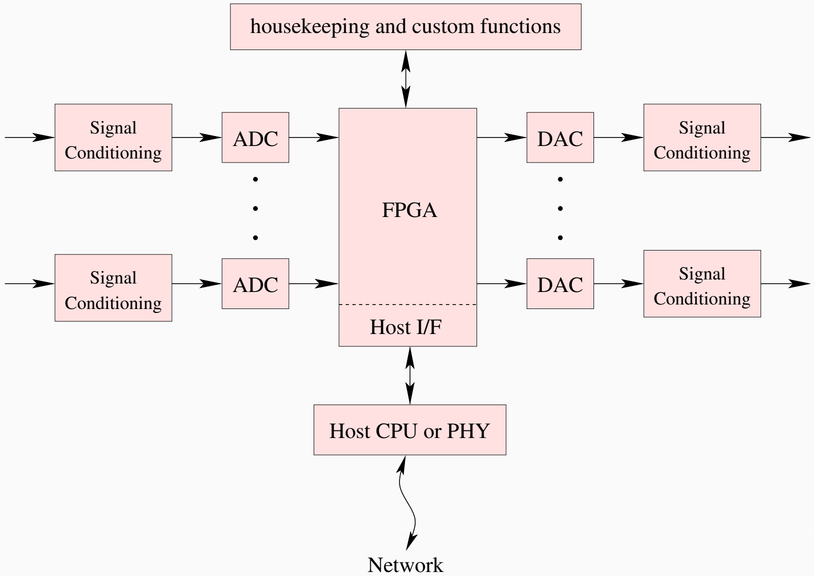
Overview

Low Level RF hardware has simplified over the years, now it's mostly a means of digitizing RF waveforms. Familiar block diagram dates from ∼2002.



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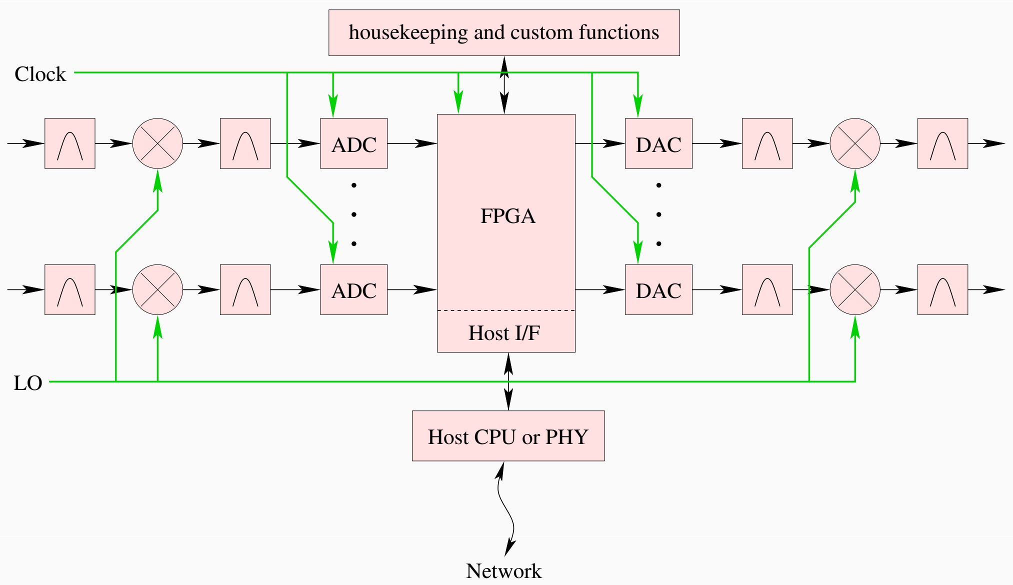


Mixers

An abstract mixer is exactly an analog multiplier.

Using traditional trig functions and real values:

$$2 \cdot \cos \omega_1 t \cdot \cos \omega_2 t = \cos(\omega_1 + \omega_2)t + \cos(\omega_1 - \omega_2)t$$

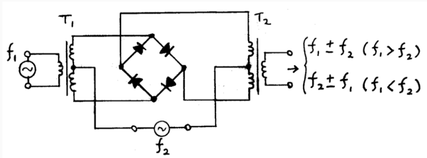
Maybe a little easier to follow with complex numbers

$$e^{\omega_1 t} \cdot e^{\omega_2 t} = e^{(\omega_1 + \omega_2)t}$$

$$e^{\omega_1 t} \cdot e^{-\omega_2 t} = e^{(\omega_1 - \omega_2)t}$$

Mixers

Real-life mixers in accelerator support electronics are almost always either



- double-balanced diode ring mixers
- Gilbert-cell active mixers

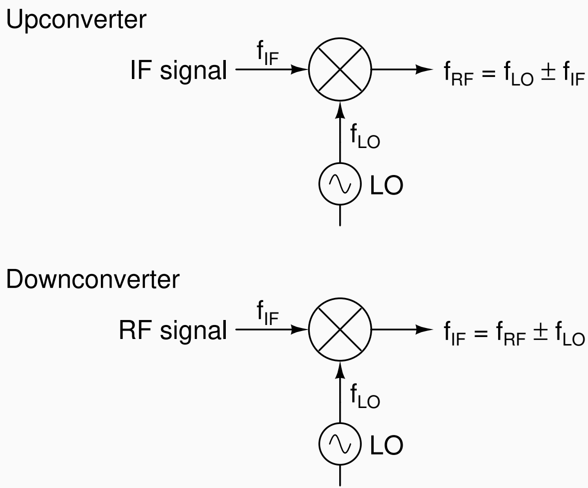
Mixers are clearly not LTI (Linear Time-Invariant) devices!

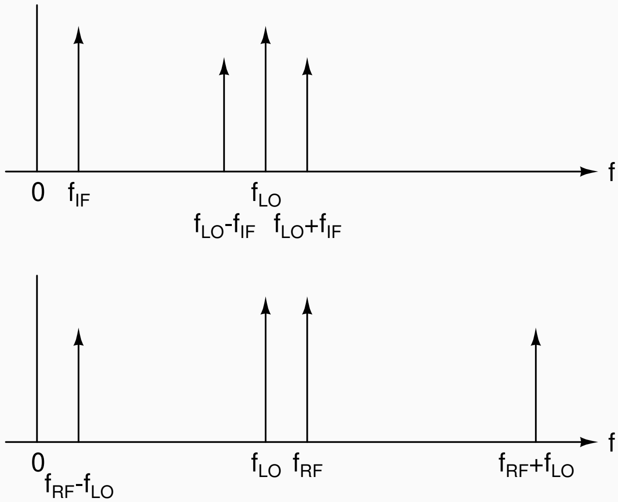
But with some approximations and interpretations they have a lot of the same properties as a linear device. With constant LO drive, acting as either upconverter or downconverter,

- Output amplitude scales with input amplitude
- Output phase (away from carrier) tracks input phase (away from carrier)

History: 1917-1918 invention of heterodyne receiver, by Lucien Lévy and/or Edwin Armstrong (subject of a bitter patent fight)

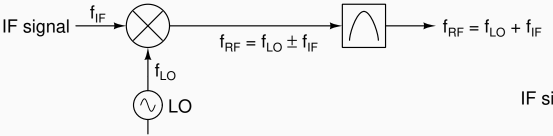
Frequency conversion



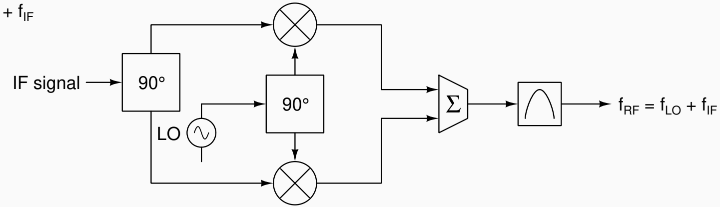


Four ways to generate controlled RF output:

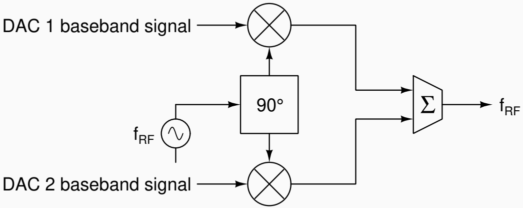
DSB Upconverter plus sideband-select filter:



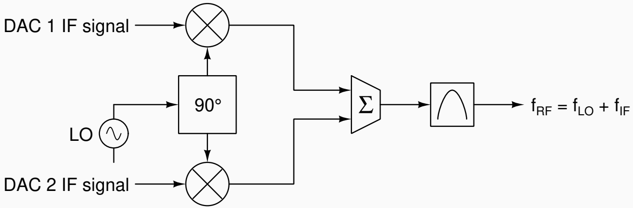
Single-DAC SSB Upconverter plus cleanup filter:



Dual-DAC Vector Modulator:



Dual-DAC SSB Upconverter plus cleanup filter:



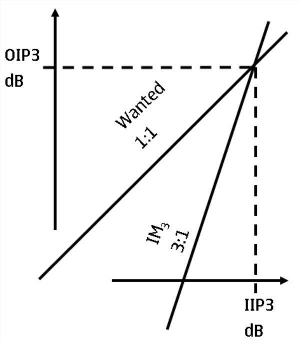
Mixers

Double-balanced mixer properties

- -6 dB or -7 dB conversion loss
- Noise Figure (N.F.) dominated by post-amplifier
- Third-harmonic distortion performance - figure of merit is its third-order intercept point (IP3)

Quoting Wikipedia:

> *The intercept point is a purely mathematical concept and does not correspond to a practically occurring physical power level. In many cases, it lies far beyond the damage threshold of the device.*



Mixers

Focus on third harmonic instead of second harmonic

- Mixer designers can and often do use symmetries to cancel most second harmonic output
- Unlike second harmonics, presence of third harmonic output implies corruption of fundamental amplitude

Output amplitude of a *nearly* linear (not LTI) device depends on the input in a power series:

$$v_o = a_0 + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \ldots$$

with rapidly decreasing coefficients; a_3/a_1 is always negative, representing compression. Injecting a sine wave into that equation and analyzing the harmonics of the result shows fundamental gain (a_1 at low amplitudes) is not affected by a_2, but is decreased by a_3.

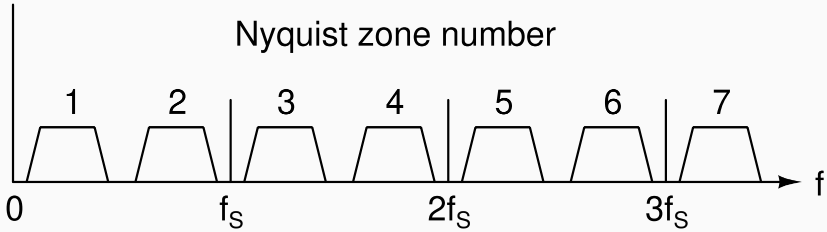
That equation also confirms the ideas shown on the chart on the previous slide.

Sampling

- ADC - wide-band delta-function-ish sampling
- DAC - wide-band step-function-ish output, spectral line power falls off as $1/f^2$

(Almost) always have an anti-alias filter on ADC input to reject preamplifier noise

Typical preamplifier gain is 15 to 20 dB to balance S/N and mixer distortion



Sampling

Currently fashionable to talk about very high-speed ADCs with direct (no downconversion) sampling.

- No mixer distortion
- Fewer parts (maybe)
- High power dissipation
- Expensive chips and bleeding-edge toolchains
- Clock noise sensitivity moves from mixers to ADC
- Small transistor geometry predicted to increase $1/f$ noise (see Rubiola's book)

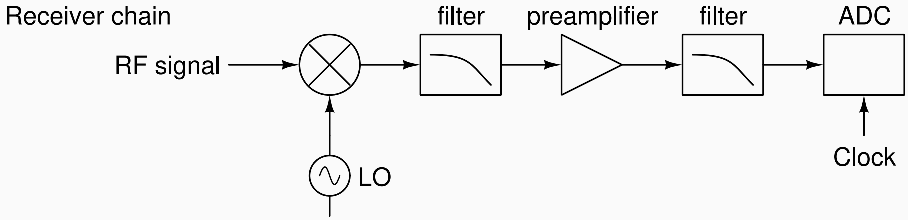
Noise

Additive white Gaussian noise (AWGN) - Mostly what communication engineers worry about

$1/f$ noise - Read Rubiola's book for the long story. Based on modulation, so multiplicative, and won't show up unless a carrier signal is present.

crosstalk - not really noise, but a really insidious corruption of the input signal

Receiver Chain



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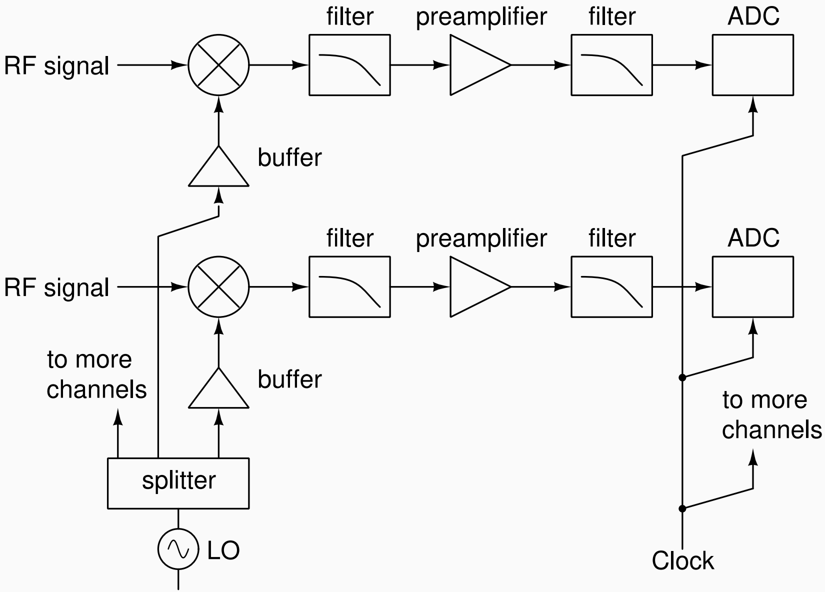
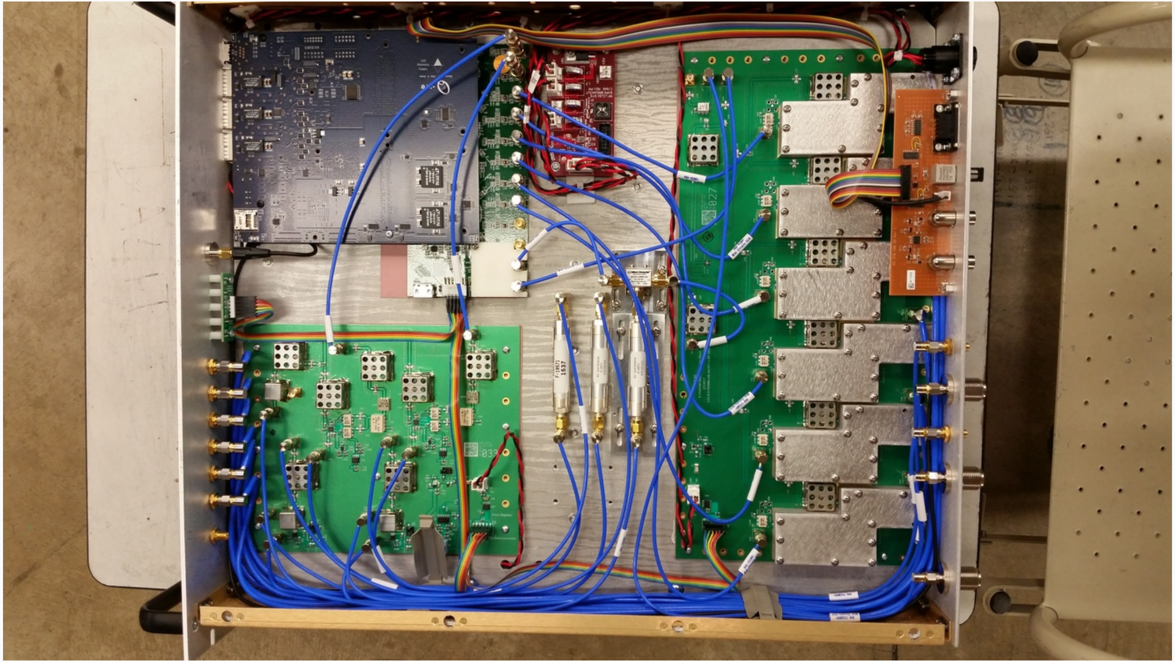


Chassis Construction

LCLS-II 1300 MHz chassis, quantity 210+, custom RF converter boards



Chassis Construction

LCLS-II 186 MHz chassis, quantity 3, connectorized components