Introduction to Software Defined Radio

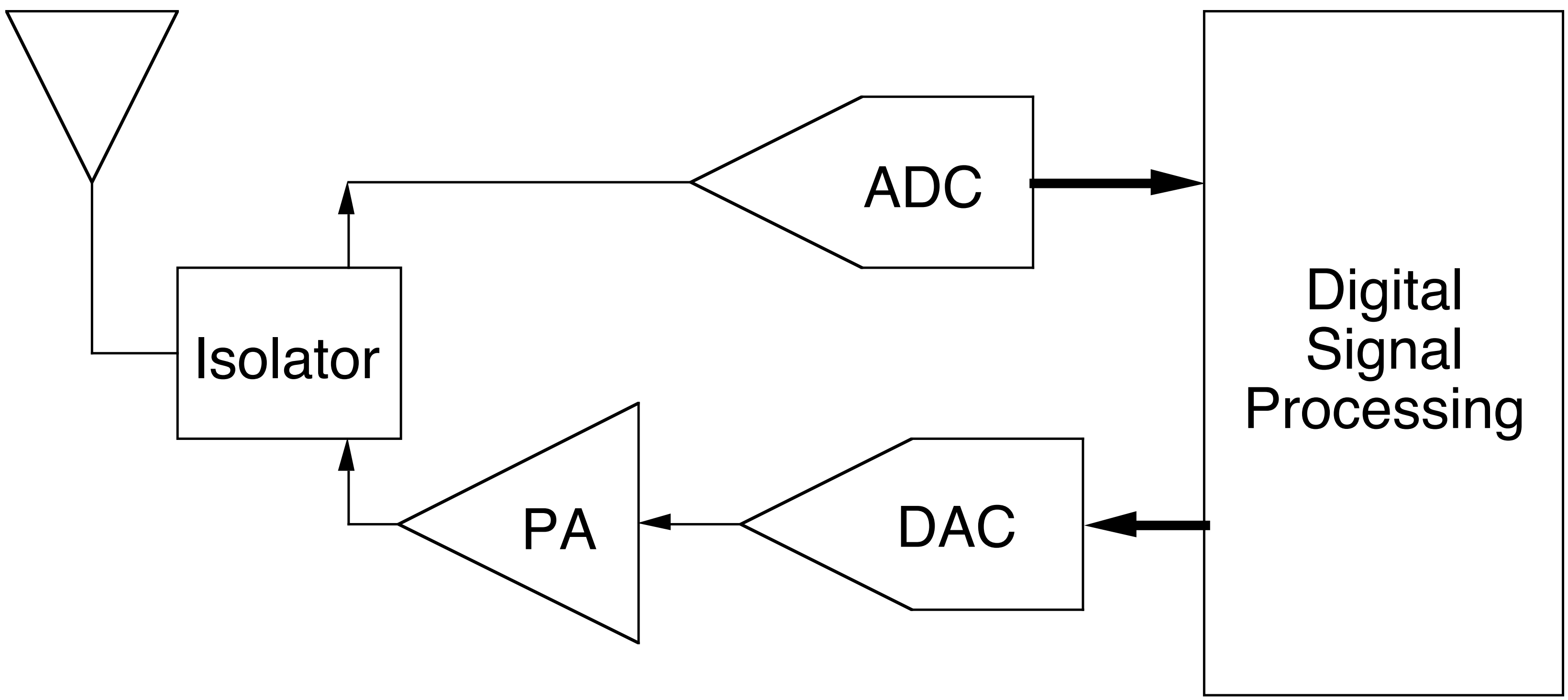
Richard C. Jaeger

Professor Emeritus

ECE Department

Auburn University

Mitola's Software Defined Radio



Software Defined Radio (After Mitola - 1992 and Abidi)

SDR Advantages

- Minimum of "Expensive" Analog Hardware
- Maximize Use of VLSI Technology
  - High density, low cost, low power
- Maximum Flexibility
  - Implement new standards or additional modes
  - Incorporate new modulation/demodulation methods
  - "Easy" to correct design errors
- High Accuracy Quadrature Mixing

SDR Practical Limits

Does One Really Want Implement the Mitola Model?

- Direct Sampling Couples a Signal Out the Antenna (FCC not happy)
- Why Sample the "World" Instead of the Desired Band
  - Wastes power & dynamic range
- High Speed ADCs Consume Large Amounts of Power
- A More Realistic Situation is the Direct Conversion Receiver

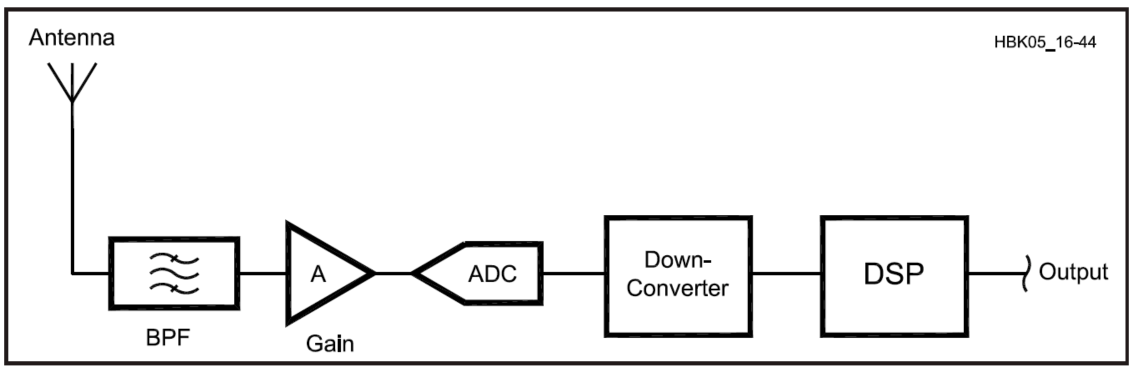


Fig 16.44—Block diagram of digital direct-conversion hardware.

From the 2007 ARRL Radio Handbook Chapter 16

SNR and Dynamic Range Limits

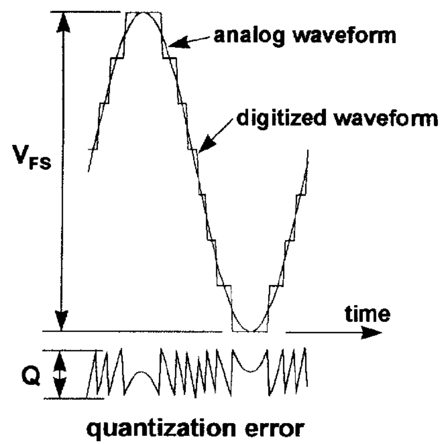
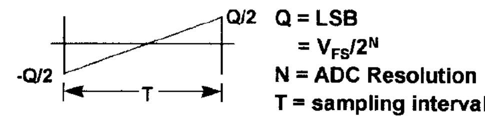


Fig. 2. Example of quantization error. V_{FS} is the full-scale voltage range, and Q is the size of the LSB.



$$e(t) = Q \cdot \left(\frac{t}{T} - \frac{1}{2}\right)$$

$$NP_0(rms) = \sqrt{\frac{1}{T}\int_0^T \left[Q \cdot \left(\frac{t}{T} - \frac{1}{2}\right)\right]^2 dt} = \frac{Q}{\sqrt{12}}$$

$$SNR(dB) = 20 \cdot \log_{10}\left(\frac{V_{FS}(rms)}{NP_0(rms)}\right)$$

$$= 20 \cdot \log_{10}\left(\frac{V_{FS}}{2\sqrt{2}} \frac{1}{\frac{V_{FS}}{2^N\sqrt{12}}}\right) = 6.02 \cdot N + 1.76$$

Fig. 3. Random approximation for quantization error. All errors within the range $\pm Q/2$ are equally likely. The resulting SNR is linear in the number of bits of resolution N.

$MDS = 0.3\mu V_{RMS}$ Maximum Interferer = $30mV_{RMS}$

Dynamic Range of 10^5 (100 dB) $\rightarrow$ 16 bits plus sign

IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 17, NO. 4, APRIL 1999

Analog-to-Digital Converter Survey and Analysis

Robert H. Walden, *Member, IEEE*

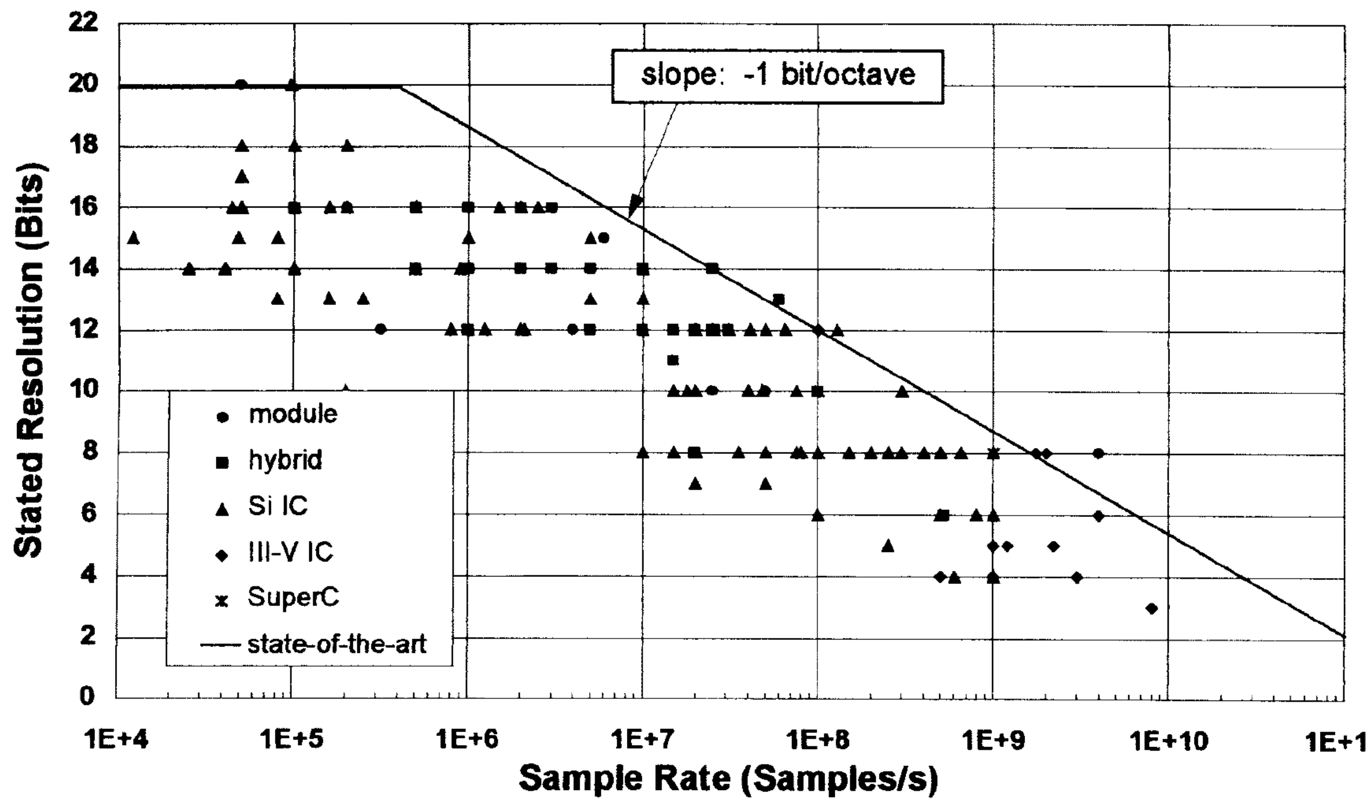


Fig. 1. Survey of ADC's.

IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 17, NO. 4, APRIL 1999

Analog-to-Digital Converter Survey and Analysis

Robert H. Walden, *Member, IEEE*

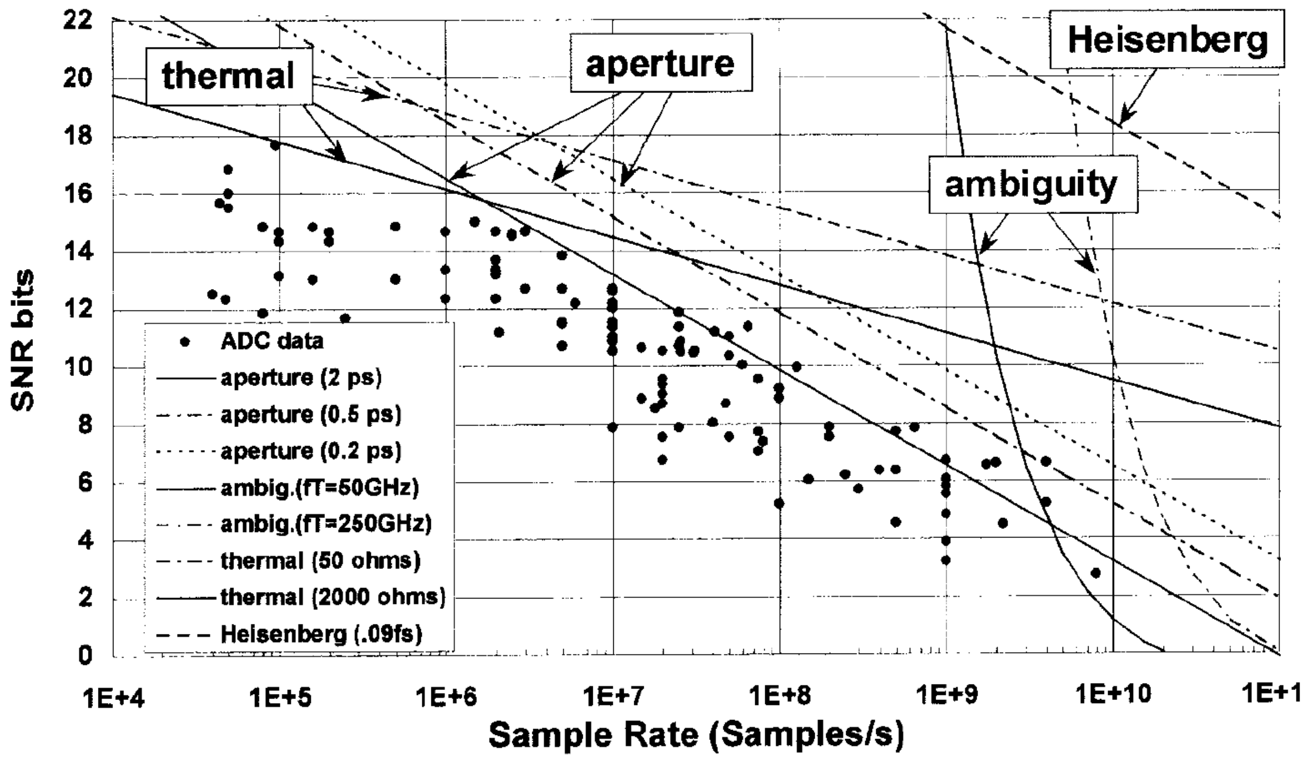


Fig. 7. Signal-to-noise ratio according to SNR-bits = (SNR(dB) − 1.76)/6.02. Three sets of curves show performance limiters due t
uncertainty, and comparator ambiguity. The Heisenberg limit is also displayed.

Analog-to-Digital Converter Survey and Analysis

Robert H. Walden, *Member, IEEE*

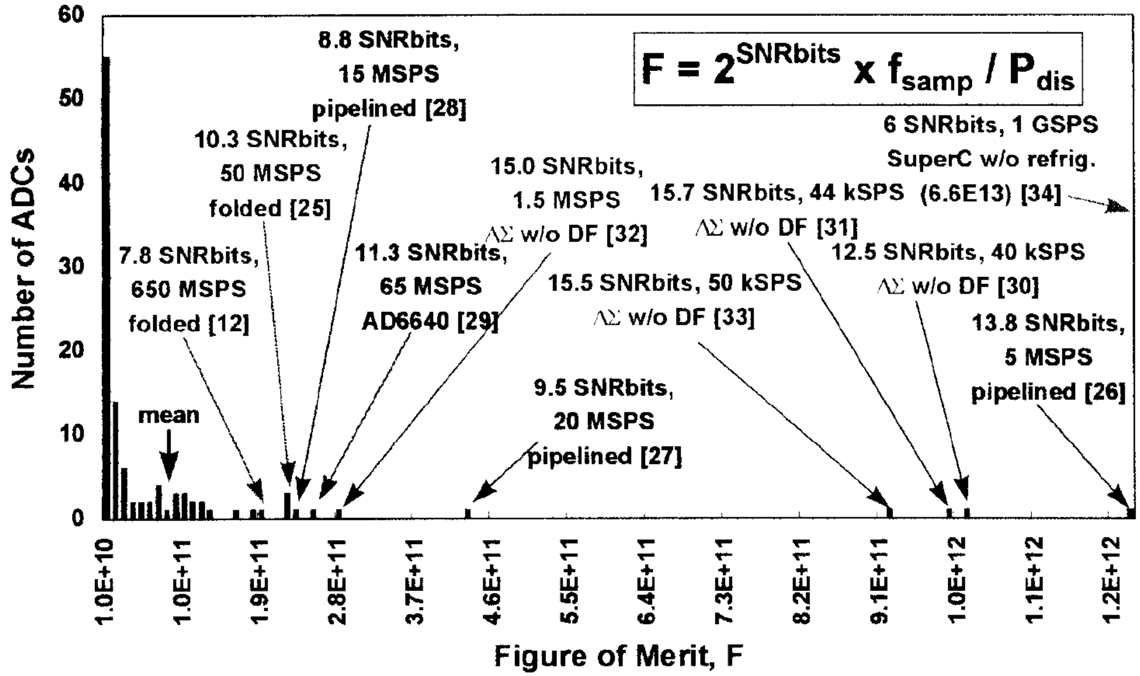


Fig. 9. Histogram of the figure of merit F. The most power-efficient ADC's have been reported within the past six years.

$$P = \frac{2^{SNRBits} \; x \; f_S}{FOM}$$

$$P = \frac{2^{14} \; x \; 10^{10}}{1.2x10^{12}} = 137 \; W$$

Analog-to-Digital Converter Survey and Analysis

Robert H. Walden, *Member, IEEE*

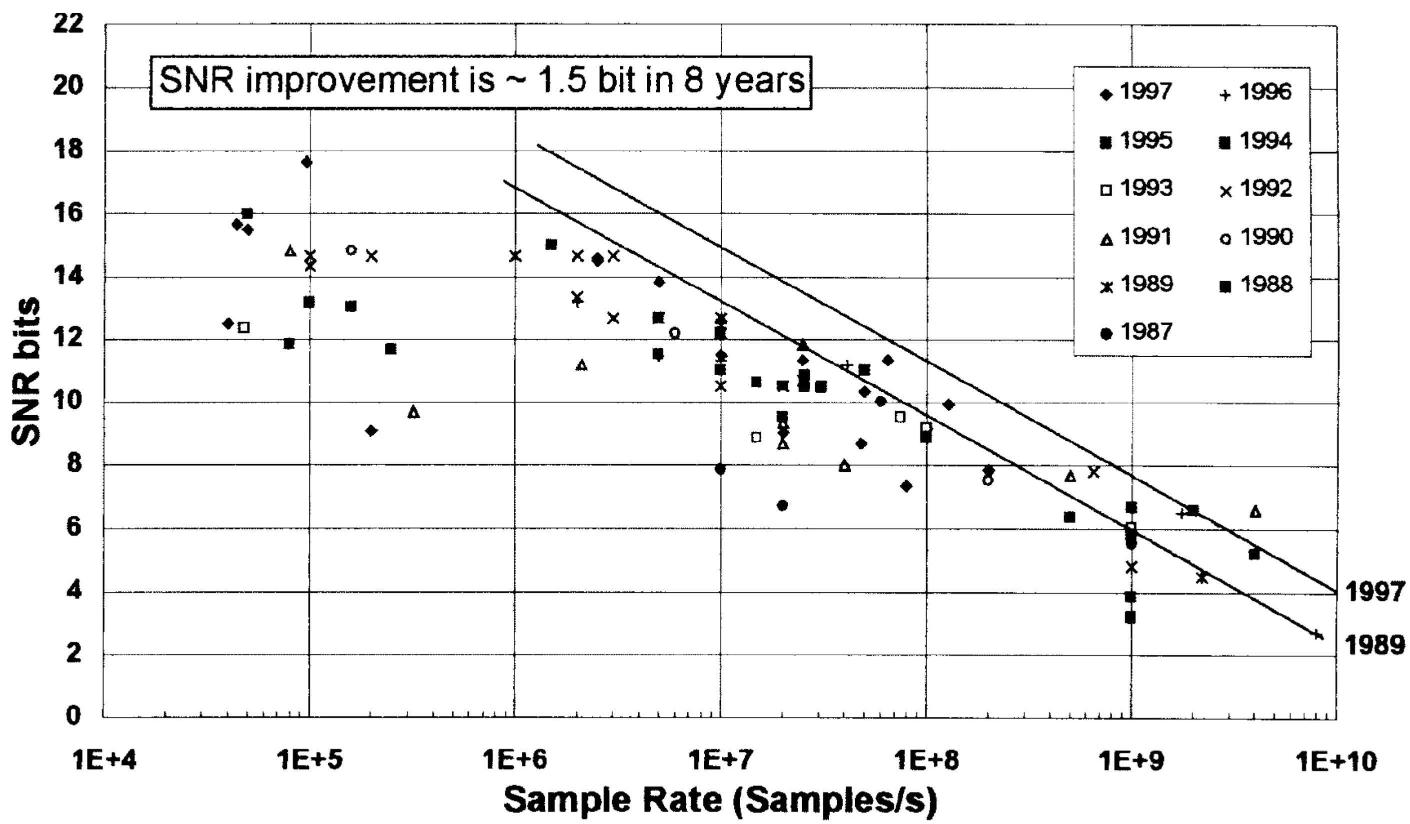


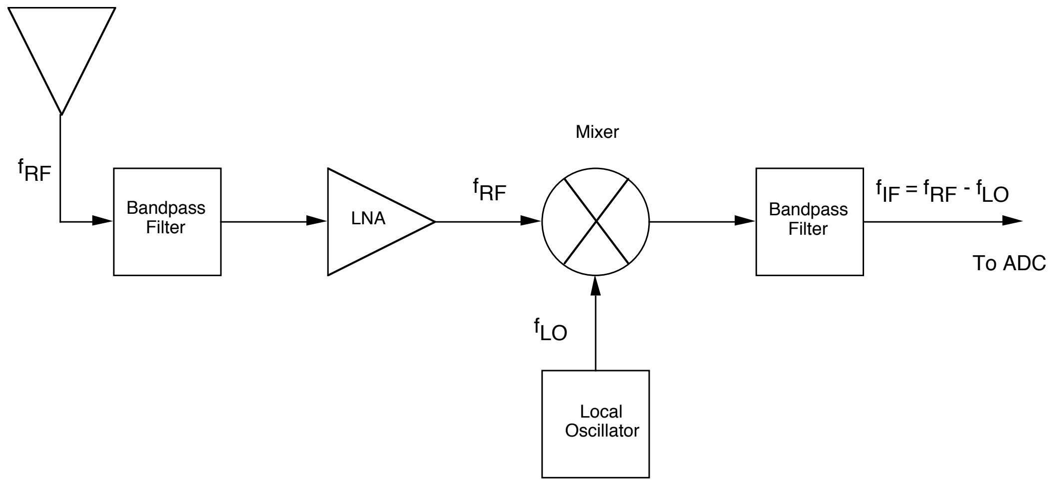
Fig. 10. Trend in SNR bits over time.

Sample Rate Reduction

- Analog Front End
  - Bandpass Filtering
  - Low Noise Amplification
  - Down Conversion to Reduce Frequency
- Sub-Sampling
  - Bandpass Sampling, IF Sampling

Analog Front End - Down Converter

LNA, LO, Mixer, Filtering



- Low noise amplifier
- Mixer
- Local Oscillator
- Bandpass Filtering (often several filters)

Impulse Sampling

Impulse Sampling of Signal s(t): $s(t) \leftrightarrow S(f)$

$$y(t) = s(t)\sum_{-\infty}^{\infty}\delta(t - nT_S) \quad \rightarrow \quad Y(f) = \frac{1}{T_S}\sum_{-\infty}^{\infty}S(f - nf_S)$$

Sampling Replicates of the Spectrum

Spectral Copies are Created Above and <u>Below</u> the Original

The Sampling Process Can be Utilized to Directly Up- or Down-Convert a Signal

Sub-Sampling Theory
(Bandpass, IF Sampling)

- Only need to sample at greater than twice the signal bandwidth
- Sample rates carefully chosen to prevent spectral aliasing
- Example - FM broadcast band 88 MHz - 108 MHz
  - f_C = 98 MHz, B = 20 MHz

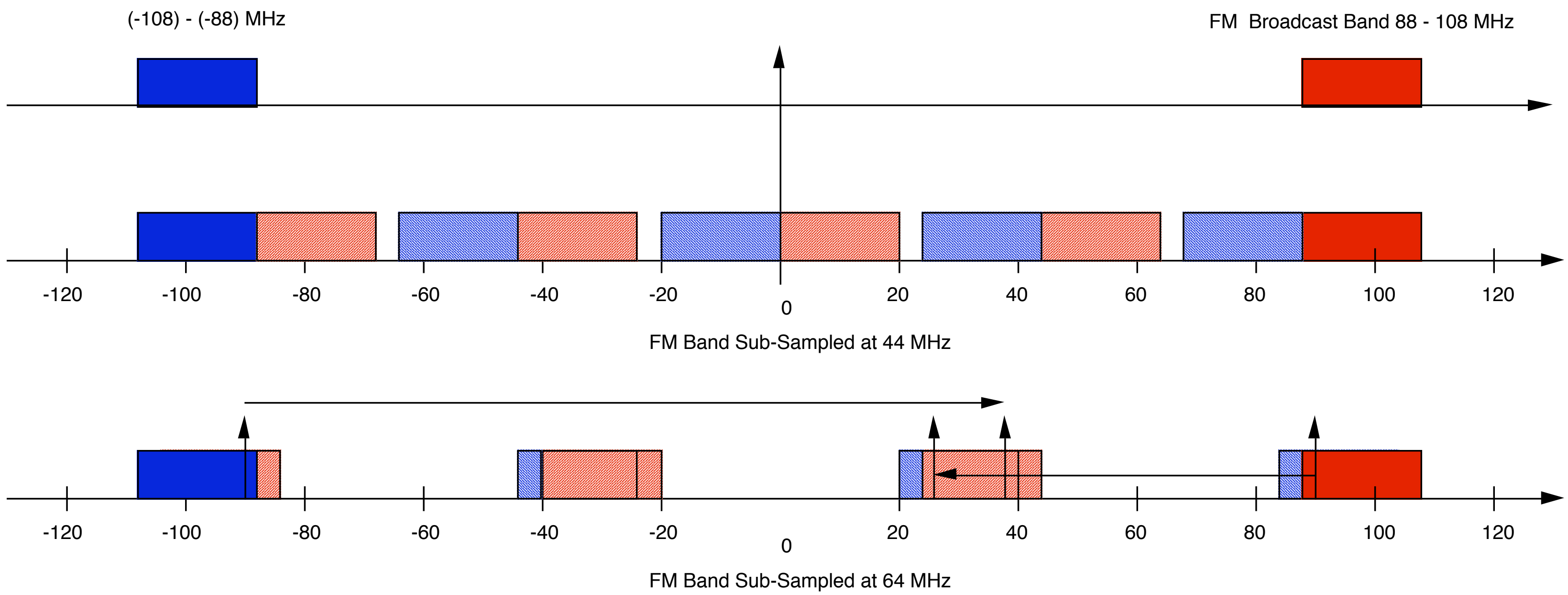
$B = Bandwidth$

$f_C = Band\ Center\ frequency$

$$\frac{2f_C + B}{m+1} \le f_S \le \frac{2f_C + B}{m}$$

Sample Rate Bounds for FM Broadcast Band		
m	Lower Bound (MHz)	Upper bound (MHz)
1	108	176
2	72.0	88.0
3	54.0	58.7
4	43.2	44.0
5	36.0	35.2
6	30.9	29.3

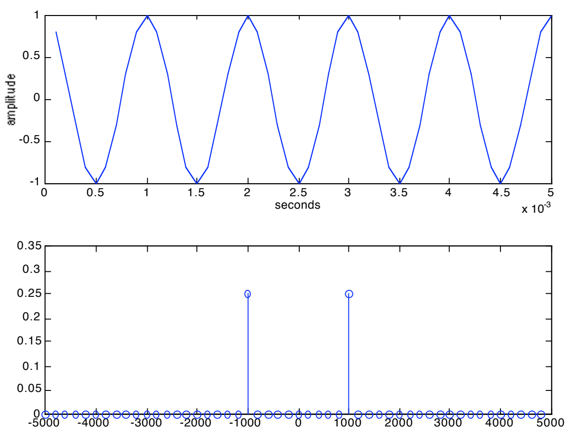
Sub-Sampling
FM Broadcast Band Example



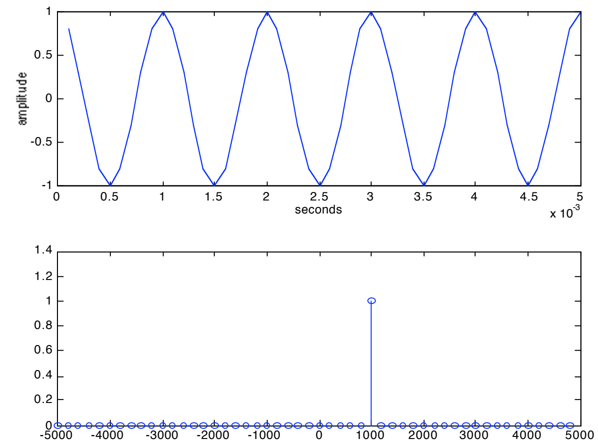
64 MSPS: 91.1 MHz Signal is Aliased to 100.9 MHz

Down Conversion Example
Higher Frequency Copies are Not Shown

Analytic Signals



$\cos(2000\pi t)$



$\cos(2000\pi t) + j\sin(2000\pi t)$

$\cos\omega t = \dfrac{e^{j\omega t} + e^{-j\omega t}}{2}$ contains two spectral components at $\pm\omega$

$e^{j\omega t} = \cos\omega t + j\sin\omega t$ (an analytic function) contains one spectral component at $+\omega$

Half-Complex Mixer

Quadrature Mixing - Real Input Signals

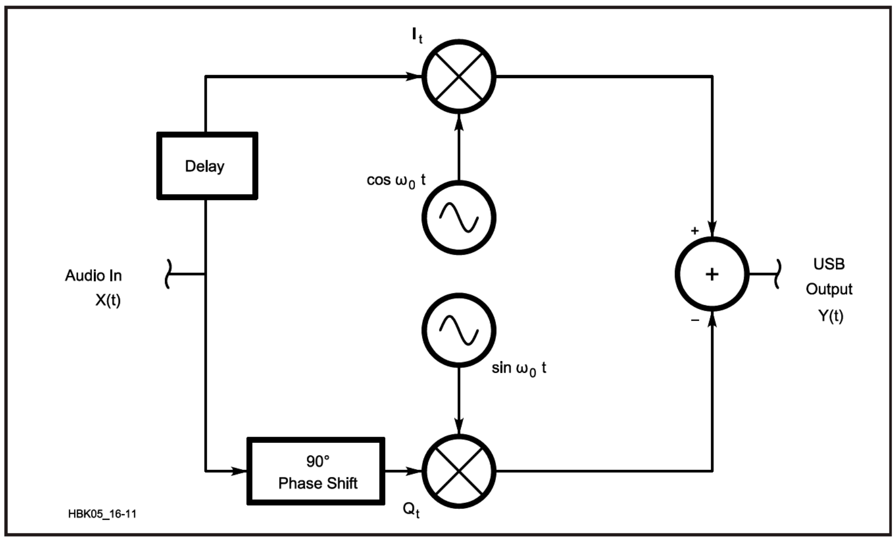


Fig 16.11—Block diagram of a half-complex mixer.

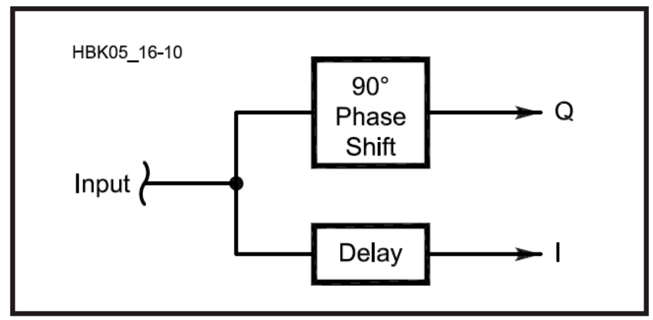


Fig 16.10—Hilbert transformer producing an analytic signal.

$$y(t) = x(t)\left[\cos\omega_o t + j\sin\omega_o t\right] = I(t) + jQ(t)$$

Quadrature Demodulation
AM & FM Signals

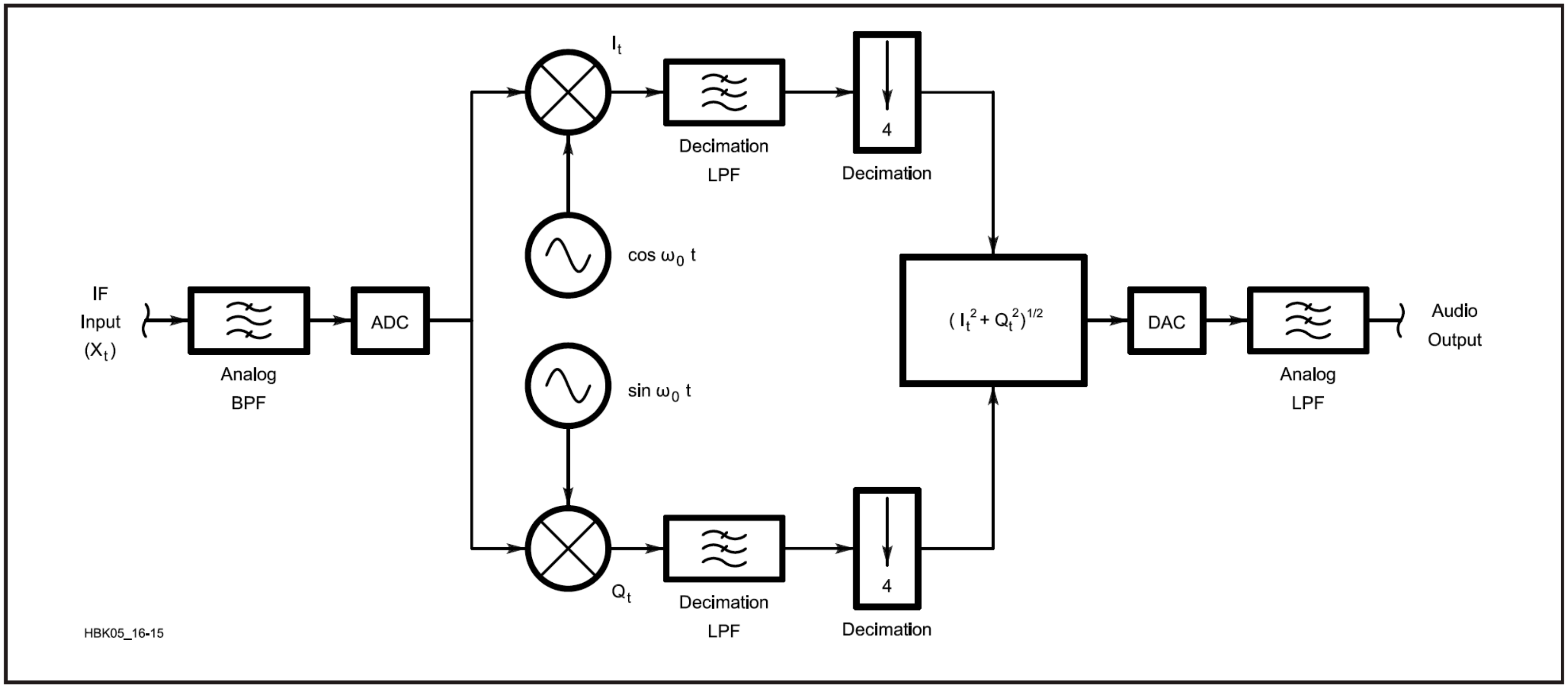


Fig 16.15—Block diagram of a digital AM demodulator.

$$A(t) = \sqrt{I^2(t) + Q^2(t)} \qquad \phi(t) = \tan^{-1}\left(\frac{Q(t)}{I(t)}\right) \qquad \omega = \frac{d\phi(t)}{dt}$$

From the 2007 ARRL Radio Handbook Chapter 16

Gnu Radio

Universal Software Radio Peripheral (USRP)

- Open Source Software
  - Linux, Windows, Mac
- USRP
  - 4 64 MSPS ADCs
  - 2 128 MSPS DACs
  - FPGA
    - DDC
    - USB Interface (32 MB/Sec)
- USRP 2
  - 128 MSPS ADCs
  - 256 MSPS DACs
  - Gb Ethernet Port

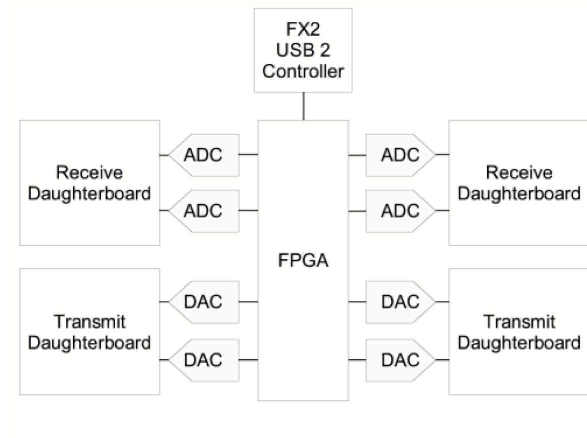


Figure 2: The USRP board

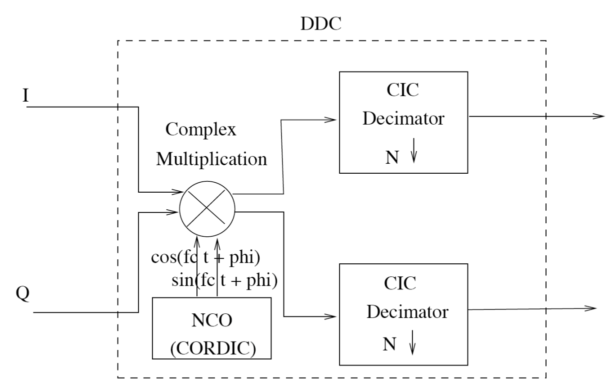
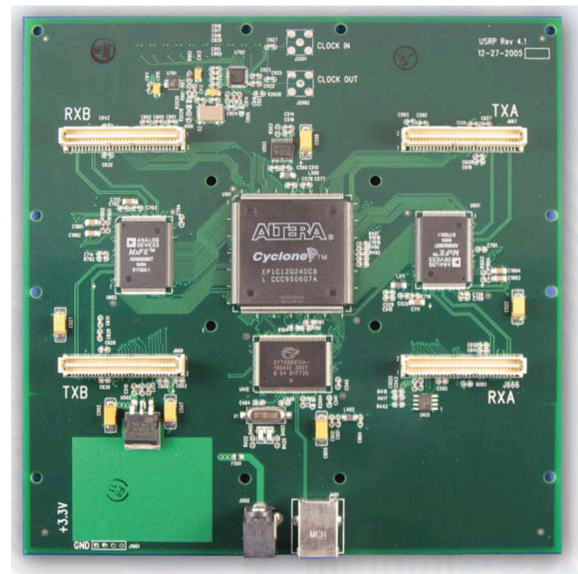


Figure 3: The block diagram of the USRP receive path

USRP Demonstration

- USRP and PC running Linux
- AM BC Receiver
- FM BC Receiver (WB)
- HF AM Receiver
- NBFM Receiver



Some SDR Sources

• Gnu Radio	gnuradio.org/trac
• HPSDR	hpsdr.org
• Pentek	pentek.com
• TenTec	tentec.com
• Flex Radio	flex-radio.com

- TI, Analog Devices, …
- Many More