Software and Software-Defined Radio

Part 1 – The Basics

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May 16, 2017

SECTIONS

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  - Architectural comparison of Superhet v. SDR
    - SDR versus IF/AF DSP
  - Advantages of SDR
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ITU-R Definition of Software Defined Radio

Recommendation SM.2152-0 Section 1

"A radio transmitter and/or receiver employing a technology that allows the RF operating parameters including, but not limited to, frequency range, modulation type, or output power to be set or altered by software, excluding changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard."

Simplified Definition of Software Defined Radio

"Performs the majority of signal processing in the digital domain using programmable DSPs with some analog hardware support, typically in the RF and IF circuits."

Definition of Software Radio

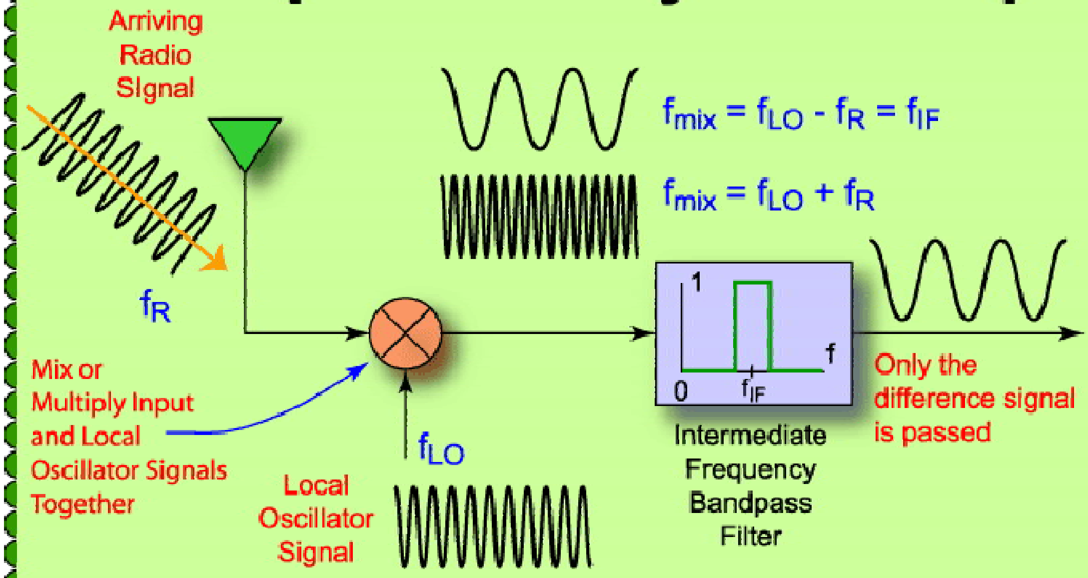
"All signal processing is done in the digital domain, with the antenna connected directly to an ADC/DAC tied to fully programmable high speed DSPs. All functions, modes, applications, etc. can be reconfigured by software."

Superheterodyne Analog Receiver

"In electronics, a superheterodyne receiver (often shortened to superhet) uses frequency mixing to convert a received signal to a fixed intermediate frequency (IF) which can be more conveniently processed than the original carrier frequency. It was invented by US engineer Edwin Armstrong in 1918 during World War I. Virtually all modern radio receivers use the superheterodyne principle."

"Heterodyne: a method of changing the frequency of an incoming signal by adding it to a locally generated signal in order to produce fluctuations or beats of a frequency equal to the difference between the two signals."

The Superheterodyne Principle



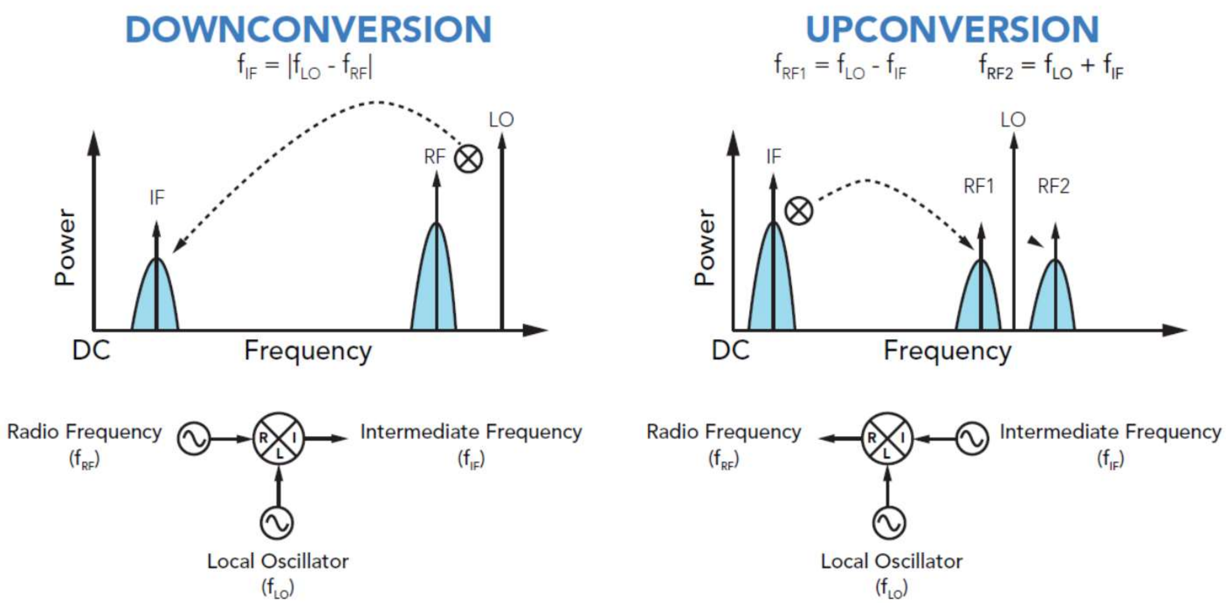
- To receive an AM broadcast station at say 1040 kHz we need to set f_{LO} above or below 1040 by f_{IF}.
- In our case f_{IF} = 455 kHz, so if we tune f_{LO} above 1040 kHz we set

f_{LO} = 1040 + 455 = 1495 kHZ

What a Superheterodyne Approach Buys Us

- The IF frequency allows us to move the desired signal into a region where cheaper and more linear components can be used for amplification, filtering and other processing
  - Analog processing for amplification and filtering
  - Digital processing for filtering and other DSP functions (IF DSP)
- Enhanced sensitivity and selectivity over earlier designs (e.g., TRF)
  - Tuned Radio Frequency (TRF) radios were quickly replaced by superhets
- Better stability versus earlier designs
  - A stable tunable oscillator is much easier to build than a tunable amplifier

Down-conversion vs. Up-conversion



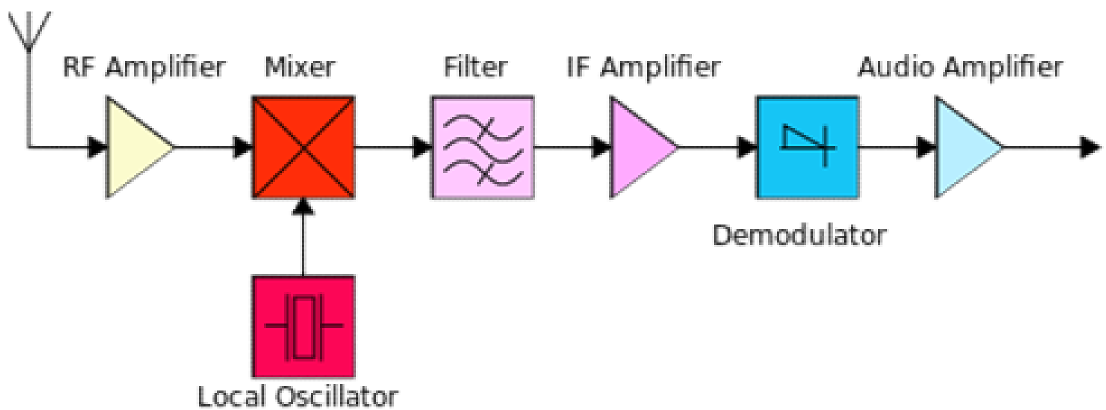
PROs and CONs of Downconversion

- PROs:
  - Improves selectivity as analog filters can be very sharp and still be affordable
    - Need to get selectivity as close to the antenna input as possible, and this does it
- CONs:
  - While a low IF frequency permits better selectivity, it exacerbates the image rejection problem
    - A serious problem in crowded RF spectrum
  - Double/Triple Conversion was supposed to be the answer
    - First IF used upconversion to enhance image rejection with the second IF using downconversion; however, this pushed selectivity further away from the antenna, producing higher intensity unwanted signal levels which resulted in cross and intermodulation problems
      - Triple Conversion was supposed to be the answer to that problem, using an ultra-low frequency for the first IF
      - Filtering becomes expensive with IF DSP filtering being the norm today

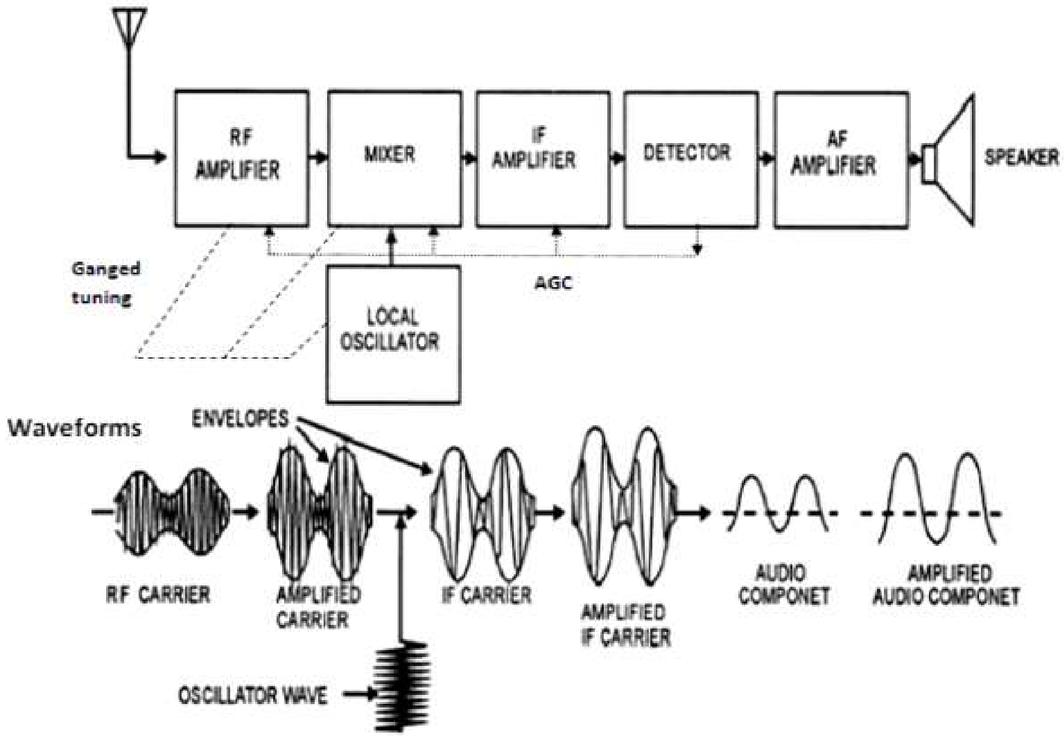
PROs and CONs of Upconversion

- PROs:
  - Made possible by the appearance of affordable stable synthesizers and high frequency narrow crystal filters
  - Upconversion to a frequency higher than the desired signal in combination with a low pass filter led to inexpensive superhet receivers w/o expensive tuned circuits
    - Suffered from poor intermodulation performance and additional IMF problems in the crystal filters
- CONs:
  - Moves selectivity further away from the antenna, allowing unwanted signals to get amplified BEFORE the selectivity stage
    - Makes filtering out unwanted signals more challenging, especially when close-in to weaker desired signals
    - DSP processing in the second IF can help with this challenging task

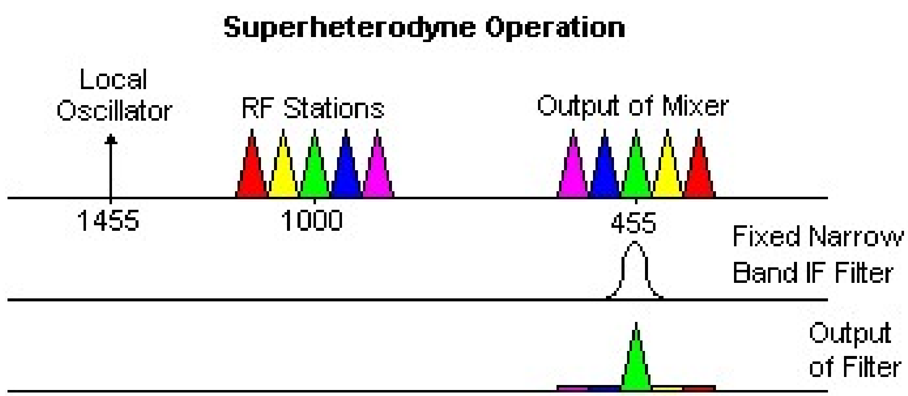
Superheterodyne Receiver Block Diagram



RF Processing



Superheterodyne Operation



Tuning in a station is achieved by changing the frequency of the local oscillator so that the desired signal now appears in the mixer's output

Challenges in Superhet Radio Design

- Only certain nonlinear devices make ‘good’ mixers
  - Schottky diodes, GaAs FETs and CMOS transistors
    - Noise Figure of the device limits MDS
  - Conversion losses result in less power in the IF output signal
    - Typically 4.5 to 9 dB
- Phase noise and jitter in the LO as well as various nonlinear features in the mixer cause many products to appear in the mixer output
  - Harmonic mixing
- Signal compression
- LO leakage into the RF port
- Intermodulation Distortion (IMD)
  - Single and multi-tone

Challenges in Superhet Radio Design

- Image Frequency
  - An undesired input frequency equal to the station frequency plus twice the intermediate frequency
    - Results in two stations being received at the same time
  - Strategies for image rejection
    - Bandpass filter in the RF front end (“preselector”)
    - Filter in front of the mixer
    - LO frequency far away from the bandpass frequency for better bandpass filtering
    - Attenuating features built into the mixer
    - IF DSP processing which removes the image frequency
  - Image rejection ratio in decibels is a key metric in superhet receivers

Challenges in Superhet Radio Design

- Local oscillator radiation
  - LO acts like a low-power CW transmitter
  - Sensitive modern radios nearby can see that as interference
  - Equipment designed to detect this at distance can determine the presence of a receiver and what it's tuned to
    - MI-5 Operation RAFTER: detection and monitoring of clandestine Soviet agents and radio transmissions by embassy personnel during the Cold War era
    - Police department radar detector detectors
  - Strategies to reduce LO radiation
    - RF amplifier before mixer
    - Shielding the LO and mixer
    - Keep traces short which carry these signals and put them between ground planes in multilayer PCBs

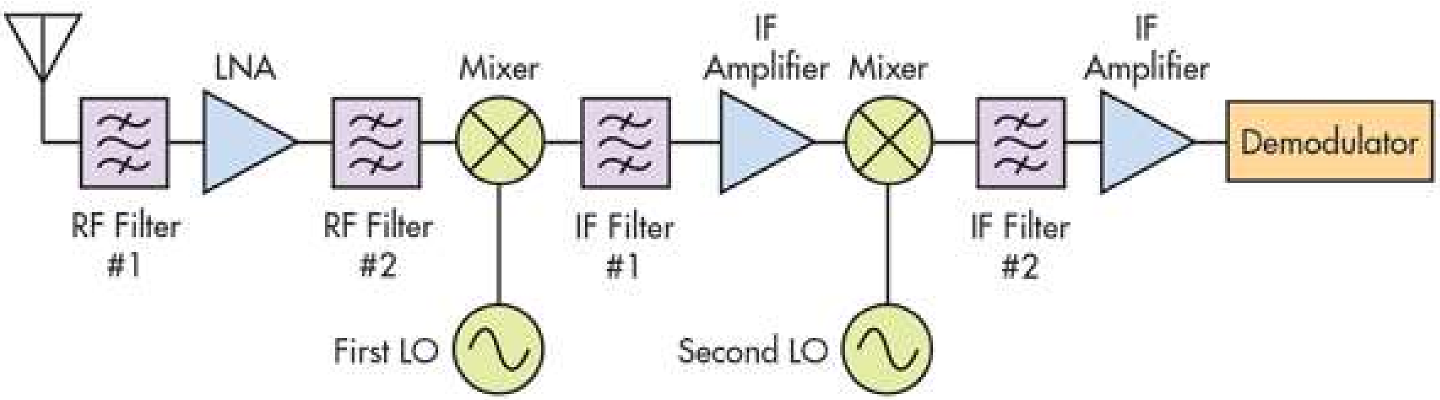
Challenges in Superhet Radio Design

- Local Oscillator sideband noise
  - Modern LO designs have negligible AM modulation but some phase modulation from LO phase noise
    - Either type generates noise in sideband frequencies
  - Phase noise is minimized by designs which keep the LO very linear in operation
  - Phase noise is measured as dBc/Hz
    - The power ratio of a signal relative to a carrier at a certain frequency offset
    - Higher number is better
    - Sherwood engineering: http://www.sherweng.com/table.html

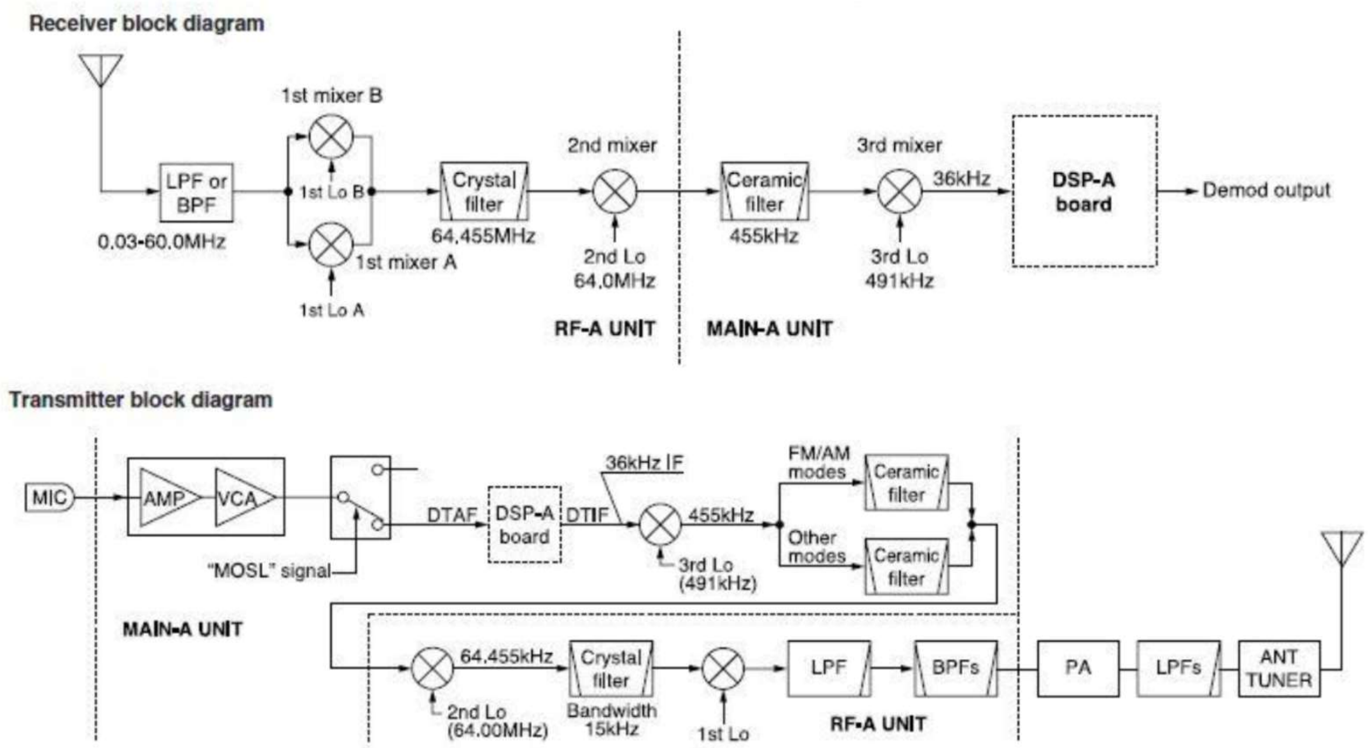
Advantages/Disadvantages of Multiconversion

- Advantages:
  - In combination with modern analog filters, low phase noise and low jitter oscillators, improved mixers and IF DSP, the modern multiconversion receiver offers vastly improved selectivity and image rejection
- Disadvantages:
  - Spurs and “birdies” become significant self-induced problems
    - EXAMPLE: Kenwood TS-2000 (Quad Conversion) has numerous birdies, many in the middle of the amateur satellite frequencies
  - Close-in strong signal rejection is still difficult and costly to deal with
    - A weak signal is still easily swamped by a nearby strong signal

Modern “Double Conversion” Superhet



Typical Legacy HF Transceiver

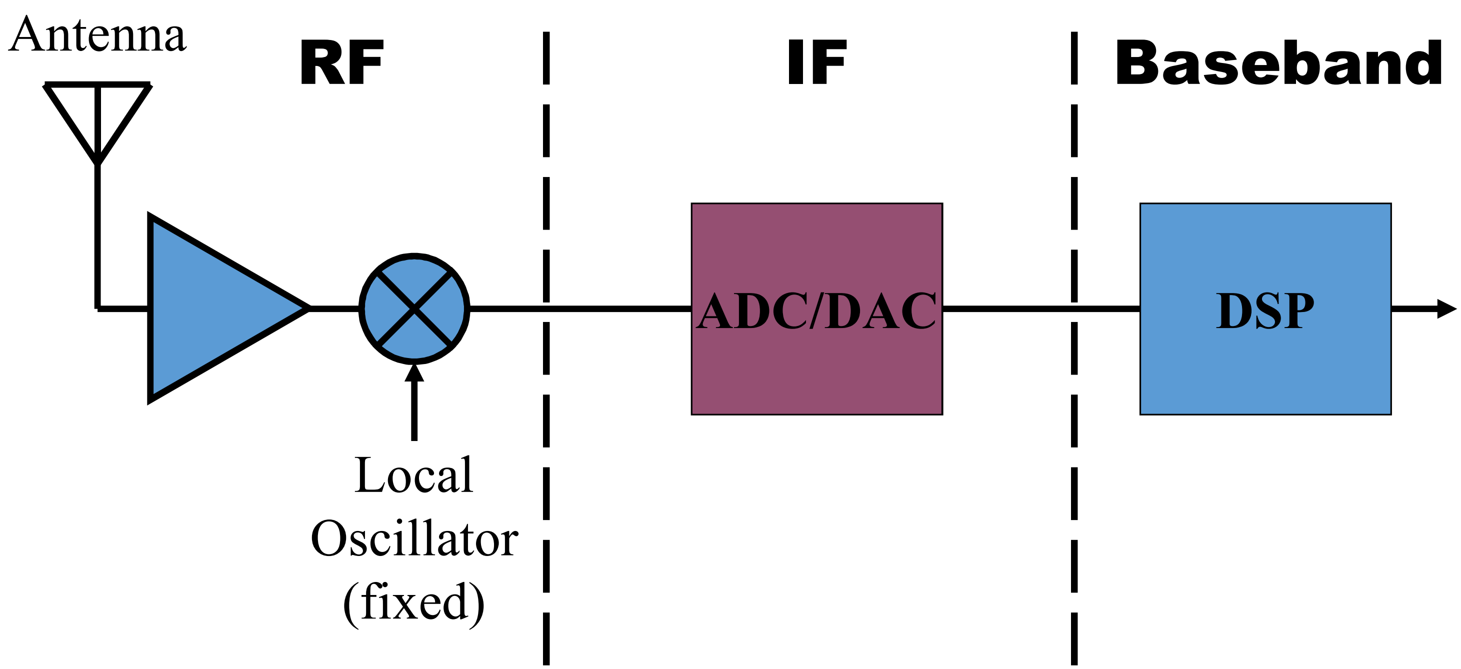


- In a direct-sampling SDR RX, the ADC and FPGA replace all the blocks between the LPF/BPF and the DSP. Input.
- In a DUC TX, the FPGA and DAC replace all the blocks between the DSP output and the exciter LPF/BPF group.
- The DSP, with its input ADC and output DAC, is in effect a "mini-SDR" operating at the 36 kHz IF.

Why Software & Software Defined Radios?

- Analog radio technology has advanced about as far as possible
- Analog designs are very rigid and not readily extensible; whereas SDR facilitates experimentation and enables a wealth of new capabilities:
  - Doesn’t suffer from the myriad problems with superhet analog designs
  - Ability to ‘see’ large chunks of RF spectrum at once (Panafall display)
  - New modulation methods/modes and secure comm capabilities
  - Advanced filtering algorithms with 1Hz edges
  - More efficient use of limited spectrum
  - Simultaneous voice, data and video
  - Networkable
  - Reduced obsolescence
- Reduced cost due to substantially reduced parts count
  - Enhanced reliability

Typical Software Defined Radio Receiver

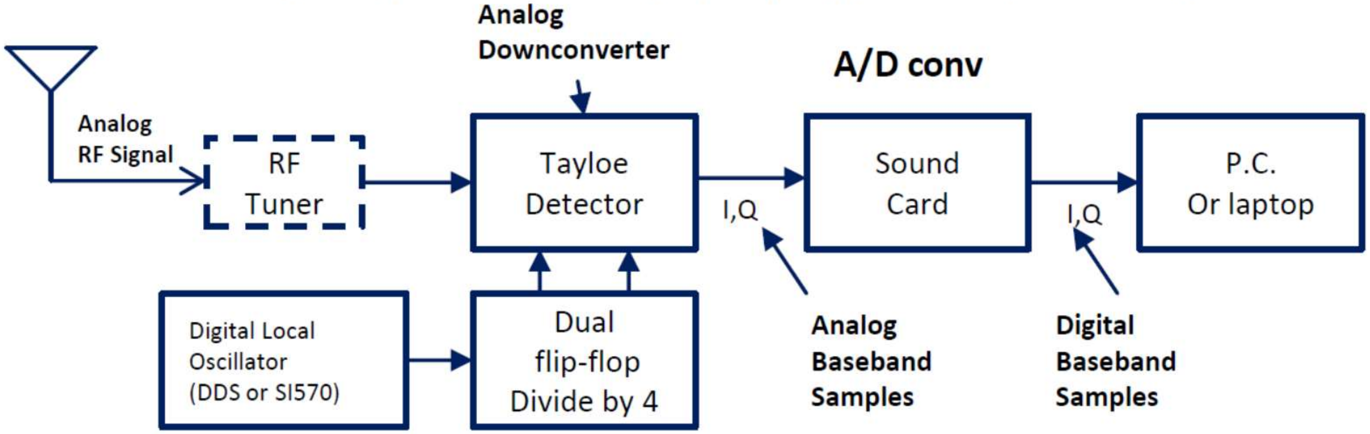


Digitization of RF Signals

- In an SDR radio, the incoming RF signal is digitized into a data stream of values that can be subjected to mathematical processing ("DSP")
- That data stream is called an "I/Q Data" stream
- Advanced mathematical algorithms can be applied to that stream to:
  - Identify individual signals
  - Demodulate signals
  - Perform advanced filtering
  - Isolate weak signals
  - Basically anything that can be done mathematically, something that analog filters could never do
- The next slide shows how this is typically done in most SDR radios

Typical SDR Quadrature Sampling Detector

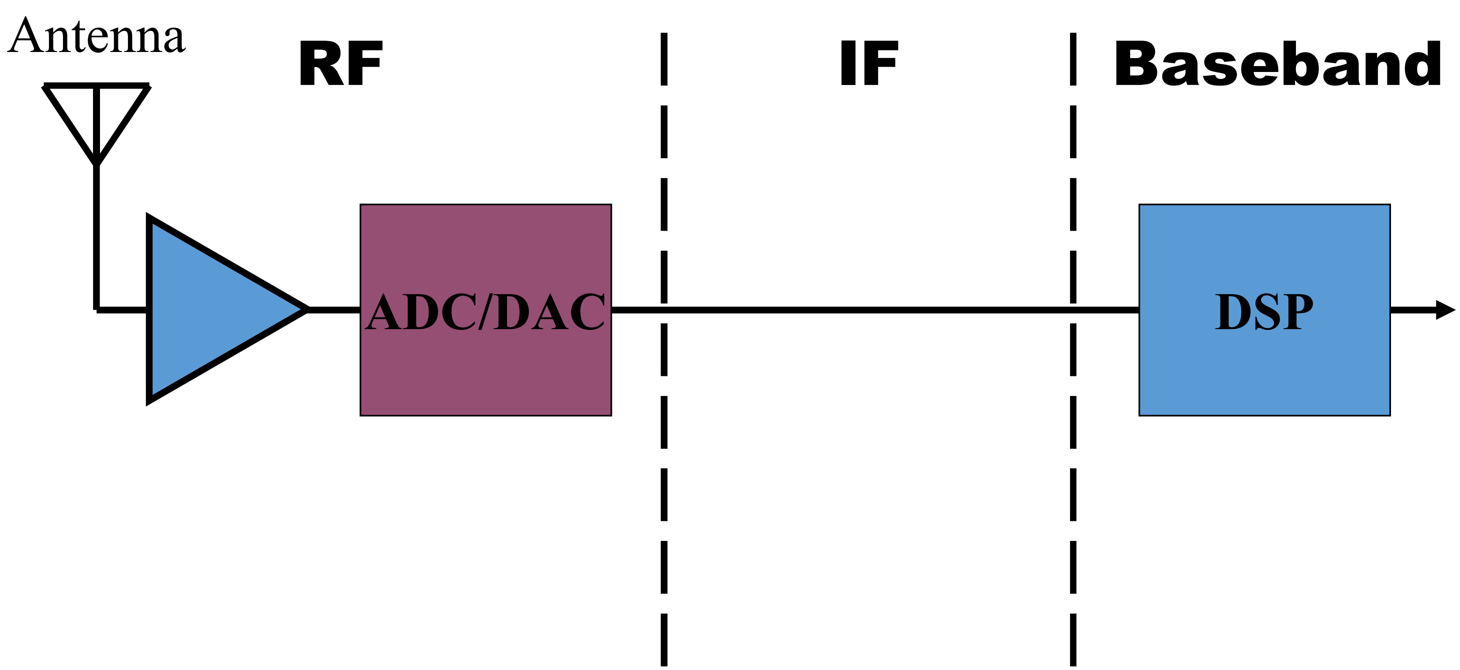
Quadrature Sampling Detector (QSD) type – A/D samples at baseband



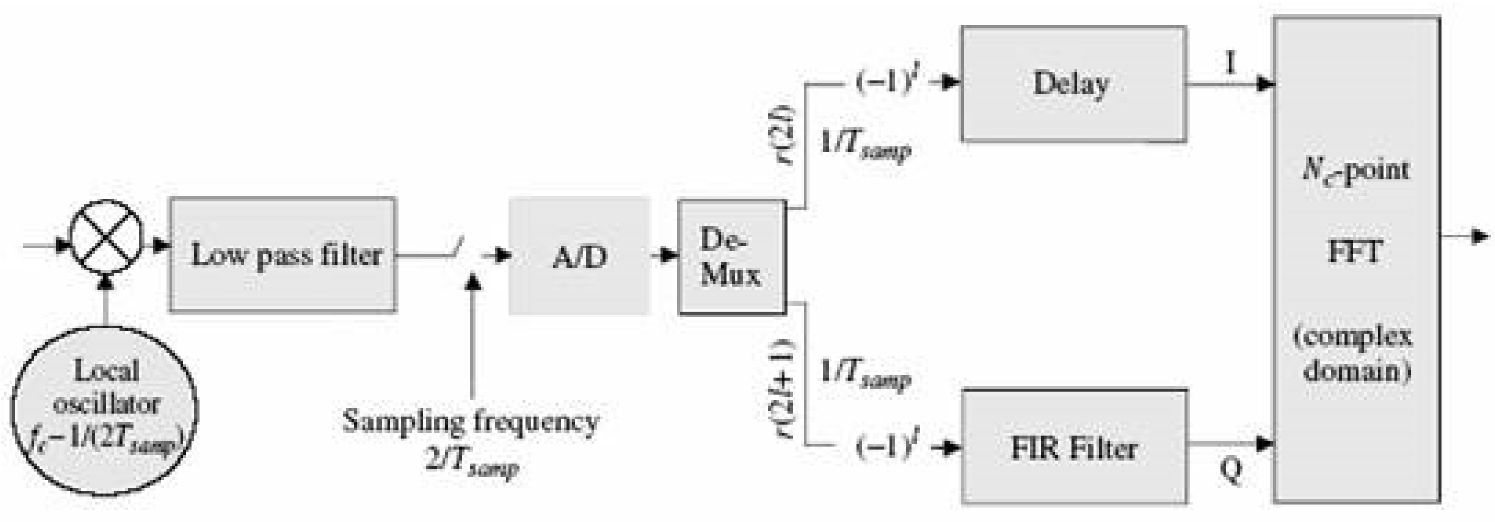
Note: An exciter is known as a quadrature sampling exciter (QSE)

Typical Software Radio Receiver (Direct Conversion)

Eliminates problems associated with analog mixers



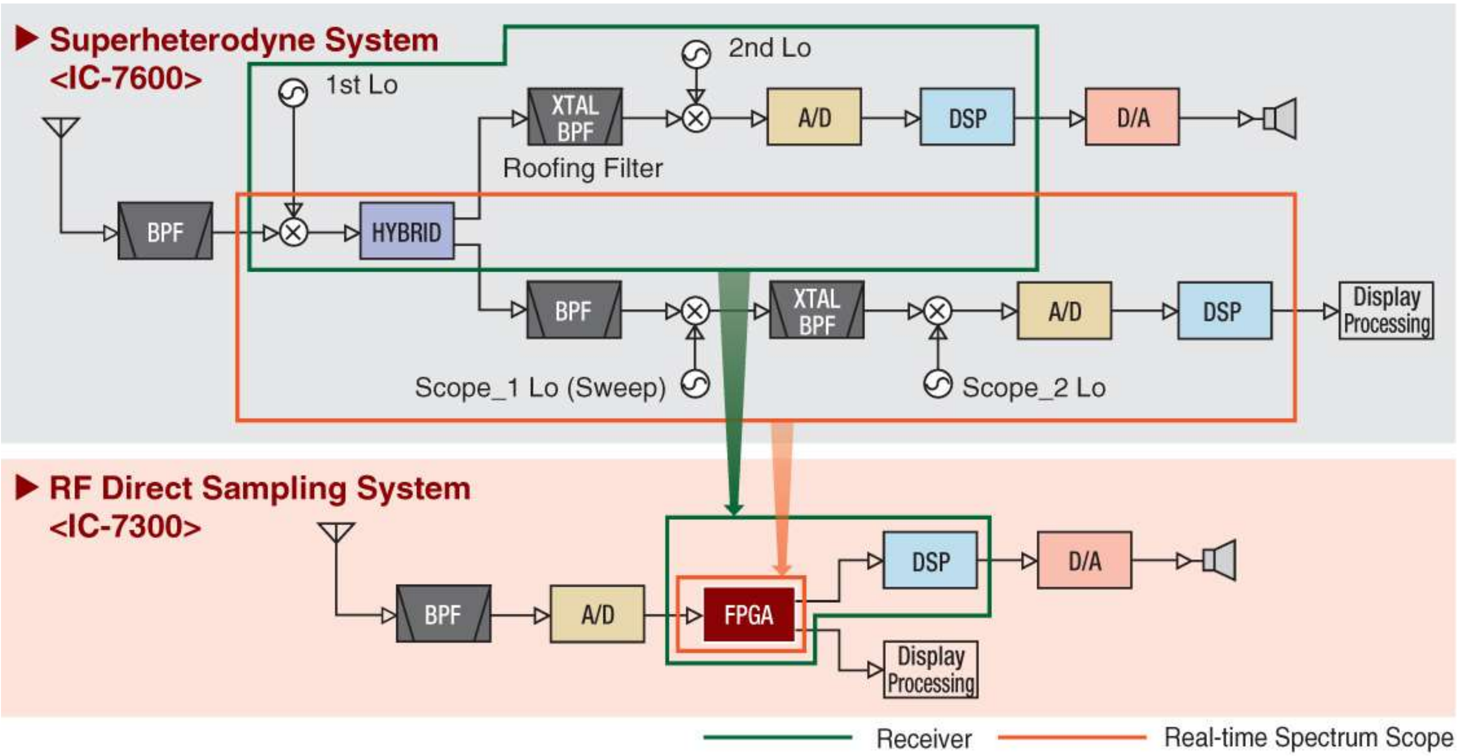
Digitally Decoded I/Q



Nyquist-Shannon Sampling Theorem

- Only applies to mathematical functions involving a Fourier Transform that is ‘zero’ outside of a finite range of frequencies
  - A Fourier Transform (FT) reduces a signal into the frequencies and phase relationships of which it’s composed
- The theorem defines a formula for perfectly reconstructing a signal from a limited number of samples
  - The fidelity of these reconstructions can be verified by Bochner’s Theorem
- The theorem demonstrates that a sampling rate of twice the frequency being sampled is sufficient to faithfully reproduce it
  - Therefore, the ‘speed’ (sampling rate) of an ADC governs the maximum frequency signal it can process
    - Higher speed = greater cost

Real World Case: ICOM IC-7300



Current street price: $1350

HF+50MHz（SSB/CW/RTTY/AM/FM）100Wトランシーバー

IC-7300

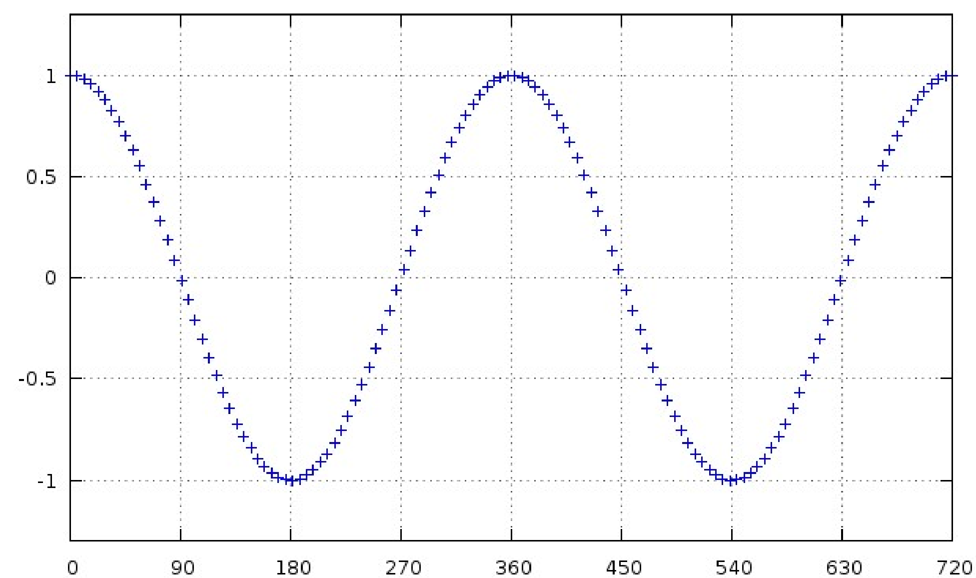
2 アマ免許

●IC-7300M＜50Wタイプ＞ 3 アマ免許

●IC-7300S＜10Wタイプ＞ 4 アマ免許

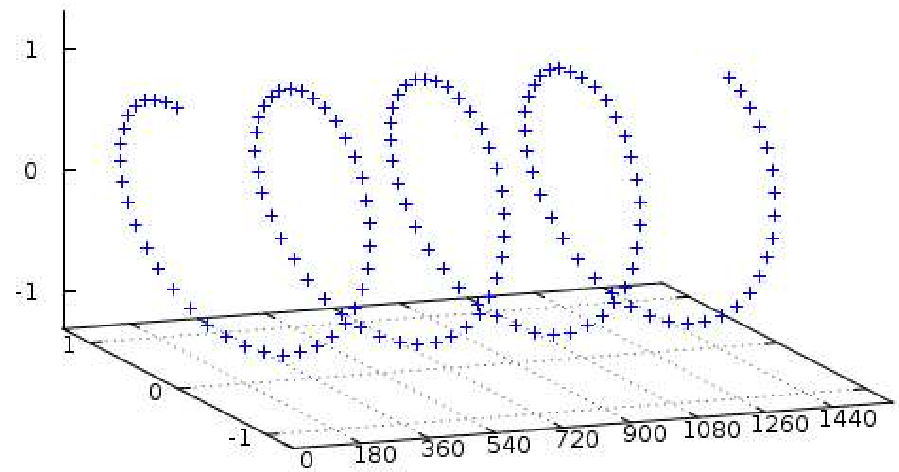
What's Up with this I/Q Sampling Thing?

- I/Q (aka "analytic signal") is a means of representing a signal more precisely than by a simple series of amplitude samples:
  - What's the frequency of that plot?
  - Is it positive or negative?
  - What is the power of the signal?



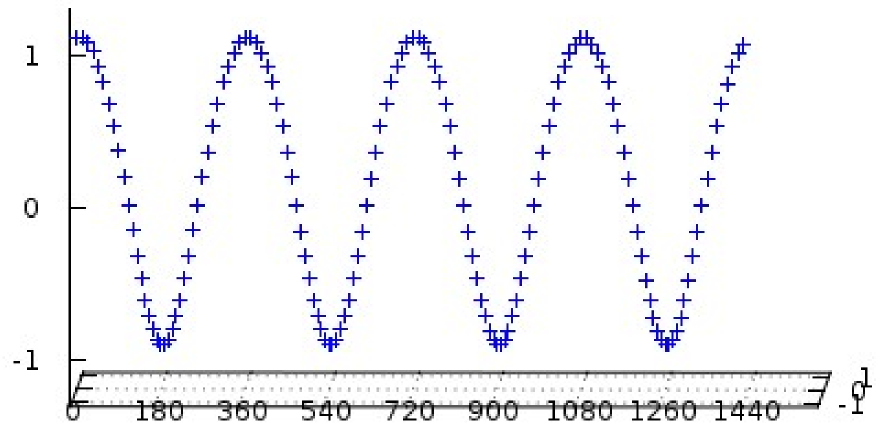
I/Q Representation

- I/Q data is '3D', like a corkscrew:
  - Winds counter-clockwise for positive frequencies; clockwise for negative
    - "I" remains the same, but "Q" signal will be different



I/Q Representation – Side View

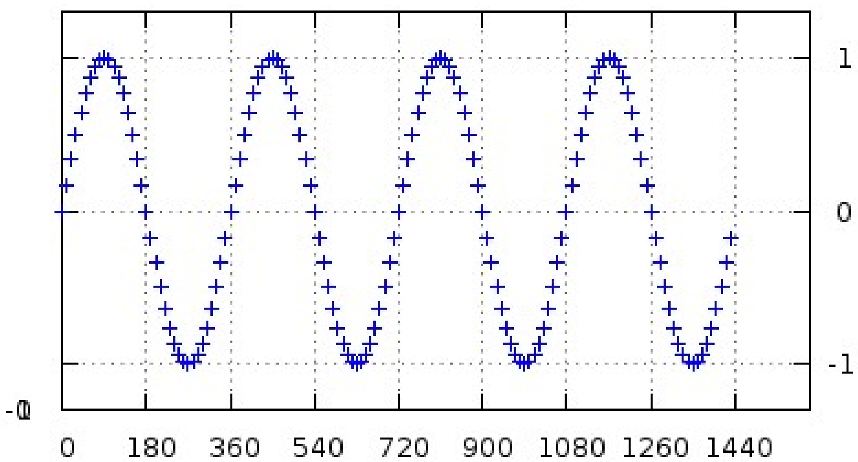
- Look at the curve from the side and you get the original plot
  - This is the “I” in I/Q



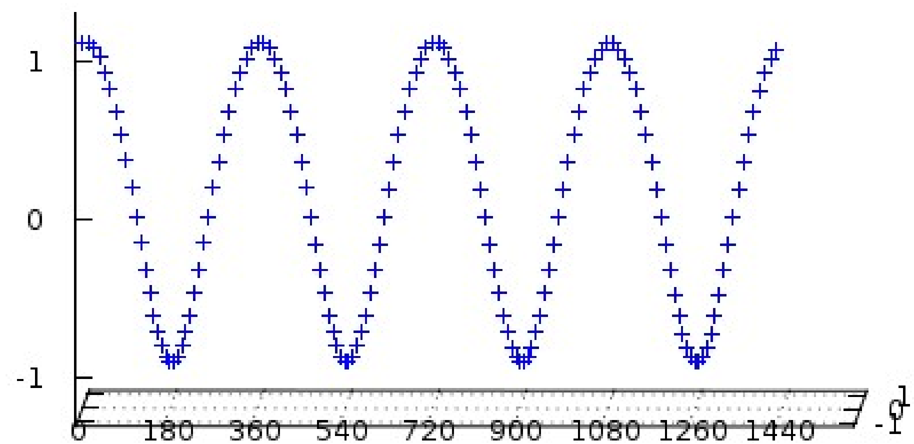
I/Q Representation – Top View

- Look at the curve from above and it looks similar but it’s 90 degrees out of phase
  - This is the “Q” in I/Q

TOP

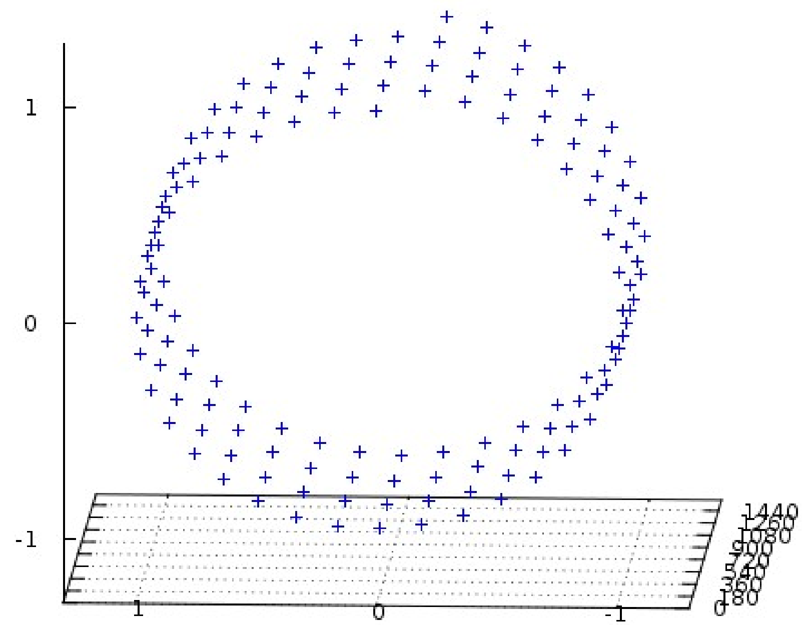


SIDE



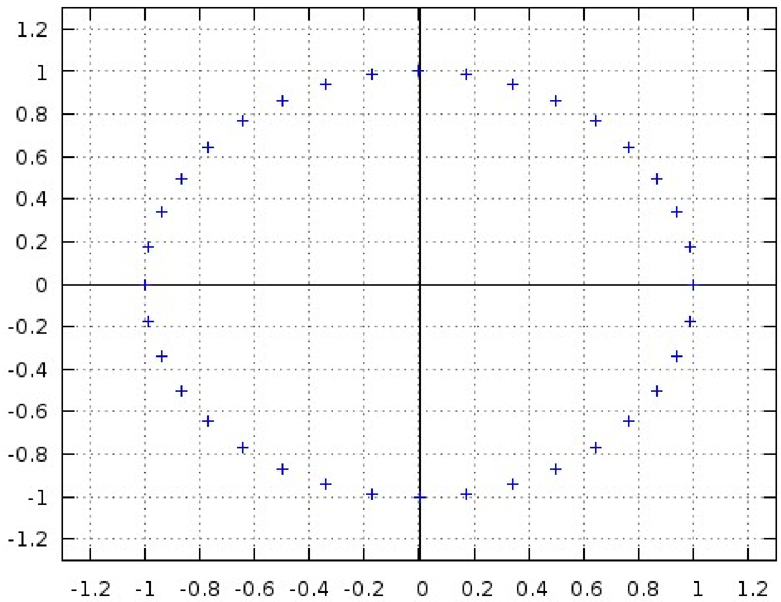
Amplitude Encoding in I/Q Data

- Radius of the corkscrew represents the amplitude of the signal
  - If ‘I’ is small, ‘Q’ is large and vice versa



I/Q Data Summary

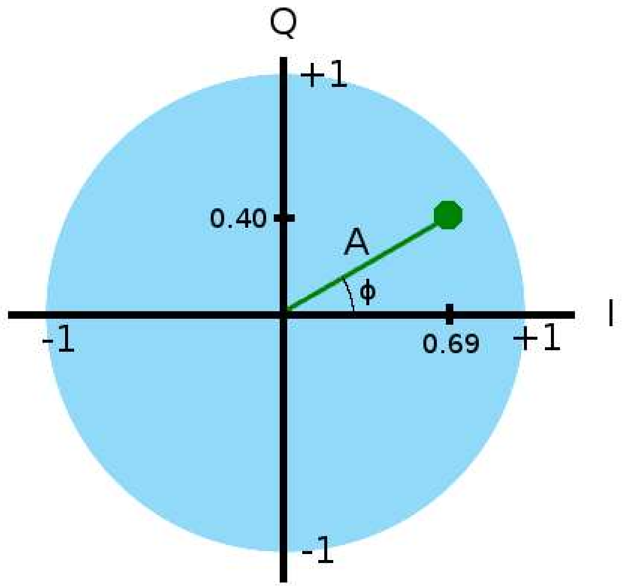
- I/Q is the coordinates of the signal as seen down the time axis of the corkscrew:



Every single point of your signal can be described as the function I = A·cos(φ)

I/Q Data Example:

- 'I' = 0.69 ; 'Q' = 0.40
- Momentary amplitude = 'I'
- Pythagoras tells us the amplitude 'A' of the cosine wave is $(0.69^2 + 0.40^2)^{1/2} = 0.8$
- Trigonometry informs us that our angle is $+30^o$ into our cosine wave
- Thus the real signal is $I = 0.8 \cdot \cos(30^o)$
- Since there are four quadrants, this is why our detector is called a "quadrature detector"



Demonstration of I/Q Mapping to Real Signal

- Two I/Q signals (Red v. Blue) on the left
- Real projections on the right
- They obviously differ in signs in I/Q, although the signs aren't obvious in the real signal component (neither 'I' nor 'Q' separately)

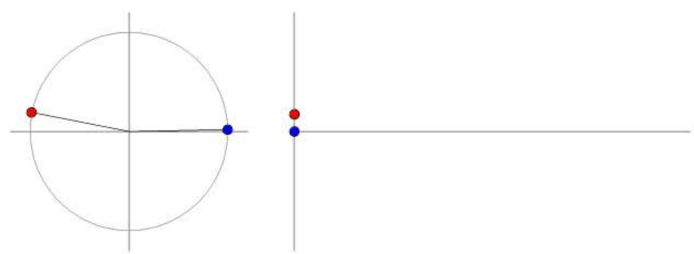
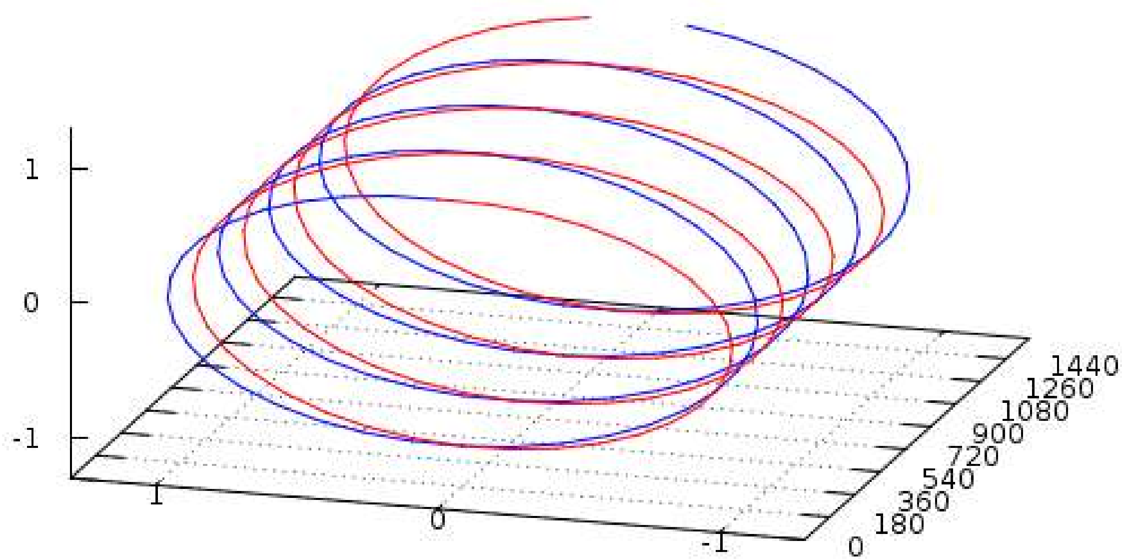
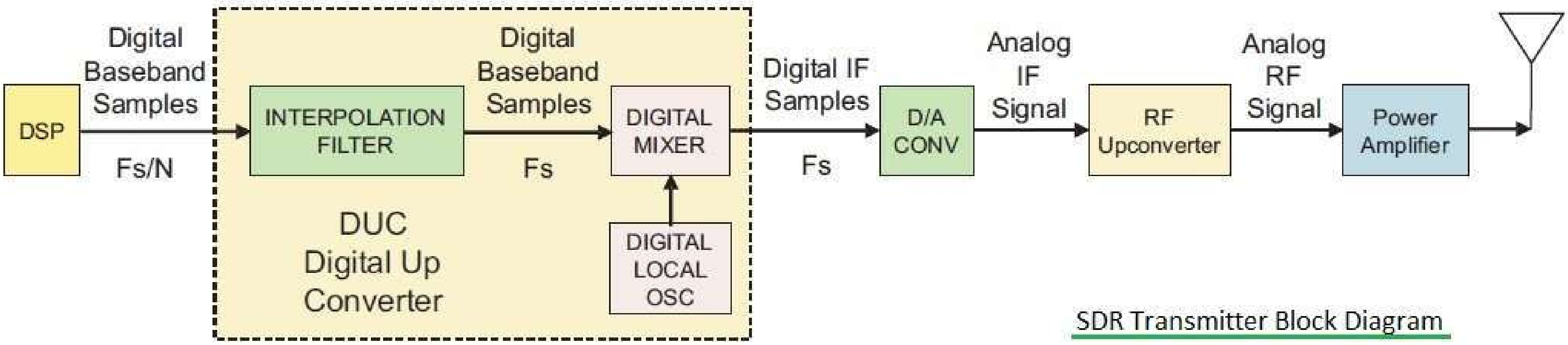


Image courtesy of whiteboard.ping.se

Same two I/Q Signals Charted in 3D



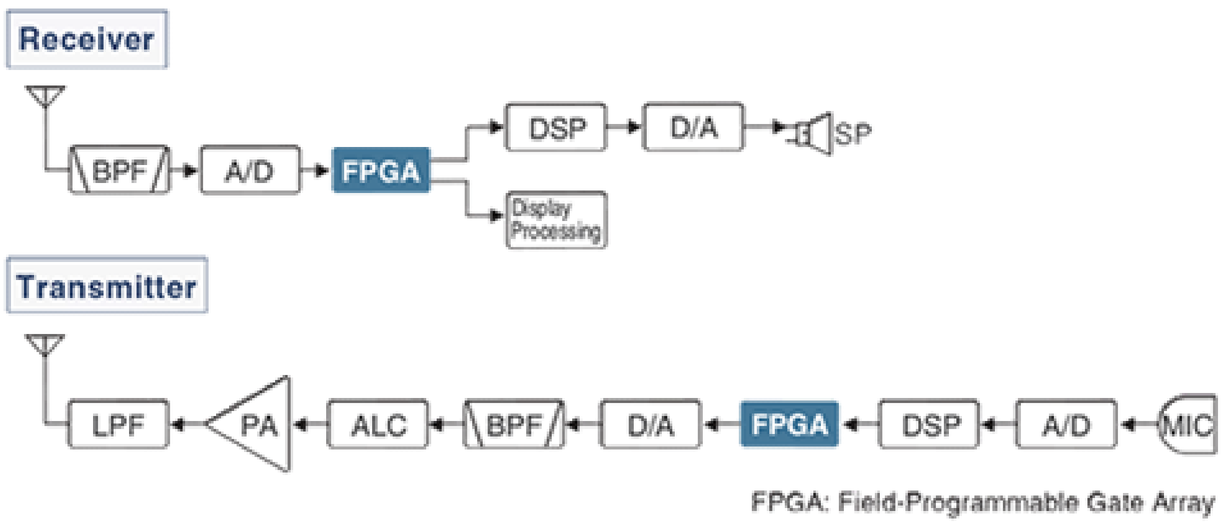
Typical SDR Transmitter



SDR Transmitter Block Diagram

- Mixer generates one output sample for each of its two input samples
- Sample frequency at the mixer output = DAC sample frequency (Fs)
  - LO sample rate must also equal Fs
- Input baseband sample rate is usually much lower; hence the interpolation filter

Real World Case: ICOM IC-7300



Why You Might Want an SDR Radio

- Performance which meets or exceeds the performance of high end radios such as the Icom IC-7851 ($12,499), but at one-fourth the price
- You get a new radio with every firmware/software update
- Real-time spectrum and waterfall display and multiple receivers at an affordable price
- Your radio can be easily networked and remotely accessed
- You'll simply be amazed at its performance compared to any other analog radio you've ever operated
- If you must have knobs and buttons, you can
  - Icom IC-7300 and IC-7610

Future Applications of SDR

- Smart Radios that automatically configure themselves to the communication task at hand
- Cognitive Radios that learn about their environment (e.g., interference, noise, location, elevation, power available, etc.) and adapt to maximize efficiency and effective communication
  - Unjammable military and emergency comms

Q&A