Practical Software Radio

Why Things Don't Always Match the Textbooks

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September, 2011

Outline

1. Introduction
2. Measurements
3. Radio Architectures
4. Impairments
   - Hardware Inherent
   - Architecture Specific

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Essentially, all models are wrong, but some are useful.
– George E. P. Box

Topics

- Making measurements
- Radio Architectures
- Real-world impairments
  - What they are
  - How to recognize and diagnose them
  - How to fix them

Signals of Interest

- Sine waves (single and multi-tones)
- FSK
- PSK/QAM
- OFDM

Radio Architectures

- Heterodyne
- Direct conversion

Impairments

- Hardware independent
  - AWGN
  - Multi-path
  - Frequency and phase offset
  - Symbol rate and timing offset
- Hardware Inherent
  - Non-linearity
  - Quantization
  - Phase Noise
  - Passband shape and group delay
- Architecture Specific
  - DC Offset
  - IQ Balance

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Interpreting Spectrum Analyzer measurements

- What is Noise floor?
- Bandwidth
- Measuring power
  - Parsevals theorem
  - Scalloping "loss"
- Spectral estimation
- Averaging
- Windowing
- The differences between swept and FFT spectrum analyzers

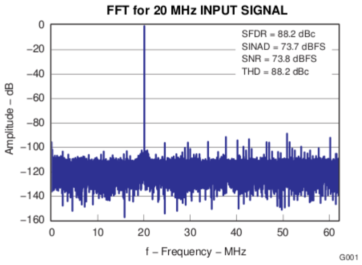
Windows

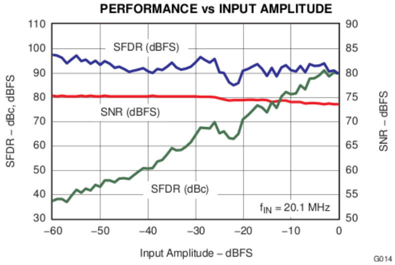
- None (aka square)
  - Narrowest BW
  - Most leakage
- Hamming
  - Good narrow BW, high sidelobes
- von Hann (aka "Hanning"), Blackman-Harris
  - Good general-purpose
- Flattop
  - No scalloping
  - Wide BW

Metrics and Definitions

- What is SNR?
  - SNR, SNDR, SINR
  - CNR (C/N0)
  - Eb/N0
  - The misunderstood "Noise Floor"
  - Noise figure
- What is Sensitivity?
- What is dynamic range?
  - SFDR
  - IP3
  - Power handling
  - Gain control range
- Universal figures of merit

Example Specs





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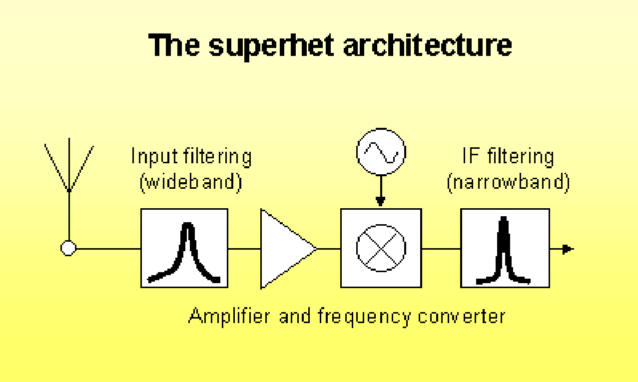
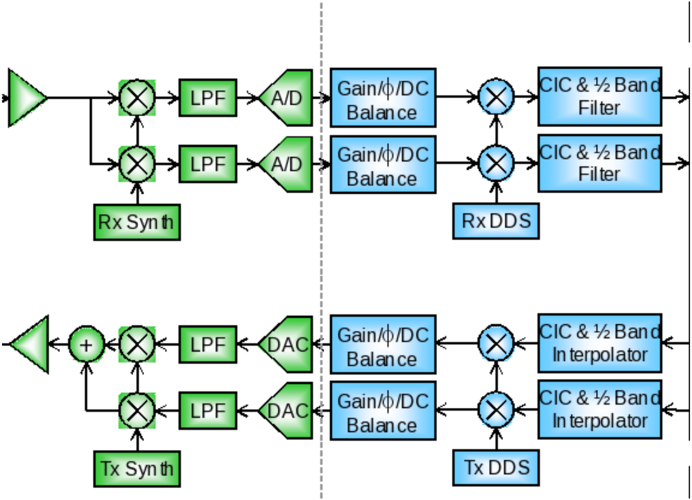
Heterodyne


The superhet architecture
Input filtering
(wideband)
IF filtering
(narrowband)
Amplifier and frequency converter

Direct Conversion



Heterodyne Vs. Direct Conversion

- Heterodyne is simpler
- Wideband easier in Direct Conversion
- Fewer spurs in DC, but harder to fix them
- RF vs. IF vs. BB Filtering
- Component matching critical in DC

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Hardware Inherent

- Non-linearity
- Quantization
- Phase Noise
- Passband Shape and Group Delay

Non-linearity

- Output not a multiple of the input
  - Transfer function depends on amplitude
- Primary mechanism in semiconductor amps is clipping behavior as you approach maximum output
- $V_{out} = k_1 V_{in} + k_2 V_{in}^2 + k_3 V_{in}^3 + \ldots$
  - $cos^2 x = \frac{1+cos2x}{2}$
  - $cos^3 x = cos(3x) + 3cosxsin^2 x$
  - Output contains frequencies not in the input (harmonics and mixing products)
- Not just amplifiers (mixers, capacitors, inductors, even connectors)
- More complex models
  - Volterra Series
  - AM-AM and AM-PM

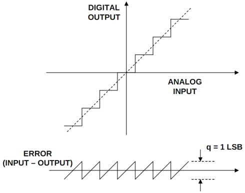
Third order non-linearity

- Third order the most important
- Typically modeled with third order intercept (IP3, IIP3, OIP3)
  - Intercept point is the [extrapolated] point at which intermod products would equal desired products
  - Typically ~10dB above P1dB
  - Don't actually operate at that point!
- $P_{IMD3} = 3P_{signal} - 2IP_3$
  - IMD3 products increase 3x as fast as input
  - IMD products appear at $2f_1 \pm f_2$, $2f_2 \pm f_1$, $3f_1$, $3f_2$

Second order non-linearity

- 2nd order products fall at DC, $f_1 \pm f_2$,$2f_1$, $2f_2$
- DC IMD2 product often mistaken for DC offset
- Only a problem in certain situations
  - Band of interest is greater than 1 octave
  - Band of interest includes DC
  - Direct Conversion receivers

Quantization



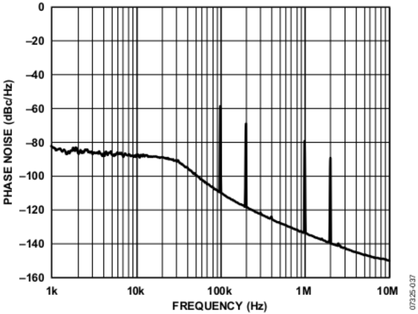
- Not to be confused with discretization (i.e. time steps)
- Inherent in digital systems
  - Finite bit widths in ADC, DAC
  - Costs of digital processing, storage, transmission
    - Cost of a Multiply operation is proportional to bits^2
  - Even floating point numbers are quantized

Quantization, cont'd

- Quantization results in noise
  - Often modeled as AWGN
    - Beware of correlated quantization noise ($f/f_s \backsimeq M/N$)
  - $SNR = 6.02N + 1.76dB$
- Non-ideal ADC/DAC behavior causes similar problems to correlated noise

Phase Noise

- Random phase perturbations on an oscillator
- Specified as dBc/Hz at an offset from carrier
  - i.e. -100dBc/Hz at 100kHz offset
- Modeled by the Leeson phase noise equation
- Spurs are a related phenomenon with similar symptoms



Phase Noise, cont'd

- Always causes self noise
  - increasing signal doesn't help
- -100dBc/Hz doesn't sound like much
  - Over a 10 MHz BW signal that equates to -30dBc
    - No QAM 256 for you!
- Total integrated phase noise often specified
  - I.e. 1.5 degrees RMS in a 20kHz to 80 MHz BW
- On TX causes adjacent channel emissions, broadband noise floor
- On RX mixes strong adjacent signals onto desired signal

Passband Shape

- Rolloff at edges of passband are common
  - causes loss of signal energy
  - can cause inter-symbol interference (ISI)
- Many filters have ripple, like:
  - SAW filters
  - Chebyshev filters
  - Parks-McClellan FIR filters
- A transfer function which is not flat in the frequency domain is not an impulse in the time domain
- Spread in the time domain can smear adjacent symbols

Group Delay

- Group delay is the frequency derivative of the transfer function:
  - $D(\omega) \triangleq -\frac{\partial}{\partial \omega} \measuredangle H(\omega)$
- Linear phase means constant group delay
- Many filters do not have linear phase:
  - IIR filters
  - non-symmetric FIR filters
  - all analog filters
- Non-constant group delay means dispersion
  - Like ISI, but can be worse
    - 4FSK example
- Filters can be designed to compensate for group delay variation

Architecture Specific

- DC Offset
- IQ Balance

DC Offset

- Causes
  - Component mismatch
  - LO leakage
  - 2nd order distortion
- Varies with time, temp, frequency, voltage, moon phase, etc.
- Produces self interference
- Remedies
  - Ignore DC (use low-IF or ignore DC bin in OFDM)
  - AC-couple
  - Highpass filter (receiver only)
  - Estimate and subtract in either analog or digital domains
    - must be done at true baseband
    - much easier on the receiver

IQ Imbalance

- Magnitude imbalance caused by gain mismatch between paths
- Phase imbalance caused by
  - imperfect 90 degree phase shift in LO
  - mismatched phase or group delay between I and Q paths
- Varies with time, temp, frequency, voltage, moon phase, etc.
- Effects
  - Self interference
  - Out of channel leakage on transmit
  - Susceptibility to out of channel interference on receive
  - Inherently non-LTI since it generates new frequencies

Fixing IQ Imbalance

- Remedy is
  - estimate the relative I and Q magnitude error and scale appropriately
  - estimate the relative phase and rotate components appropriately
  - Must be done at true baseband
  - Much easier on the receiver
- May be baseband frequency selective
  - Must scale magnitude and phase differently for different frequencies
    - Requires multi-tap filter