Managing RF Spurs

HW Front End Architectures vs. Spurious Responses

GNU Radio Conference 2018

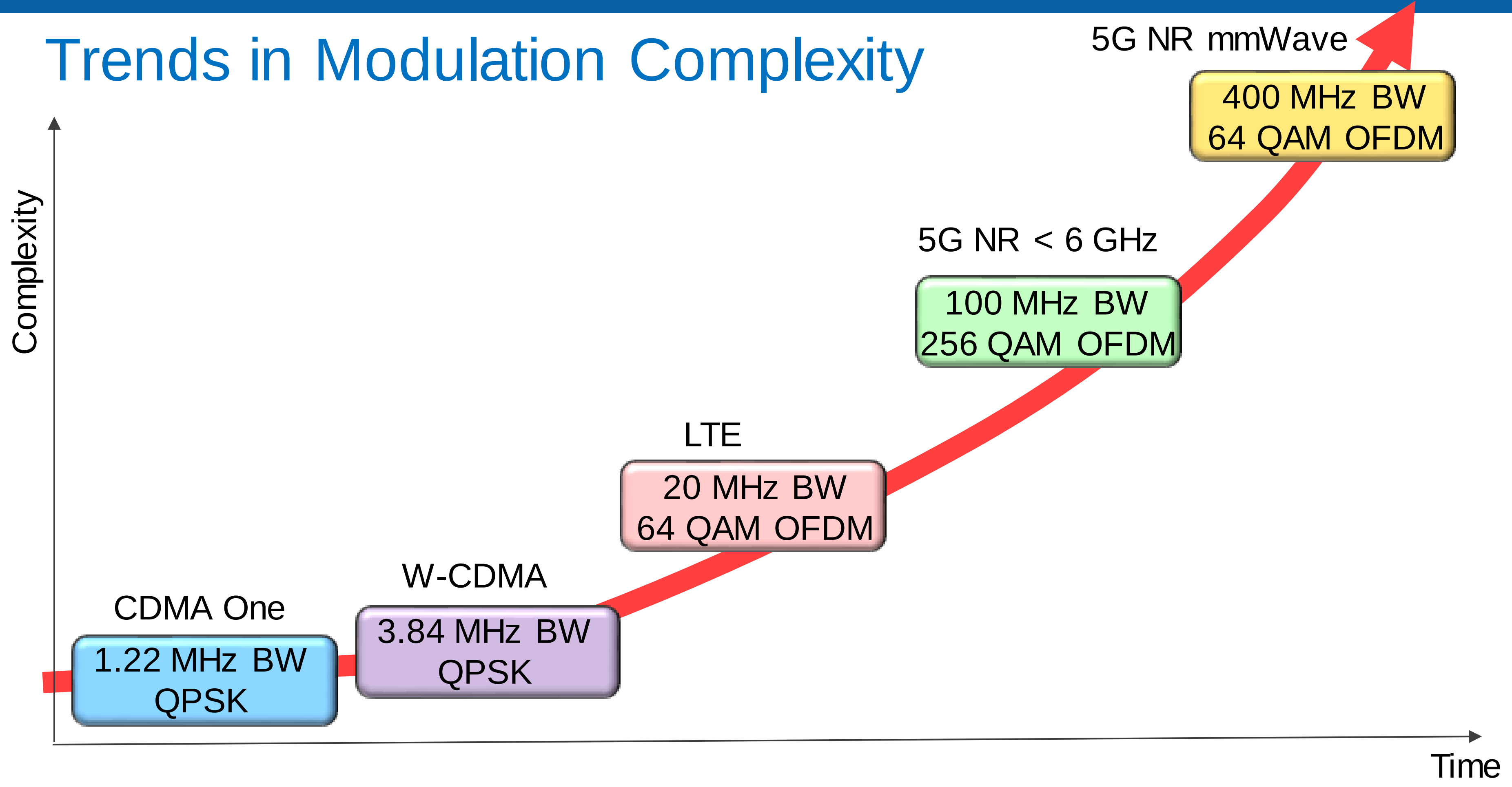
Brian Avenell

National Instruments Corporation

Agenda

- Trends in SDR RF Architectures
- Refresher
- Direct Conversion
- Low IF
- Super-Heterodyne
- Single Sideband (SSB)

Trends in Modulation Complexity



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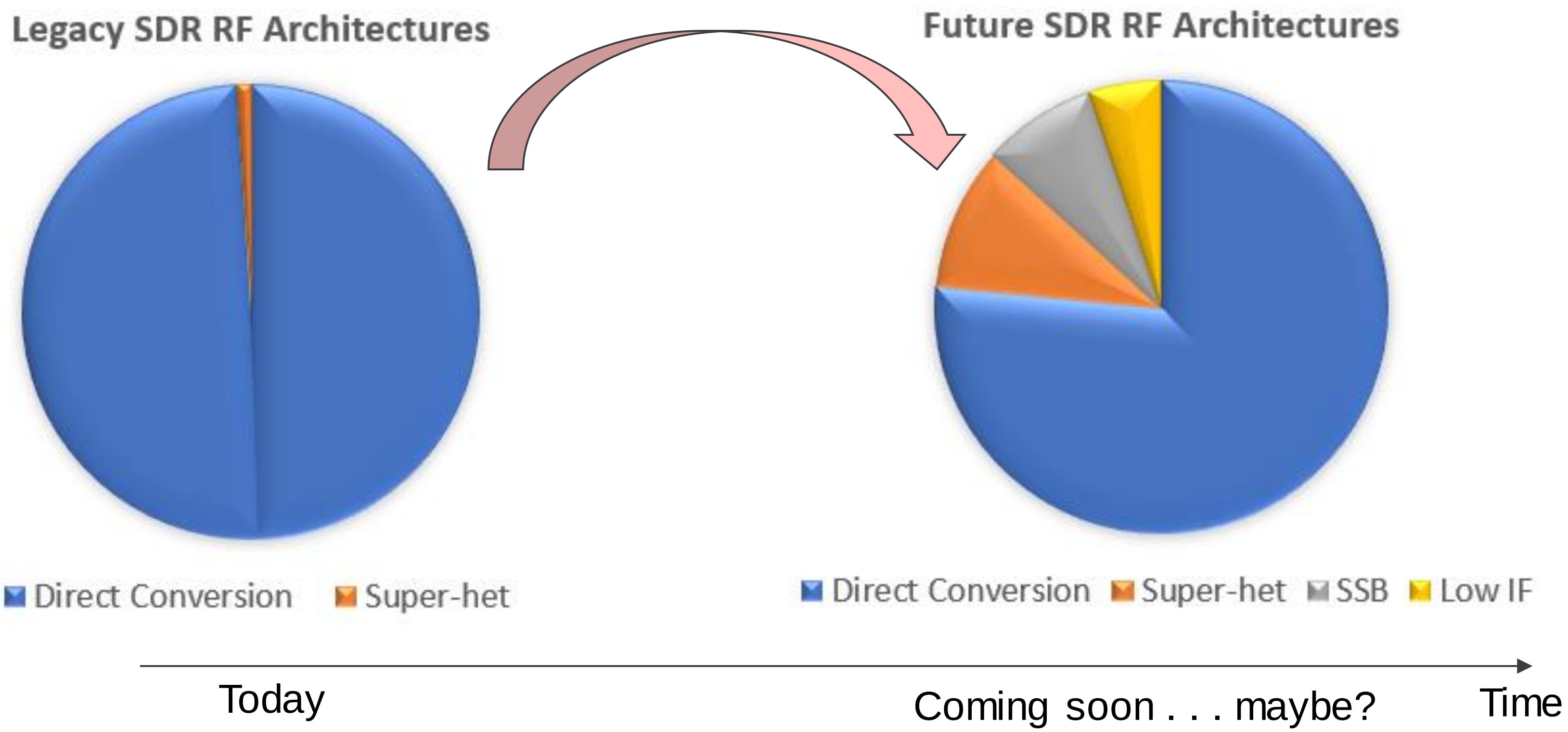
Possible Trends in SDR RF Architectures



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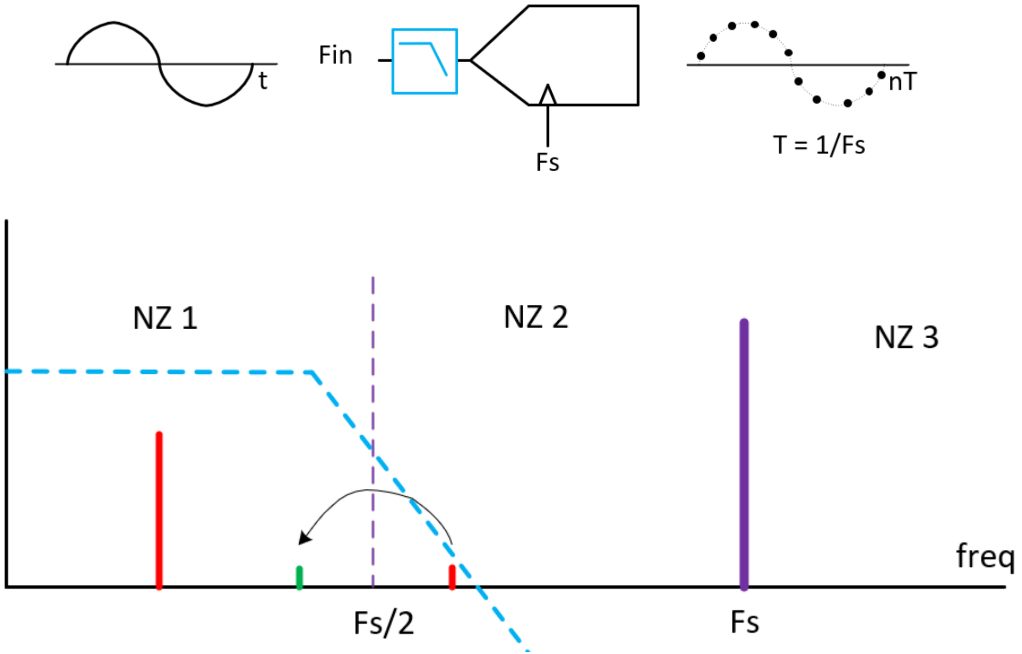
Sampling Theory Refresher

- Nyquist theorem dictates that the sample rate be > 2x the signal bandwidth
- Nyquist zones describe maximum signal BW and valid frequency ranges
- Signals in zones above NZ1 will fold into NZ1 → Aliasing
- Add anti-alias filter to attenuate alias signals
    - Maximum bandwidth of the analog filter is ~ 40% of Fs



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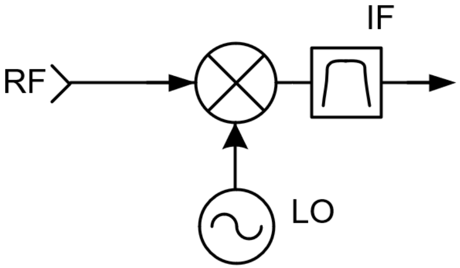
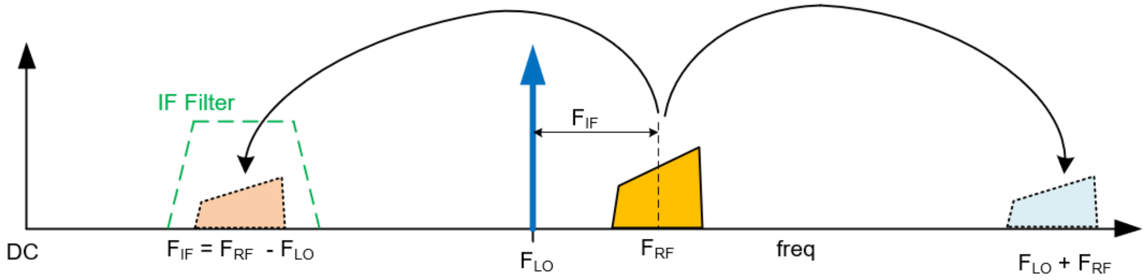
Some Mixing Theory . . .





A mixer performs frequency translation. From basic trig Identities, multiplying two sinusoids results in sum and difference tones:

$$\cos(\omega_{RF}t) * \cos(\omega_{LO}t) = \frac{1}{2}\cos\big((\omega_{RF} - \omega_{LO})t\big) + \frac{1}{2}\cos\big((\omega_{RF} + \omega_{LO})t\big)$$

For a modulated signal centered at f_{RF}, the result is two frequency shifted copies:

$$M(f_{RF}) * \cos(2\pi f_{LO}) = \frac{1}{2}M(f_{RF} - f_{LO}) + \frac{1}{2}M(f_{RF} + f_{LO})$$

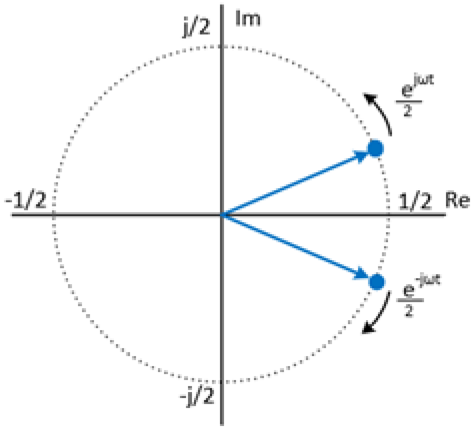
Negative Frequency Representation of Sinusoids

- Negative frequency representation is a mathematical construct.
- But necessary in the analysis of direct conversion architectures

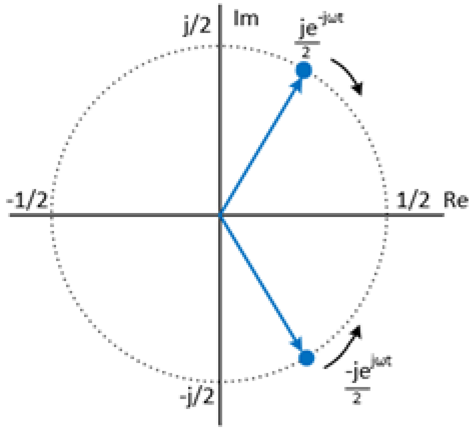
- Euler’s identity shows that sinusoids can be represented by a pair of phasors
- One rotates about the Real/Imaginary plane in the positive direction and one rotates in the negative direction

- Sin(ωt) includes the j operator, which is a 90 deg shift of the phasor

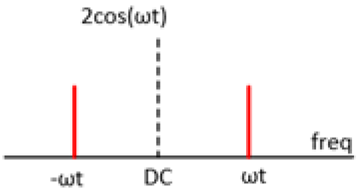
- The spectrum of these phasors shows content in the positive and negative frequency axes.

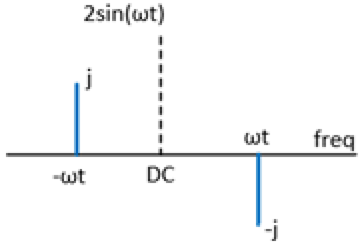


$$\cos(\omega t) = \frac{e^{j\omega t} + e^{-i\omega t}}{2}$$

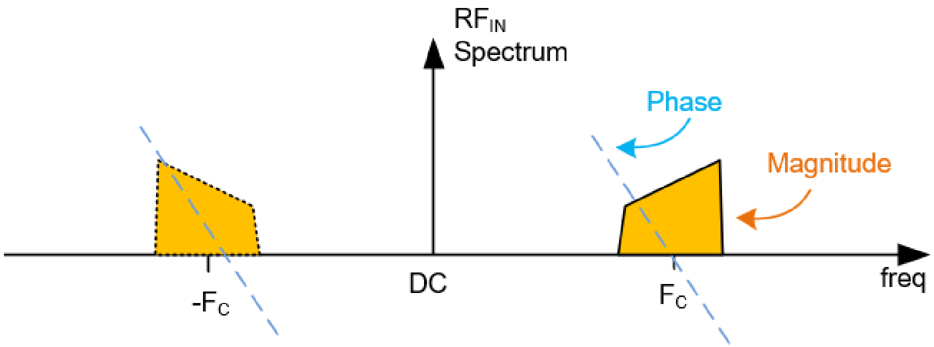


$$\sin(\omega t) = \frac{-je^{j\omega t} + je^{-i\omega t}}{2}$$





Frequency Spectrum Representation of Real Signals



- Broadcast signals, either over-the-air or cabled, are *real* signals
- Mathematically, *real* signals are represented with content in the positive and negative frequency axes
- *Real* signals exhibit
  - Even symmetry about DC for the magnitude response
  - Odd symmetry about DC for the phase response

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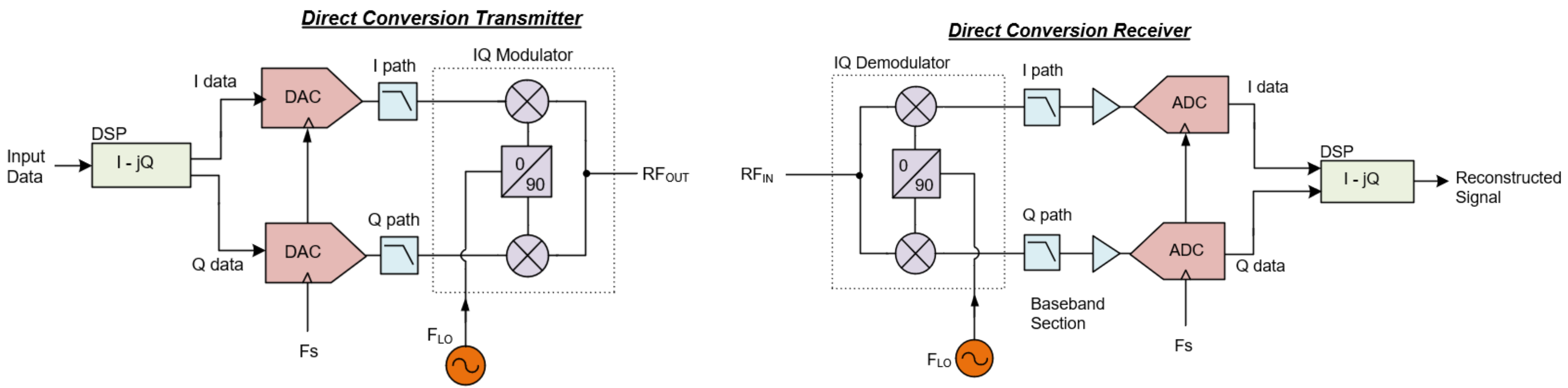
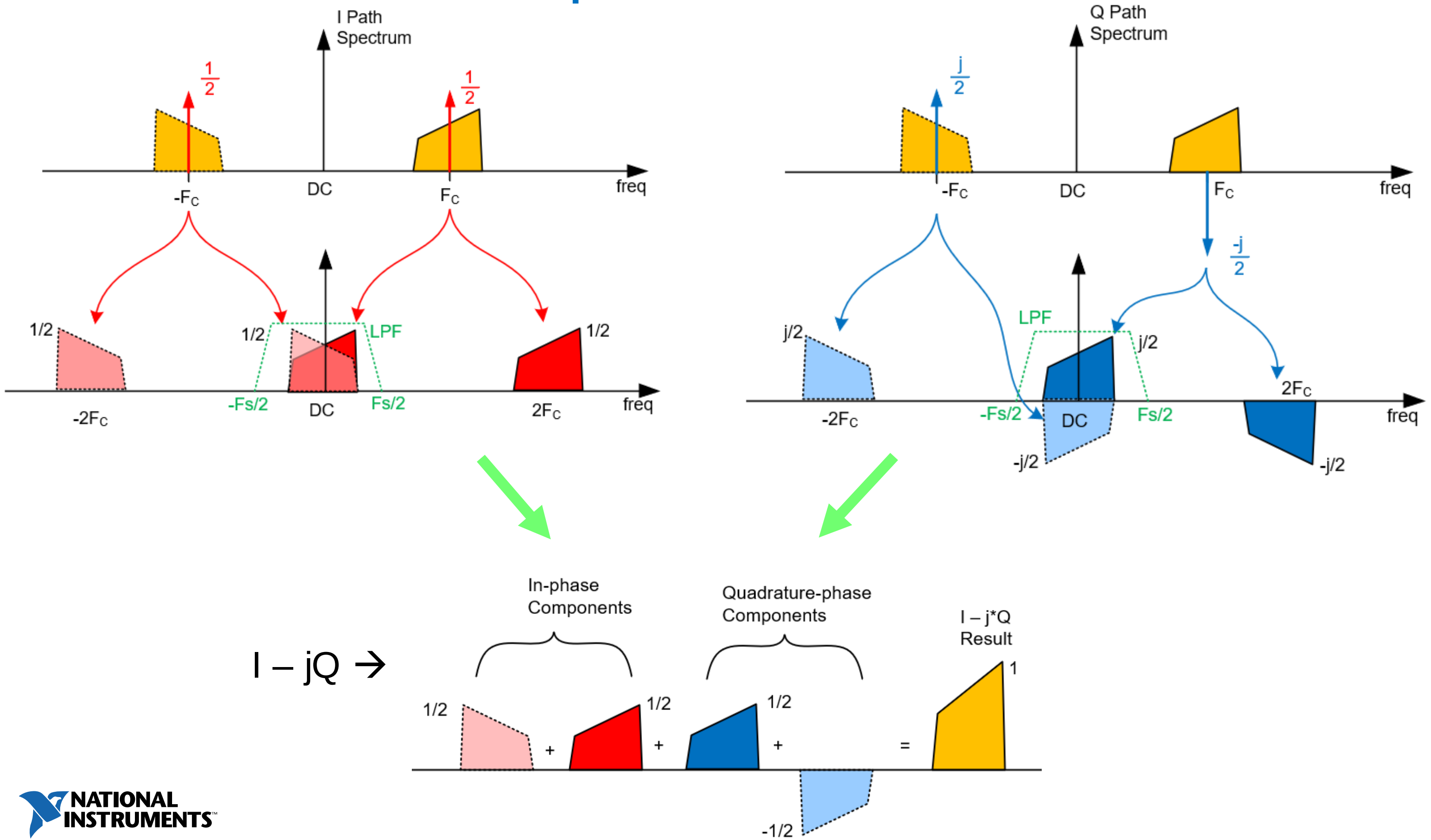
Direct Conversion Block Diagram

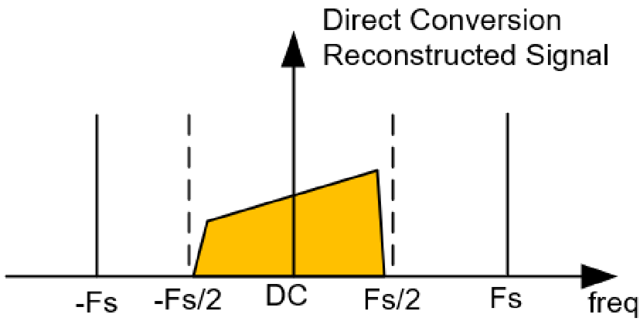


- Direct Conversion transmitter and receiver are mirrors of each other
- Simplicity: dual data converters, single mixer stage, single LO
- For the Receiver:
  - LO freq is tuned to the center of the RF input signal band
  - IQ Demod mixes down to I and Q path. Identical paths with a 90 deg phase shift between the two
  - After data conversion, DSP is used to reconstruct the transmitted signal

Direct Conversion Operation



Direct Conversion Final Result



- The reconstructed signal is surprising:
  - Spectrum straddles two Nyquist zones
    - Apparent violation of Nyquist Theorem
    - Each I and Q path does follow Nyquist theorem
  - No even magnitude symmetry
    - Complex signal does not show same symmetry trait as a real signal
- The above analysis assumes perfectly matched I and Q paths (both amplitude and phase), perfect quadrature in the Mod/Demod LOs and zero DC offsets in the system
- The following slides show what happens when non-ideal conditions exist

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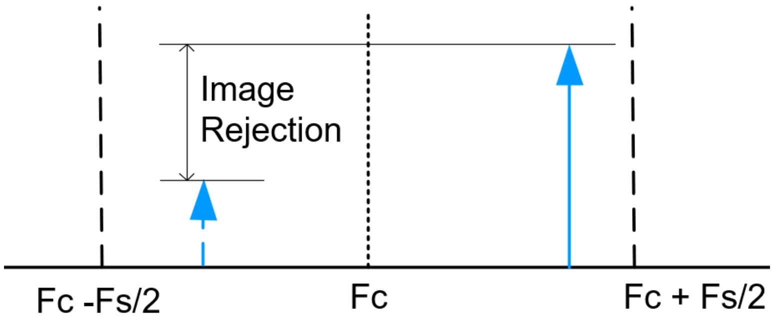
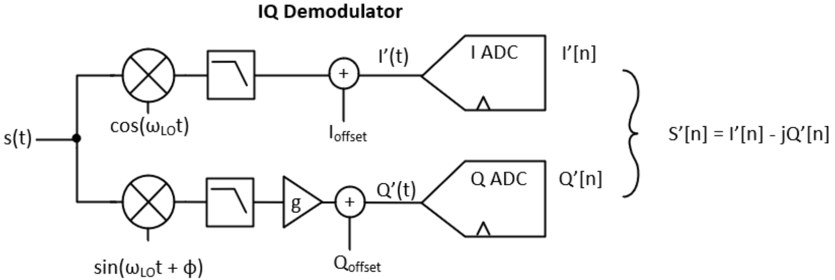
IQ Imbalance Images

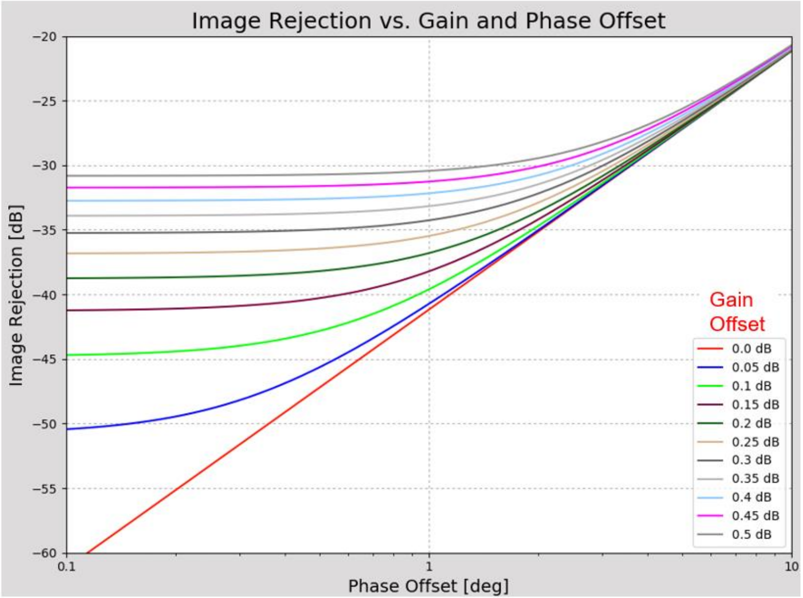
- Images: Tone in one half the spectrum produces a copy of itself in the other half
- Gain and Phase offset between I and Q paths are responsible for images





$$Image\ Rejection = 10log\frac{1+g^2-2gCos(\emptyset)}{1+g^2+2gCos(\emptyset)}\ [dB]$$

where $g = 10^{(\text{Gain Imbalance dB}/20)}$



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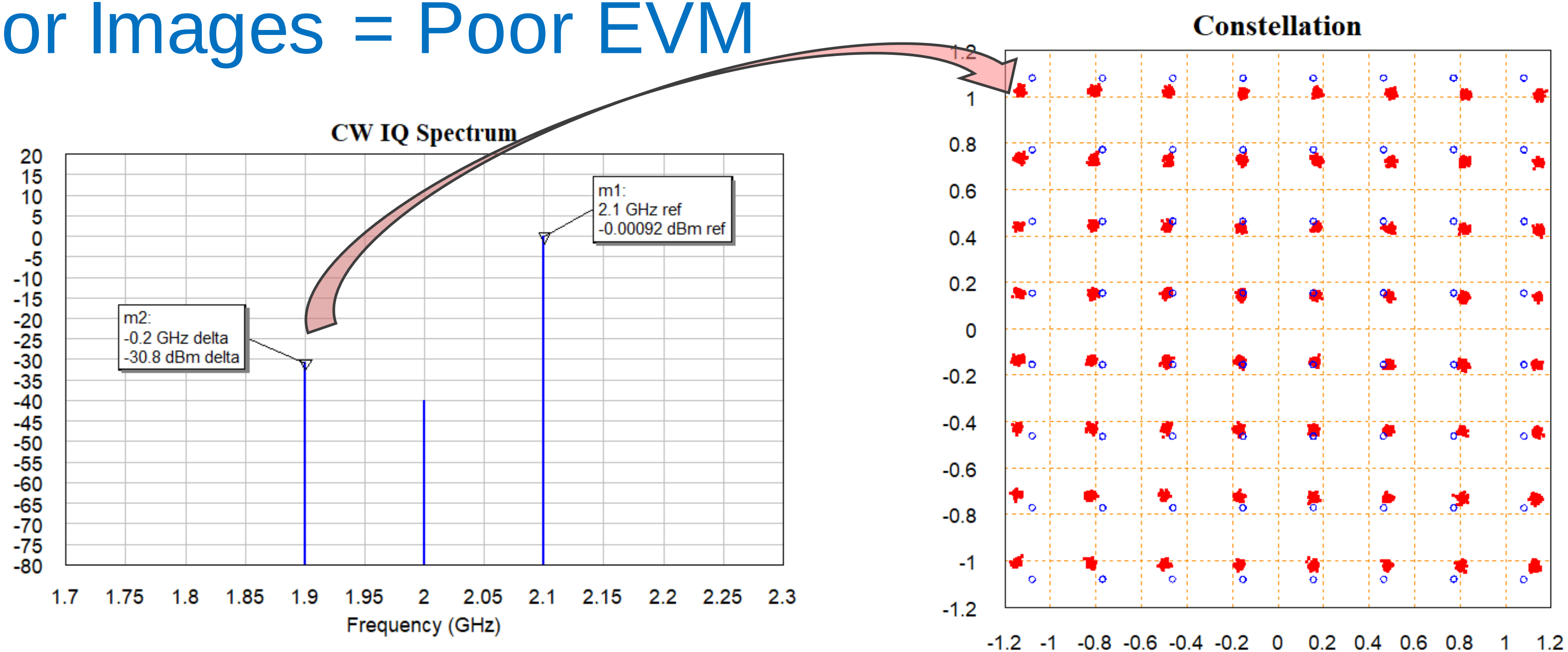
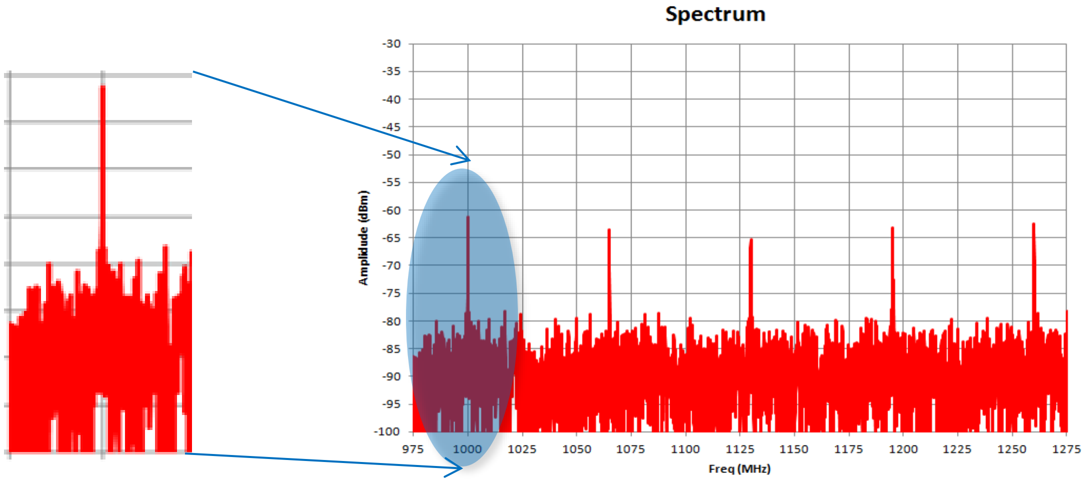
Poor Images = Poor EVM



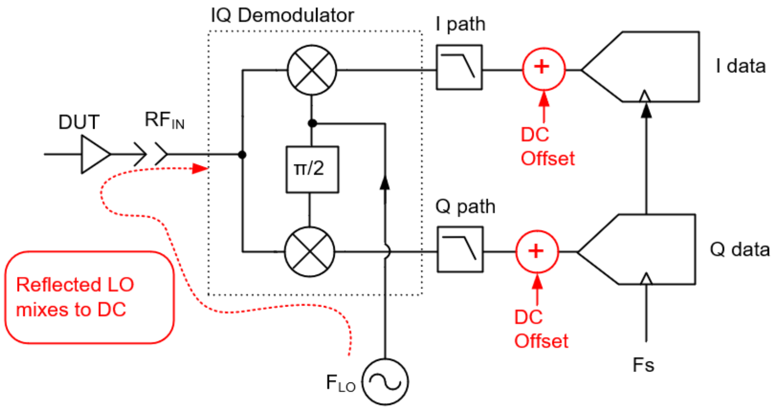
- EVM is a direct correlation to image rejection performance
  - A -30 dBc image rejection value results in -30 dB (3.16%) EVM performance

DC Offset

- DC Offset appears as a CW tone in the center of the complex spectrum



- Several causes for DC Offset:
  - Actual DC differences in the I and Q paths
  - DC differences in the data converters
  - LO reflections mixing down to DC



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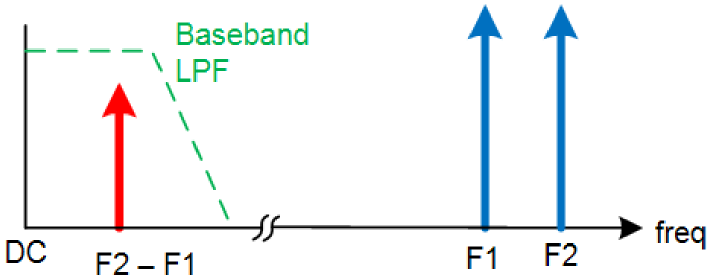
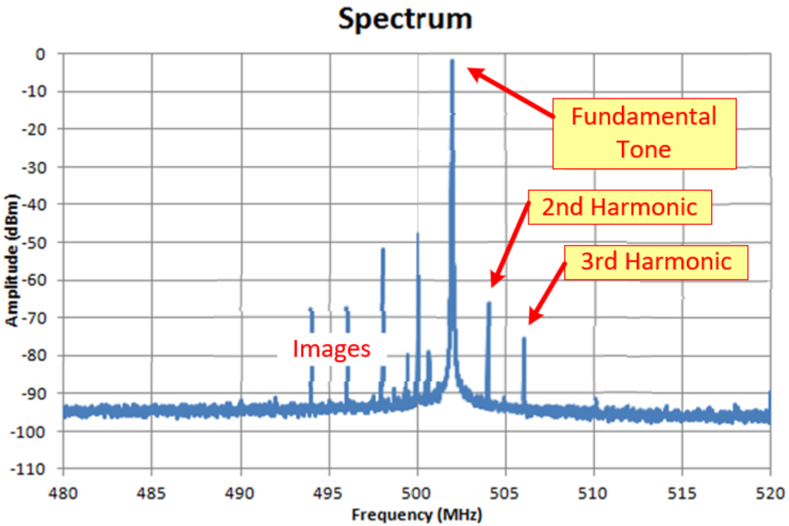
Other Direct Converter Spurs

- Second Order Intermodulation (IP2)
  - Difference tone of multiple input tones falls within the baseband frequency range
  - These tones could be over-the-air broadcast signals



- Baseband Harmonics
  - Baseband covers an infinite number of octaves
  - Impossible to filter out the harmonics generated by baseband amplifiers and data converters



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Direct Conversion Good/Bad

The Good
Low parts count, low cost, small space req'd
Simple RF filtering requirements

The Bad
IQ imbalance images and DC offsets
Could require IQ imbalance calibration
Prone to IP2 and baseband harmonic distortion

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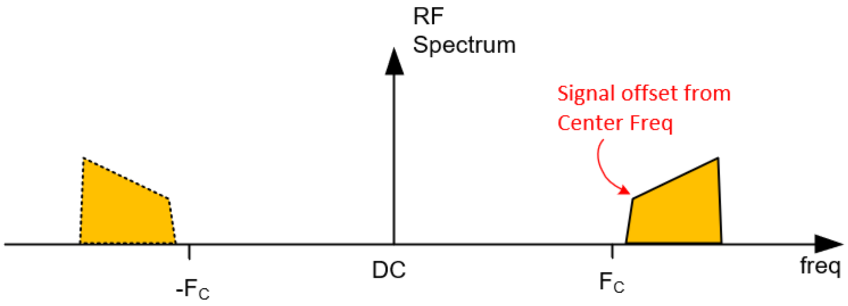
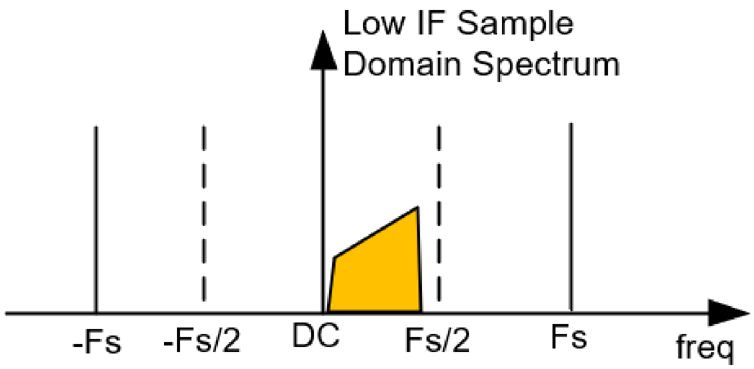
Low IF Operation





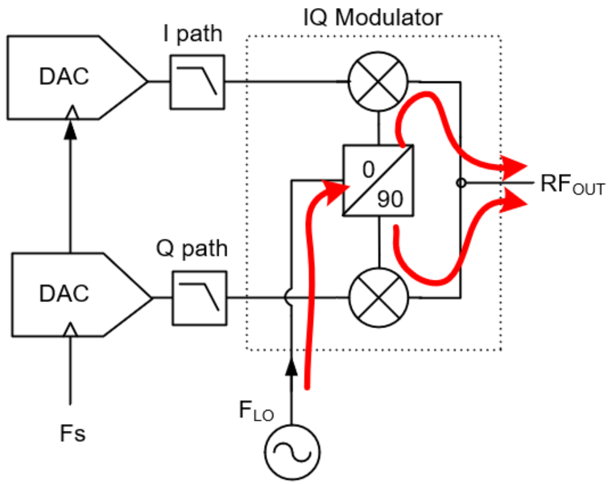
- Identical hardware as direct conversion architecture
- RF signal is offset from the center frequency

- Advantages:
  - DC offset and IQ imbalance images are no longer in band
- Disadvantage
  - Bandwidth is < ½ available bandwidth of direct conversion structure

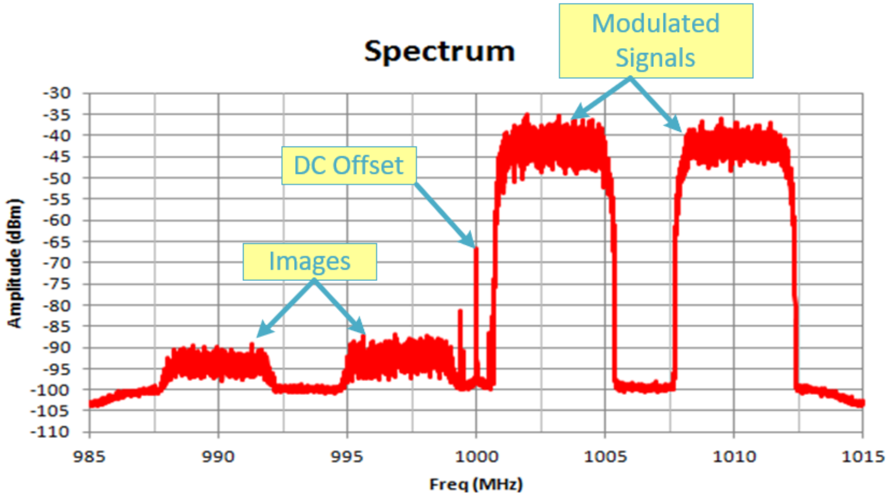
- With lower cost, higher sample rate data converters becoming available the penalty in BW reduction can be overcome with higher sample rate while giving the advantages of no in band IQ imbalance spurs

Transmitter Low IF

- For Tx, the DC Offset and Images will still appear at the output
  - At least these are out of band
- For a clean spectrum, IQ imbalance calibrations will still be needed
- DC Offset suppression is especially difficult for Tx as the IQ Modulator LO > RF leakage will appear as a DC offset term



- Shown is the transmit spectrum with two modulated tones
  - DC offset and images are visible



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Low IF Good/Bad

The Good
Low parts count, low cost, small space req’d
No in-band IQ images and DC offset
Same hardware as direct conversion. DC and Low IF modes possible

The Bad
Reduced Bandwidth compared with direct conversion
Images and DC offsets present for Tx
Could require IQ imbalance calibration for Tx

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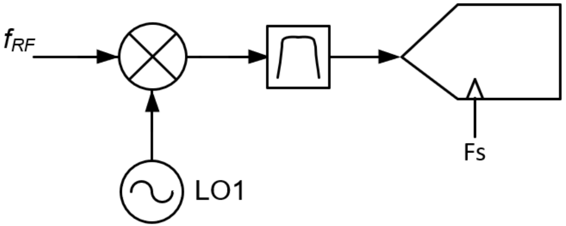
Super-Het Configurations

- Super-het uses mixer to perform frequency translation
- Frequency translates to an intermediate frequency (IF), not baseband

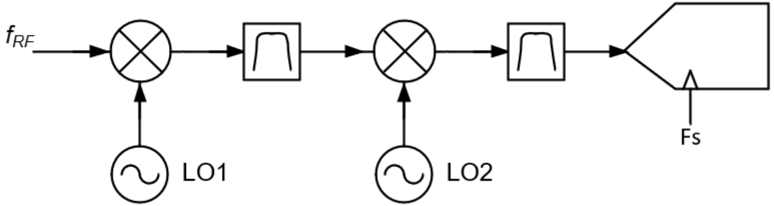
- Single and multiple stage architectures

- Super-het can be combined with direct conversion
    - Popular with mmWave structures

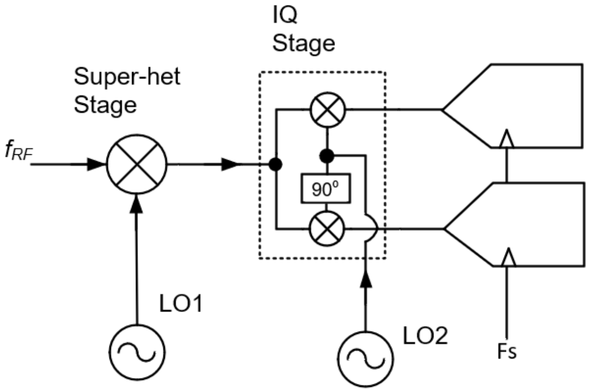
Single Stage



Multiple Stage



Super-Het +
Direct Conversion



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Mixing Equation

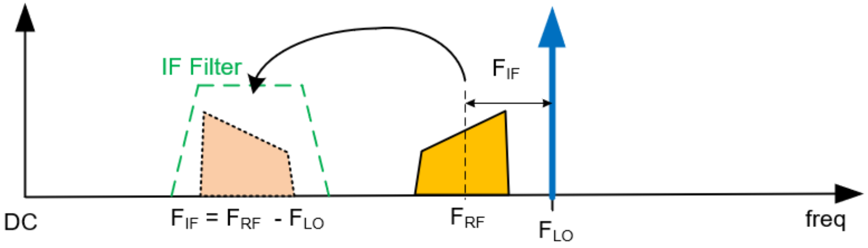
- Mixing equation:

$$M * F_{RF} + N * F_{LO} = F_{IF} \qquad \mathrm{M,N} = 0, \pm 1, \pm 2, \ldots$$

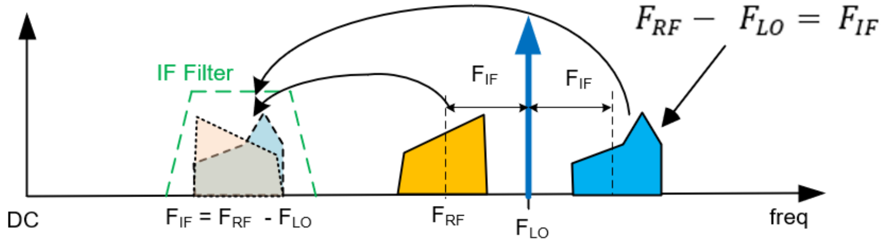
- Mixing equation supports all possible combinations of M,N. Shown here is a signal at the image frequency (M,N = 1,-1)

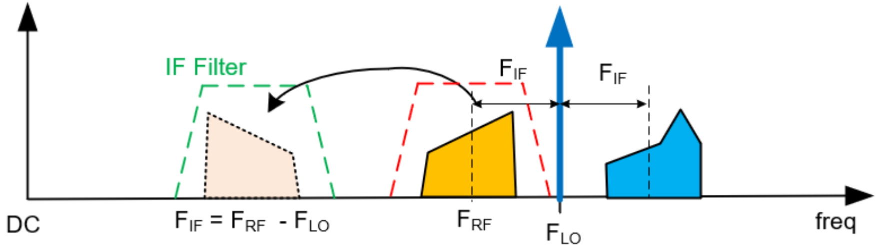
- At IF, cannot distinguish between desired and image.
- Signals at desired and image frequencies will combine at IF

- RF filtering required to eliminate image response



$$-F_{RF} + F_{LO} = F_{IF} \qquad \mathrm{M,N} = -1,1$$





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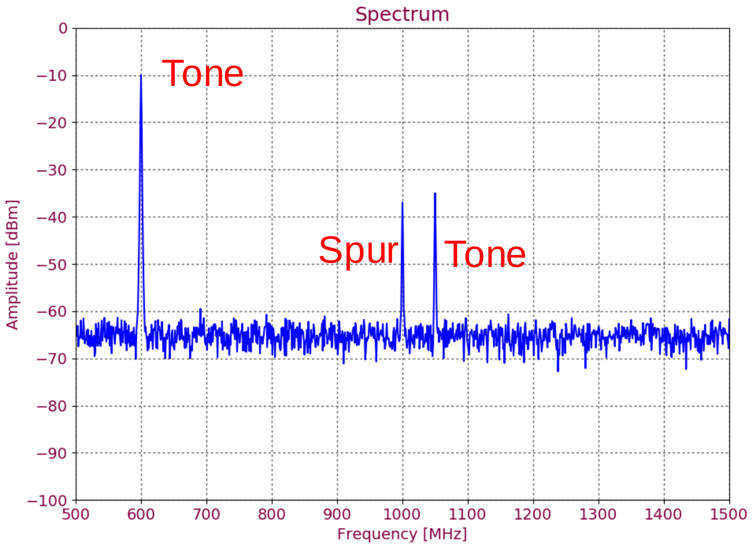
General M,N Spurs

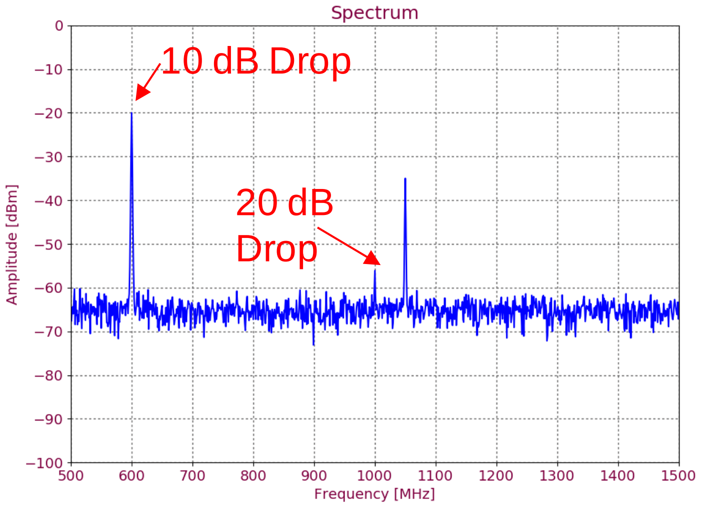
$$M * F_{RF} + N * F_{LO} = F_{IF}$$

Shown is an example of a M,N = 2,-1 spur.
The RF input frequency is 600 MHz, and the mixer produces a 2,-1 spurious response at 1 GHz

There is an actual signal at 1.05 GHz.
Distinguishing the spur from the actual signal is difficult.



Spur amplitudes drop proportional to the M order. In this example with M = 2, a 10 dB drop in the fundamental tone results in a 20 dB drop in the spur.



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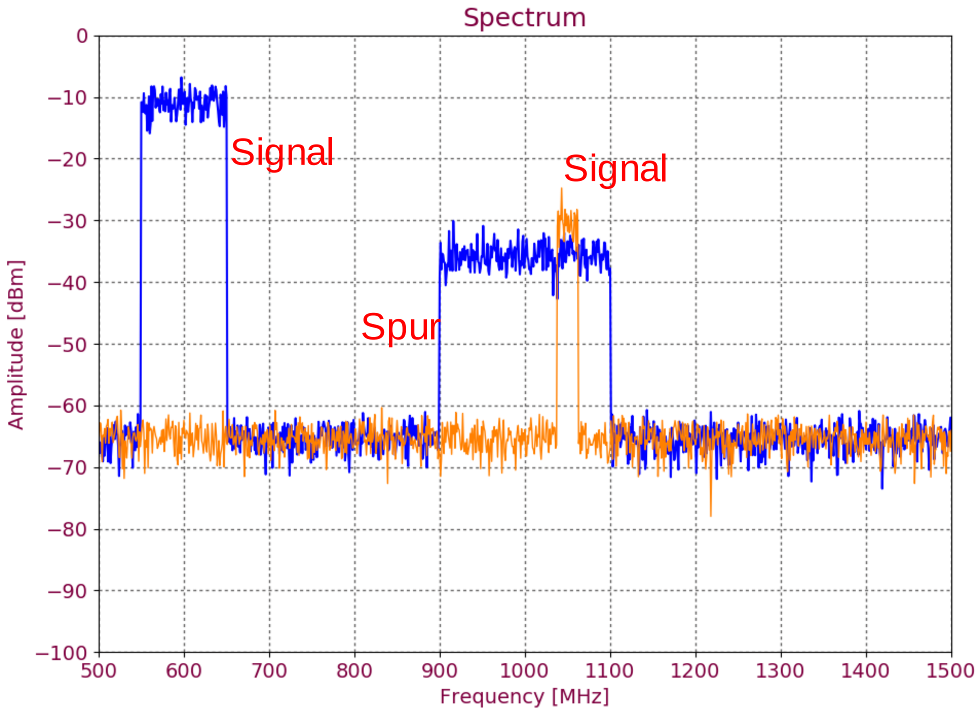
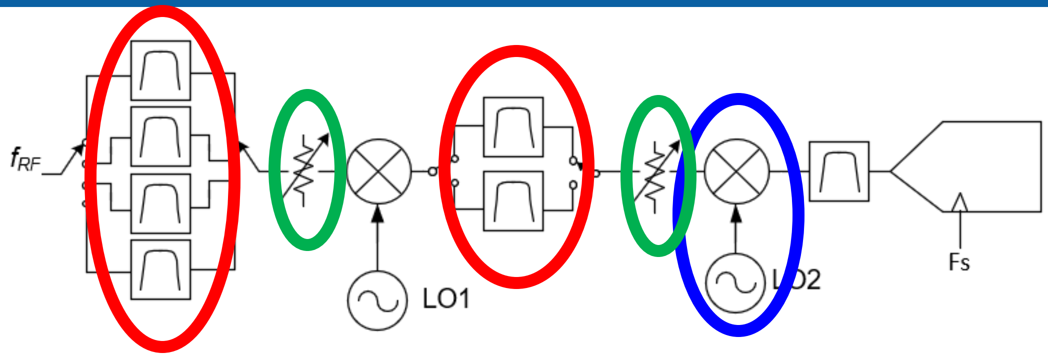
M,N Spurs with Modulated Signals

- With modulated signals, the spur will spread in frequency proportional to M
- The blue trace shows the M,N = 2,-1 with the actual signal centered at 600 MHz and the spur centered at 1 GHz
- The orange trace is an actual signal
- The spur could mask the actual signal

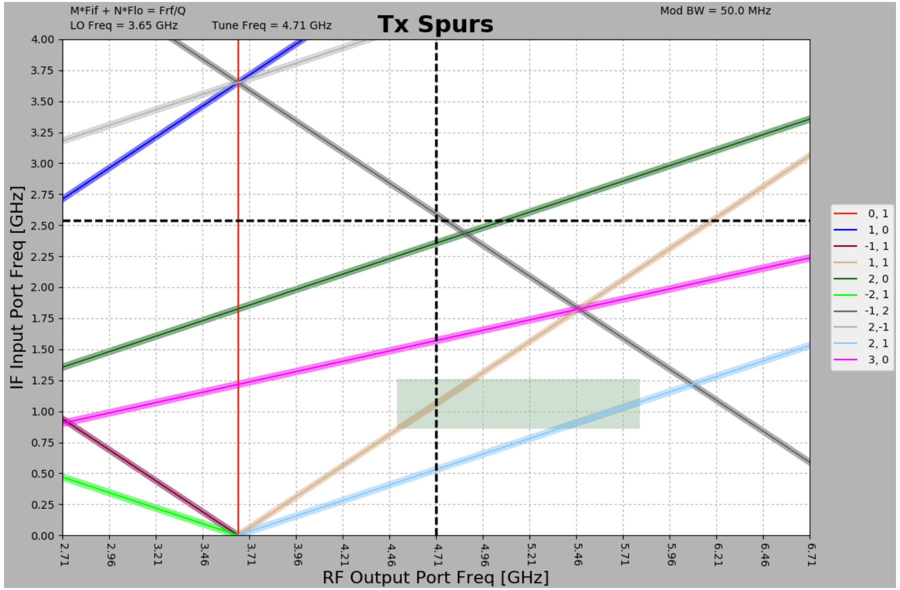


Spur Mitigation Techniques



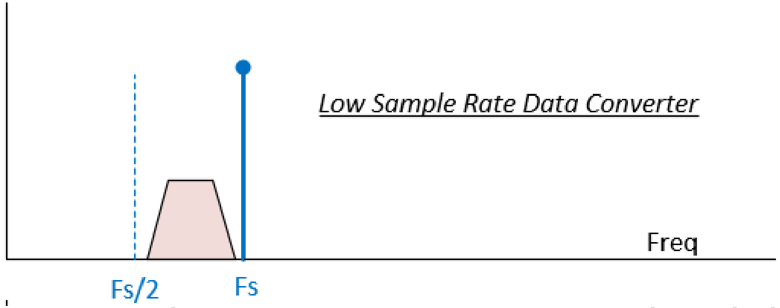
- More filters
- Additional conversion stages
- Gain ranging

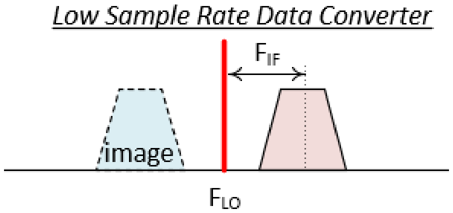
- Rigorous frequency planning



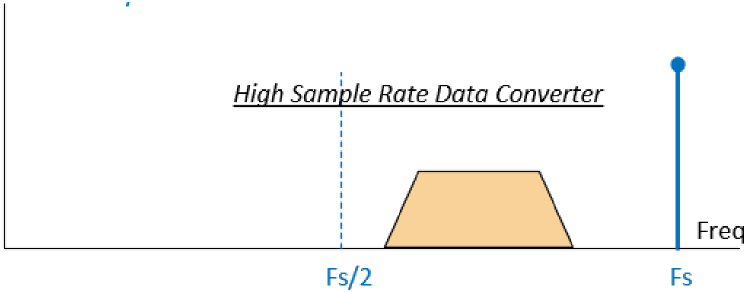
- Highlights the disadvantage of the super-het structure: added components

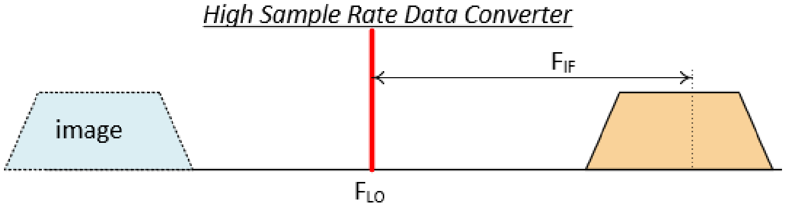
Possible Trend in SDR Architectures





- Low data rate converters: Low bandwidth and harder to filter mixer images





- Data converter sample rates are increasing into the GHz range, while maintaining high SNR, SFDR performance.
- Wider bandwidths + easier spur management due to higher IF frequencies
  - Simpler architectures due to fewer conversion stages and lower cost, smaller sized filters

Super-het Good/Bad

The Good
No IQ imbalance spurs
Calibration not req’d for good EVM/BER performance
Lower cost, high sample rate data converters simplify architecture

The Bad
More filtering and frequency conversion stages compared with direct conversion

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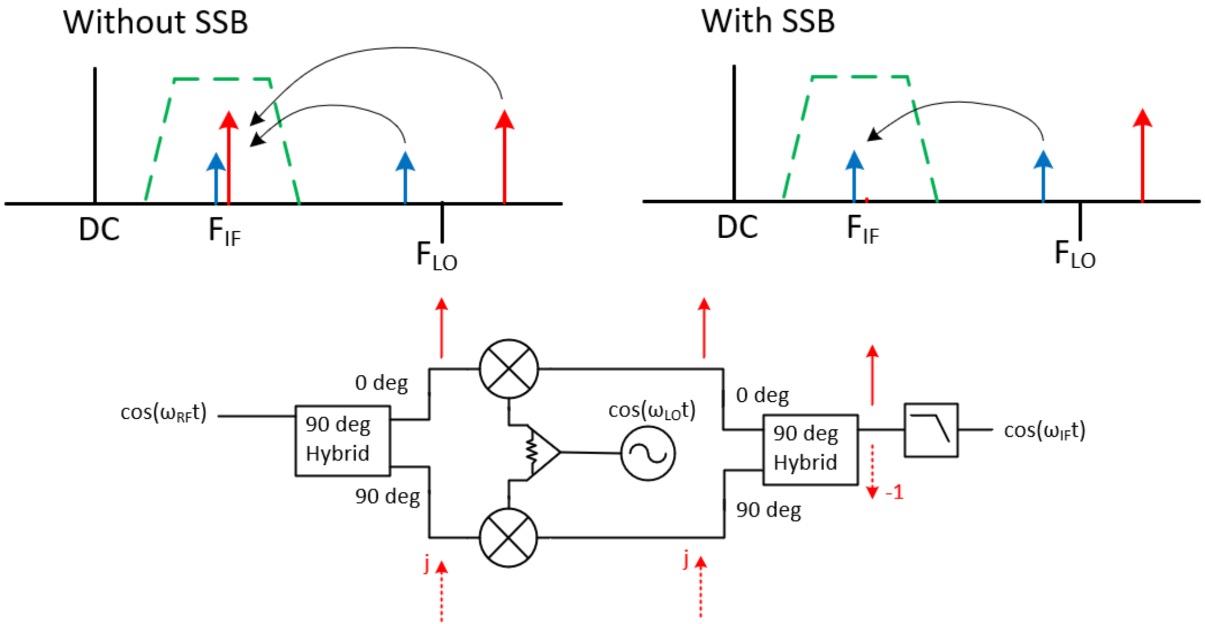
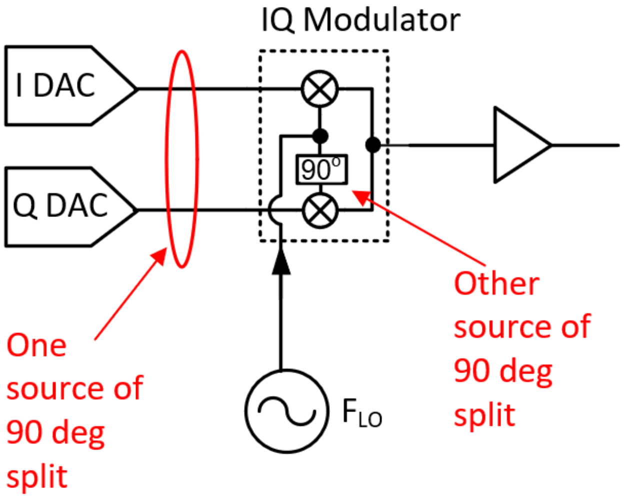
Single Sideband



- Single sideband traditionally used for narrowband modulation
- Technique to allow one sideband to be preserved, while the other sideband is greatly attenuated

Possible Trend in SDR using SSB



- Traditional SSB limited by sub-octave 90 deg splitters
- Newly available wideband IQ Mod/Demod + high sample rate data converters allow several octaves of tuning range with wide bandwidth
- The benefits of suppressed images reduces the filtering requirements
- Added benefit: single LO and single frequency translation

SSB Good/Bad

The Good
Suppressed images reduces filtering needs
Single conversion, single LO

The Bad
Requires calibration to suppress the images

Summary

- To date, vast majority of SDR transceivers use direct conversion
- Direct conversion has served the needs well with today's communications standards
- As emerging standards demand wider bandwidth and increased bits/symbol, the SDR hardware may need to evolve
- Fortunately, with the price of wide bandwidth data converters dropping, some alternative structures can be considered

Thank You