The Complex IF Transmitter

(An introduction to radio architectures)

Outline

- **Review of complex signals in communications**
  - **Orthogonal Signals and Trigonometry**
  - **The convenience of complex math**
  - **Complex vs. Real frequency spectrum**

- **Transmit radio architectures**
  - **The process of radio transmission**
  - **Baseband or 0 IF**
  - **Real IF**
  - **Complex IF**

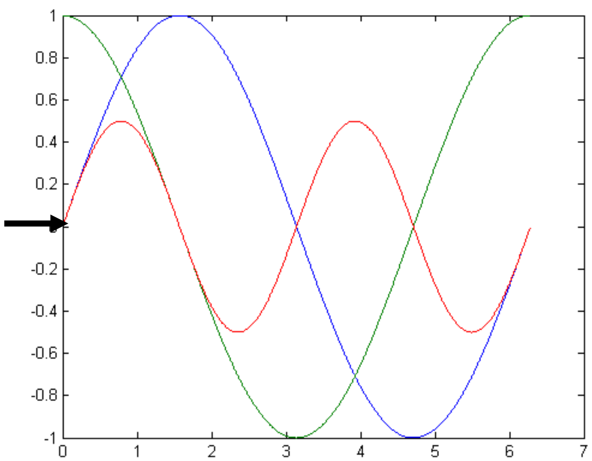
- **Summary of trade-offs between architectures**

- **Example signal chains**

Starting with Some Trigonometry

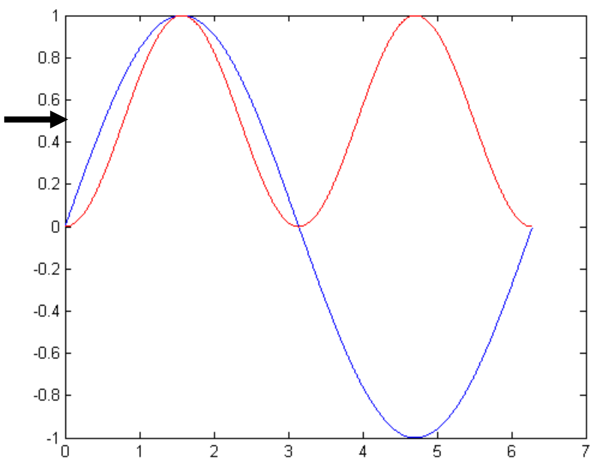
$$\sin(x)*\cos(x) = \tfrac{1}{2}*\sin(2x)$$
$$\sin(x)*\sin(x) = \tfrac{1}{2} + \tfrac{1}{2}*\sin(2x))$$
$$\cos(x)*\cos(x) = \tfrac{1}{2} + \tfrac{1}{2}*\cos(2x))$$

DC = 0



Sin*Cos

DC = ½



Sin*Sin
Cos*Cos

Sin*Cos does not have a DC term

Combining Orthogonal Signals on a Carrier

- **Orthogonal signals are independent**
- **Say that the I(t) and Q(t) are slowly varying (<< ω) functions**
- **Generate two waveforms:**
  Signal1 = Q(t)*sin(ωt)
  Signal2 = I(t)*cos(ωt)
- **Now combine the signals:**
  Signal3 = Signal1 + Signal2 = Q(t)*sin(ωt) + I(t)*cos(ωt)
- **We can recover I(t) and Q(t) by multiplying by sin(-ωt) and cos(-ωt) and Low pass filtering:**

  Example, recovering Q(t) (similar for I(t)):

  [Q(t)*sin(ωt) + I(t)*cos(ωt)]*sin(ωt) =

  Q(t)*sin(ωt)*sin(ωt) + I(t)*cos(ωt)*sin(ωt) =

  $$\tfrac{1}{2}*(Q(t) + Q(t)*\sin(2\omega t) + I(t)*\sin(2\omega t)) \xrightarrow[\text{LPF}]{} \tfrac{1}{2}*Q(t)$$

Complex vs. Real Signals

- **Complex signal always have two separate signals**
  - **Digital complex signals are separate bits**
  - **Analog complex signals are separate wires**

- **The only way to transmit a complex signal through 1 path is to modulate onto a carrier (ω) and recover at the receiver**

- ***A complex signal can have unique negative frequencies. For a real signal, negative frequency amplitudes are a mirror image of positive frequency amplitudes – see next slides***

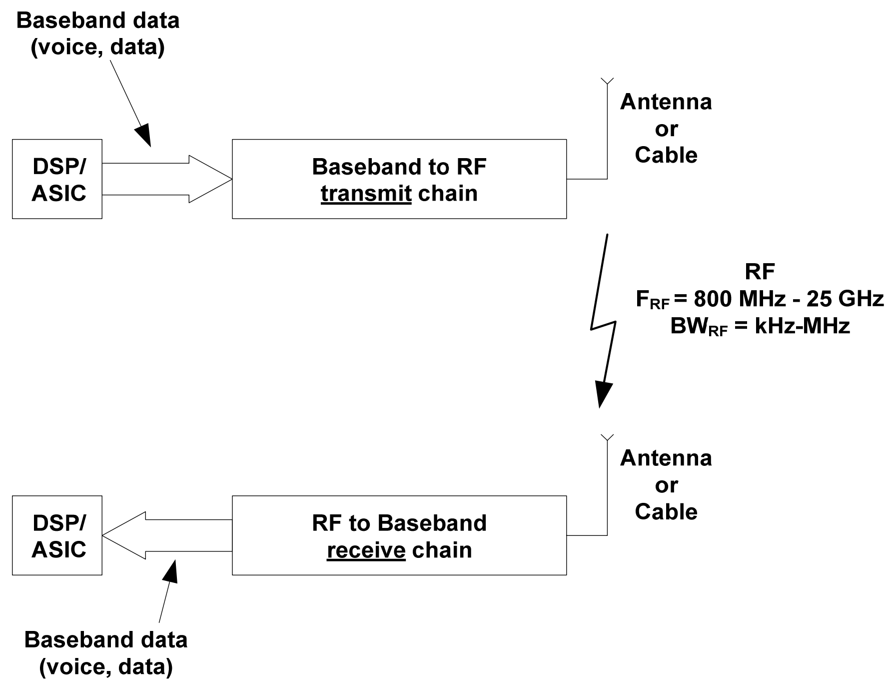
Complex vs. Real Signals: Sine & Cosine

- All signals in time can be generated by a sum of sine's and cosine's of various frequencies and magnitudes
- Cosine and sine are made up of positive and negative frequencies:
- Euler's Equation: $e^{j\omega t} = \cos(\omega t) + j*\sin(\omega t)$
- $\mathrm{Cos}(\omega t) = (e^{j\omega t} + e^{-j\omega t})/2$ $\mathrm{Sin}(\omega t) = (e^{j\omega t} - e^{-j\omega t})/2j$
- Cosine and sine have equal positive and negative frequency terms

  - amplitude of positive and negative frequencies are equal
- A complex signal (e.g. $e^{j\omega t}$) is simpler – only 1 frequency term

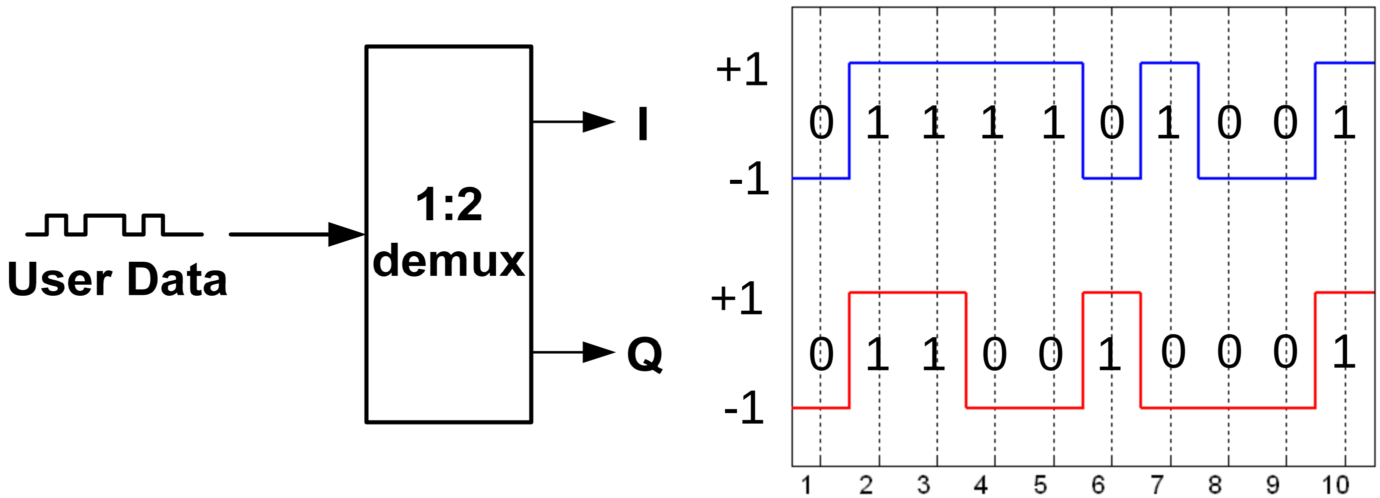
Next Section:
Example of the Wireless Transmission Process

- User data to Baseband Data
- Mixing with carrier
- Recovering data at receiver
- Baseband filtering
- Other modulation types

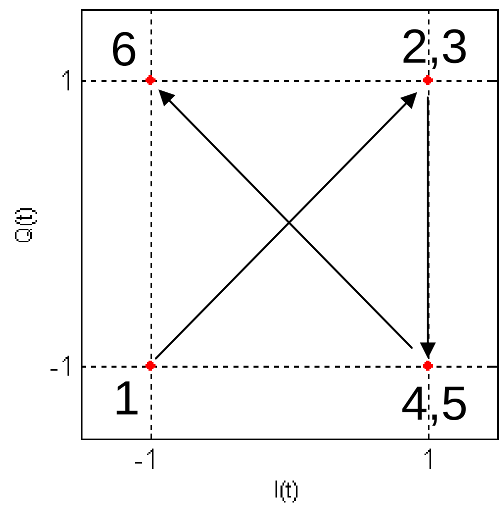


Transmission Process: Step 1 (QPSK)

Step 1: Converting User Data to Baseband Data



Constellation Diagram plots I(t) vs. Q(t)



Other modulation types discussed later

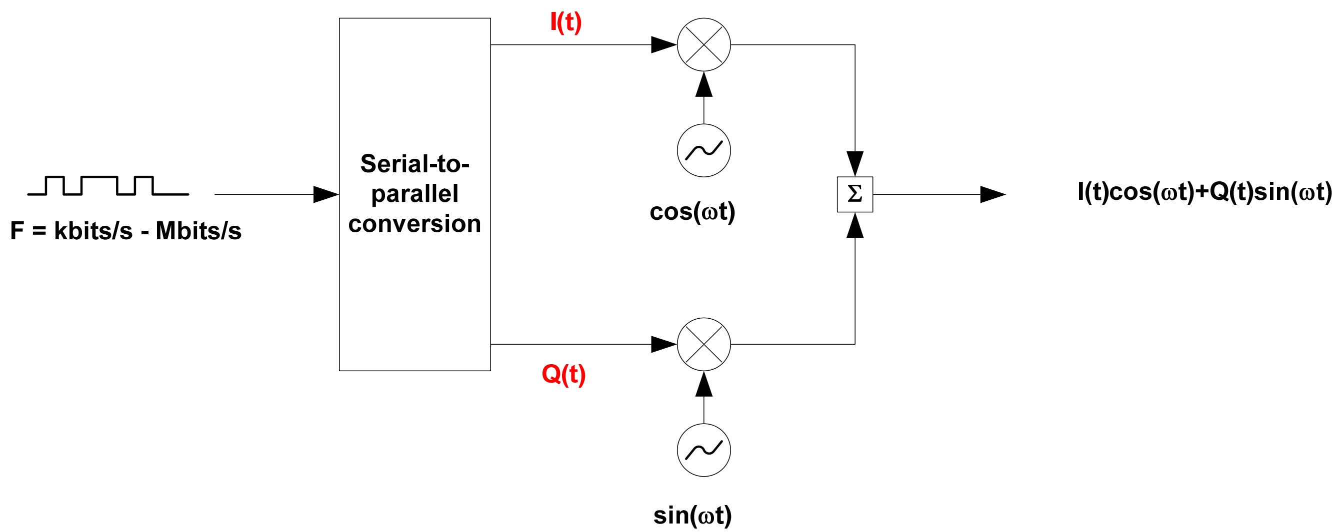
Transmission Process: Step 2

Step 2: Mix with carrier at frequency ω

Signal1 = $I(t)*\cos(\omega t)$

Signal2 = $Q(t)*\sin(\omega t)$

Signal3 = Signal1 + Signal2 = $I(t)*\cos(\omega t) + Q(t)*\sin(\omega t)$



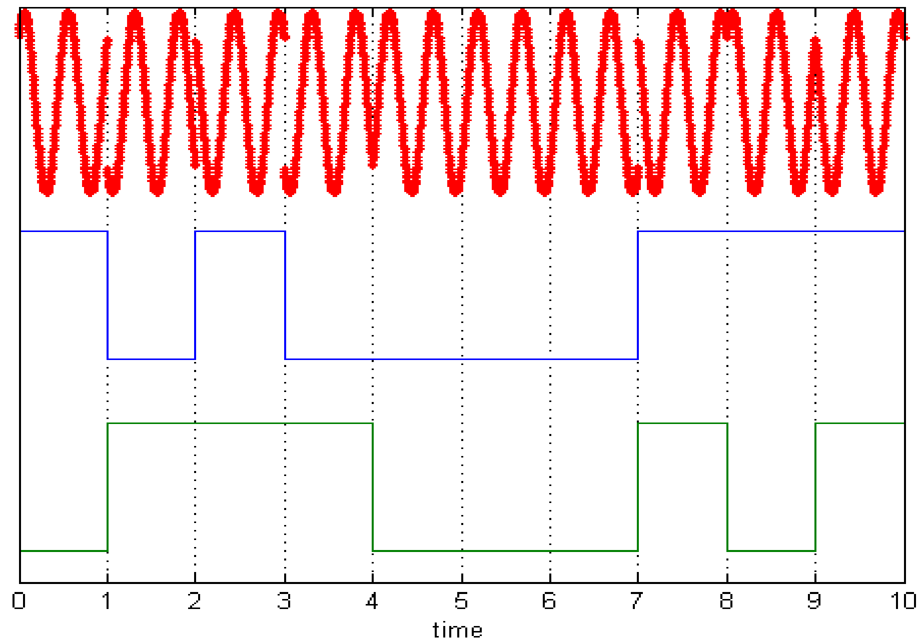
Transmission Process – RF Signal

A very low frequency used here for clarity

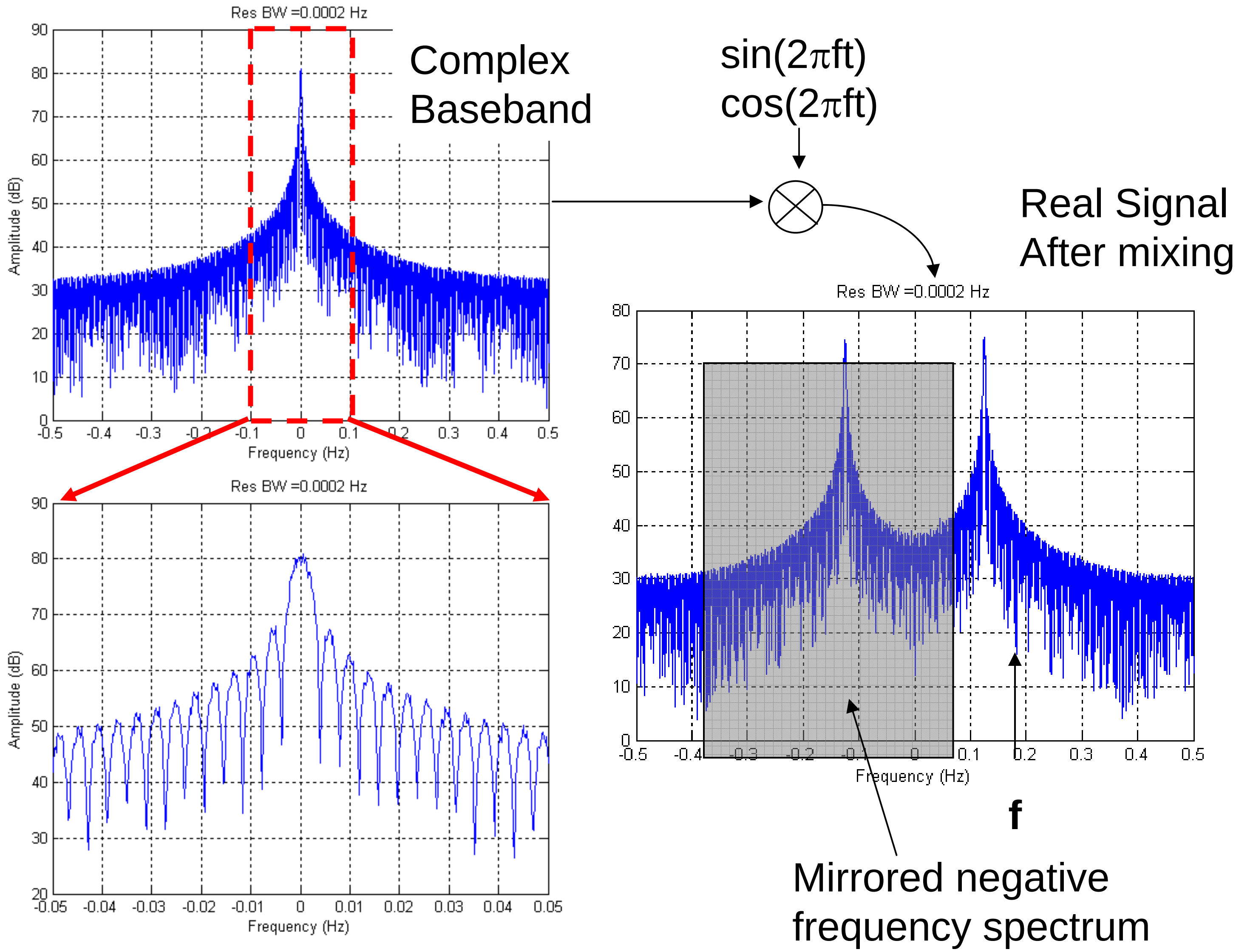
I(t)*cos(ωt) + Q(t)*sin(ωt)

I(t)

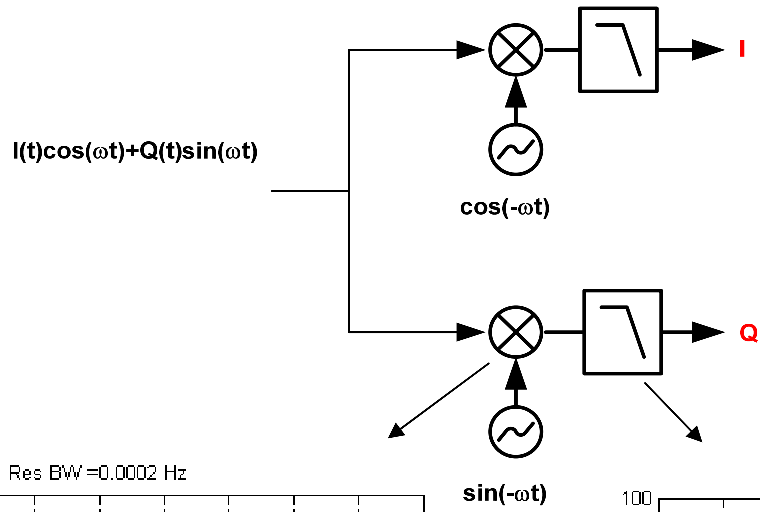
Q(t)



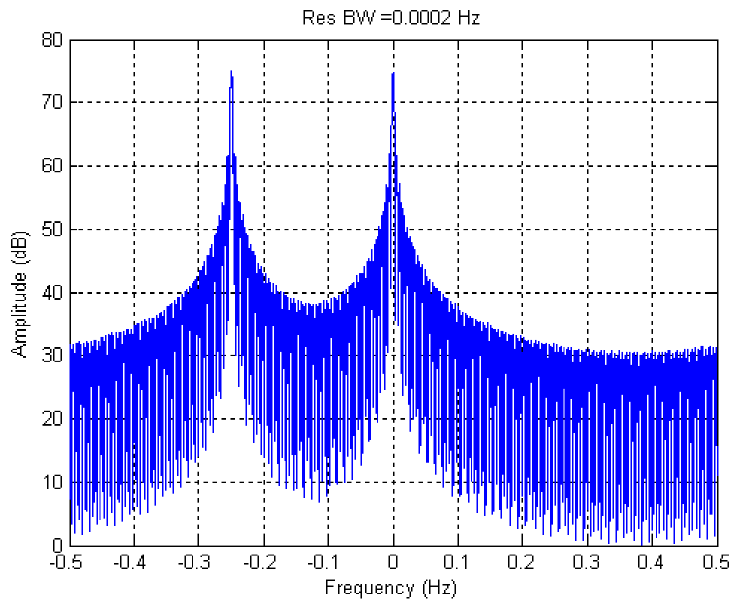
The Simplest Radio: Frequency Spectrum



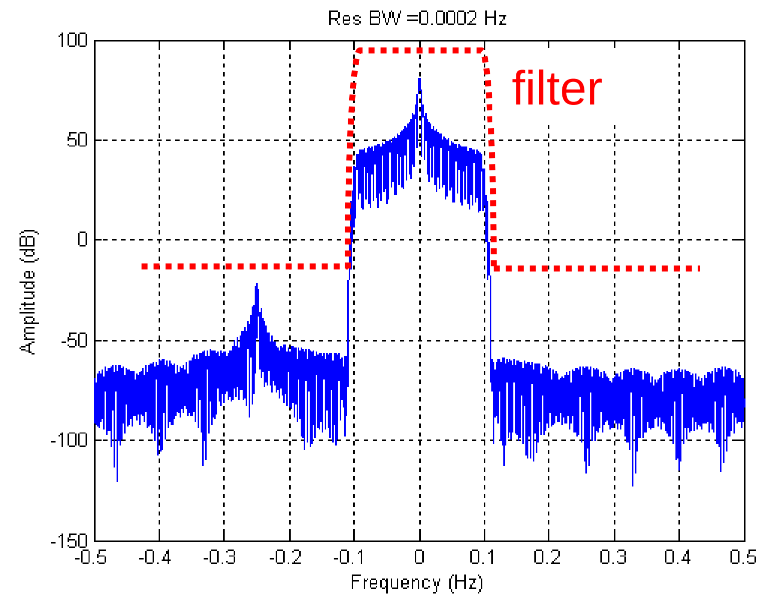
The Simplest Radio: Recovering the data



Back to complex signal after mixing

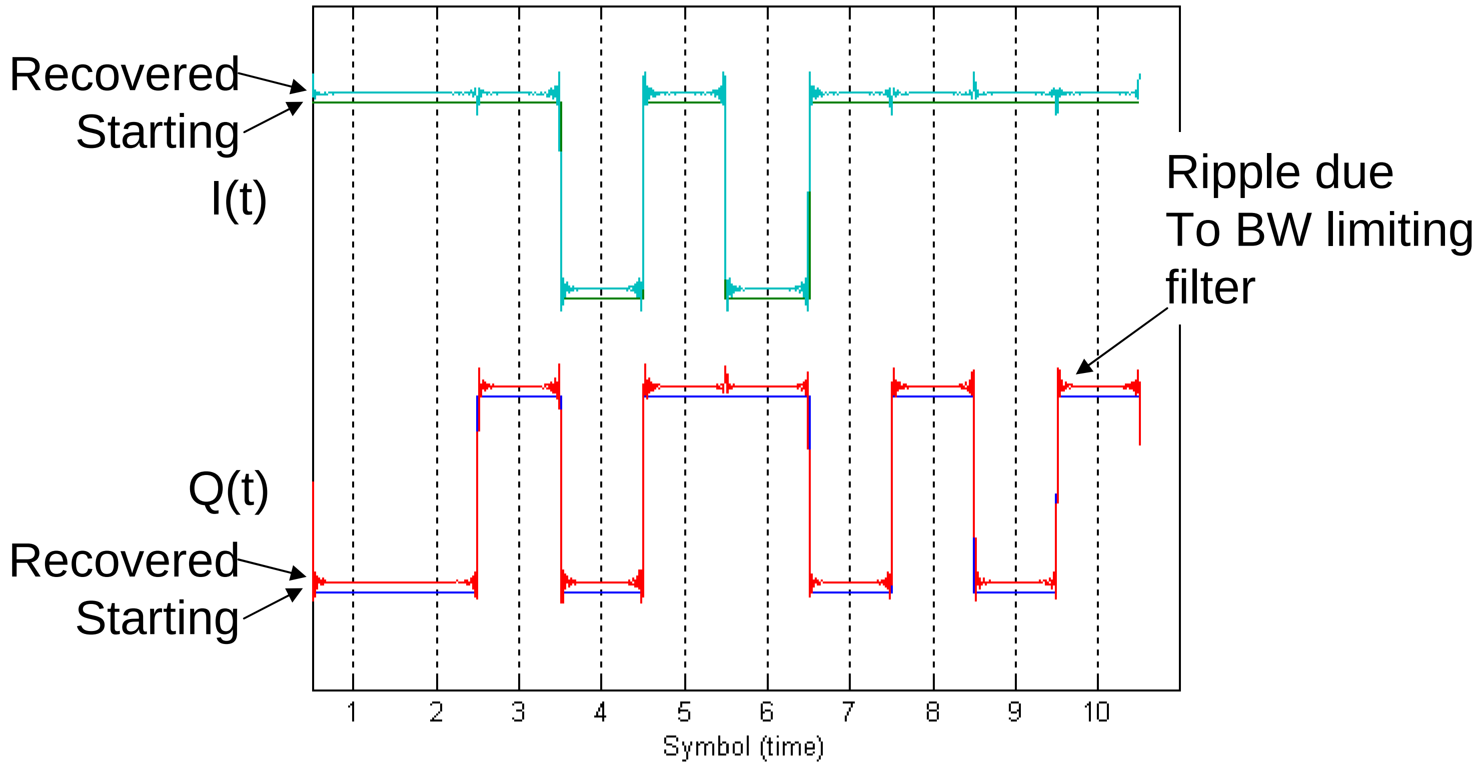


Step 1: Mix with carrier -ω



Step 2: Low Pass Filter

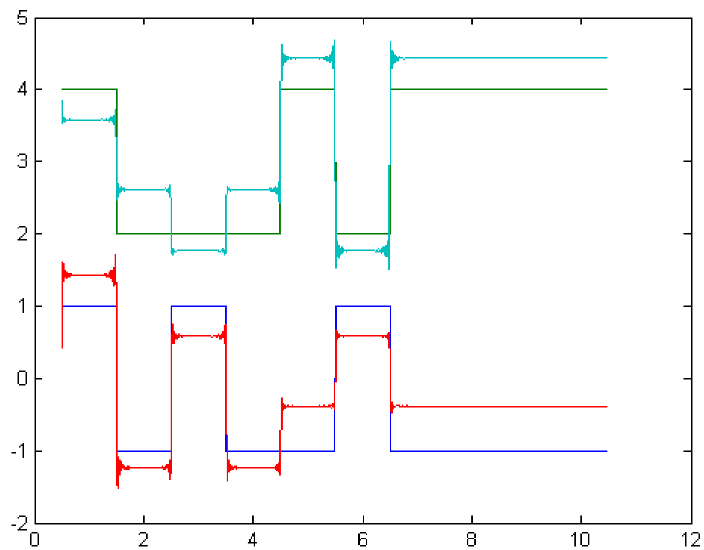
The Simplest Radio: Recovering the data

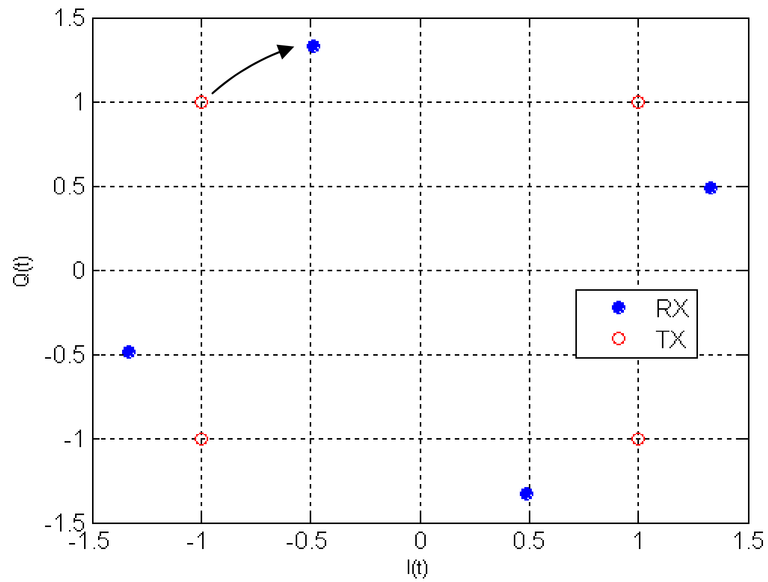


1/2 of the recovered data amplitude is lost to filtered sideband

Small offset to recovered signal added for clarity

What if RX ω is a different phase?

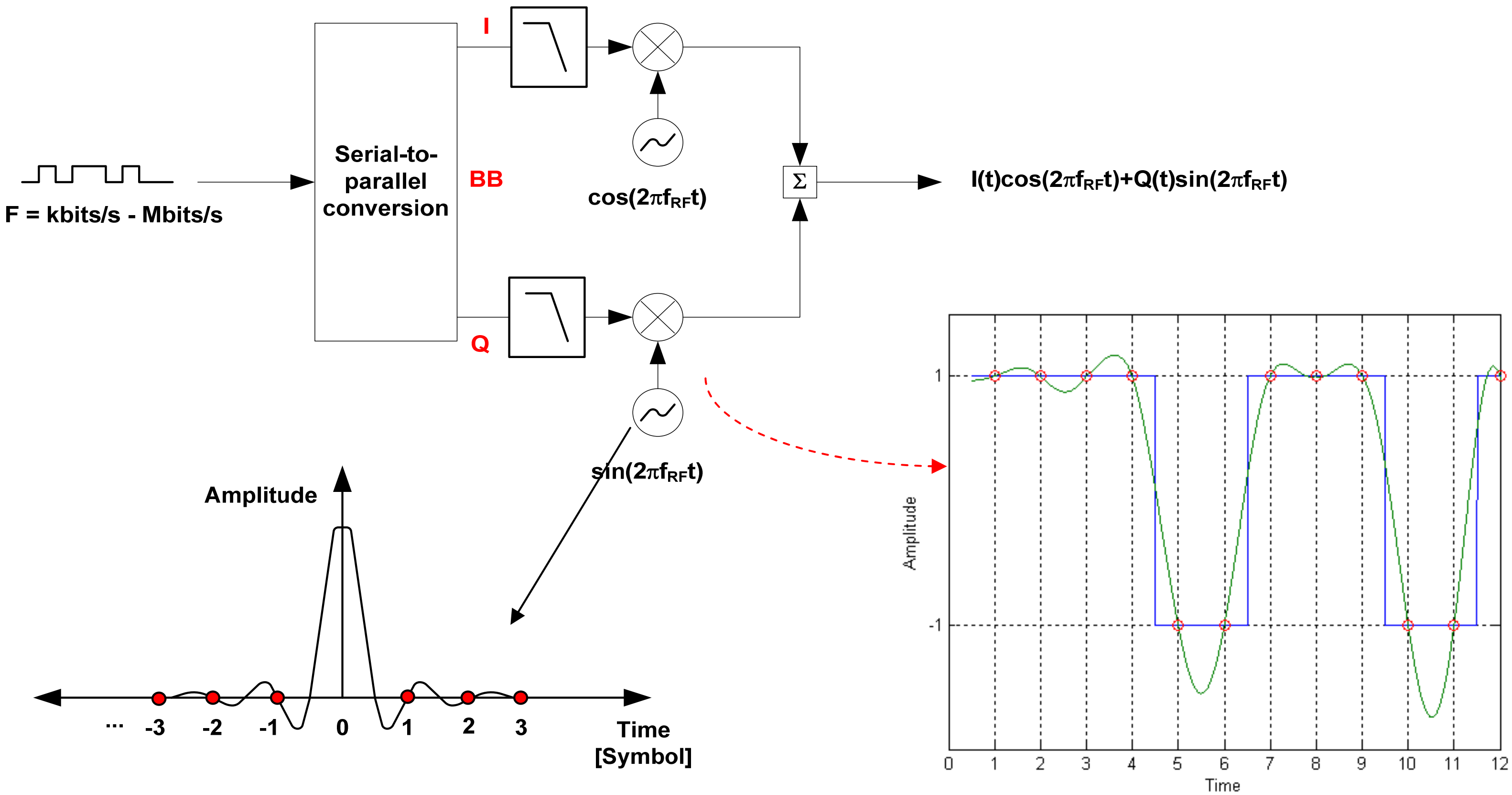




Phase difference simply results in a station rotation of the constellation
- Receiver can adjust ω phase to compensate

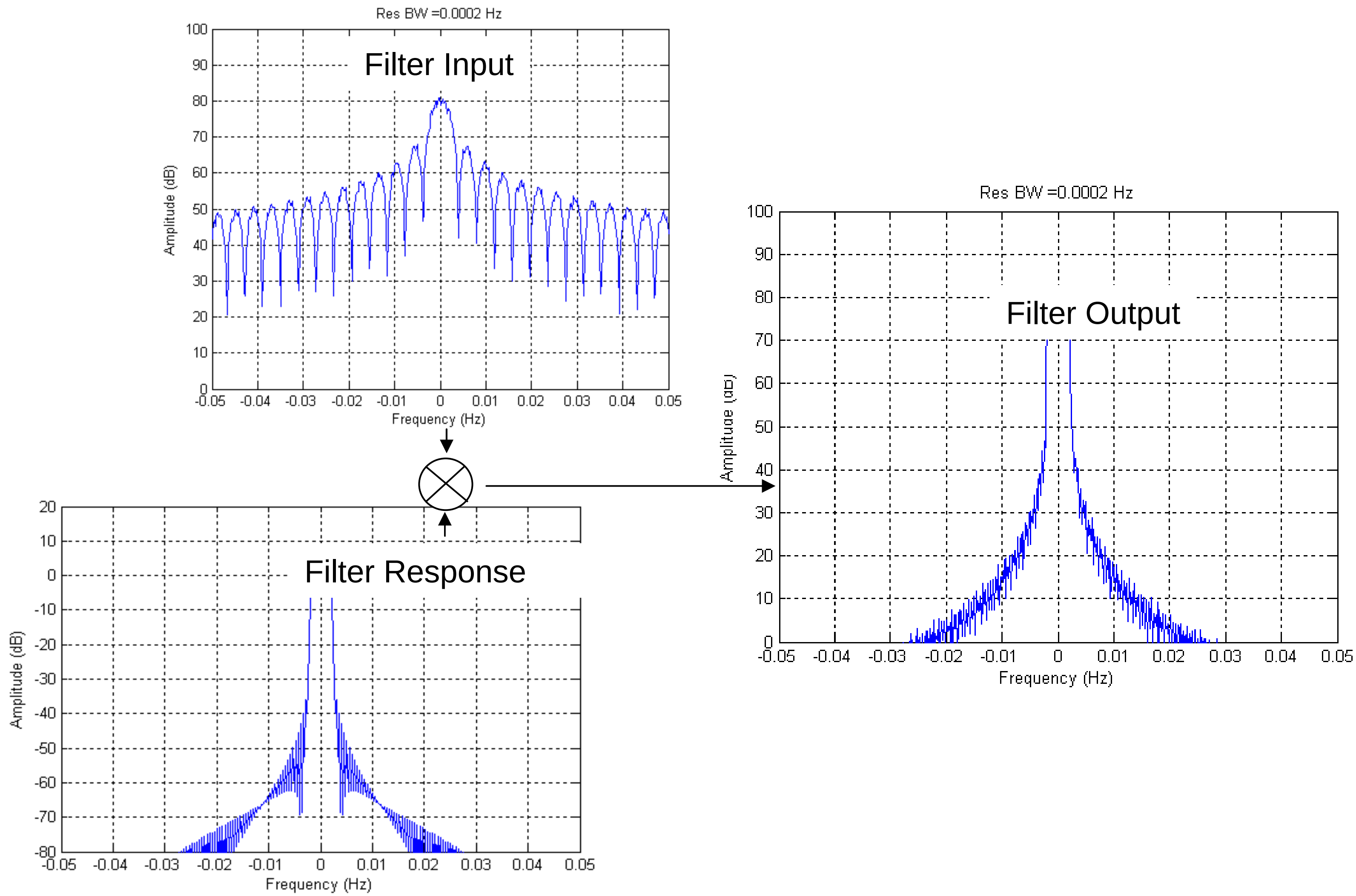
Nyquist Filtering: Smoothing the baseband transitions

Transmit (and receive) spectrum of filtered signals needs to be limited to prevent interference into other radio channels



Special Nyquist filters used to prevent InterSymbol Interference (ISI)
→ Filter response zero at integer multiples of the symbol time period

Nyquist Filtering: Frequency Spectrum



Modulation Types

QPSK: **2-bit combination of 1-bit I-Channel and 1-bit Q-channel**

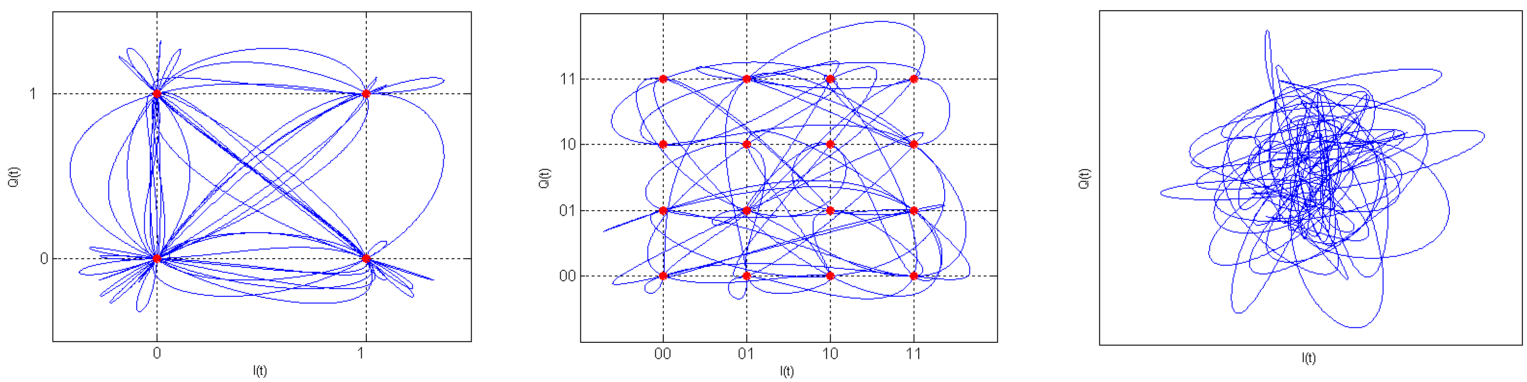
QAM: **Combination of multi-value I Channel and multi-value Q Channel**

(W)CDMA: **I and Q amplitude determined by combining multiple (e.g. 64) code channels of arbitrary amplitude (sums to I,Q Gaussian amplitude)**

OFDM: **Multiple (e.g. 256) QAM modulated sub-carriers combined. The modulation for each sub-carrier is relatively slow – high data rates comes from the large # of sub-carriers.**

Red – Symbols

Blue – filtered waveform



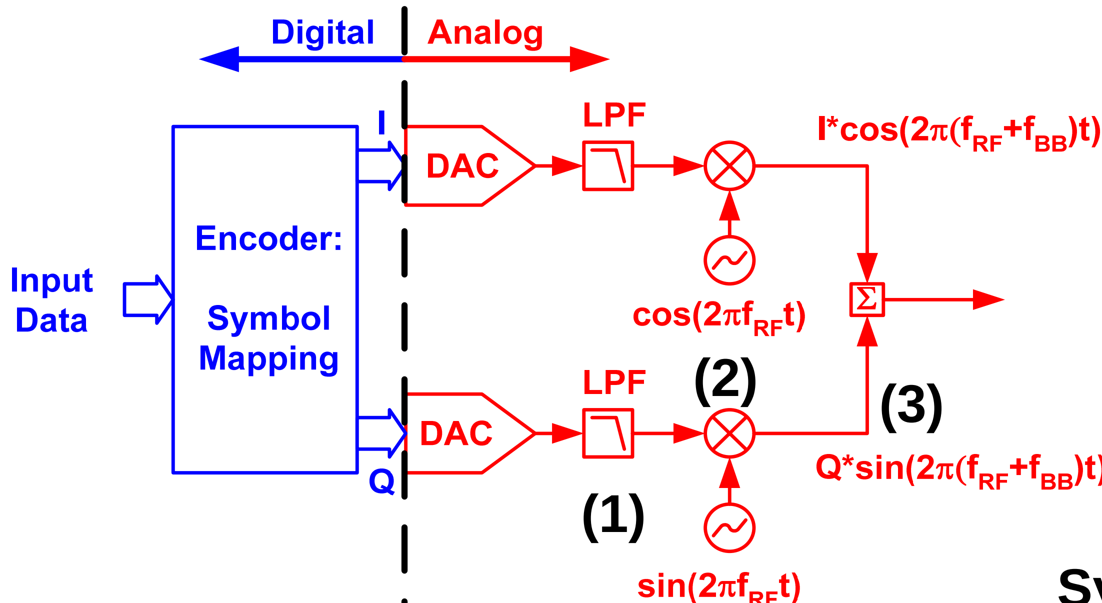
QPSK **16QAM** **WCDMA (OFDM similar)**

Next Section: Transmit Radio Architectures

- **All Analog Radio**
- **Baseband or 0 IF**
- **Real IF and Dual Real IF**
- **Complex IF**

Analog QAM Modulator

Digital to analog conversion at symbol rate

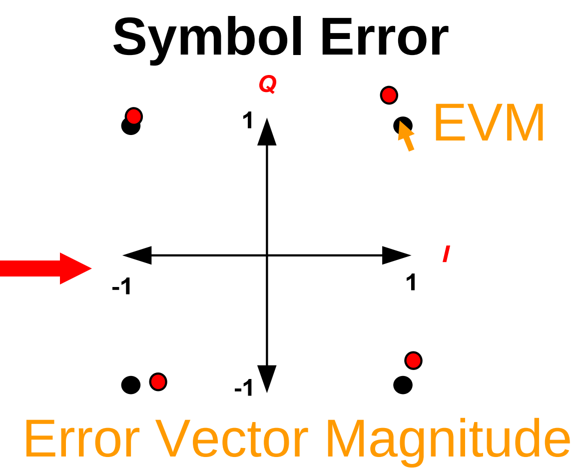


Analog Imperfections:

(1) Low Pass Filter
- a) Response
- b) I and Q LPF matching

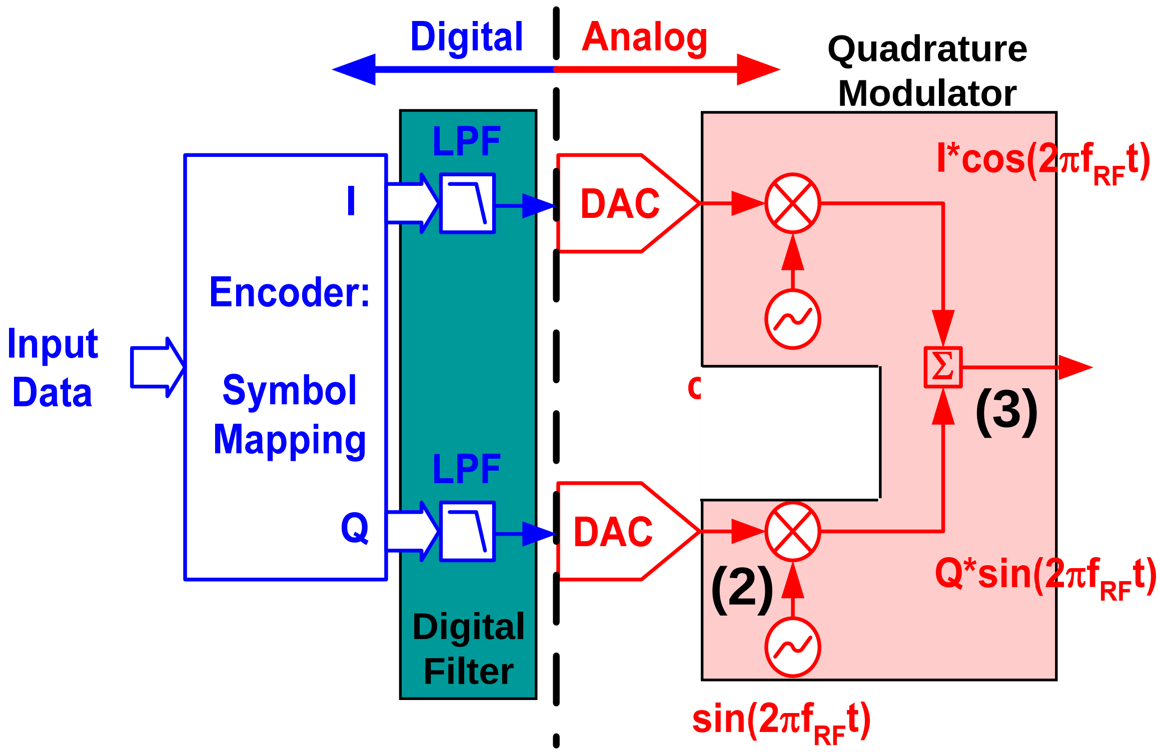
(2) Sine and Cosine
- a) phase error
- b) carrier feedthrough

(3) I and Q gain



Baseband or 0 IF Transmitter

Digital to analog conversion after Low Pass Filter (LPF)



Analog Imperfections: ~~(1) Low Pass Filter~~

(2) Sine and Cosine

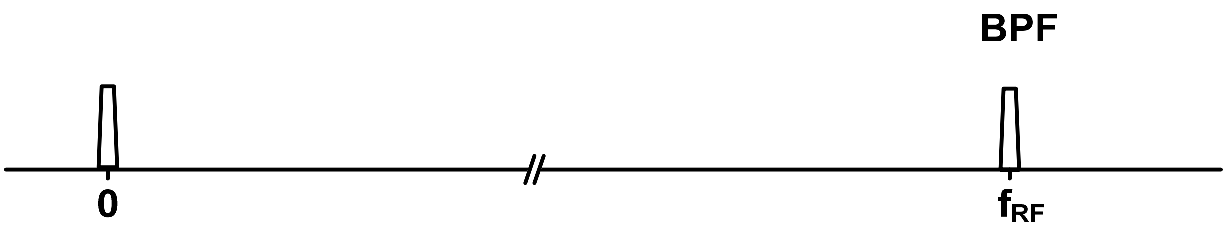
a) phase error

b) carrier feedthrough

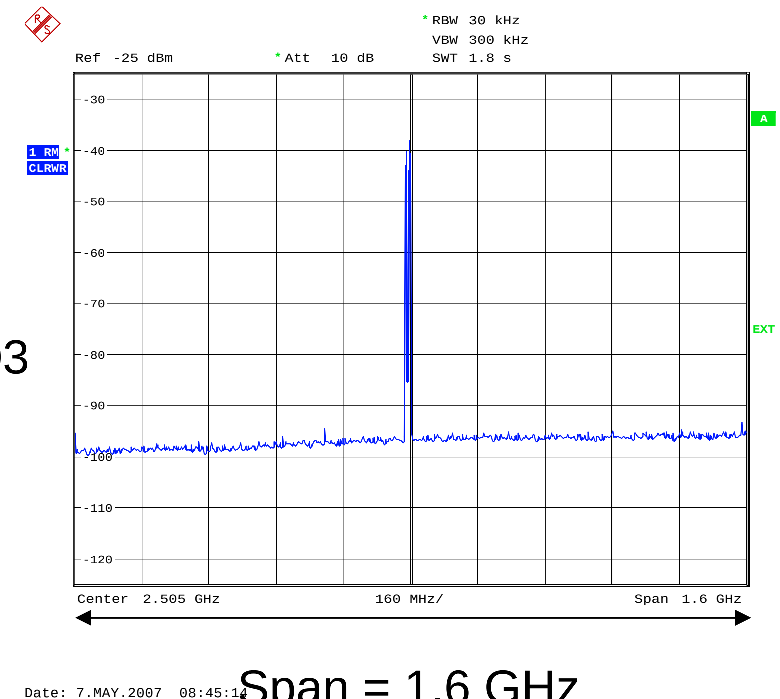
(3) I and Q gain

Baseband or 0 IF Transmitter

Big Advantage: Very easy RF spectrum – no images to filter



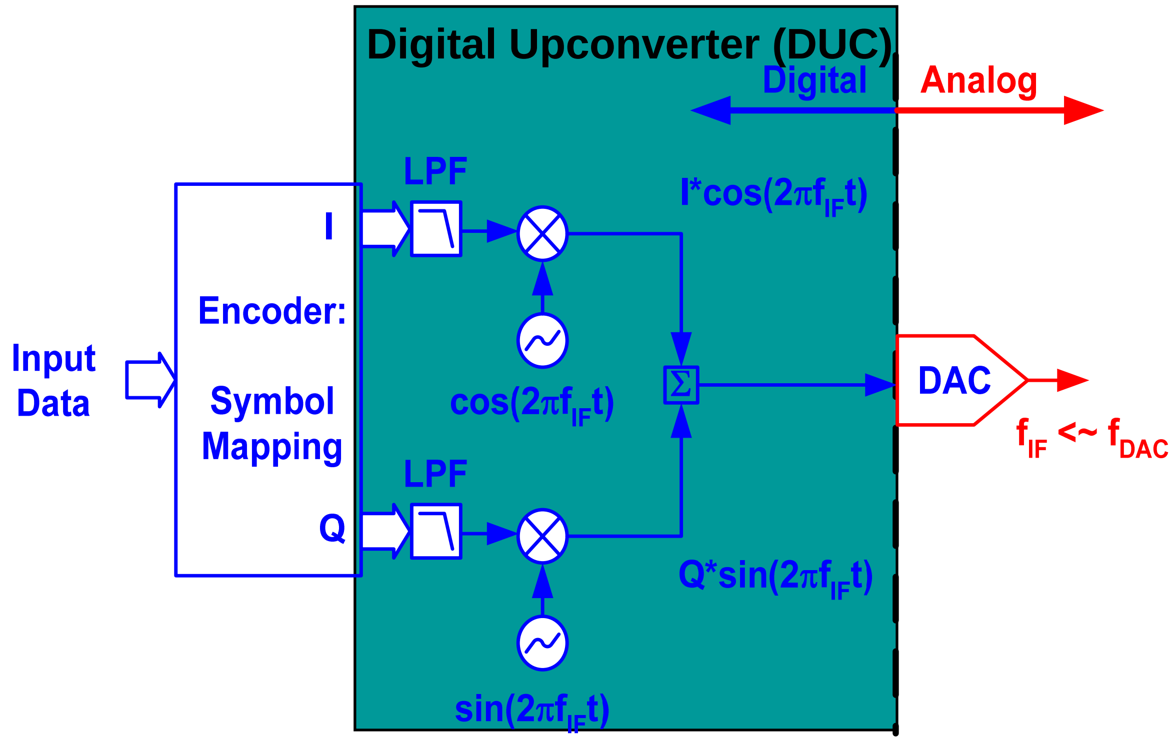
Example:
DAC5688 + TRF3703
20 MHz WCDMA
Fdac = 800 MHz
RF LO = 2.5 GHz



Span = 1.6 GHz

Digital Quadrature Modulation

Digital to analog conversion after Quadrature modulation



~~Analog Imperfections: **(1)** Low Pass Filter~~

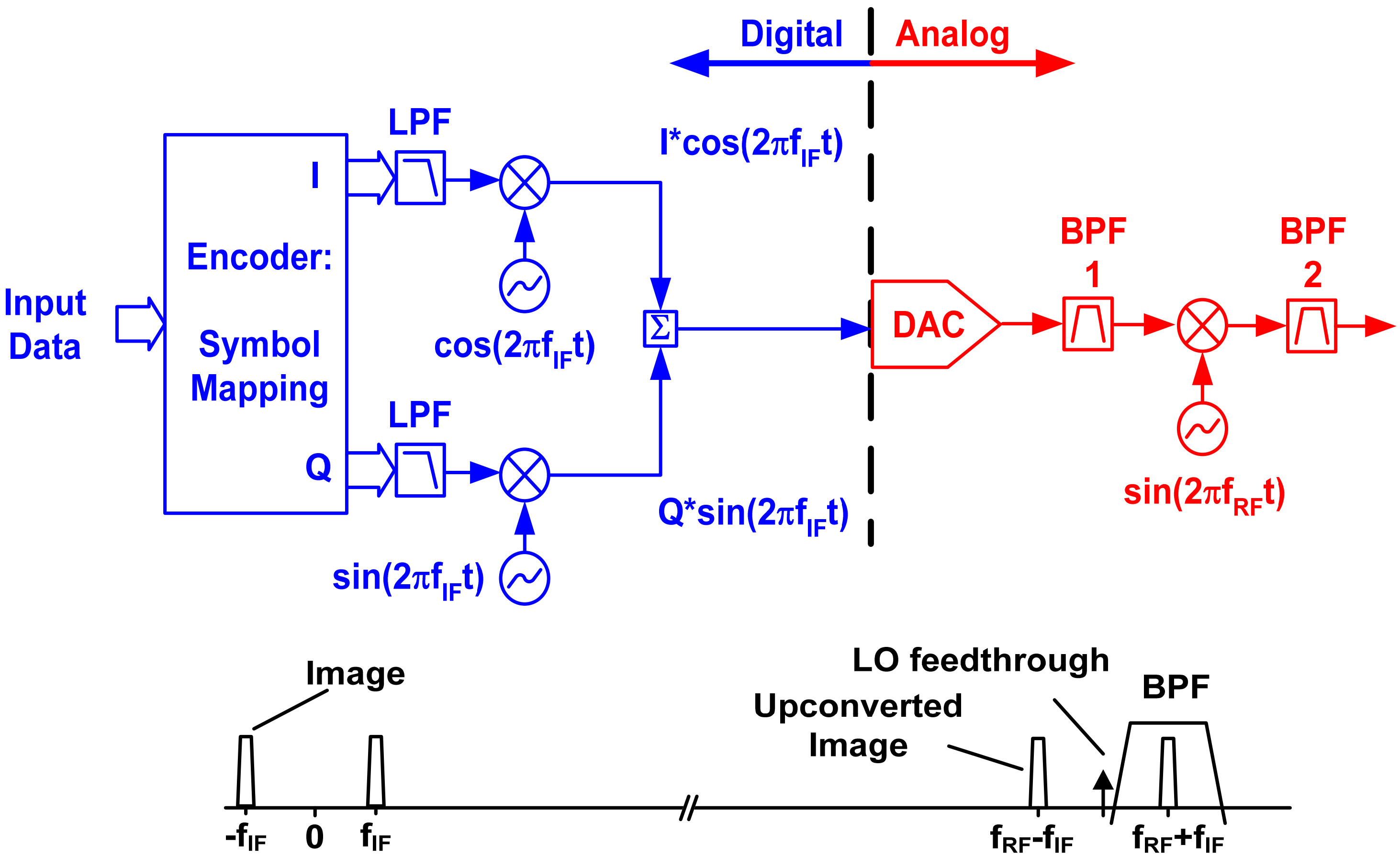
~~**(2)** Sine and Cosine~~

~~**(3)** I and Q gain~~

No analog imperfections, but output frequency IF limited by DAC sample rate, typically, f_{IF} <~ $1/3*f_{DAC}$

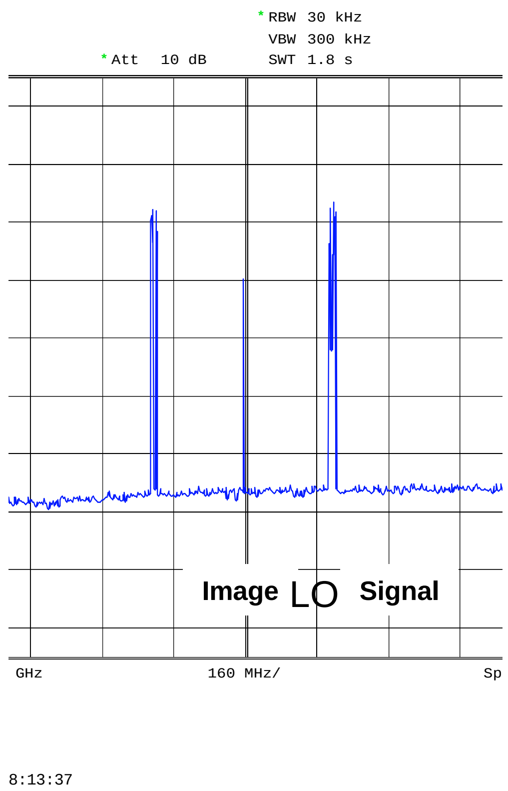
Heterodyne (Real IF) Transmitter

Add analog mixer stage to increase frequency



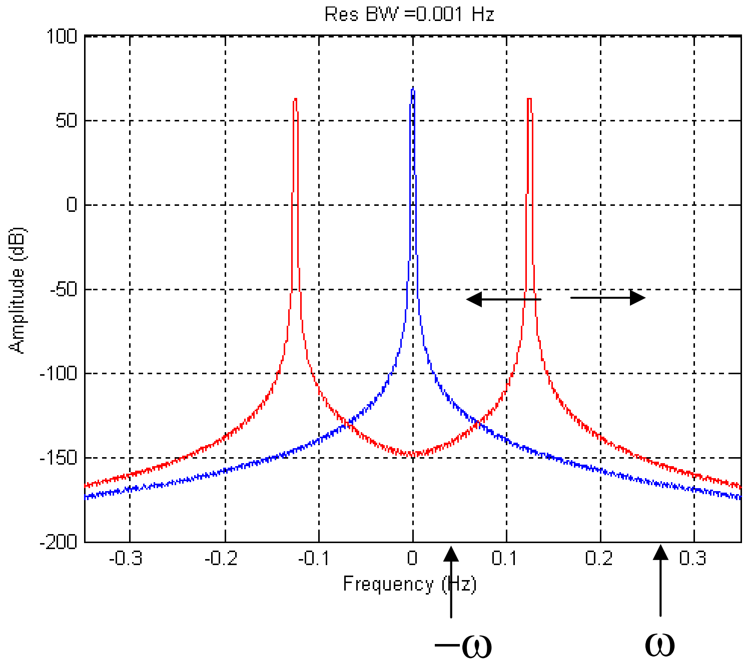
Heterodyne (Real IF) Transmitter: Spectrum

Example:
DAC5688 + TRF3703
20 MHz WCDMA
Fdac = 800 MHz
Real IF = 200 MHz
RF LO = 2.5 GHz



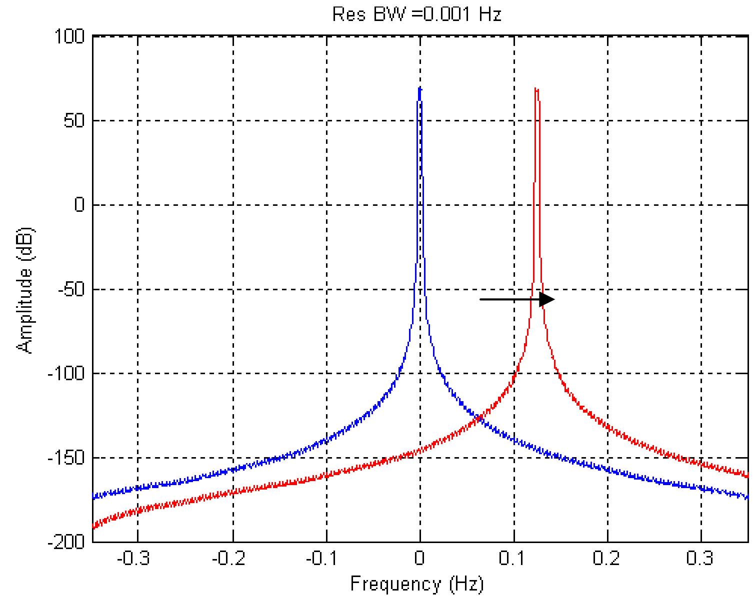
Complex IF Transmitter: IF Frequency Spectrum

Complex to Real Mixing



remember – negative freqs
Are mirrored for real signals

Complex to Complex Mixing

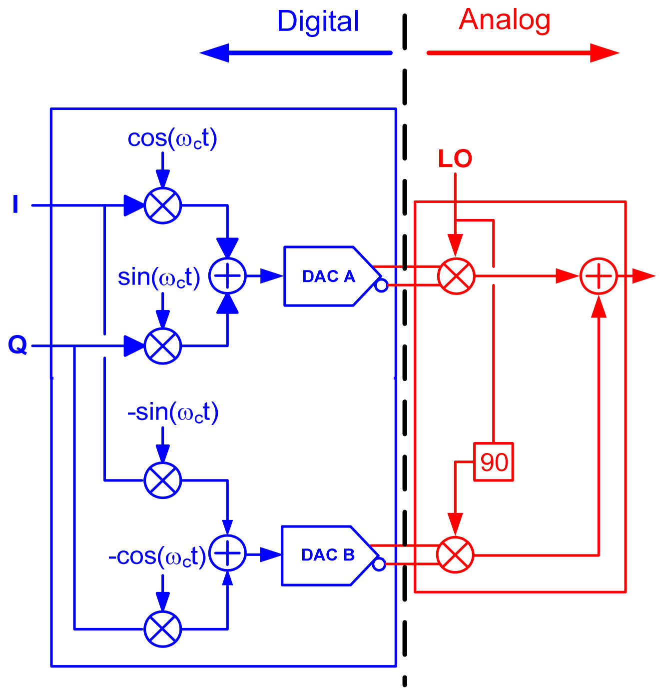


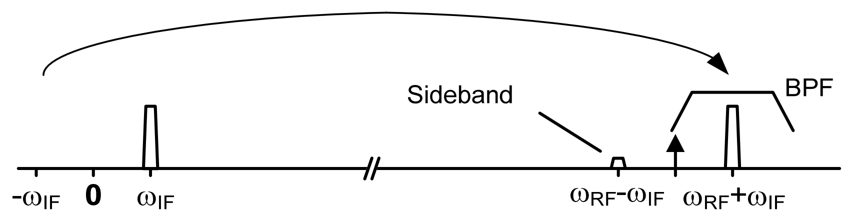
Complex mixing to complex
output shifts the spectrum

Complex IF Transmitter: IF to RF

$$[I_{IF}(t)+j^*Q_{IF}(t)]^*e^{i\omega_{RF}t} =$$

$$[I\ (t)+j^*Q\ (t)]\ ^*\ e^{i\omega_{IF}t}\ ^*e^{i\omega_{RF}t} = [I\ (t)+j^*Q\ (t)]^*\ e^{i(\omega_{IF}+\omega_{RF})t}$$

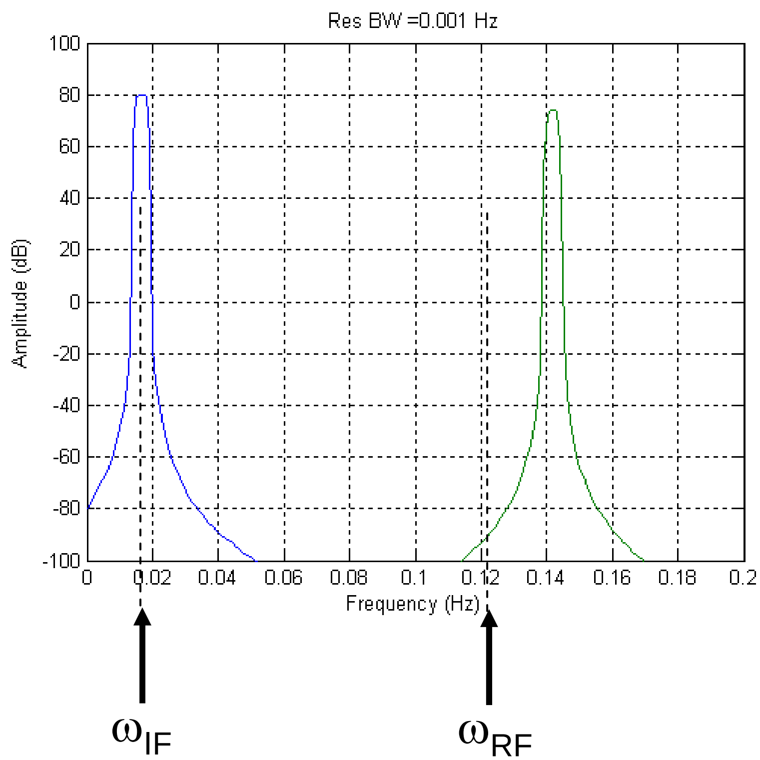




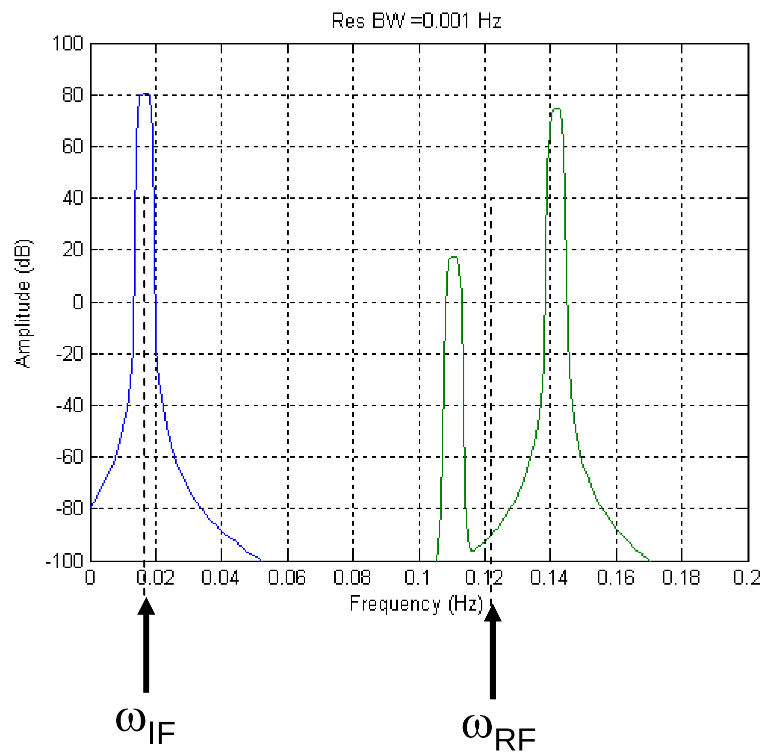
Benefit #1: Sideband Suppressed by IQ modulator

Complex IF: Effect of Analog IQ Imperfections

Perfect IQ Modulator

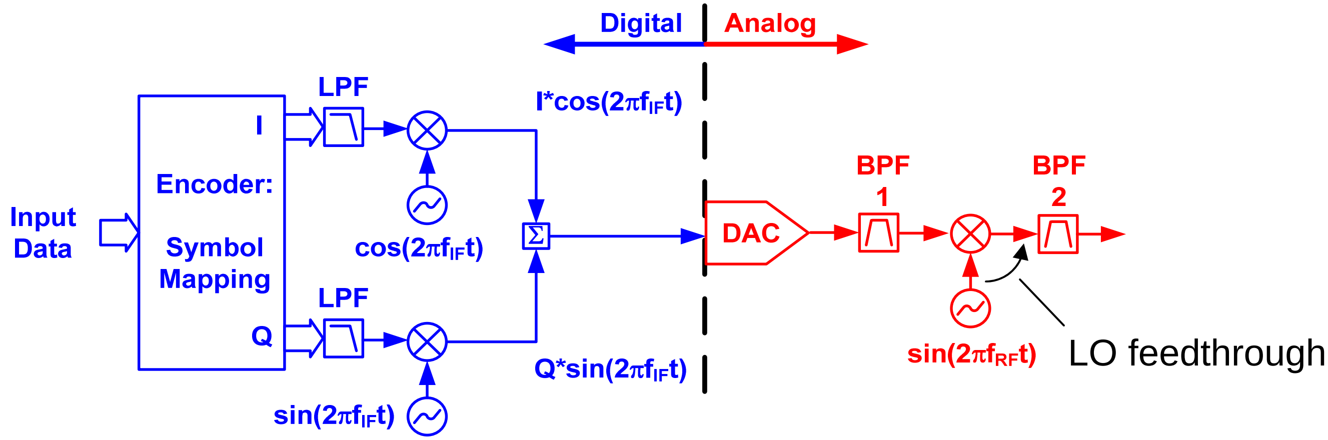


IQ Modulator with Phase or Gain Imbalance



Benefit #2: Analog phase and gain imbalance results in less sideband suppression, not signal degradation (EVM).

Complex IF: Cancelling LO feedthrough

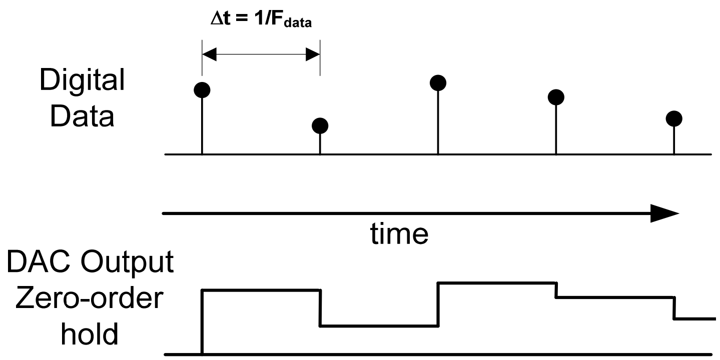


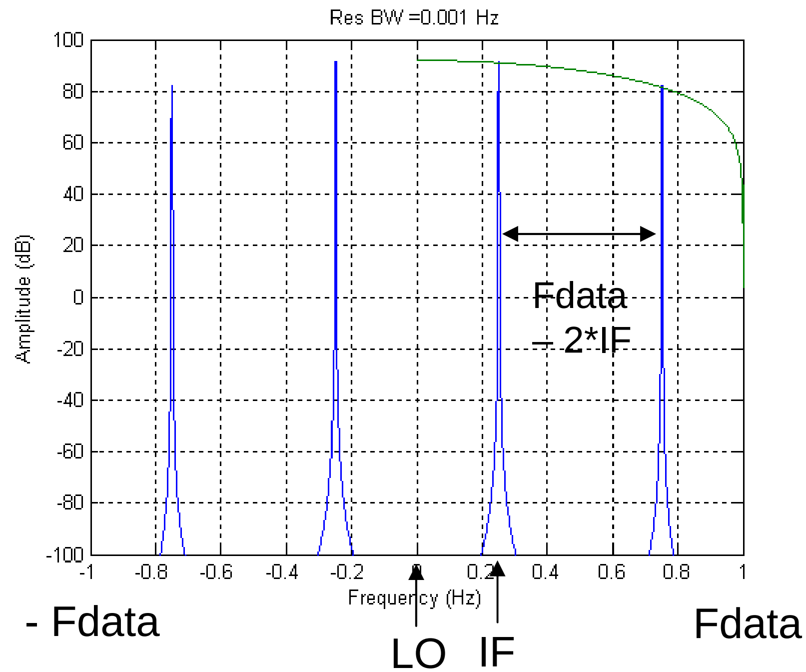
- **LO feedthrough can be caused by:**
  - **offset at mixer input**
  - **Incomplete isolation on PCB**
  - **Incomplete isolation in mixer**
- **The phase δ of the LO feedthrough is not well controlled**
  Feedthrough = $\sin(\omega t + \delta) = A^* \sin(\omega t)+B^*\cos(\omega t)$
  where $A = \cos(\delta)$ and $B = \sin(\delta)$ are constants
- **For a real IF system, a DC offset at the input can only cancel the $\sin(\omega t)$ term, leaving the $\cos(\omega t)$ term.**

Benefit #3: For a complex IF system, DC offset to I and Q can be used to generate the sin(wt) and cos(wt) terms – LO feedthrough can be completely cancelled (if exact phase is known).

DAC Images for Real IF

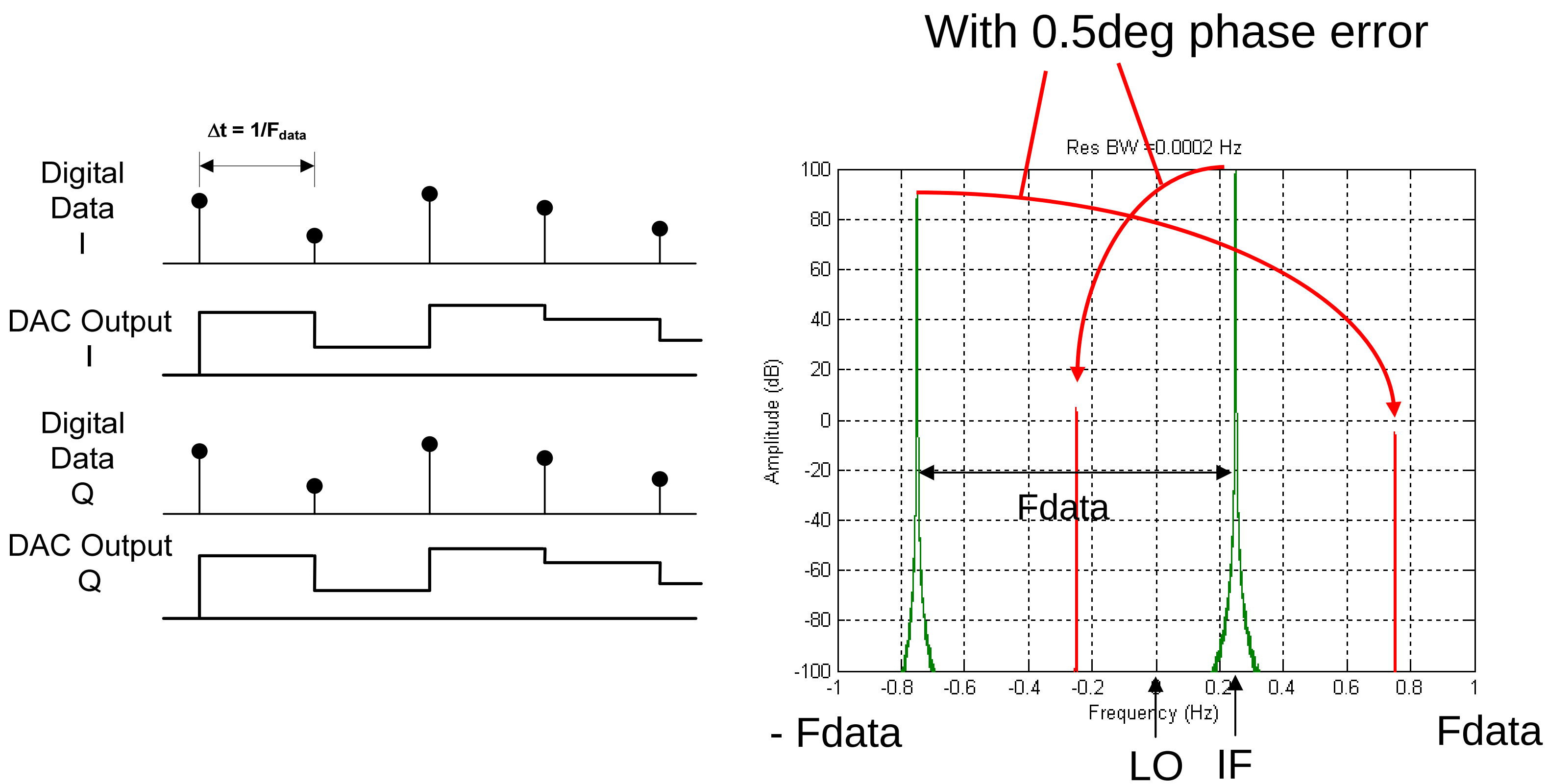
Conversion from the digital signal (discrete points in time) to analog Signal (continuous in time) typically done by holding the value for 1 clock period (called zero-order hold)





For Real IF, 2nd Nyquist zone image offset by Fdata – 2*IF

DAC Images for Complex IF

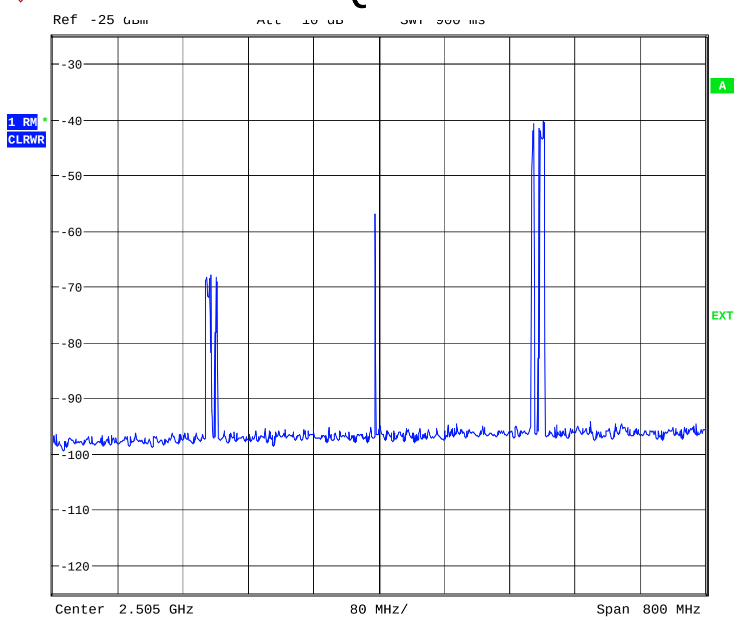


Benefit #3: For complex IF, 2nd Nyquist zone image offset by Fdata
Image offset at Fdata – 2*IF is suppressed to IQ balance level

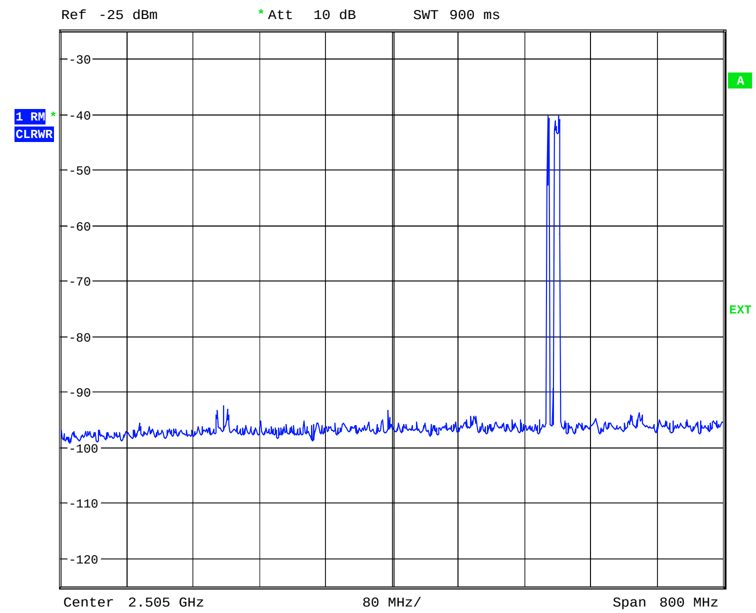
Complex IF Transmitter: Spectra

Example:
DAC5688 + TRF3703
20 MHz WCDMA
Fdac = 800 MHz
Complex IF = 200 MHz

Without IQ Correction



With IQ Correction*



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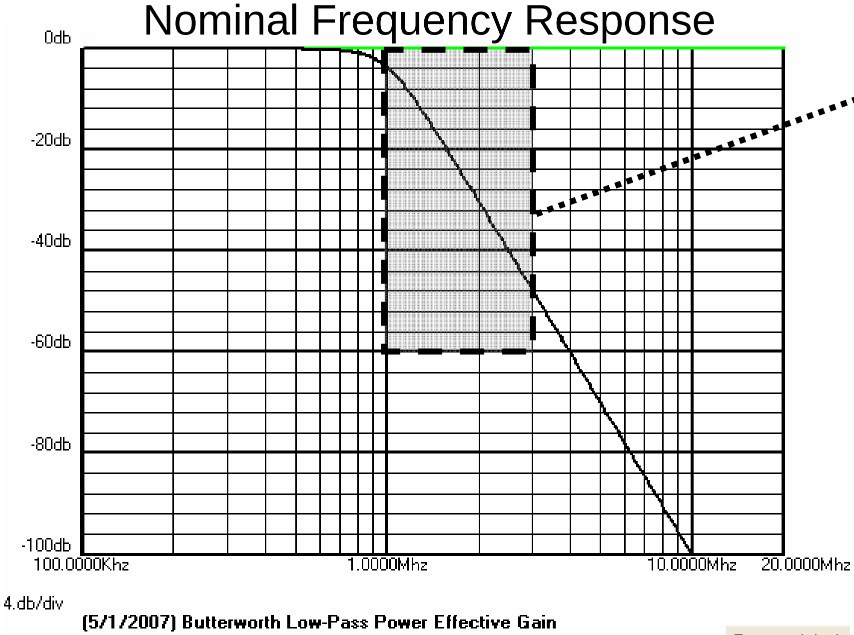
*Need to know values to correct – works well with feedback

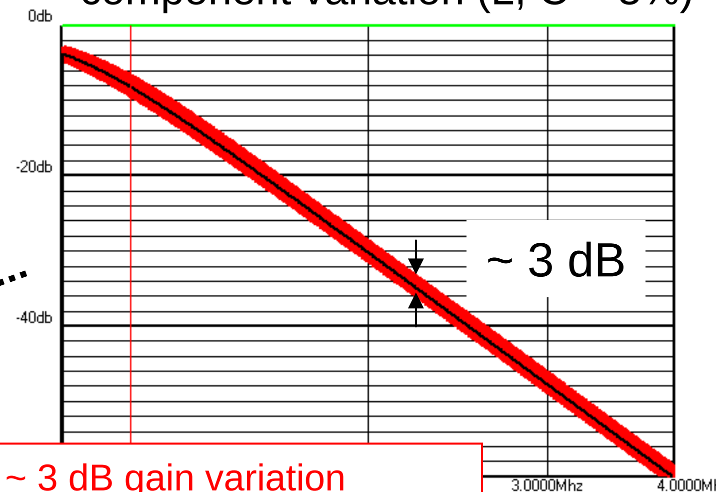
Complex IF: Beware IF Filtering

Example:
- 5th Order Analog LC filter
- Two filters needed for I and Q
- How well can they be matched?

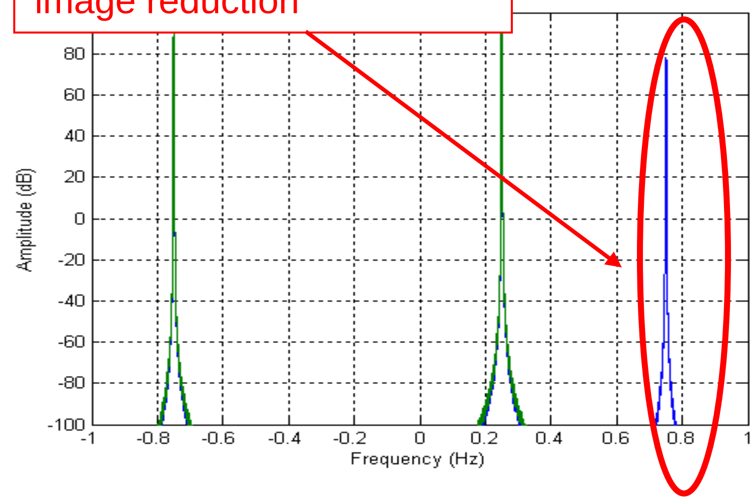
Nominal Frequency Response



Statistical analysis for
component variation (L, C = 5%)



~ 3 dB gain variation
eliminates benefit of
image reduction



In most cases, our recommendation
Is not to do IF filter with complex IF

Summary of Complex IF & Applications

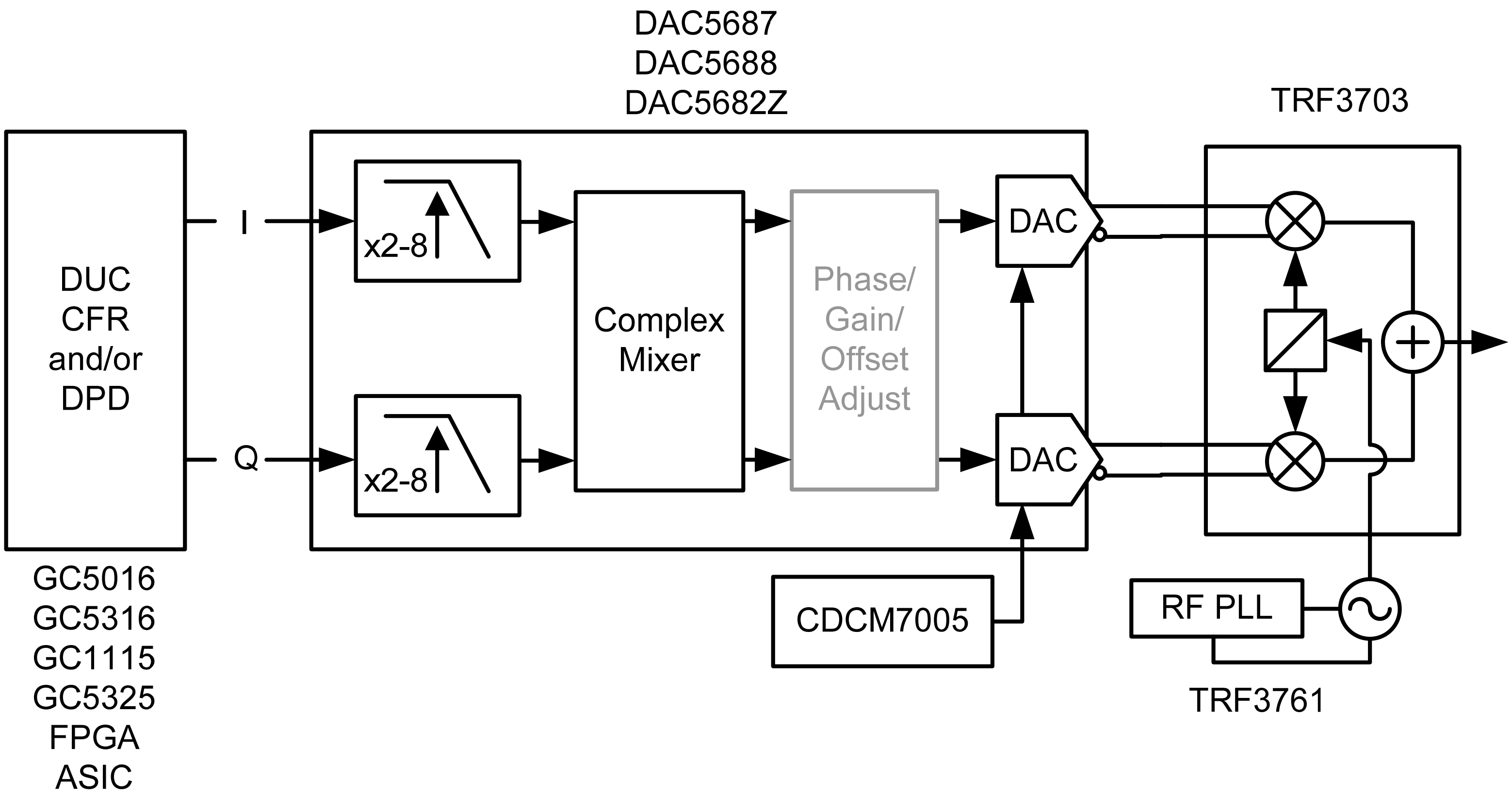
<u>Complex IF Advantages</u>

1. **RF image (sideband) suppressed by analog IQ modulation**
2. **No degradation in signal quality (EVM) from IQ imbalance**
3. **LO feedthrough can be eliminated**
4. **2nd Nyquist zone image offset at RF by F_{data}**

<u>So What?</u>

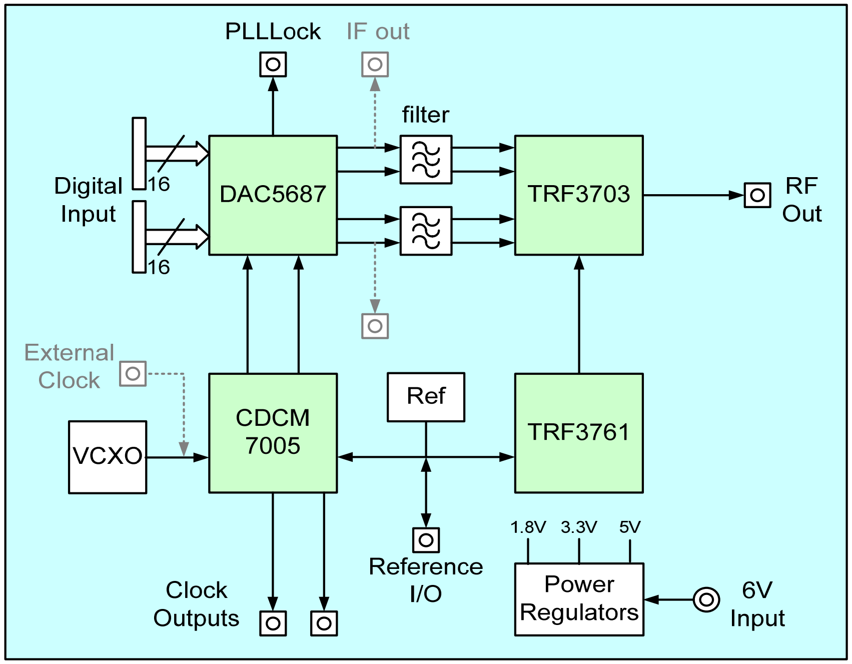
- **These advantages translate into reduced RF filtering requirements.**
- **This is most important in wideband applications (harder to filter)**
- **A rule of thumb is that a real IF system would require an IF twice as high as complex IF for equivalent RF filtering**

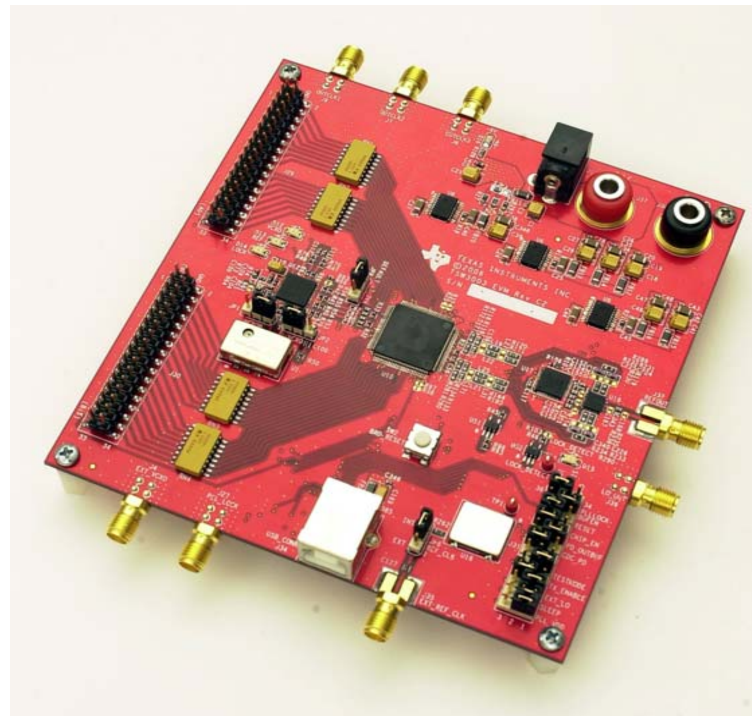
TI Parts for Complex IF



TSW3003: TX Digital to RF Solution

Our Tool for demonstrating Complex IF (or 0 IF) Transmitter





Also, DAC5688 or DAC5682 EVMs include clock and TRF3703