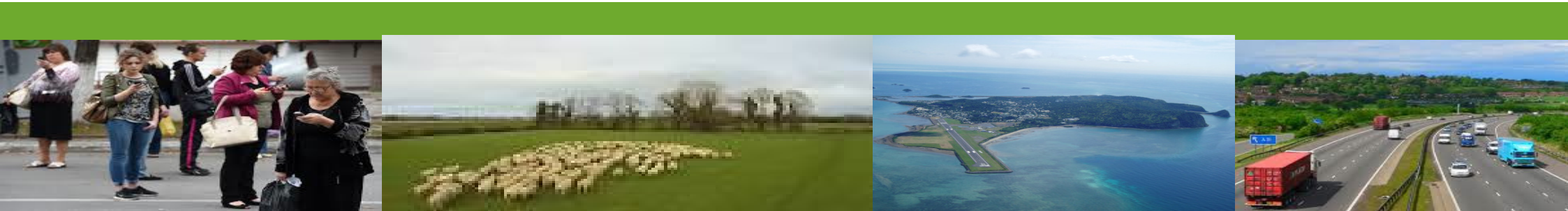




# What is the LimeSDR

Danny Webster



# Table of Contents

1. Introduction
2. The Analogue Half of the LMS7002M
3. The Digital Half of the LMS7002M
4. The LimeSuiteGUI
5. Using the LimeSDR Well
6. The FPGA
7. Summary

# 1. Introduction



# LimeSDR and The LMS7002M

## RF Parts

Antennas  
SAW Filters  
RF Switches  
Power Amps  
'Hackable'

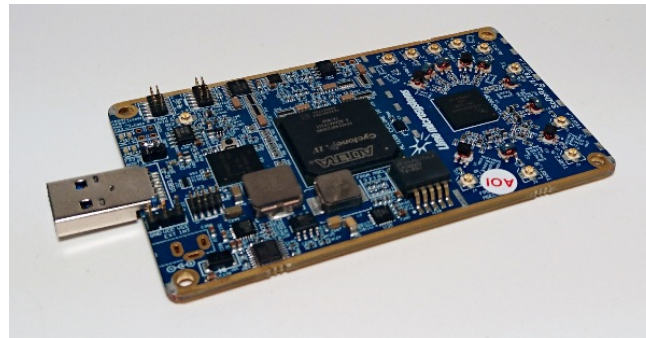
Radio is more than just a chip. Performance is critically linked to RF antennas, filtering and matching which end user selects/modify

## TRX RFIC

LMS7002M

## FPGA

Cyclone IV



Open Source  
Software/Apps

## COMPUTER

Multicore  
GHz Processor  
And Memory

WiFi/Ethernet/  
ADSL Network

PCIe  
Link

USB3  
Link

## LMS7002M

- **2<sup>nd</sup> Generation All CMOS Transceiver**
- **Low Power <2W**
- **Originally designed for 4G MIMO Femto and Pico Cell applications.**
  - Home base stations
  - 64-QAM OFDM
  - 2.5dB NF
  - -15dBm CW Blocker
  - Requires external PA for Femto/Pico Applications
- **Designed with Digital Predistortion for 4G in mind**
  - PCIe version of LimeSDR
    - USB3 5Gb/s->640MB/s->80Ms/s
  - >50MHz IF Bandwidth
    - TX IF Bandwidth 100MHz
    - RX IF Bandwidth 80MHz
  - High speed ADC/DAC >100Ms/s
    - DAC 640Ms/s
    - ADC 160Ms/s
  - High speed digital interface
    - 120Ms/s MIMO DDR CLK=480, MCLK=240
    - 160Ms/s SISO DDR CLK=640, MCLK=160



# LMS7002M FPRF Transceiver Block Diagram

High level of integration, including dual 12-bit ADC and DAC

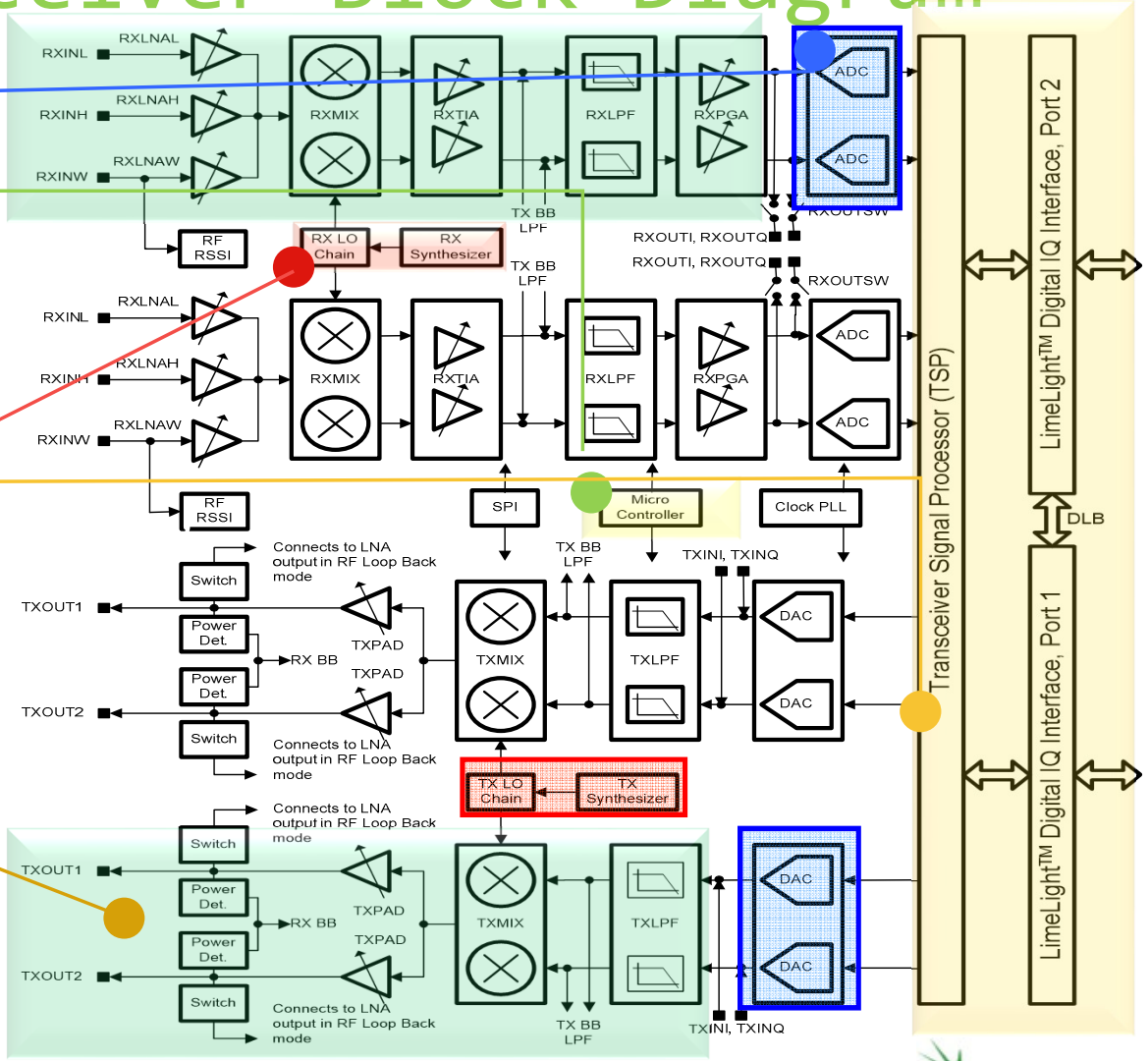
Integrated 8051 MCU

Transceiver Signal Processor block and LimeLight interface

Frequency  
100KHz – 3.8GHz

Field Programmable RF

Highly configurable RF gain and IF filter with numerous bypass options



LMS7002M



# LMS7002M is very complicated!!!!

- **Lets break it down a bit**
- **MIMO Transeiver**
  - Up to 2 TX can operate simultaneously
  - Up to 2 RX channels can operate simultaneously.
- **Each TX channel**
  - 2 outputs
  - Low band (for <2.5GHz)
  - High band
- **Each RX channel**
  - 3 Inputs
  - Low band (opt for 800MHz)
  - Wide band (general purpose)
  - High band (opt for 2-3.8 GHz)
- **Synthesisers x3**
  - SXT – TX Synthesiser
  - SXR – RX Synthesiser
  - CLKGEN – Digital Circuits
- **Now let's explore the details, gradually...**



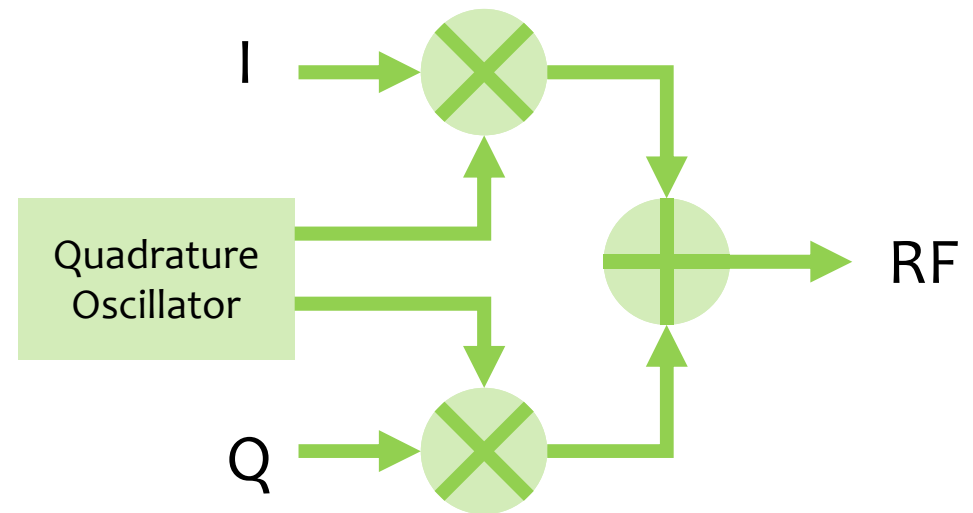
## 2. The Analogue Half of the LMS7002M





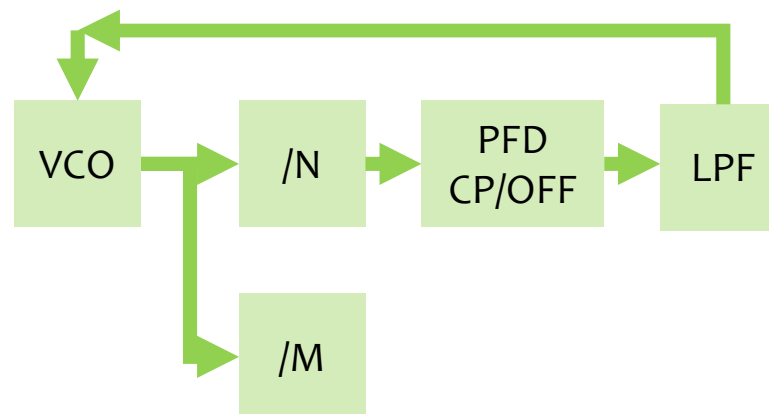
# Simplified Vector (Homodyne) Transmitter

- **Homodyne 1930s**
  - Commonly called Zero IF
  - Similar to Hartley SSB Modulator
- **Analogue I,Q input signal**
  - describes a vector of amplitude and phase described by Cartesian co-ordinates  $\{I, Q\}$
  - Usually generated by software.
- **Frequency Mixer**
  - Converts I,Q into RF



# Lime RF Synthesisers

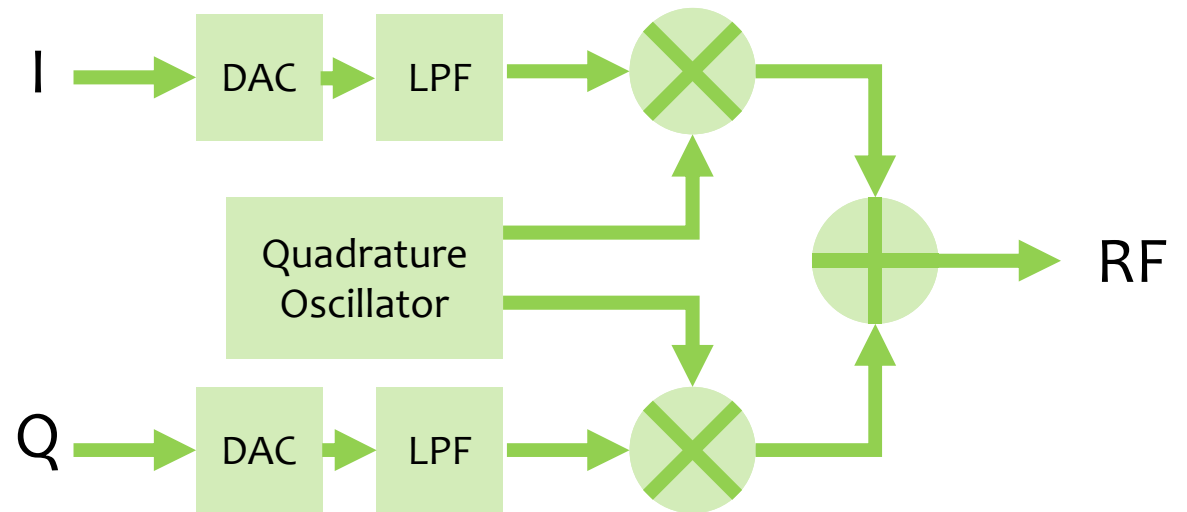
- **30.72MHz TXCO** (Note boundary spurs)
- **Typically -90dBc Phase Noise Plateau**
  - -100dBc with very low noise LDOs and very low phase noise TXCO
- **Integrated Phase Noise (LimeSDR)**
  - 0.14deg 100MHz
  - 0.17deg 215MHz (1024 QAM)
  - 0.31deg 500MHz
  - 0.46deg 850MHz (256 QAM)
  - 0.98deg 2145MHz (64 QAM)
  - 1.32deg 450MHz
- **Typically -155dBc Far out phase noise**



- **Delta Sigma Fractional N Type Synthesiser**
- **Programmable charge pump**
- **Programmable offset current**
- **Programmable loop filter**
- **TDD Mode SXT drives TX and R**

# Digital Vector Transmitter

- **Digital I,Q data**
  - Converted to analogue by Digital to Analogue Converter (DAC)
  - DAC output cleaned by Low Pass Filter
    - Removes Aliases



# Sampled Data Systems and Nyquist

- **Sampled data systems**

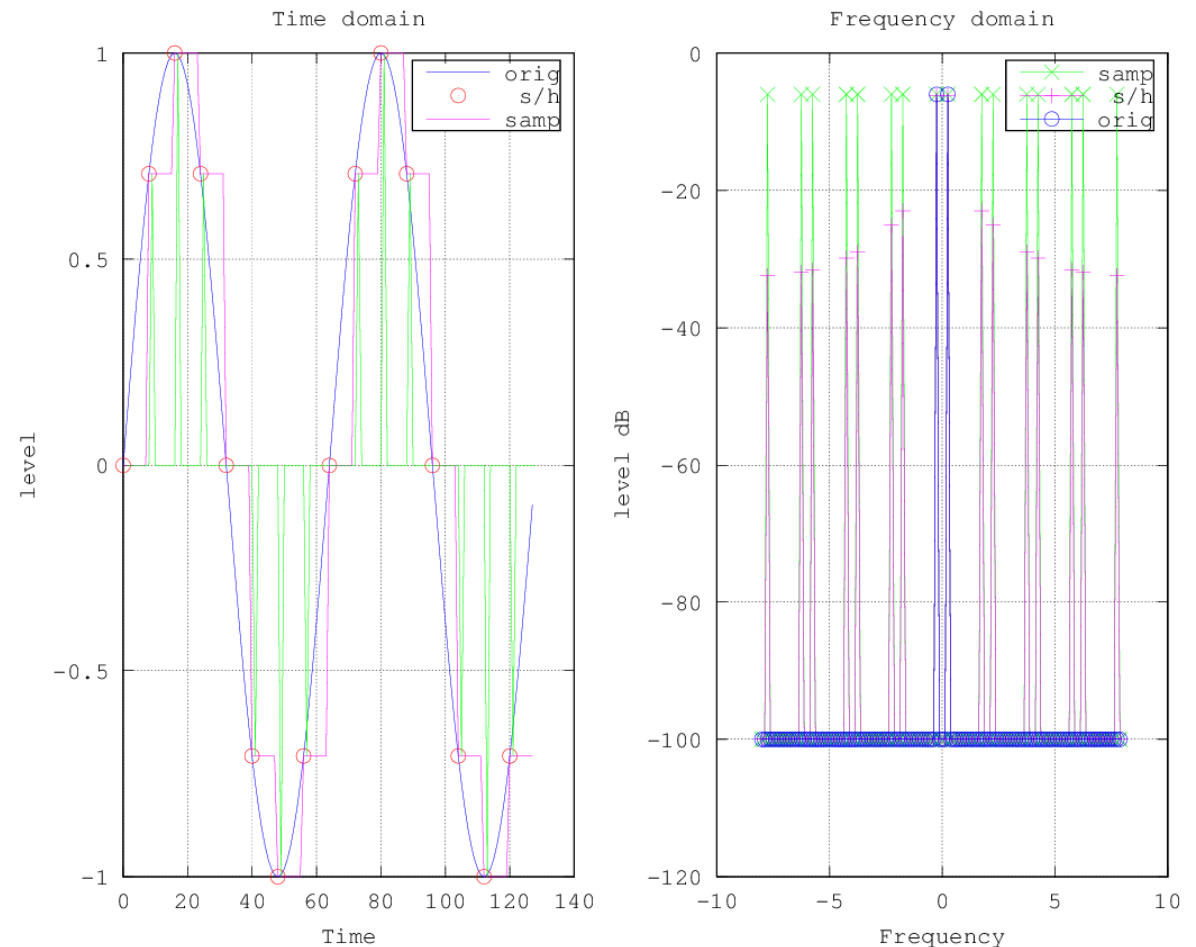
- look at a waveform only at fixed moments in time,
- Points usually equally spaced.

- **Nyquist Sampling**

- Input signal frequency less than sampling rate

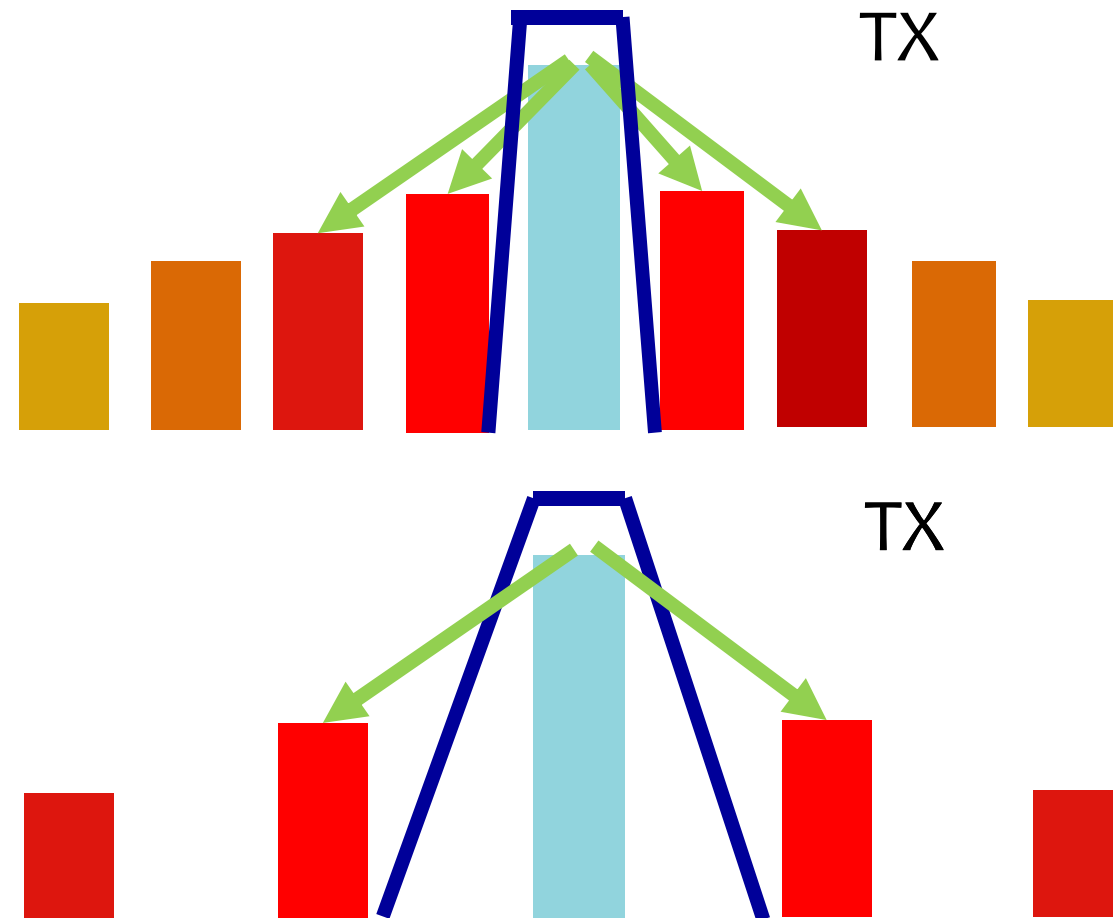
- **Reconstructed signal**

- Sample and Hold
- Aliases occur above the sample rate.



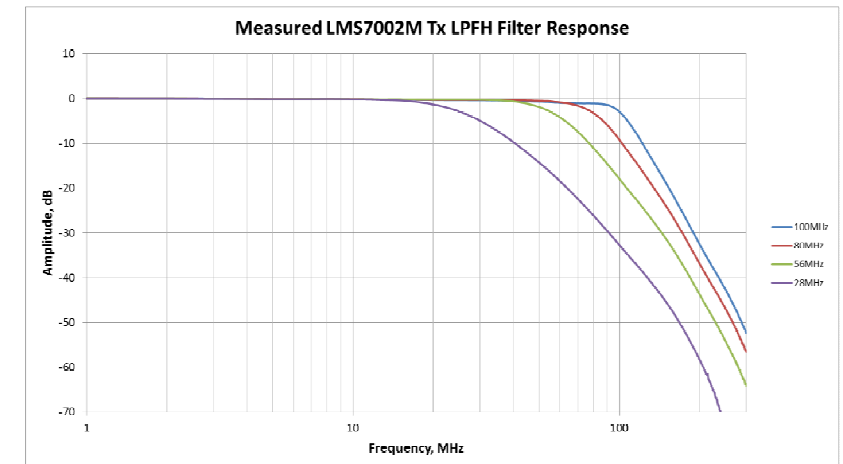
# Aliasing and the Adjacent Channel TX

- **TX**
  - Aliases lead to transmitting interference in adjacent channels.
  - Not easy to filter.
  - Bad Neighbour (ASBO from OFCOM)
- **What happens if we double the sampling rate?**
  - Oversampling
  - Aliases are further away.
  - Filter specification can be relaxed



# LimeSDR TX Active Filters

- **LPFL**
  - 4<sup>th</sup> Order Chebychev
  - Optional Real Pole
- **LPFH**
  - 2<sup>nd</sup> Order Butterworth



# Quantisation and Noise

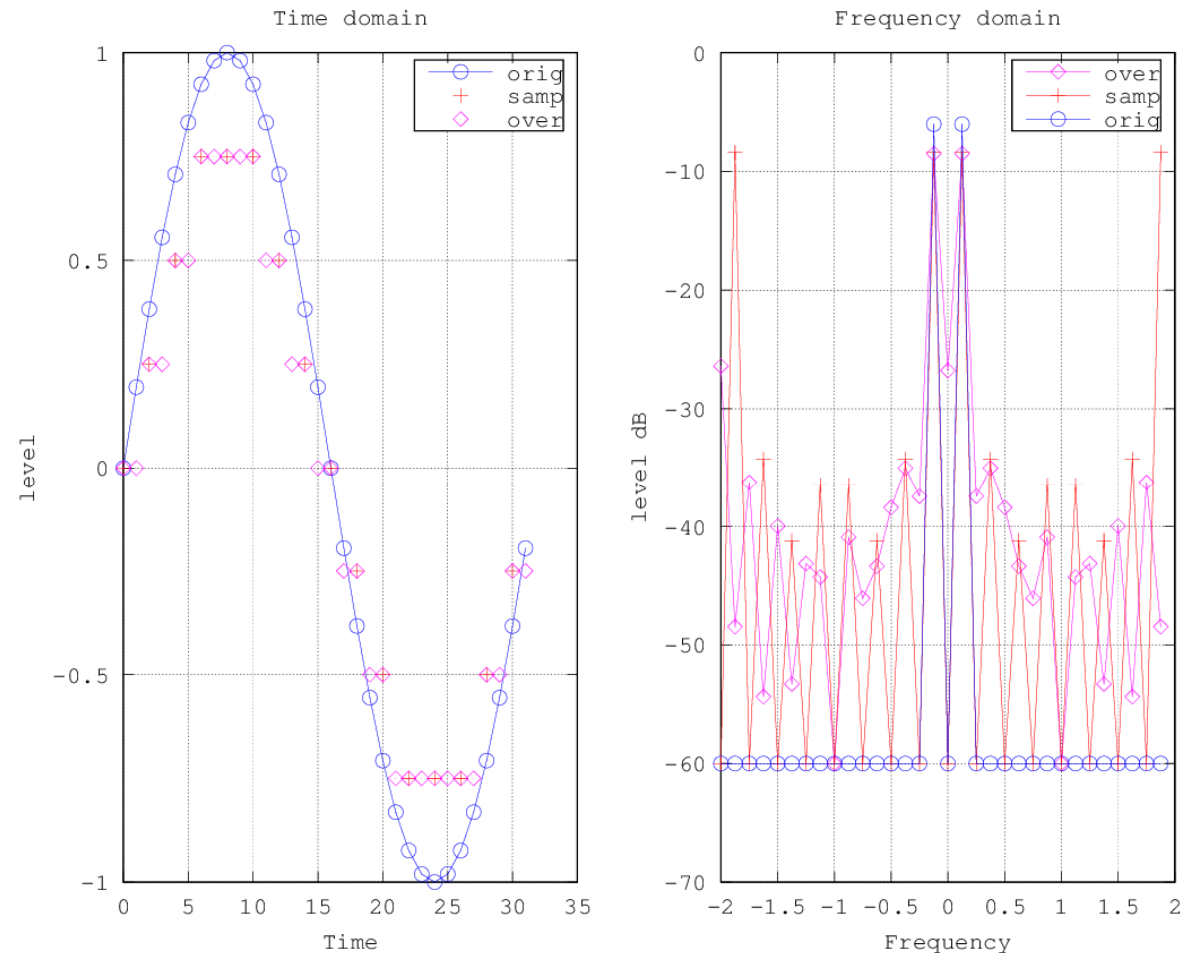
- **ADCs/DACs finite number of bits.**

- Quantised data never completely accurate.
- LMS7002M ENOB >= 9 bit.
  - >56dB Dynamic Range

- **Illustrate with 3 bit ADC**

- 8 levels available
- Not all levels are normally used
- Every sample point contains an error.
- Looks like noise spread over the frequency domain.
- Over sample to reduce noise.
  - 1 bit for ever x4 oversampling

$$DR = 6.02 * N + 1.76dB$$



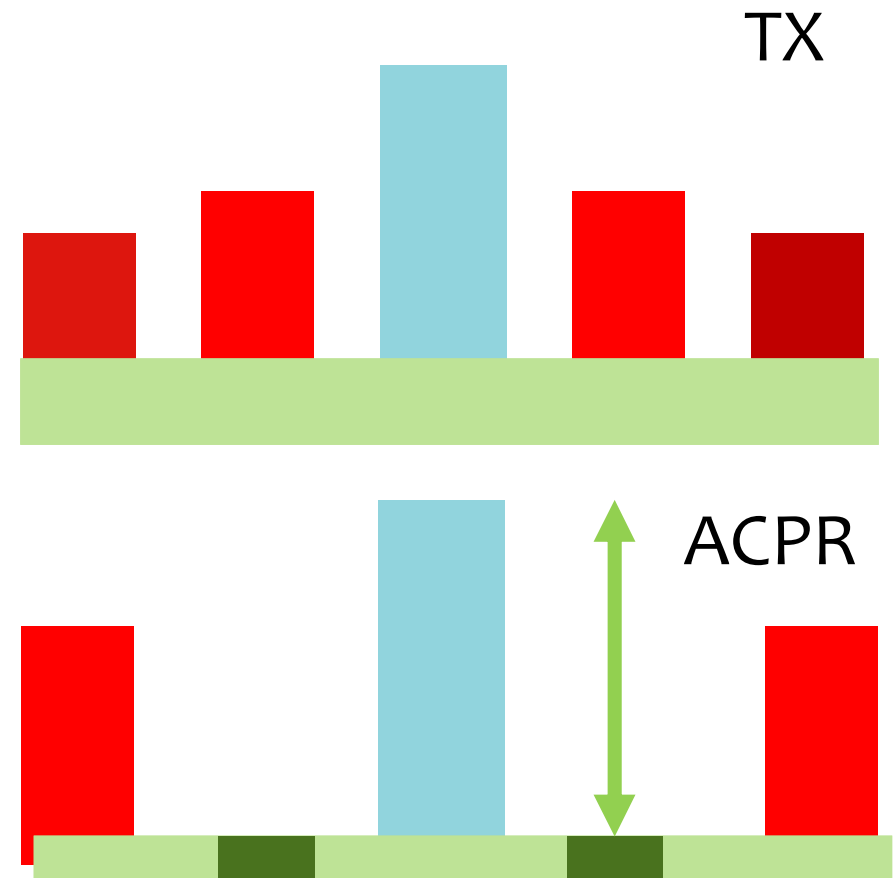
# TX Oversampling and Quantisation Noise

- **Oversampling**

- Reduces quantisation noise
- Removes aliases away from signal
- Improving Adjacent Channel Power Ratio (ACPR)
- Good Neighbour

- **LimeSDR**

- Intended to work with high oversampling.
- E.g. 3G/4G Base station
  - Data Rate 30.72Ms/s
  - TX 245.76Ms/s x8 Oversample
  - RX 61.44Ms/s x2 Oversample

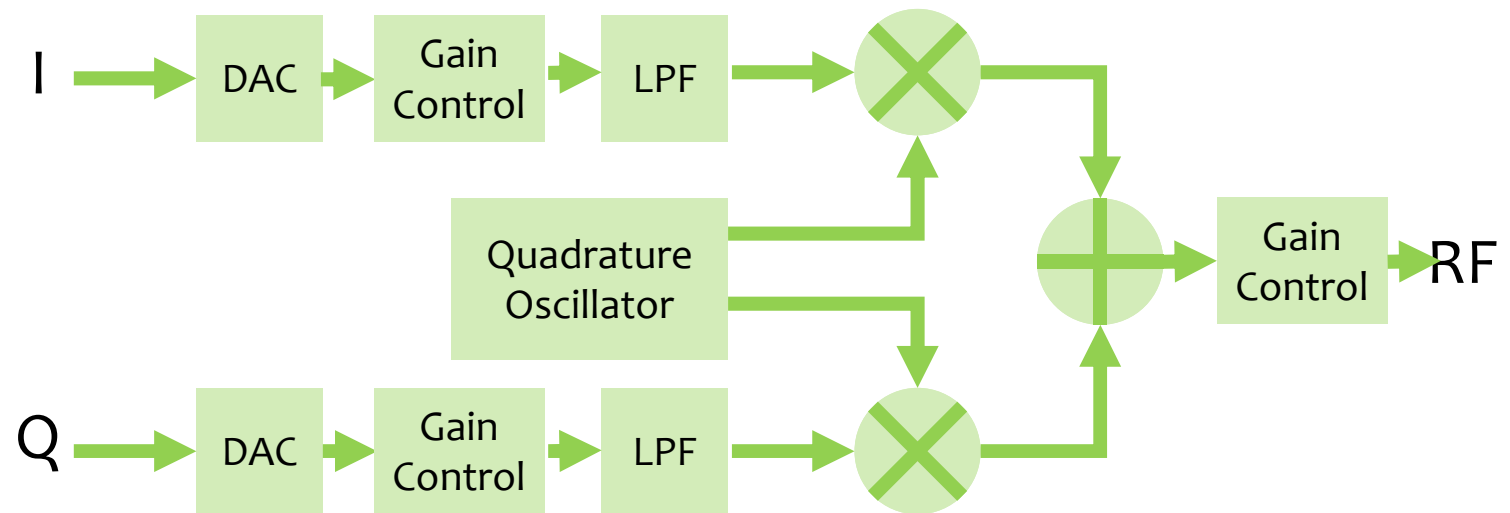




# Digital Vector Transmitter

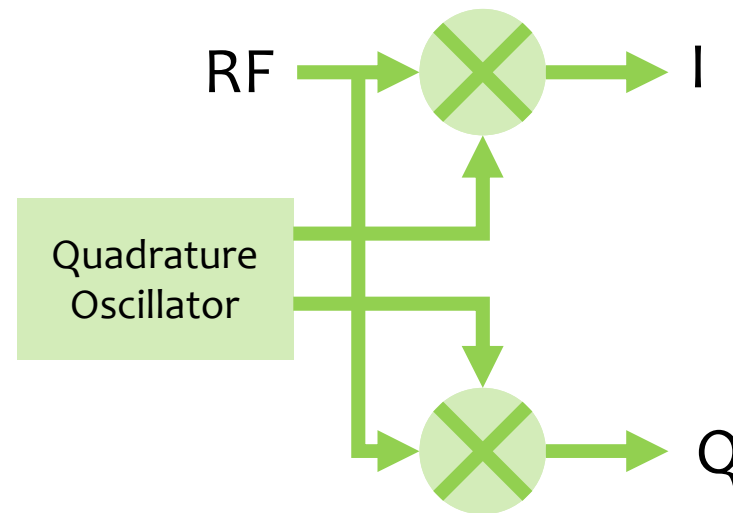
- **DACs and Mixers work best with optimum signal levels.**

- Need gain control at input of mixer
  - LMS7002M IAMP
- Need gain control to vary output level.
  - LMS7002M TPAD
  - Power ramping for TDD systems e.g. GSM/EDGE
  - Power control for multiple access systems e.g. W-CDMA



# Digital Vector Receiver

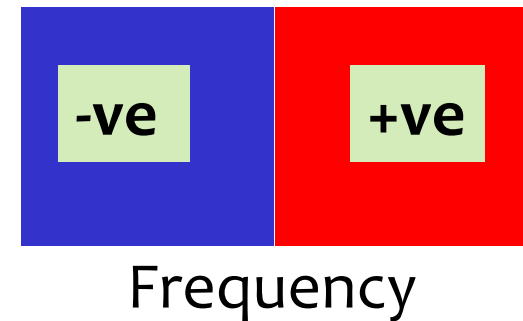
- **Zero IF Receiver**
  - Image Rejecting Mixer
- **Quadrature outputs processed by baseband.**
  - Noise of I and Q uncorrelated.
  - Better SNR



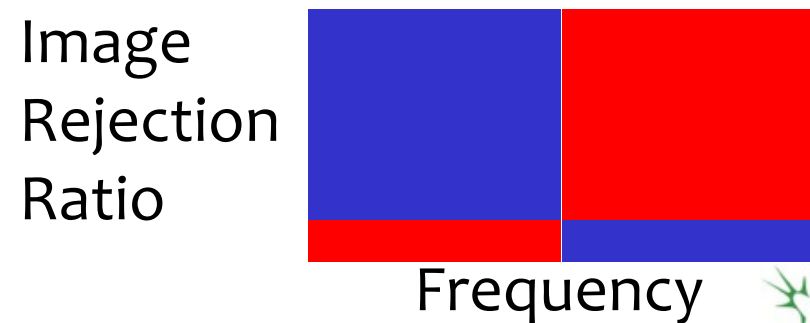
# The Image Rejection Problem

- **Real modulation signals**
  - Positive frequency different to negative frequency.
- **Hetrodyne Type Receivers**
  - Image separated from Wanted signal by a frequency gap.
- **Homodyne Type Receivers**
  - Image shares the same frequency space.
  - Image frequency looks like noise floor to the wanted signal.
  - Image rejection affects SNR and EVM
  - Correct by calibration and digital techniques

## Perfect Signal

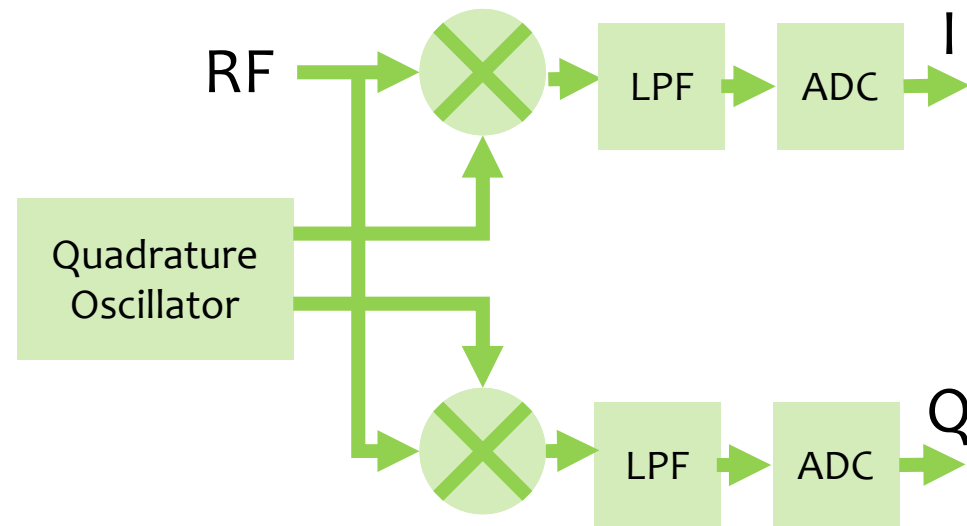


## Real Received Signal



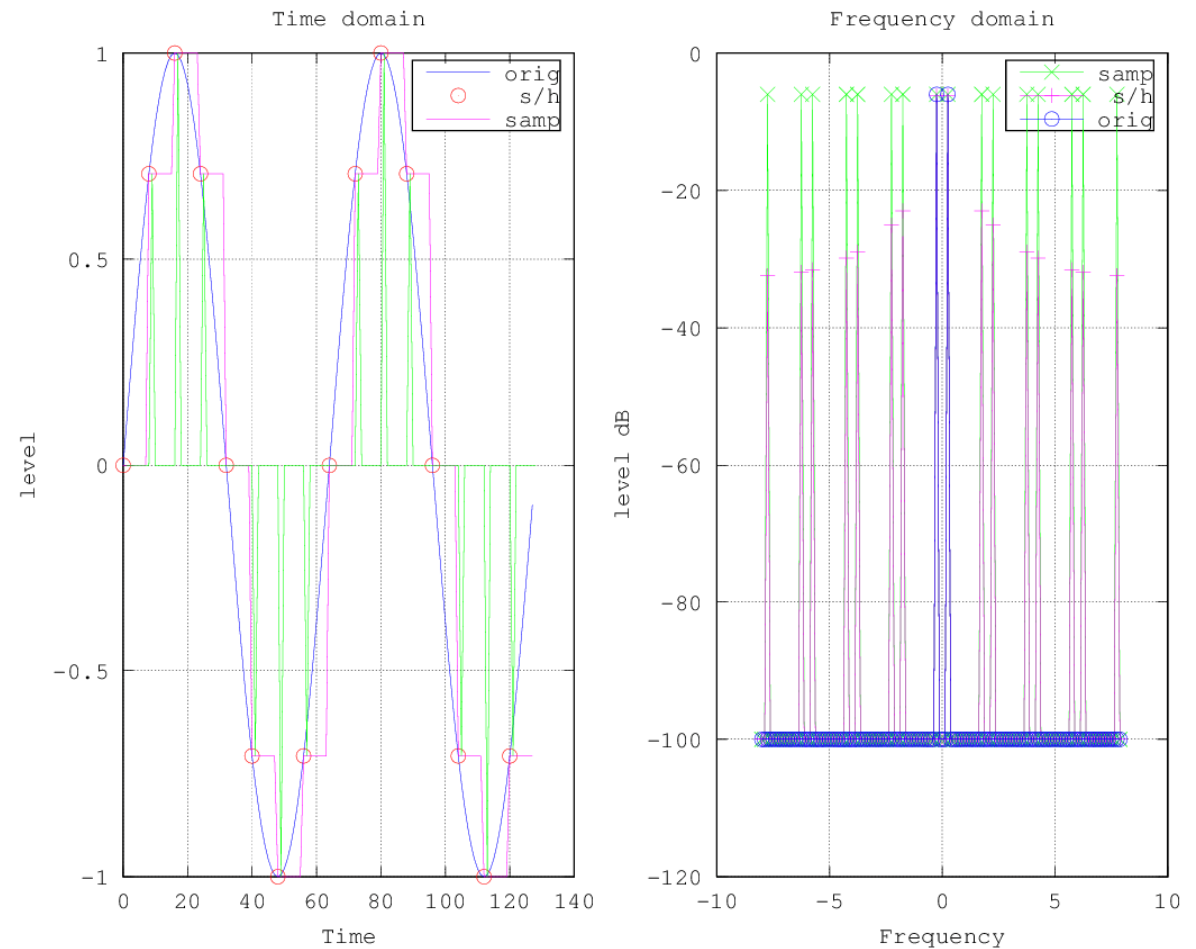
# Digital Vector Receiver

- **I and Q channels filtered before quantisation.**
  - Prevents aliases
  - Reduces noise
- **Analogue to Digital Converters**
  - Convert analogue IF signals to digital.



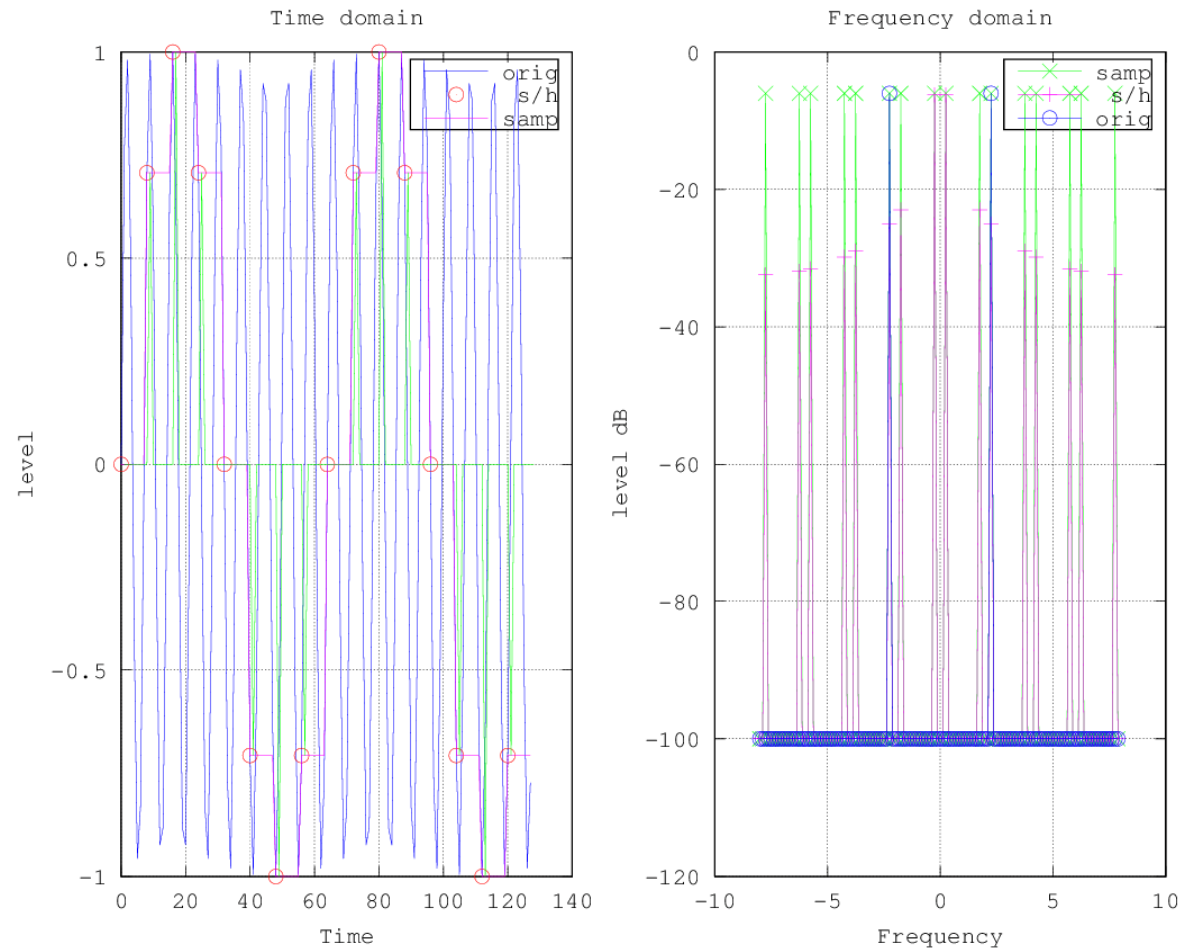
# The wanted signal digitised

- **ADC Reverse of DAC process**
- **Almost...**
  - All aliases seen equally.
  - Unlike sample and hold case.



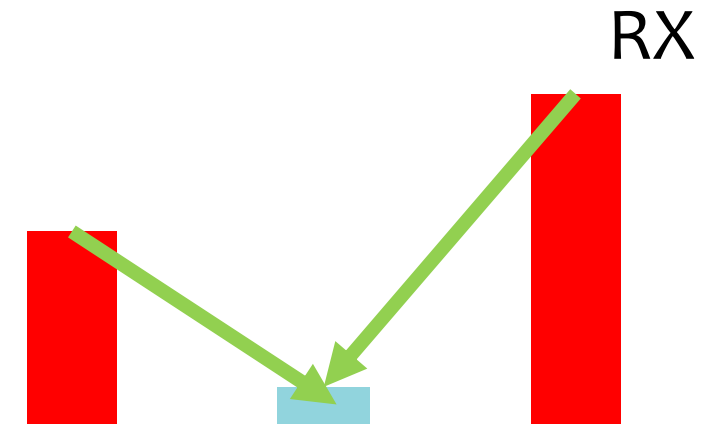
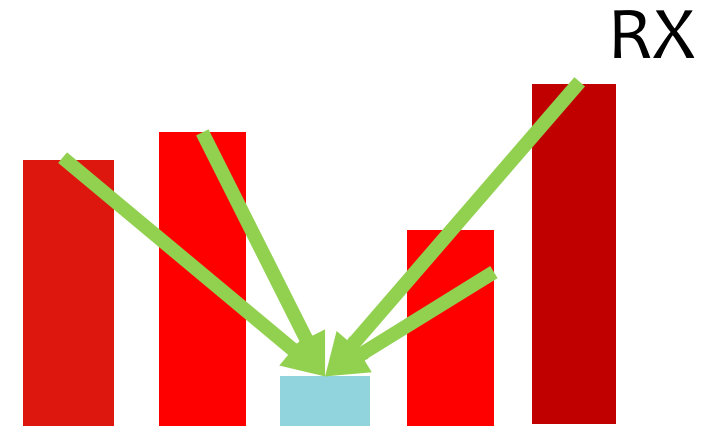
# Let's meet an alias signal

- **If we violate Nyquist Sampling,**
  - injecting an input signal whose frequency is higher than the sampling rate.
  - Cannot tell it apart from a signal that was lower than the Nyquist Sampling Rate.
- **Must filter before sampling to prevent interference.**



## Aliasing and the Receiver

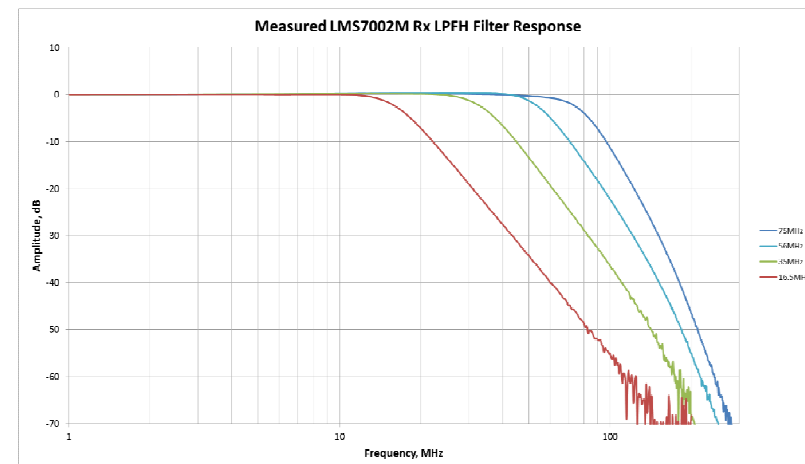
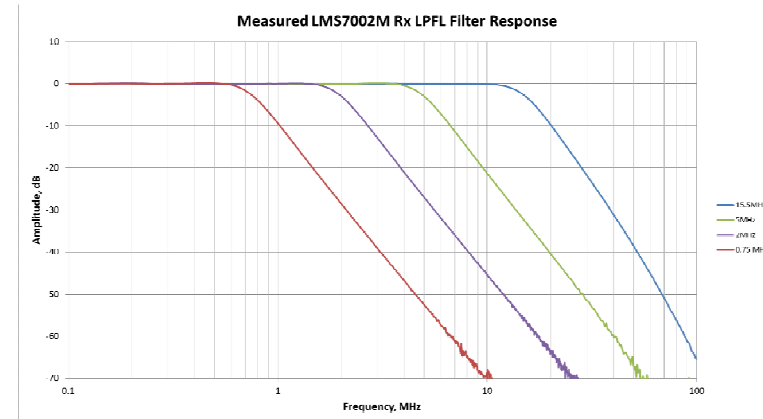
- **Adjacent channels are superimposed on the wanted signal degrading sensitivity.**
  - Common figure of merit Adjacent Channel Rejection.
- **Performance improved by**
  - Analogue IF filtering before ADC
  - Oversampling of ADC to move alias outside the bandwidth of IF and RF channel filters
- **Real Systems**
  - Adjacent channel rejection is a function of ADC bits, IF filtering and Forward Error Correction Coding.



# LimeSDR RX Active Filters

- **Nominal Filter Spec**

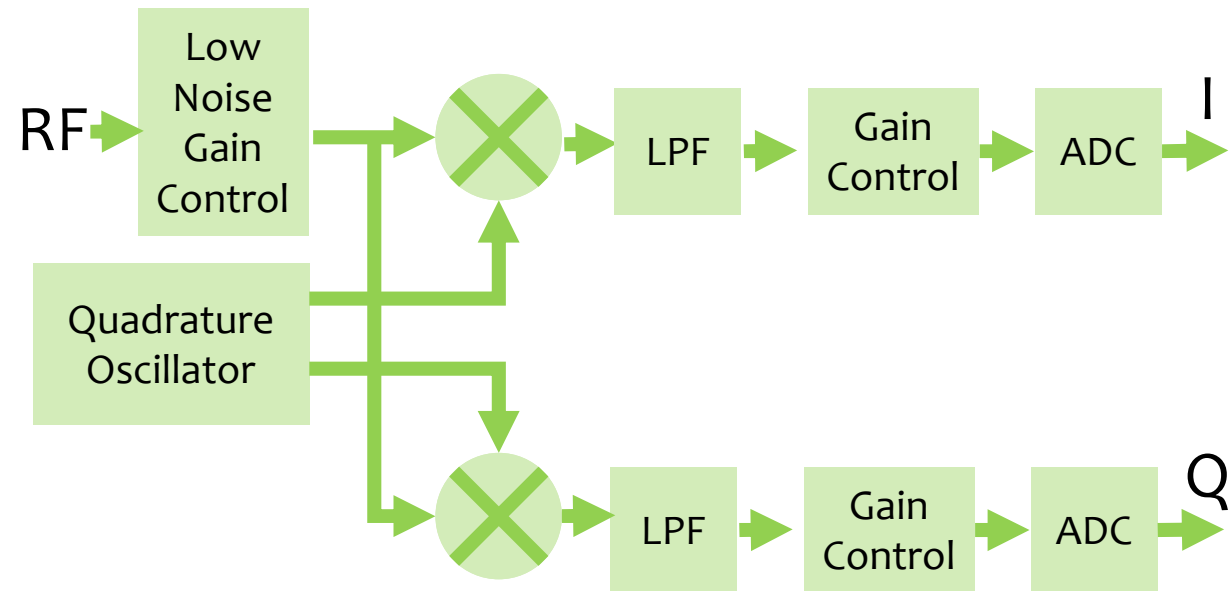
- 0.5dB Ripple Chebychev
- 3<sup>rd</sup> Order
- TIA – Real Pole
- LPFL/H – Complex Pole Pair
- Ratio of TIA and LPF capacitance set filter shape.





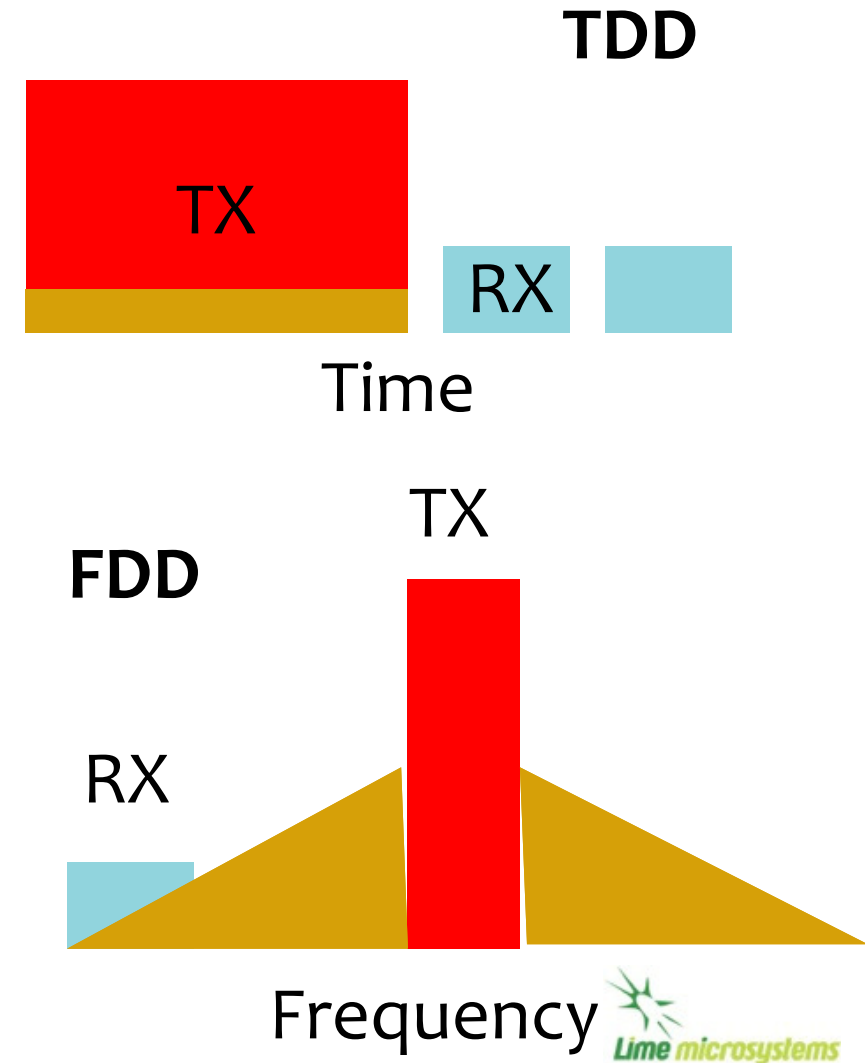
# Digital Vector Receiver

- **Mixers give best performance when levels are right.**
  - Variable gain Low noise LNA before mixer.
  - Avoid Mixer Overload for best dynamic range.
- **ADCs like big signals**
  - Variable gain before ADC (PGA)



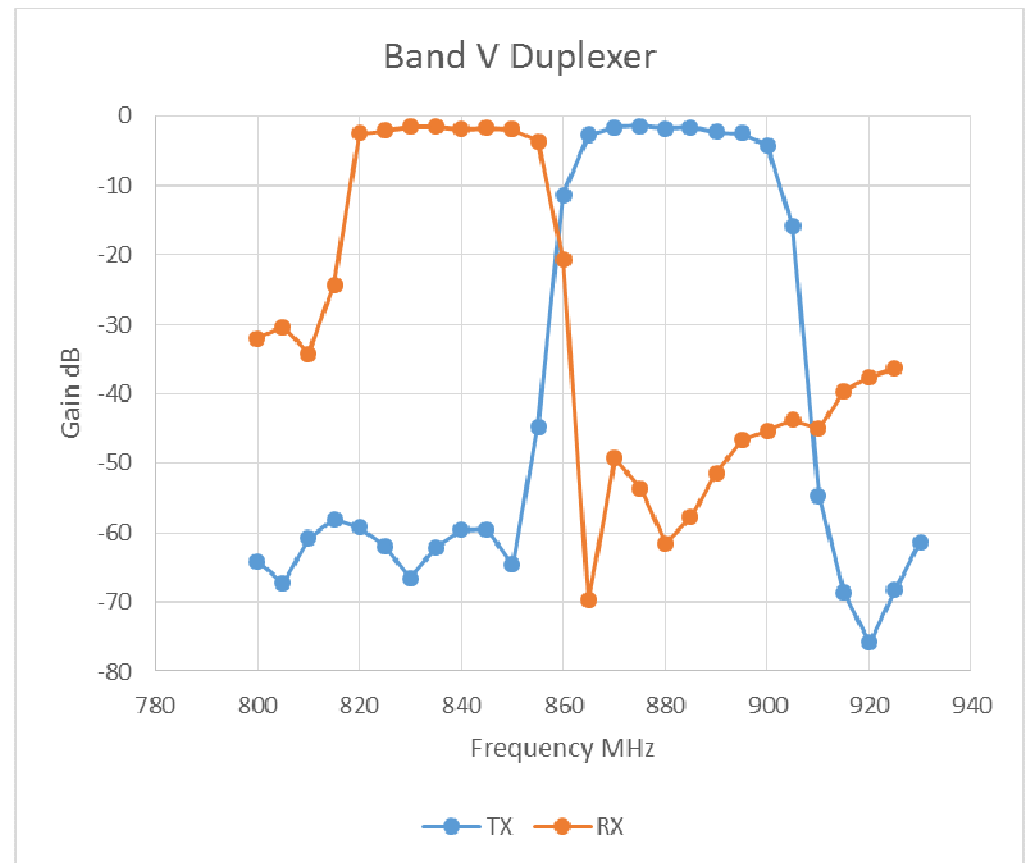
## TX Phase Noise Problem

- **Your TX is often your worst interference signal**
  - Quantisation and Active Filter Noise
  - Far Out Phase Noise
  - Can deafen receiver, especially if TX is amplified before transmission.
- **Time Division Duplexing (TDD)**
  - Transmitter switched off during receiving.
  - Cannot receive or transmit continuously!
- **Frequency Division Duplexing (FDD)**
  - Transmit and receive at different frequencies.
  - Duplexer filter to isolate TX and RX. Typ 50dB
  - $+25\text{dBm} - 155\text{dBc} - 50\text{dB} = -180\text{dBm/Hz}$  (Below thermal noise + NF  $-171.5\text{dBm/Hz}$ )



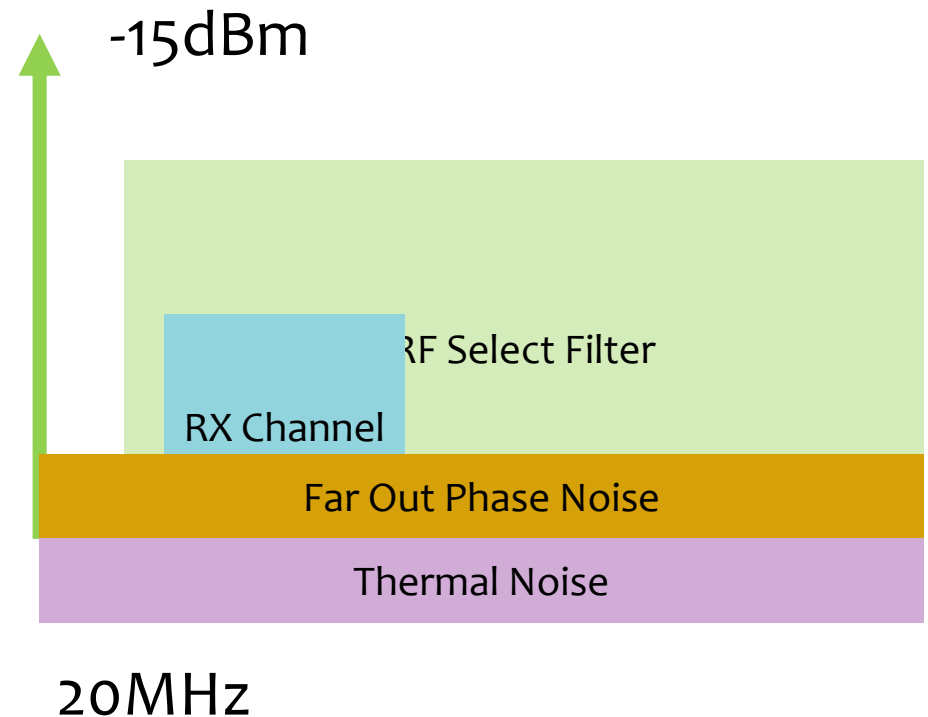
## Example SAW Duplex Filter

- Duplexer isolates TX and RX from one another, whilst sharing the same antenna.
- Low cost SAW Duplexer filters are commonly used in handsets and femto cell base stations.
- Expensive cavity filters used in high power transmitters.



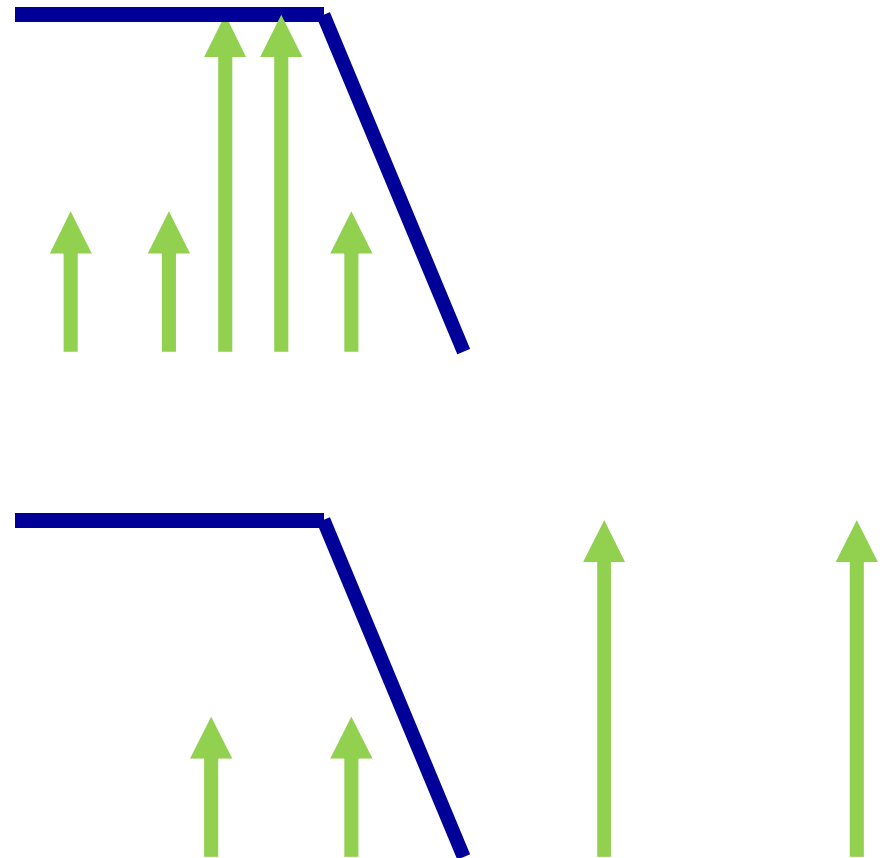
# RX Phase Noise Problem

- 3G/4G Blocker Requirement
- -15dBm CW Blocker 20MHz from band edge of RF filter.
- RF Filter provide partial filtering of CW Blocker 5-20dB and 2dB loss.
- P1dB of LNA >-25dBm
- Far out phase noise of synthesiser must be around -155dBc
- Phase Noise -20dBm-155dBc=-175dBm/Hz
- Thermal Noise -174dBm+2.5dB+2dB+0.5dB
  - =-169dBm/Hz (NF=2.5dB)
- Loose about <1dB sensitivity



## Rx Inband and Out of Band IIP3

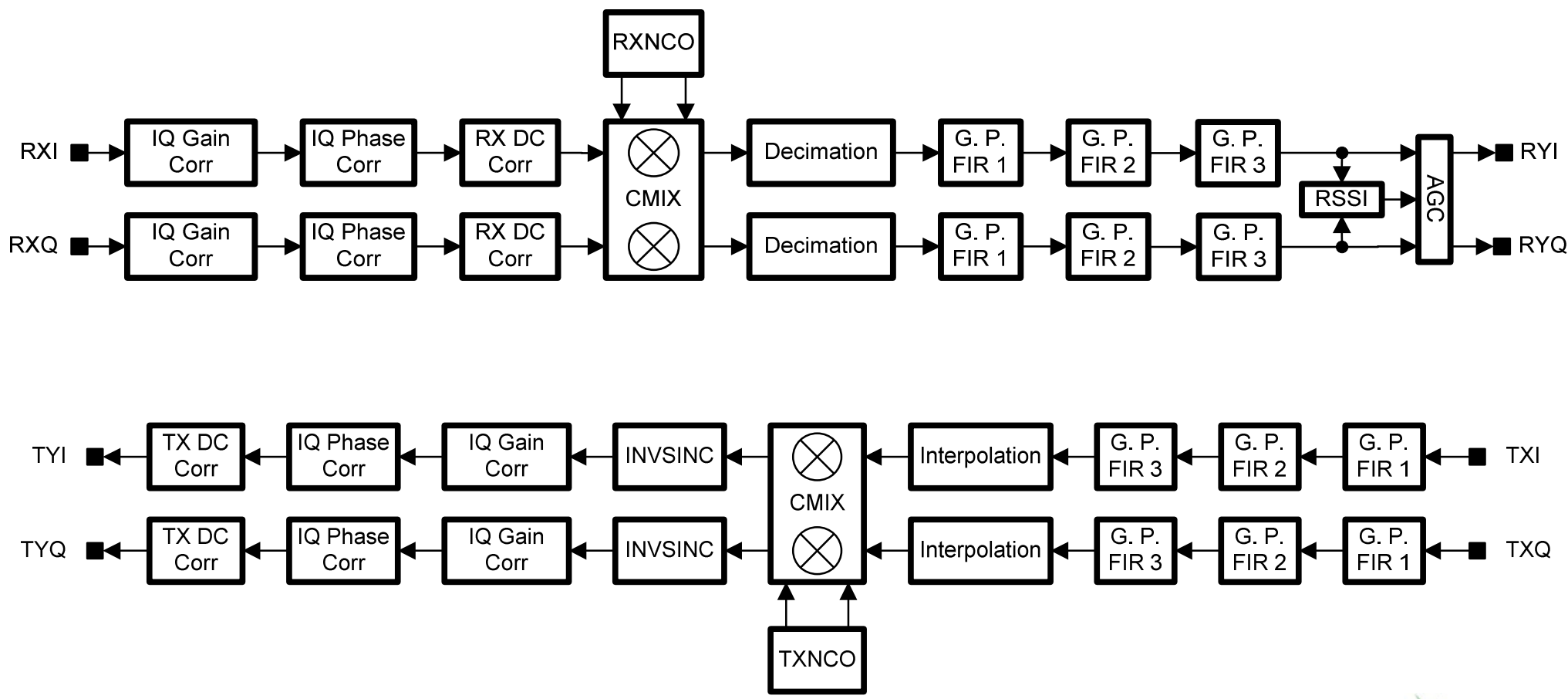
- LMS7002M has very linear mixer and LNA.
- Inband IIP3/IIP2 limited by P1dB of system
  - Gain sensitive
- Out of band IIP3/IIP2 limited by P1dB of LNA and Mixer
  - LNAL 915MHz LPF 600kHz
  - IIP3=+5.5dBm IIP2>48dBm
  - LNAH 1980MHz LPF 2.5MHz
  - IIP3=10.8dBm IIP2>40dBm



### 3. The Digital Half of the LMS7002M



# LMS7002M FPRF Transceiver Signal Processing TSP



# Digital Filtering

- **Inverse Sync (TX)**

- Sample and Hold has a frequency peak as signal approaches half sample rate.
- Inverse Sync corrects for this.

- **Interpolation (TX) and Decimation (RX)**

- Want slowest possible data rate into the LimeSDR
- Want fastest sample rate for DAC/ADC
- Interpolation=Upsampling+Filter
- Upsampling  $[P1, P2, P3] \rightarrow [P1, 0, P2, 0, P3, 0]$
- Decimation=Filter+Subsampling
- On chip decimation and interpolation allow data rate conversion.

- **General Purpose FIR Filters**

- Allows additional filtering
- Usually low pass
- High pass and band pass are possible
- Available taps depends on Decimation and Interpolation rates.
- Filter coefficients can easily be designed in Octave or Matlab.



# NCO, Complex Mixer, Test Signals and Calibration

- **Numerically Controlled Oscillator**

- Programmable precision quadrature digital oscillator
- Can be used as a test signal

- **Complex Mixer + NCO**

- Can be used as low IF receiver

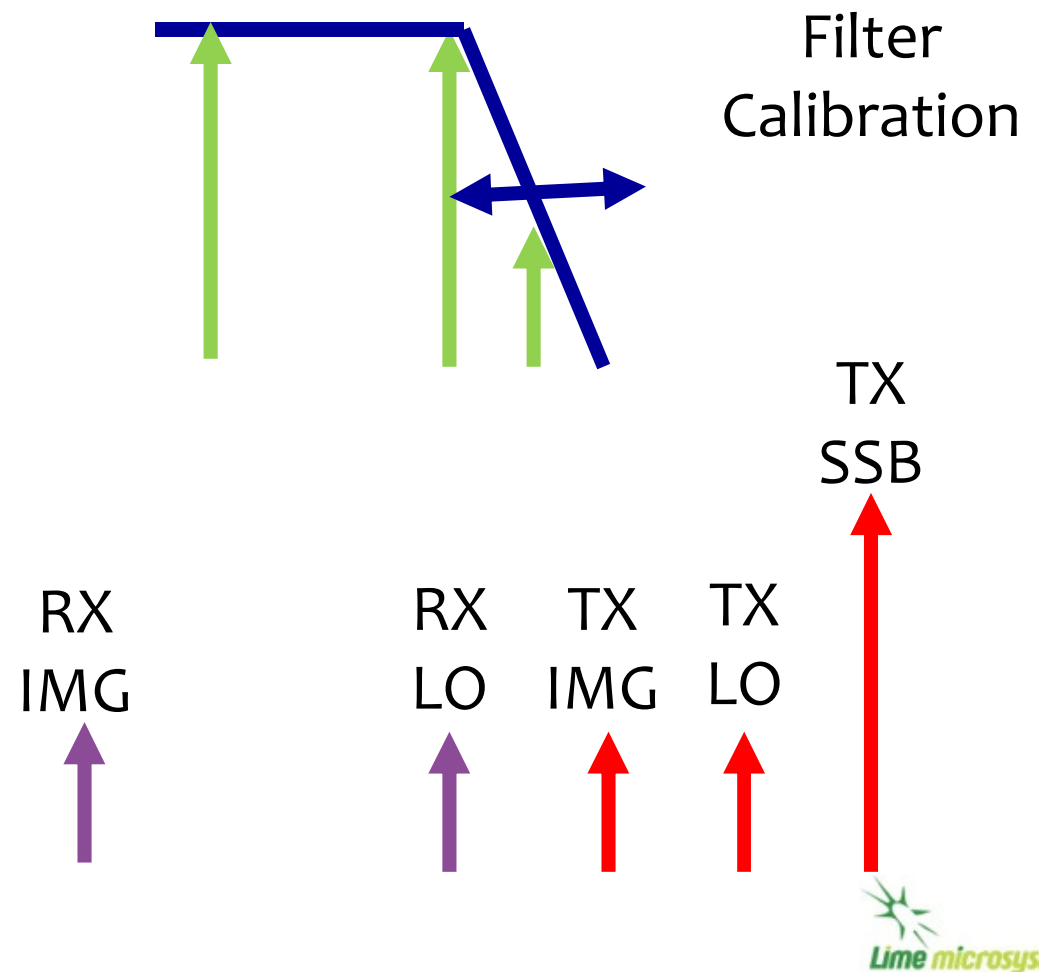
- **Filter bandwidth Calibration**

- Baseband Loop back

- **Image Rejection Calibration**

- RF Loop back
- I Q gain and phase adjusted

- **TX/RX LO Leakage Cancellation**



## Other Digital Features

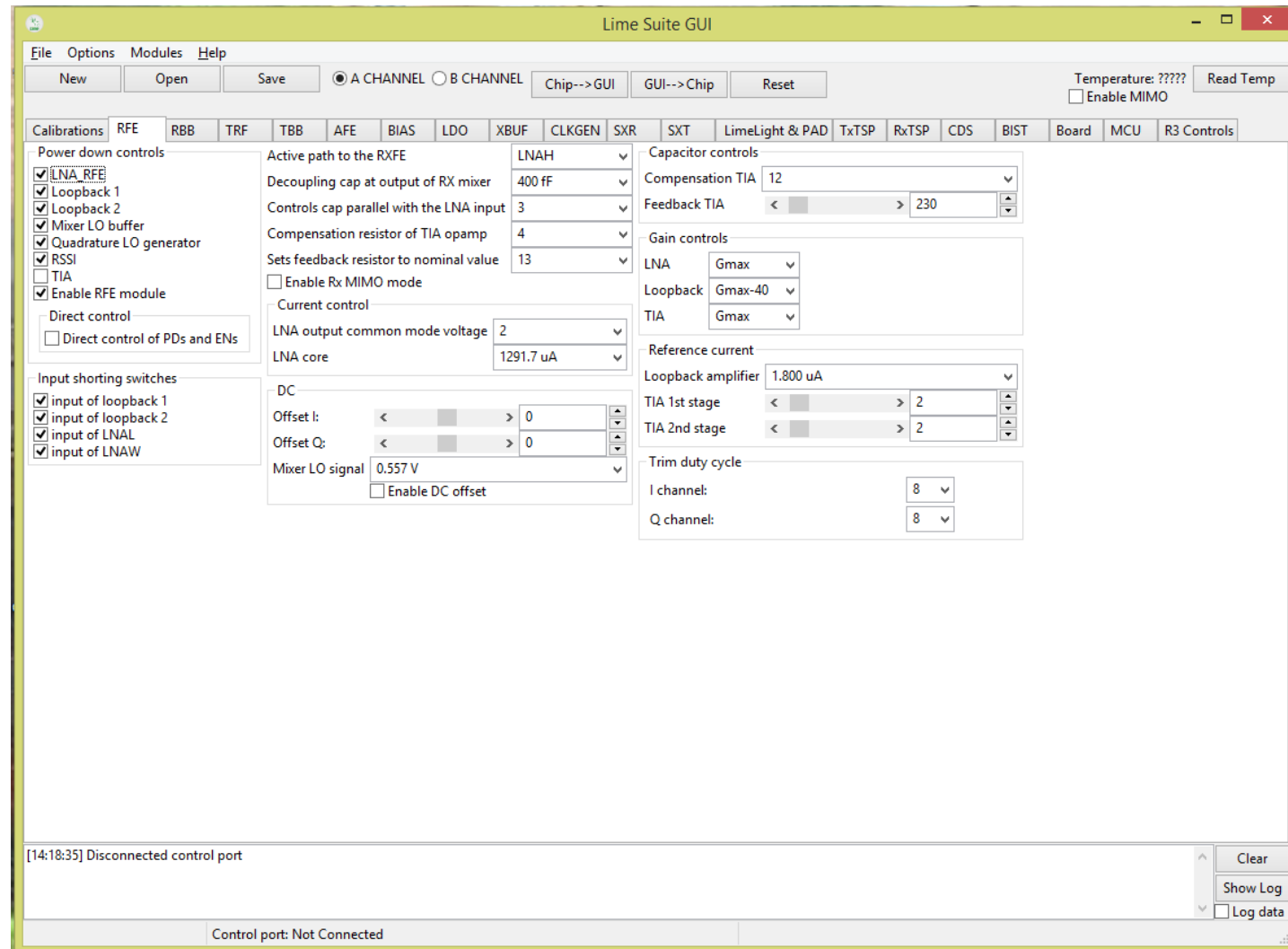
- **Digital AGC**
  - Intended for Repeater type applications.
- **Digital RSSI**
  - Intended for calibration and software controlled AGC.
- **DC Register load in Tx TSP**
- **8051 Based MCU**
  - Can execute calibration loops

## 4. The LimeSuiteGUI



# LimeSuiteGUI

- Access to ALL registers of LMS7002M
- Controls grouped into sections.
  - MIMO Controls have A and B channel
- We will use this software in our practical session.



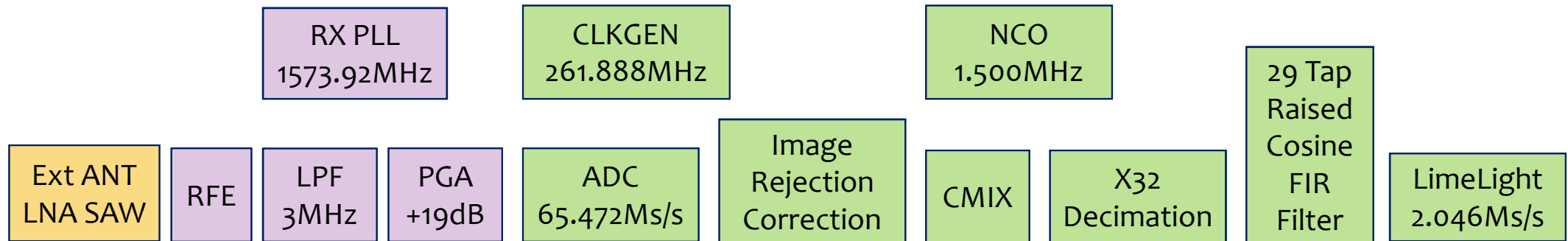
## 5. Using the LimeSDR Well



## Tips on Using LimeSDR Well

- **Always start from a working .ini file.**
- **Try out settings using FFT Viewer and known waveforms.**
- **Make frequency plan of SDR clocks**
  - Signal Bandwidth
  - Adjacent Channel Issues
  - ADC/DAC Rates → CLKGEN
  - Interface Rate → Dec/Int Factors
- **Set up for best dynamic range**
  - Use sufficient PGA gain for ADC to see noise floor.
  - Reduce LNA gain until noise floor just increases.
- **RF Match TX and RX for best output power and sensitivity.**
  - Best NF match usually a little away from best S11 match.
- **Typical settings for 900MHz 20MHz BW**
  - LNA = MaxGain-9
  - TIA = MaxGain
  - PGA = 0dB
  - CLKGEN ~ 250MHz

# LimeSDR GPS Receiver: using the LMS7002M Rx TSP



- **SAW filter in external ANT/LNA/SAW unit.**
- **LNA Gain at maximum, but can be reduce to improve interference tolerance.**
- **Analogue IF Filter programmed to 3MHz.**
  - 3<sup>rd</sup> order filter to minimise analogue filter noise.
- **Digital clock generator programmed to 261.888MHz**
- **ADC Clock programmed to 65.472Ms/s**
  - Oversampling increases number of effective bits by 4.5 bits.
- **Image rejection correction gives 50dB rejection of any image band noise and interference.**
- **Use Low IF to avoid calibration drift.**
- **Low IF to Zero IF with on chip NCO running at 1.5MHz into complex mixer. RX PLL=1573.92MHz.**
- **Use x32 decimation to reduce output data rate to 2.046Ms/s.**
- **Programme FIR filter to be 29 tap Raised Cosine to limit noise bandwidth**

## 6. The FPGA





# Modifying the LimeSDR FPGA

- **FPGA**
  - Currently provides interface between USB controller and LMS7002M Radio.
  - Also provides RAM controller for waveform playback.
- **Can I alter the FPGA**
  - Yes
- **Altera design tools**
  - Free for Cyclone 4E
  - Download from Altera
- **Code for the LimeSDR FPGA**
  - open source.
  - Download from Myriad RF
- **Design Environment**
  - Quartus Prime 16.1 Lite
- **Code modules**
  - VHDL, Verilog, Schematic or IP Blocks
- **Design test benches for code.**
  - VHDL or Verilog
- **Logic Synthesis**
- **Simulate**
  - Model Sim
- **Place and route**
- **Timing Analysis**
- **Download**

