Wireless Networks In-the-Loop: Emulating an RF front-end in GNU Radio

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Overview

Emulating an RF front-end in GNU Radio

- Introduction
- GNU Radio and the USRP
- Modeling digital signal processing
- Modeling analog signal processing
- Measurements & conclusion

Overview

Emulating an RF front-end in GNU Radio

Introduction

Faster verification and development of SRs with loop simulation

- For realistic results, effects of non-idealities need to be included in simulation
- Together with a channel emulator this facilitates loop simulation of software radio signal processing code

- Considered here: USRP with RFX2400 as an example of generic RF hardware

Emulator properties	Emulator Implementation
▪ Modular design ▪ Parametrizable ▪ Discrete representation of analog signals at an equivalent rate of 128 MHz	▪ C++ / GNU Radio block ▪ USRP interface

CEL

Overview

Emulating an RF front-end in GNU Radio

GNU Radio

Free Software Radio Framework

Properties

- Toolkit with extensive collection of atomic signal processing operations
- Signal sources and sinks offer interfaces to system and hardware
- USRP well supported

Design

- Signal processing in C++ (performance)
- Applications in Python (flow graphs)
- GNU Radio Companion offers graphical user interface

Execution

- Memory management and scheduling are handled by the GNU Radio framework

GNU Radio
the gnu software radio

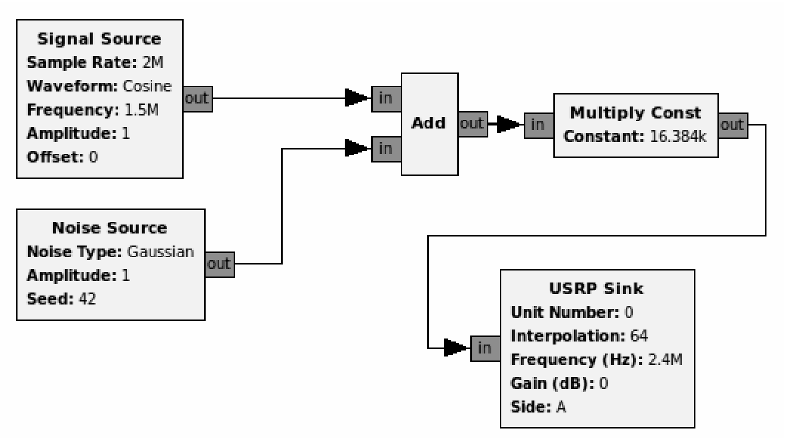


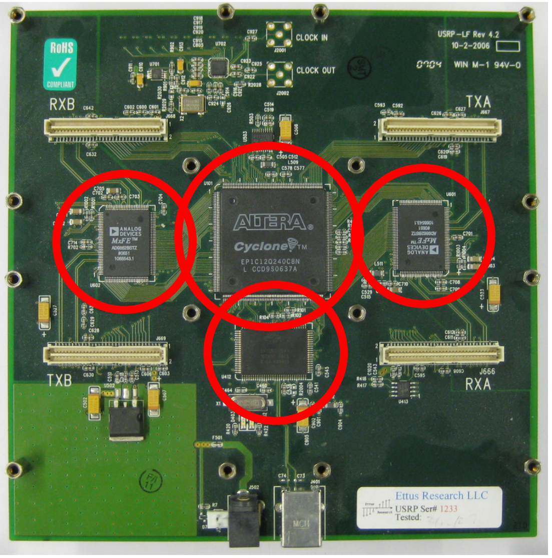
Figure source: http://gnuradio.org

Universal Software Radio Peripheral

Ettus Research USRP1 as an example of generic RF hardware

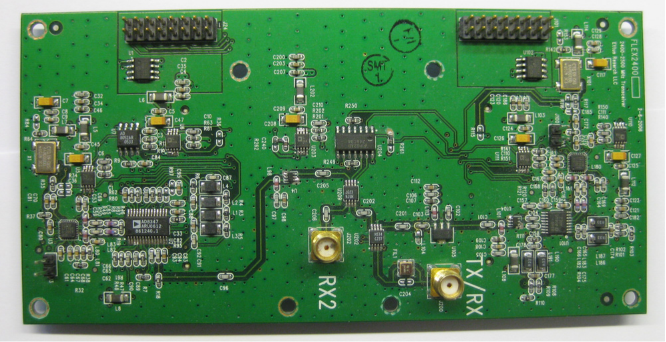
Motherboard

- Cypress FX2 USB Controller
  → Data exchange with host PC using USB 2.0
- Cyclone FPGA
  → Sample rate conversion and IF mixer
- Analog Devices AD9862 Mixed Signal Proc.
  → A/D conversion, interpolation, digital IF mixer



RFX2400 Daughterboard

- Direct conversion transceiver for 2.4 GHz band
- Two local oscillator signals, for Rx / Tx
- Maximum output power +17 dBm
- Integrated AGC (not modeled in emulator)



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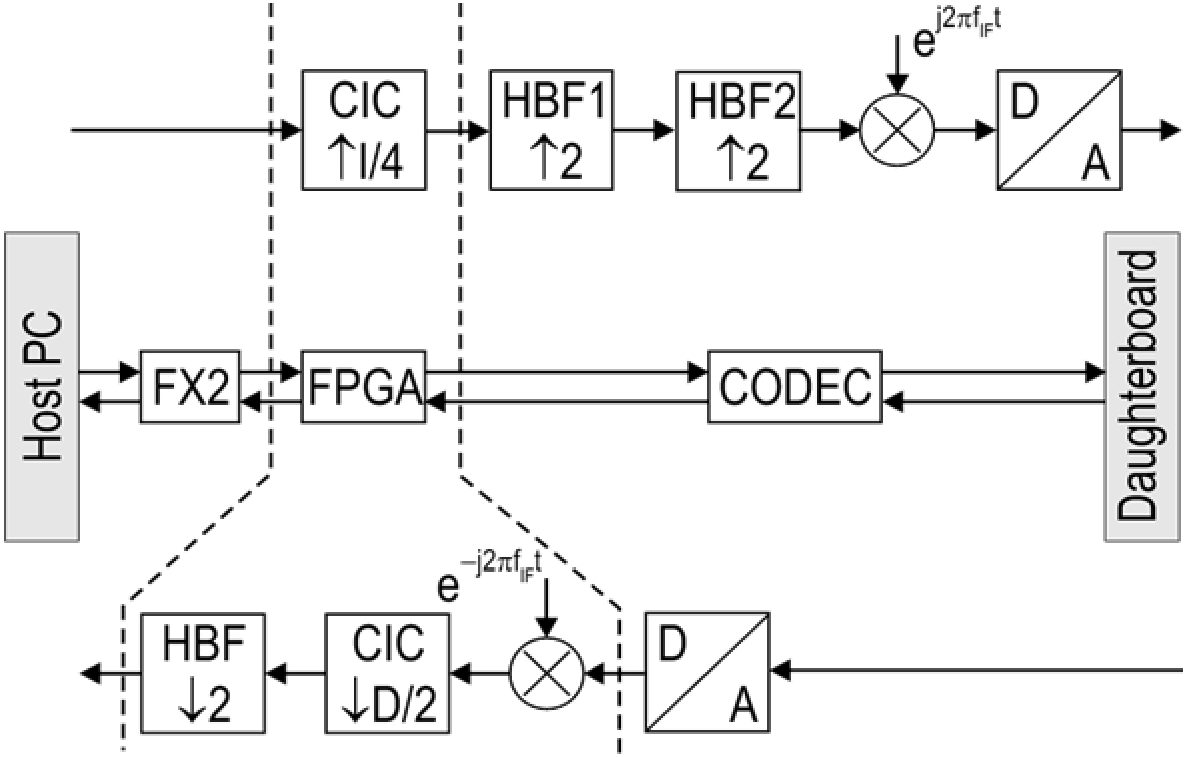
Emulating an RF front-end in GNU Radio

Model of the USRP motherboards

Overview



Elements of digital signal processing
▪ A/D and D/A conversion ▪ Digital IF mixer ▪ Variable sample rate conversion with CIC- and halfband filters

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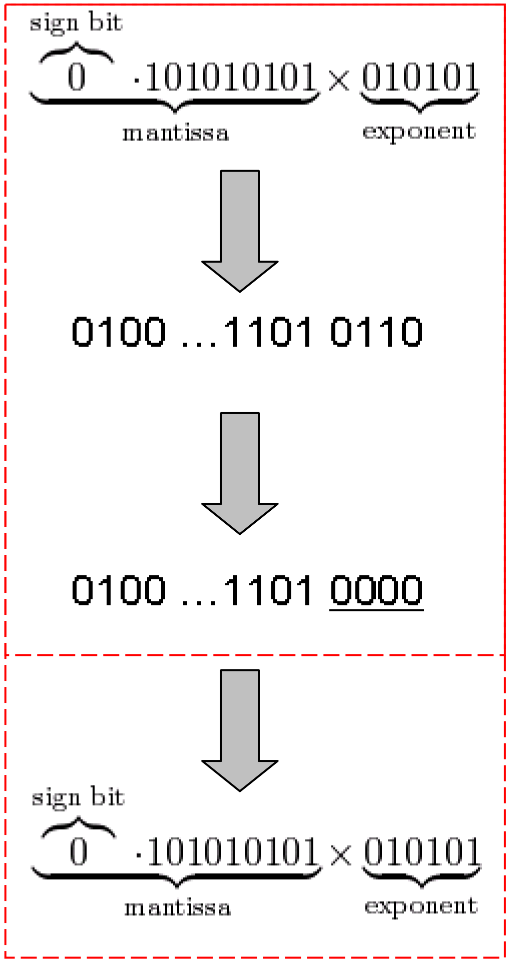
Model of the USRP motherboard

Processing in transmit and receive path

Analog/digital conversion

- Floating point to model analog signals in emulation
- A/D conversion with 12 bit/s and 64 MS/s
  → Decimation by factor 2 needed
- D/A conversion with 14 bit/s and 128 MS/s

→ Quantization noise / bit resolution by rounding



Encoding of samples

- FPGA and CODEC use fix point arithmetic
- GNU Radio framework offers high performance filters for floating point
- In emulator: floating point arithmetic for digital filters an mixers

→ Conversion to fix point between stages

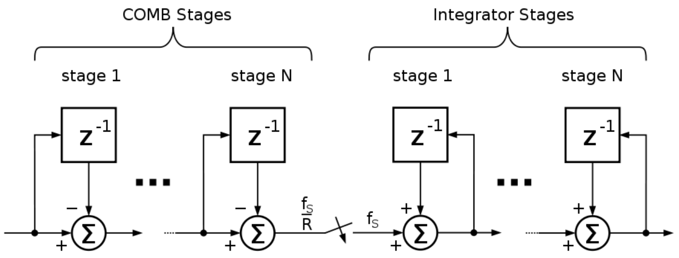
Model of the USRP motherboard

Processing in transmit and receive path

Cascaded Integrator Comb filter

- Efficient, recursive implementation of a multi-stage moving average filter for variable sample rate conversion
- USRP uses 4-stage CIC filter

→ Implemented in fix point arithmetic as GR block, scaling of output signal by bit shifting



Halfband filter

- Efficient FIR low pass filter; cut-off at band middle
- About half of all coefficients are zero

→ Used to interpolate / decimate by a factor of 2

- Tx: built as in data sheet
- Rx: coefficients as in USRP1 FPGA code

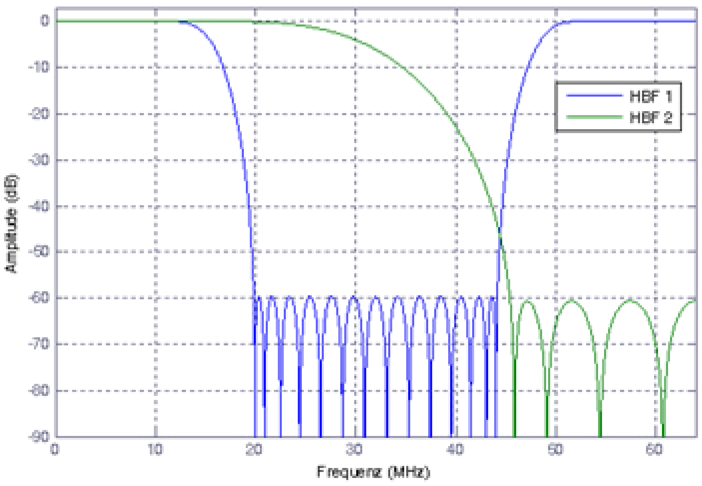


Figure source: http://de.wikipedia.org/wiki/Cascaded-Integrator-Comb_Filter

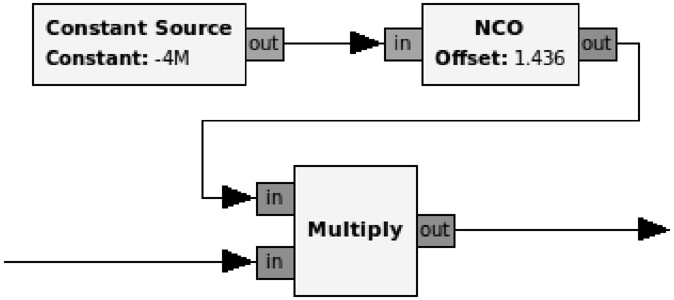
Model of the USRP motherboard

Processing in transmit and receive path

Digital IF mixer

- Digital mixer based on CORDIC algorithm
- Shifts base band signal to digital IF
- Together with analog mixer used to shift signal to carrier frequency

→ In emulator: complex multiplication with NCO, random initial phase



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- **Modeling analog signal processing**
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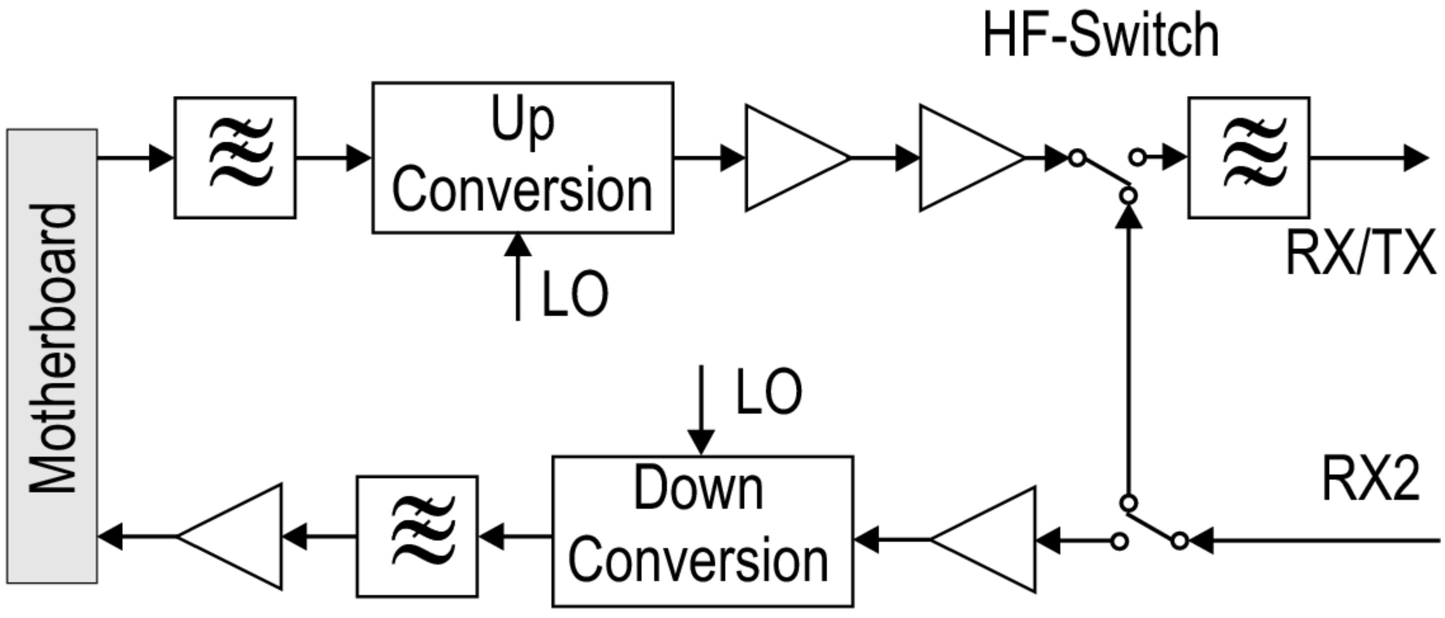
Model of the RFX2400 USRP daughterboard

Overview



Typical effects of analog signal processing	
▪ Phase noise	▪ Non-linearities
▪ IQ-imbalance	▪ Noise

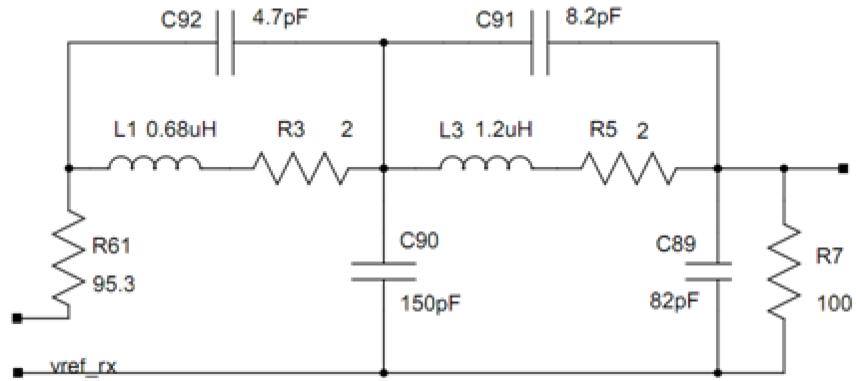
Model of the RFX2400 USRP daughterboard

Discretization of analog filters

Anti aliasing filter

- After down shifting, before A/D conversion
- 5th order IIR low pass filter, cut-off frequency 20 MHz, attenuation 6 dB
- Discretization with bilinear transform
- Additional tweaking of poles and zeros due to aliasing effects needed

→ Approximated well in pass band, higher attenuation in stop band



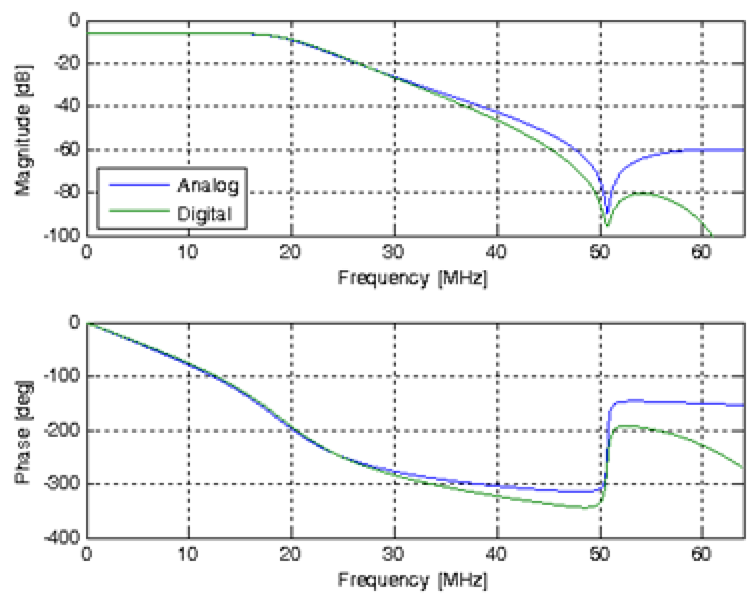


Figure source: Ettus Research LLC (http://ettus.com), data sheet RFX2400

Model of the RFX2400 USRP daughterboard

Discretization of analog filters

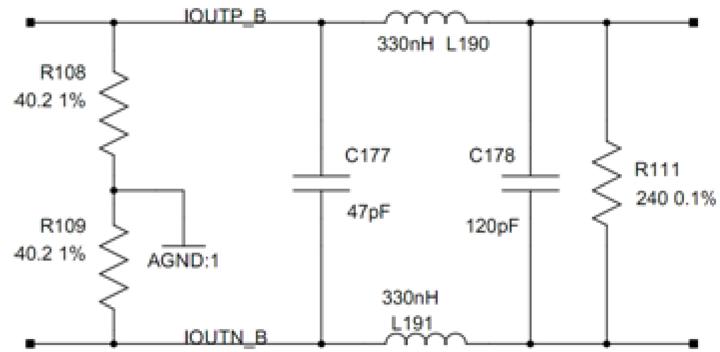
Anti image filter

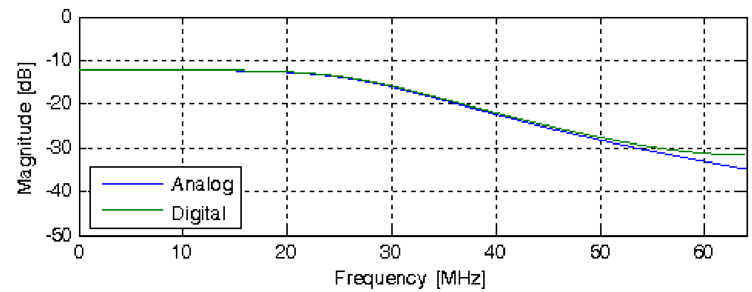
- After D/A conversion, before mixer
- 3rd order IIR low pass, cut-off frequency ~28 Mhz, attenuation 12 dB
- Discretization with impulse invariance method

ISM bandpass filter

- Magnitude response flat in simulation bandwidth
- Phase response not specified

→ Not modeled





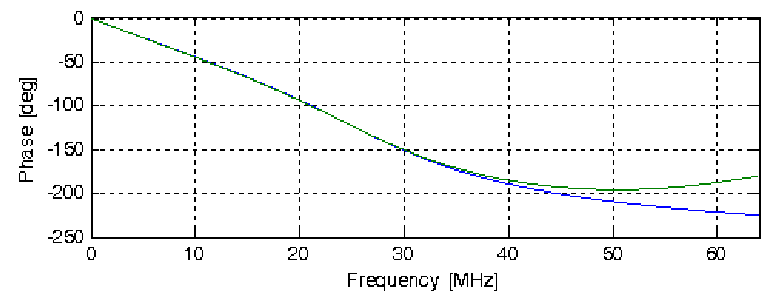


Figure source: Ettus Research LLC (http://ettus.com), data sheet RFX2400

Model of the RFX2400 USRP daughterboard

Phase noise

Phase noise

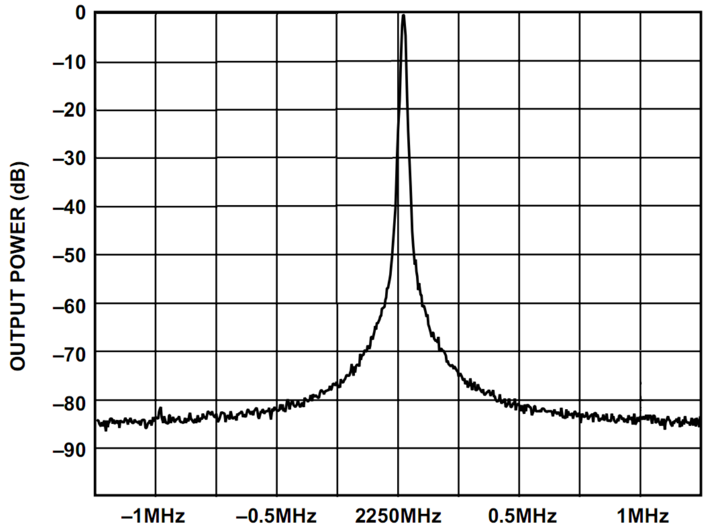
- LO signals of analog mixer are not ideal
→ 1/f-noise

- Created with noise shaping filter

$$H_{\mathrm{PN}}(z) = \frac{1}{\sqrt{1 - z^{-1}}}$$

- Approximation of IIR low pass coefficients with polynomial expansion

- In emulator: phase noise modulated onto the signal in baseband



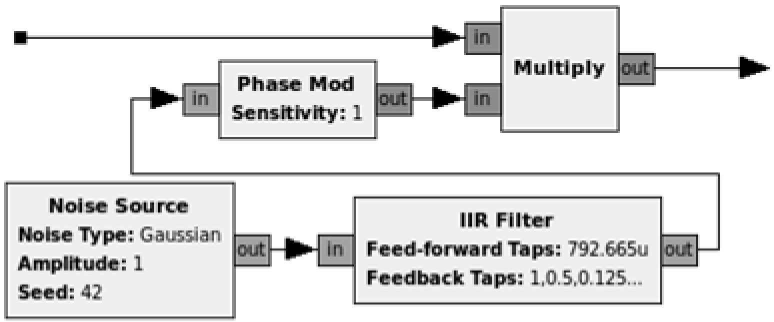


Figure source: Analog Devices, Integrated Synthesizer and VCO data sheet

Model of the RFX2400 USRP daughterboard

IQ imbalance

IQ imbalance

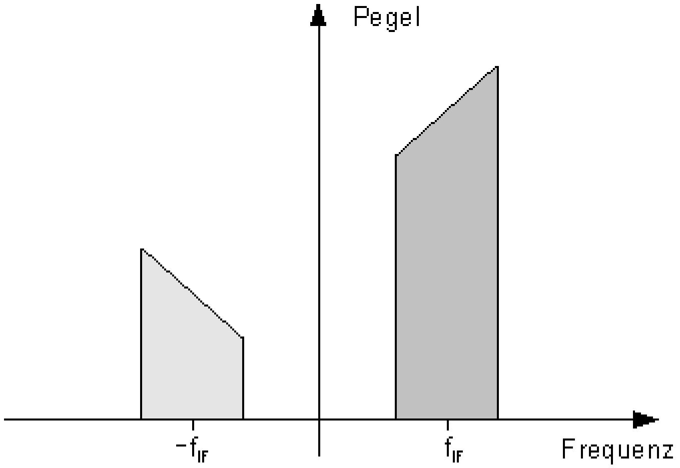
- Phase shift in mixer is not perfect
  → Variations in amplitude and phase

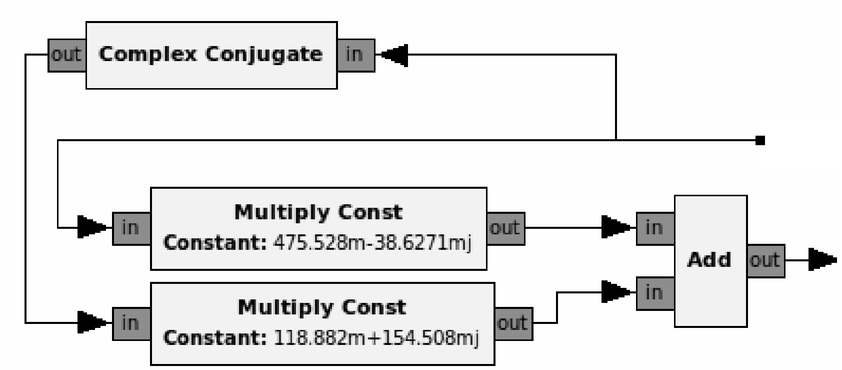
$$r'(t) = (1-\varepsilon) r_{bp}(t) \cos(\omega_c t + \phi) - j(1+\varepsilon) r_{bp}(t) \sin(\omega_c t - \phi)$$

- Image spectrum not suppressed fully

$$r'(t) = c_1 \cdot r(t) + c_2 \cdot r^*(t)$$

$$c_1 = \frac{1}{2}(\cos(\phi) - j\varepsilon \sin(\phi))$$
$$c_2 = \frac{1}{2}(\varepsilon \cos(\phi) + j \sin(\phi))$$





Model of the RFX2400 USRP daughterboard

Intermodulation products

Non-linearities

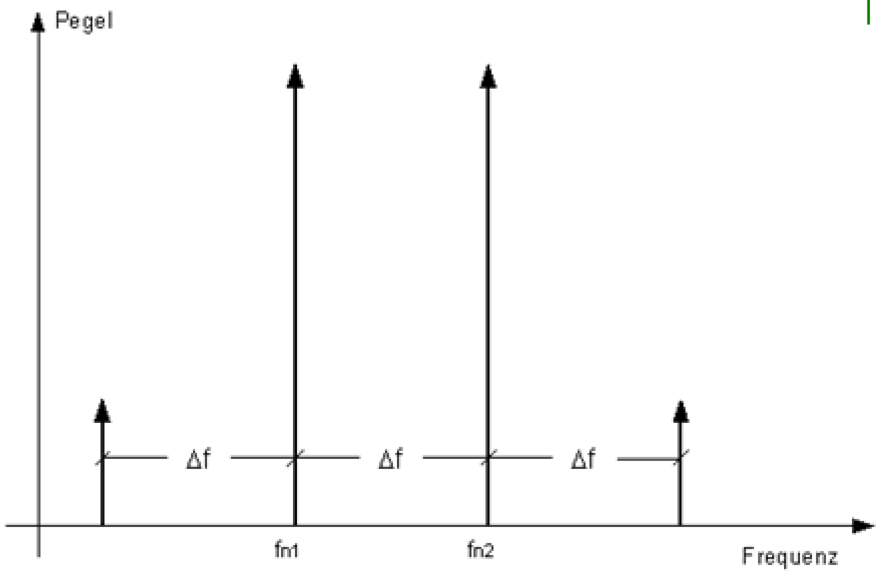
- Active components are only approximately linear (amplifier, mixer)
- 3. order intermodulation in baseband

$$y(t) = x(t) - \frac{3}{4}\alpha_3\, x^2(t)x^*(t)$$

- In model: unification of all amplifying components and their non-linearities

→ Model combined effect

- For baseband amplification quadratic mixer term is also relevant



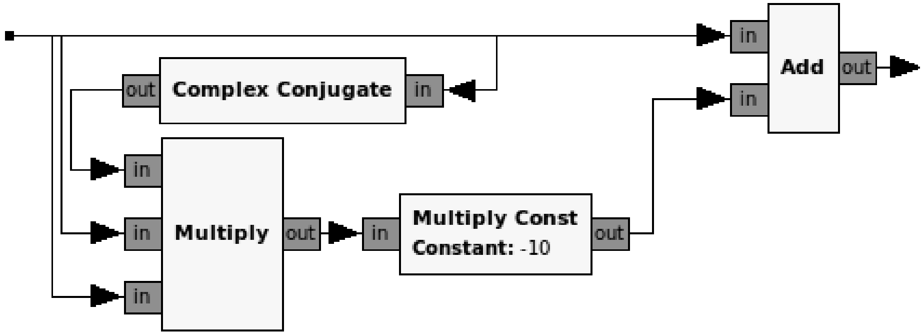


Figure source: http://de.wikipedia.org/wiki/Intermodulationsprodukt

Model of the RFX2400 USRP daughterboard

Noise figure of receiver

Receiver noise

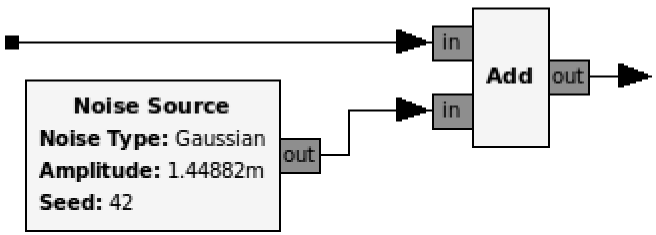
- Every component adds noise to signal and reduces SNR along the analog processing chain
  → Characterization by noise figure
- Combining noise figures and gain of all components with Friis' formula
- In model: Johnson-noise is additive white Gaussian noise

→ $\mathrm{NF} \geq 5\mathrm{dB}$ at RX2 port

- NF depends strongly on AGC level

$$\mathrm{NF} = 10\log F = \mathrm{SNR}_{in,\mathrm{dB}} - \mathrm{SNR}_{out,\mathrm{dB}}$$

$$F_{\mathrm{total}} = 1 + (F_1 - 1) + \frac{F_2 - 1}{g_1} + \frac{F_3 - 1}{g_1\, g_2} + \ldots$$



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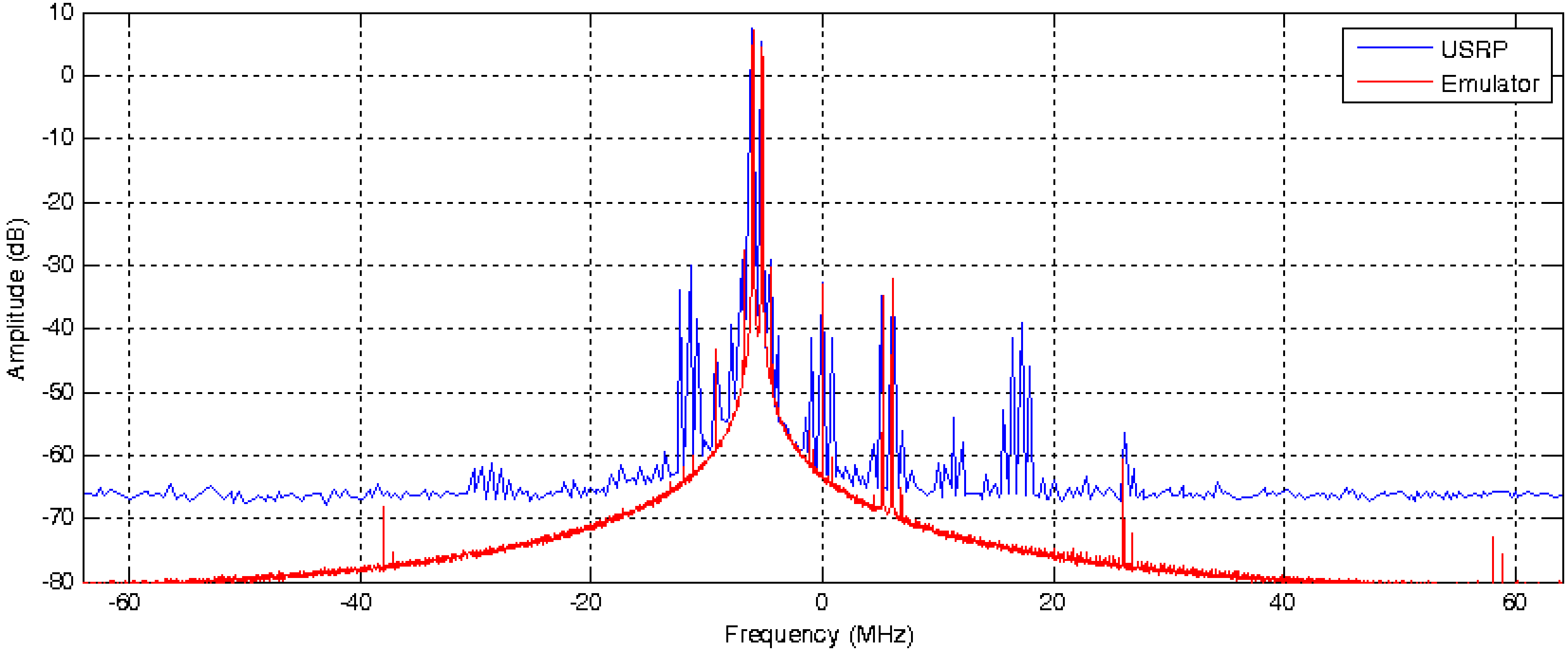
Measurements and comparison

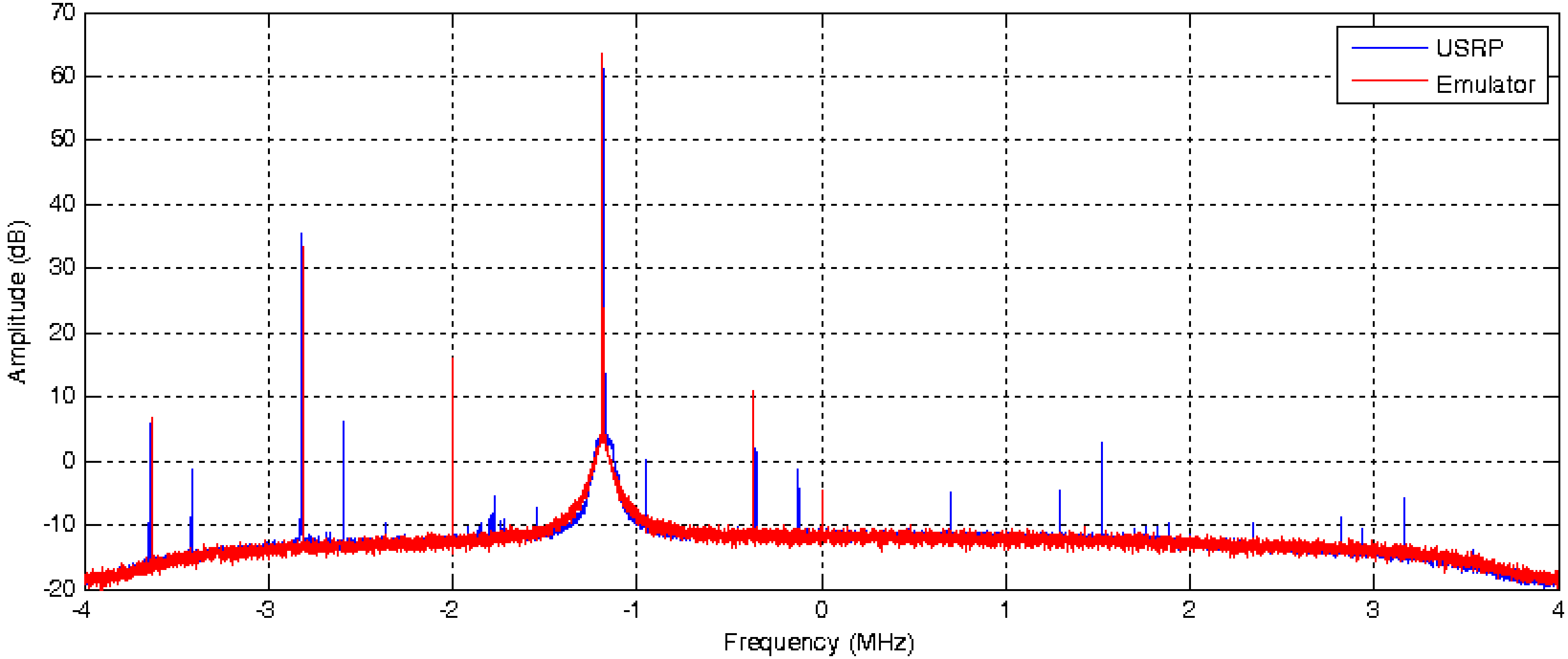
Transmit path



Measurement setup
▪ 2 tone signal with 800 kHz separation, carrier frequency 2.45 GHz, IF at -6 MHz → IQ imbalance, carrier, IM products of 3rd order, phase noise, quantization noise visible ▪ Not included: thermal noise, additional non-linearities

Measurements and comparison

Receive path



Measurement setup
▪ Sinusoid at 1.2 MHz below carrier frequency, IF at -2 MHz. → IQ imbalance, baseband non-linearities of 2nd order, phase noise

Conclusion

Emulating an RF front-end in GNU Radio

- Modeled the core elements of the signal processing chain
  - Variable sampling rate conversion with CIC- and halfband filters
  - Digital IF mixing
  - D/A & A/D conversion (limited sample resolution, quantization noise)
  - Analog filters

- Modeled effects of analog RF hardware
  - Phase noise
  - IQ imbalance
  - Receiver noise
  - Non-linearities

Q&A / Discussion

Thank you for your attention!