Department of Electrical and Computer Engineering

Ben-Gurion University of the Negev

LAB 1 - Introduction to USRP

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1 Introduction

In this lab you will use software reconfigurable RF hardware from National Instruments (NI) to build a digital communication system. This hardware can be easily configured using LabVIEW software. The RF hardware used in the lab is the National Instruments USRP (Universal Software Radio Peripheral). The PC controls the USRP through the gigabit ethernet cable connecting-. In this lab you will learn more about these modules.

2 Labs goals

1. To learn generic digital communication system structure and its building blocks.
2. To learn about RF USRP hardware.
3. To see how these blocks are implemented in our lab.
4. To introduce NI generic RX and TX tools.
5. To implement the sine wave TX.
6. To implement the generic RX.
7. Transmit and receive the sine waveform signal-, measure and characterize it.

3 Communication system block diagram

In Figure 1 the basic communication system is shown.

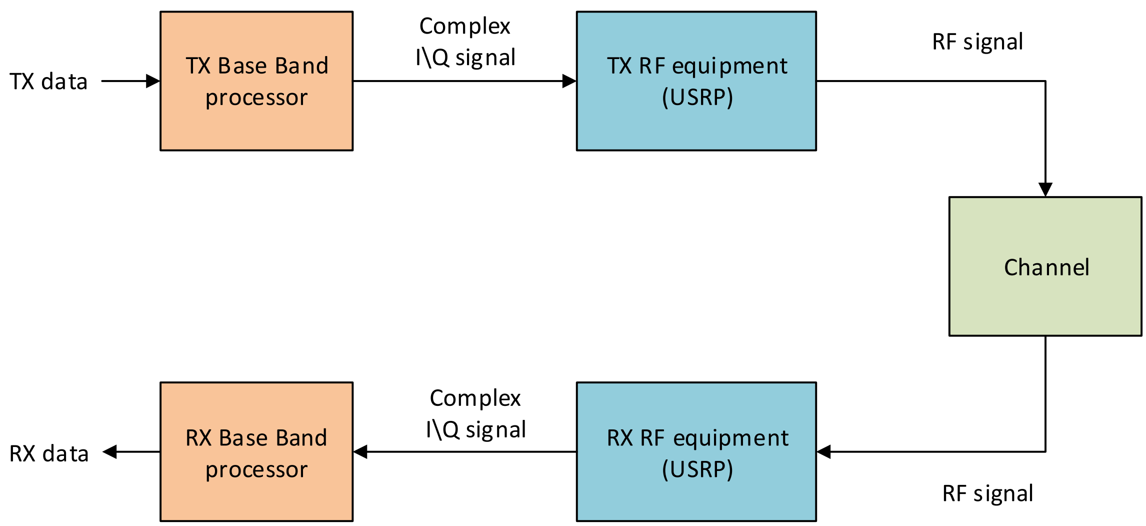


Figure 1-Generic communication system

- **TX data** can be analog (sound) or digital signal (bits) which we want to transmit.
- **TX Base Band (BB)** processor gets TX data signal and produce BB complex signal which is suitable to channel and RF equipment requirements (bandwidth, transmission rate). This unit can be implemented in software (MATLAB, NI-Labview, C) or in hardware (DSP or ASIC). In this lab we will use MATLAB which is convenient tool for implementation of signal processing algorithms.

- **TX RF equipment** obtains BB digitally represented signal, converts it to analog signal by Digital to Analog converter (DAC). Analog signal is up-converted to RF frequencies and transmitted through antenna to the channel. In this lab TX RF equipment is easy implemented by configurable NI –USRP modules.
- **Channel** can be represented by cable or wireless medium. Channel may introduce impairments, like attenuation, distortions, fading of the signal and etc. In most cases in this lab we will use cable as channel for communication between the RF units.
- **RX RF equipment** performs opposite operation to the TX RF transmitter. This unit down-converts the received signal to the BB and using Analog to Digital Converter (ADC) converts it to the digital representation of the received signal.
- **RX Base Band** processes the BB received signal in order to detect the transmitted data.

4 NI-USRP RF Hardware

The RF Hardware used in the lab is the National Instruments USRP (Universal Software Radio Peripheral). The USRP module (Figure 2) is connected to PC through the gigabit Ethernet cable. The PC controls the operation of the module. In this section you will learn more about these modules.

Figure 2 - NI USRP module

4.1 Interfaces

Figure 3 introduces the USRP unit connections used in the lab.

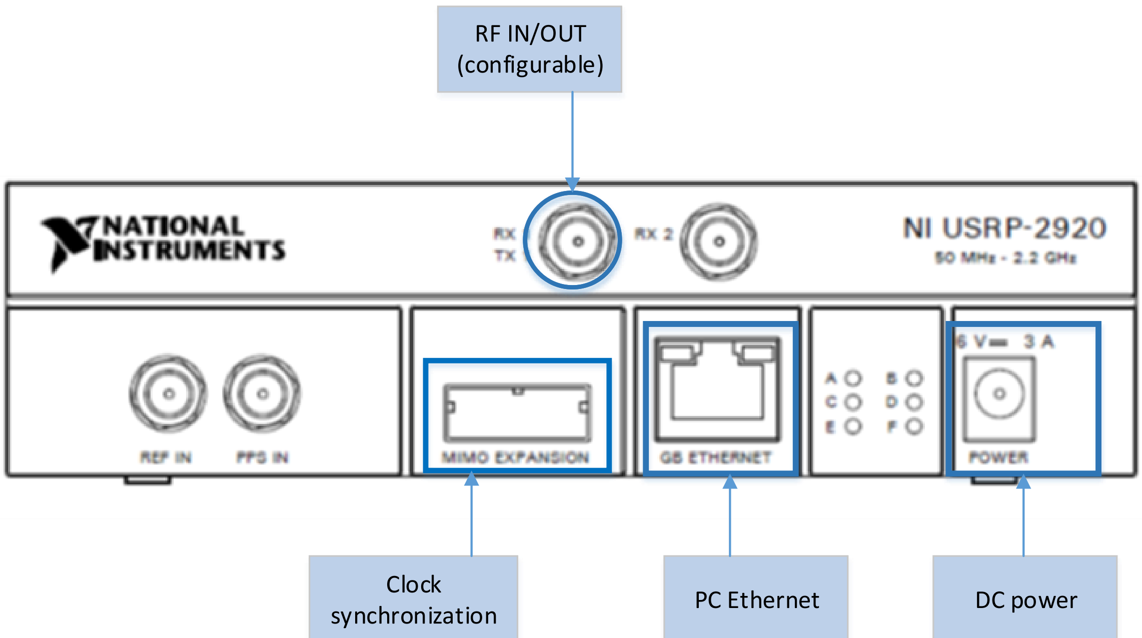


Figure 3-USRP interfaces

4.2 USRP module block diagram

Each USRP module can be configured to TX or RX operation mode. The following block diagram describes the internal structure of the each module contains TX (upper part) and RX (lower part).

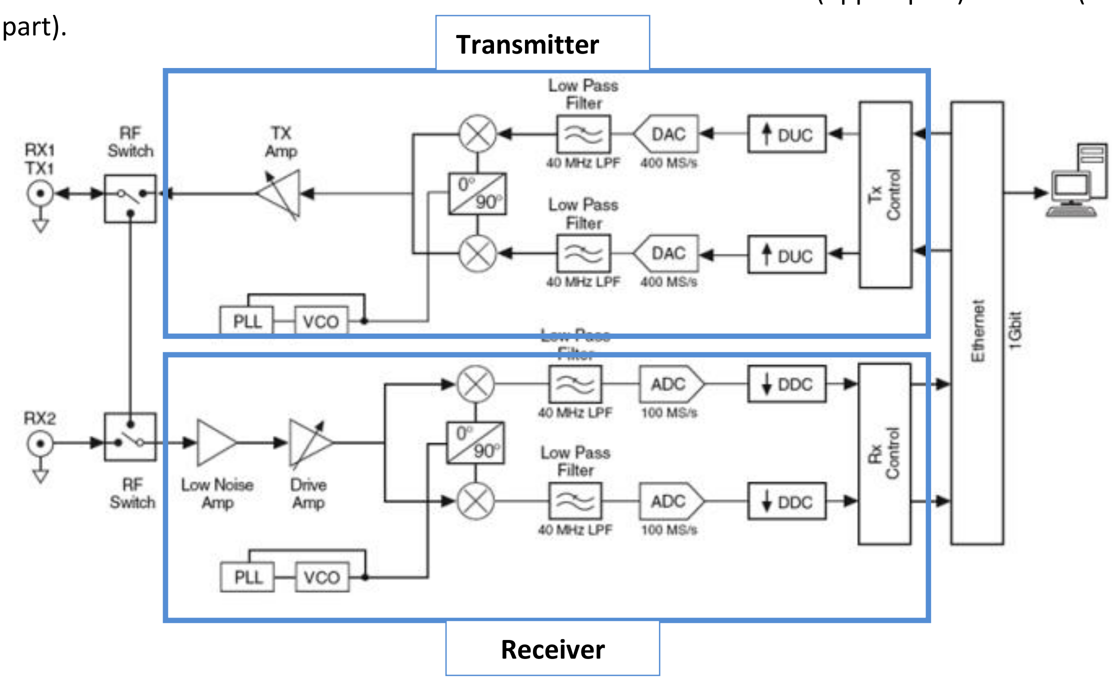


Figure 4- USRP block diagram

4.2.1 Transmitter

The USRP receives a waveform from the host PC with 16 bits of resolution sampled at up to 25 MSamples/second. This signal is up-converted to a radio frequency (RF) before being sent to an amplifier and then transmitted over the air. For more information on the NI USRP, please refer to [1].

4.2.2 Receiver

The received RF signal is mixed with a desired carrier frequency in order to down-convert it to a complex I/Q baseband signal sampled at 100 MSamples/second. The digital signal is then down-sampled to a rate specified by the user and passed to the host PC for processing.

When the ADC of the NI USRP samples at the full digitizer rate (100 MSamp/sec), it can acquire a bandwidth of 20 MHz. Sampling at such high rate with high resolution (14 bits) produces a large amount of data. However, to acquire a signal with smaller bandwidth (a narrowband signal), it is sufficient to sample at a rate at least two time larger than the signal bandwidth (according to Nyqiust sampling theorem).

NI USRP allows reducing the sampling rate of the received signal by decimation performed in HW. The decimation is desirable for the narrow band signals to reduce the storage memory size.

5 Method of transmission and receiving

In this section describes the main guide lines for performing transmission and receiving with USRP modules. Please, refer it before the labs for better understanding of work stages with USRP.

5.1 Hardware initialization

1. Verify that TX and RX modules are connected (RF cable, Synchronization cable, PC connection).
2. Turn on the modules.
3. The PC communicate with the USRP modules using IP. Check the IP addresses of the USRP modules using the following application: **Start ->National Instruments\NI-USRP\utilities -> USRP-utils.**

5.2 Transmission

5.2.1 Matlab

This section explains how to prepare BB signal and how to save it for later using in RF transmission.

1. Prepare a code producing the complex base band samples of the signal you want to transmit.

   Remarks:

   - The signal should be oversampled minimum in factor 4.

- The maximum value of the real and imaginary parts of the BB signal should be less than 1. This is because of DAC limited dynamic range. The DAC is configured to convert digital numbers within the range [-1:1] to the appropriate voltage. If the input digital sample is higher than 1, then it will be clipped to 1.

2. Save the obtained signal using MATLAB function: ***WR_bin_file.m***. This function obtains the complex vector and saves it to binary file, which will be read by LAB-View TX tool.

5.2.2 LAB-View TX tool

This section introduces the graphical interface (GUI) for USRP module, which working in the TX mode.

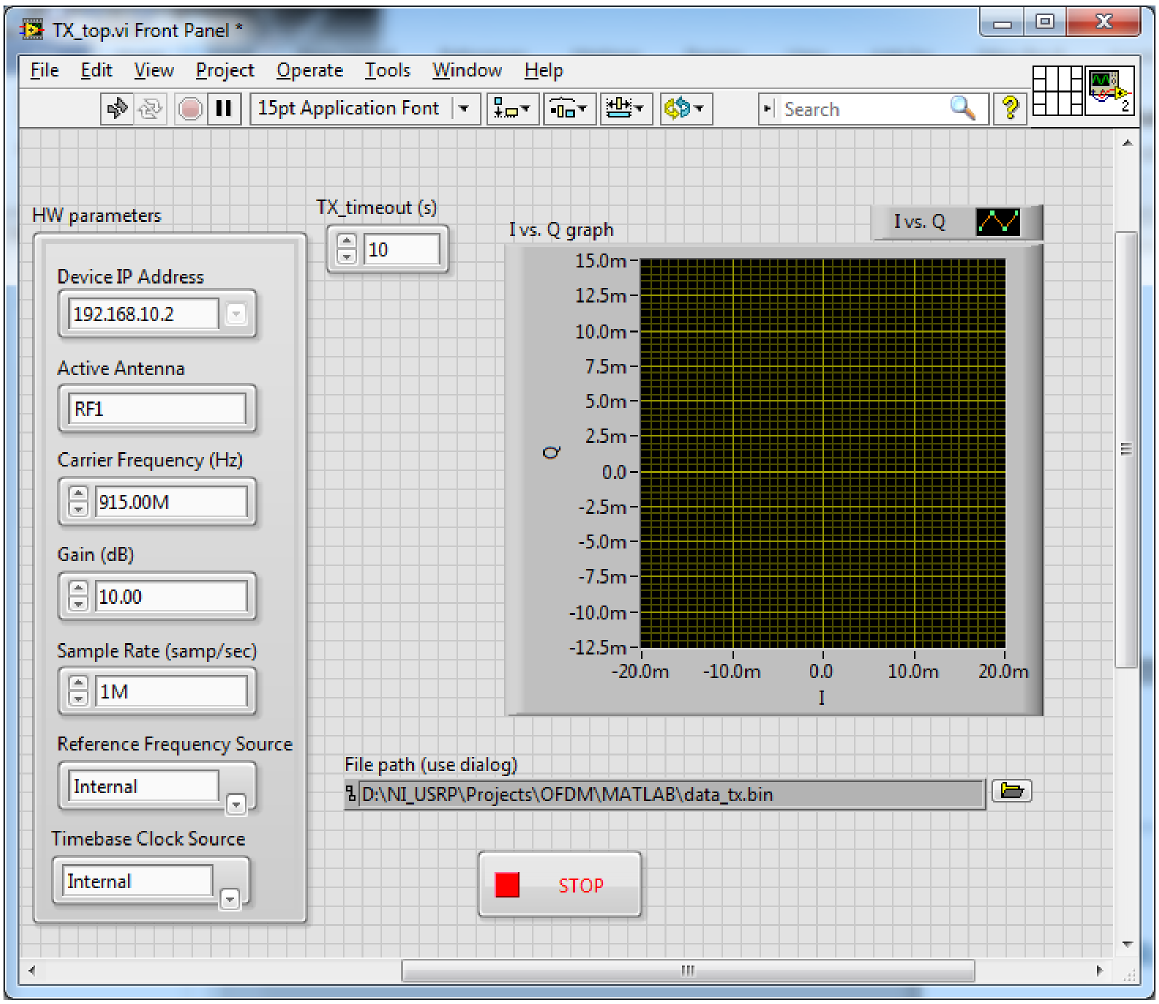


Figure 5 - TX tool

1. Define all USRP configurations: sampling rate, carrier frequency, IP. Set the reference frequency and clock sources to ***Internal***.
2. Enter the path to the TX signal file produced in Matlab.
3. Start the transmission by click on the 'play' button.

Remarks: The signal will be transmitted in the loop. Namely, when the samples in transmitted file are ended, the system will continue transmission of samples from the beginning of the file.

4. To stop the transmission press large STOP button.

5.3 Receiving

5.3.1 LAB-View RX tool

This section introduces the graphical interface (GUI) for USRP module, which working in the TX mode.

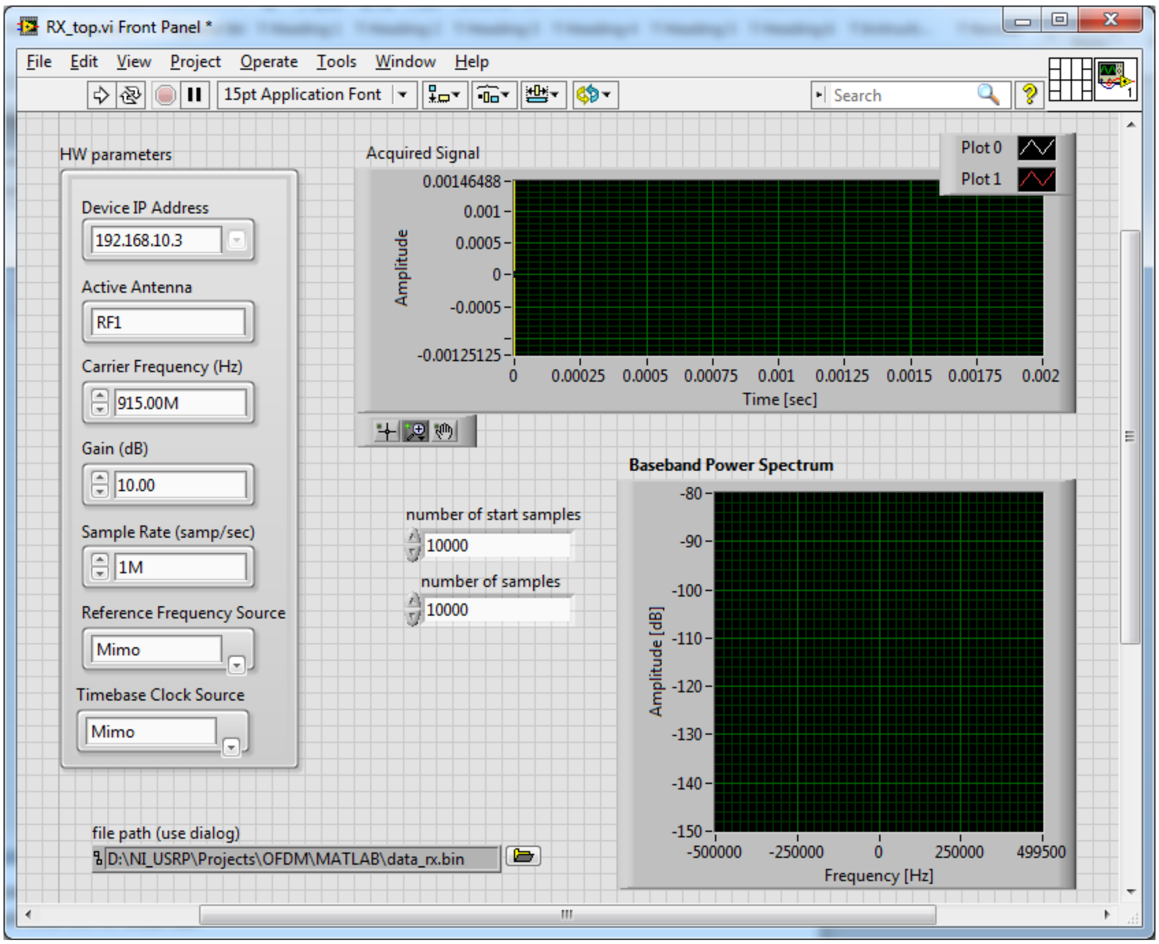


Figure 6 - RX tool

1. Define all USRP configurations: sampling rate, carrier frequency, IP. Set the clock property to ***MIMO.***
2. Specify the path, where received file will be saved. This file will be processed by Matlab.
3. Enter number of samples you want to receive. And number of initial samples you want to skip. Skipping is required due to the transient time of the RF circuits in the RX. The

transient time is about: ***10ms***, so depending on sampling rate, you can calculate the number of skipped samples.

4. Start the receiving by click on the 'play' button.

5.3.2 Matlab

1. Open the RX signal file using script: ***RD_bin_file.m***. The function returns vector with complex received samples.
2. Process the obtained samples using RX Matlab algorithms.

6 Pre-lab

6.1 Theory and Questions

Review the following subjects:

1. Bandwidth, sampling rate and Nyquist theorem.
2. Oversampling. Oversampled digital signal is signal sampled over Nyquist rate. Having Nyquist rate sampled signal we can produce oversampled signal by up-sampling. The inverse process used to convert over-sampled signal to Nyquist rate representation is called down-sampling. ([3] - Chapter 4.6(1,2), [2])
3. Base band and pass band representation of the signal.
4. I/Q modulation.
5. Power Spectrum Density (PSD).
6. Thermal noise floor, noise figure.
7. Quantization noise.
8. Raised cosine and root raised cosine shaping pulses. Review the impulse and frequency response of the raised cosine filter.
9. RF parameters appear in USRP spec [1].

Answer the following questions:

1. You have digitally represented signal in Matlab, which you want to transmit through the USRP hardware. What parameter defines the transmitted signal bandwidth?
2. What happens if you trying to receive the signal with bandwidth of 1 MHz using ADC with sample rate of 1Msamp/sec?
3. What is the mathematical description of the up-sampling\down-sampling? Describe the flowing algorithms:
    a. Time up-sampling performed in time domain.
    b. Time down-sampling performed in time domain.
    c. Time up-sampling performed in frequency domain.
    d. Time down-sampling performed in frequency domain.

4. We want to transmit sampled signal $s[n]$ with the PSD denoted by $S(\omega)$. The sampling rate is $1/T$.
   a. The problem is that you can save and transmit only finite fragment of the signal, the length of the fragment is $1000T$ $[sec]$. Find PSD of the transmitted fragment of the signal denoted $S_f(\omega)$?
   b. Now, let's assume that transmitted signal is oversampled by factor 8. And the length of the transmitted fragment wasn't changed, i.e., the fragment length = $1000T$ $[sec]$. Provide the qualitative description, what is the PSD of the transmitted signal fragment $S_f(\omega)$ in this case.
5. $s(t) = s_{\text{Re}}(t) + js_{\text{Im}}(t)$ is the base band complex signal. Write the pass band representation of this signal. Show, how I\Q modulation allows to convert BB complex signal to the pass band signal.
6. How the roll-off factor effects on the impulse and frequency responses of the raised cosine filter?
7. What is the range of allowable carrier/center frequency supported by the NI-USRP?
8. What is the maximum allowable bandwidth supported by the NI-USRP?
9. What is the maximum sampling rate of the NI-USRP?
10. What is the maximum transmission power in dBm of the NI-USRP? What is the relationship between dBm and Watt units? For comparison, find in internet: What is the transmission power of the cellular phone (e.g. IPhone), cellular base station, Wi-Fi router and FM broadcast radio transmitter?
11. What are DAC and ADC resolutions of the NI-USRP units? What is the highest possible signal to quantization noise ratio (SQNR) in the receiver (assume uniform quantization)?

6.2 Matlab Tasks

1. Download the Matlab code from the course site. This code simulates Sine wave generator and Root Raised Cosine (RRC) pulse generator.
2. Review the code and run the following functions:
   a. MAIN_SIN_TX – generates the BB sine wave and saves to a file for transmission.
   b. MAIN_RRC_TX – generates the RRC pulses wave and saves to a file for transmission.
3. Run the codes in the debug mode for better understanding of the code flow.
4. Write your own code for the following function and replace them in the provided code:
   - Sine wave generator
   - Root raised cosine
   - Result plotter

The detailed description of these functions is explained below.

You can add any input or output parameters to the functions.

6.2.1 Sine wave generator

Inputs:

- Sampling rate
- Oversampling factor
- Frequency
- Signal length in samples
- Amplitude

Outputs:

- Complex BB signal

Operation

- Produce the BB sine waveform
- Verify that sine's frequency is suitable for given sampling rate. If Nyquist criterion is not fulfilled, then report error.

6.2.2 Root raised cosine shaping pulse generator

Root raise cosine pulse is very useful waveform in digital single carrier communication. We will deal with it extensively in the next labs. In this lab we will learn the basic time and frequency properties of this signal.

Inputs:

- Sampling rate
- Oversampling factor
- Number of symbols
- Roll off factor
- Impulse response length

Outputs:

- Sequence of raised cosine pulses

Operation

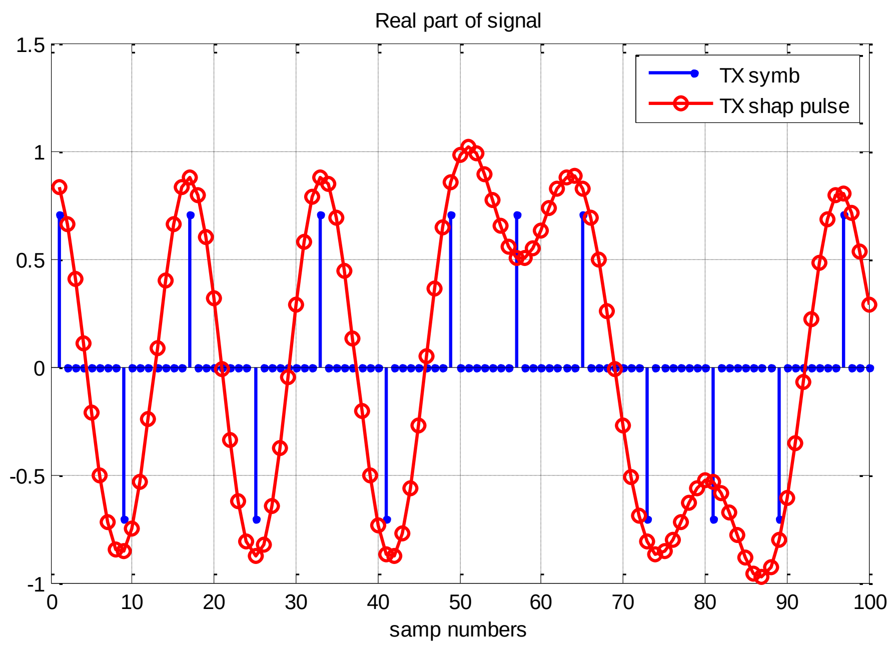
- Define the filter object using `fdesign.pulseshaping.` Use Matlab help to learn more about it. The filter should have raised cosine shape with the roll off factor given in the inputs.
- Design the filter using `design` command. Filter impulse response is denoted by $g[n]$.
- Produce the random sequence of symbols taken form the following set: $c = \{1+j, 1-j, -1+j, -1-j\}$. Amplitude is defined by *A* from the input parameters.
  $x[n] = A \cdot [c_0, c_1, c_2, \dots \dots \dots]$
- Up-sample the sequence of peaks by factor defined in input parameters.
  $x_{up}[n] = A \cdot [c_0, 0, 0, \dots, c_1, 0, 0, \dots \dots \dots \dots]$

- Filter the obtained sequence using pulse shaping:

$$s[n] = \sum_{k=-\infty}^{\infty} x_{up}[k]\, g[n-k] = \sum_{k=0}^{Q-1} g[k] x_{up}[n-k],$$

where Q is filter impulse response length.

- See the following illustration, which shows the up-sampled symbols sequence and filtered signal with up-sampling = 8.



6.2.3 Result Plotter

This function should analyze the transmitted and received signals and presents the results of this analysis.

Inputs:

- BB complex signal
- Sampling rate
- Time interval for processing

Output:

- Time domain plots for real and imaginary parts of signal
- PSD plot (Spectrum)

Operation

- Plot the time domain figure. Produce the graph for the limited interval of the signal. Set X axes in [sec].

- Plot the spectrum of the transmitted and received signal. Set X axes in [Hz] and Y axes in [dB/Hz]. *Hints:*
    - Perform FFT on the obtained data.
    - Normalize the obtained frequency signal by sampling frequency.
    - Compute the frequency scale (form (-F_samp/2) to (F_samp/2)).
    - Plot the signal in dB scale.

7 Lab experiments

All paragraphs marked by the note ''**(Lab Report)** '' should be discussed in the final report.

7.1 Sine waveform

7.1.1 BB sine waveform signal

1. Using Matlab code prepared in advance generate sin waveform with the following parameters:
    a. Number of samples = 10000
    b. Sampling rate = 1 MHz
    c. BB frequency = 100 KHz
    d. Amplitude = 0.5
2. **(Lab Report)** Show to instructor plots of the time domain signal and frequency domain signal. Assume the sampling rate is 1 MHz.

7.1.2 Sine waveform transition

1. Perform the transmission according to Section 5 'Method of the transmission and receiving'. Use the following parameters for NI-USRP configuration:
    a. Carrier frequency = 500 MHz
    b. Sampling rate = 1 MHz
    c. TX gain = 3 dB
    d. Rx gain = 0 dB
2. **(Lab Report)** Show the transmitted signal on a spectrum analyzer. Do the following measurements and observations :
    a. Show the BB spectrum of the transmitted signal in Matlab (similar to paragraph 7.1.1(2)). Compare it to the spectrum obtained from spectrum analyzer.
    b. Measure the power of the transmitted signal.
    c. Change the TX gain to 9 dB, and measure the power of the transmitted signal.
    d. Measure the frequency space between transmitted signal and carrier frequency. Is the results congruent with BB spectrum produced in Matlab. Explain.
    e. Change the sampling rate only in the TX configuration to 2 MHz. Measure the frequency space between transmitted signal and carrier frequency. Compare the measurement result to preceding result. Explain the difference.

   f. Now change the sampling rate in Matlab BB sine wave generator and in the TX configuration to 2 MHz. Compare the measurement result to preceding result. Explain the difference.
   g. Configure the transmitter's carrier frequency to 450 MHz and verify the change by scope.
3. **(Lab Report)** Receive the transmitted signal, when the carrier frequency is set to 500 MHz. Do the following tasks:
   a. Show the received signal in time domain and frequency domain (spectrum). Compare the obtained results with the transmitted signal.
   b. Evaluate the attenuation from digital BB TX signal to digital BB RX signal.
   c. Find the noise floor of the received signal. What is expected AWGN noise floor? What is expected quantization noise floor in the system? Are the theoretical and practical results congruent?
4. **(Lab Report)** Noise estimation. We will focus on two type of noises: quantization noise and thermal noise.
   a. Calculate the signal to quantization noise ratio (SQNR):
      i. Find ADC resolution of USRP [1]?
      ii. By assuming the fall scale Sin waveform in the input of ADC, calculate the SQNR.
   b. Find the signal to thermal noise ratio (SNR):
      i. Start the transmission of the sin wave, with TX gain =10dB.
      ii. Measure the transmitted signal power using spectrum analyzer.
      iii. Calculate the thermal noise power in the in bandwidth of the signal.
      iv. Calculate the SNR in receiver in this case. Take into account the noise figure of RX's RF equipment [1] and attenuators in the input of the receiver.
   c. What is the dominant noise in this case: quantization noise and thermal noise? How we can increase the SNR? How increase the SQNR?

7.2 Root raised cosine shaping pulse signal

7.2.1 BB root cosine raised waveform

1. Using Matlab code prepared in advance generate the impulse response of the root rise cosine filter with the following parameters:
   a. Sampling rate = 1MHz
   b. Oversampling factor = 8
   c. Roll off factor = 0.2
   d. Impulse response length = 20 [samples without oversampling]
2. **(Lab Report)** Plots of the impulse response of the shaping filter. Plot the frequency response of this filter.

3. **(Lab Report)** Add to the existing plots the impulse and frequency response of the filters with *roll off factors = [0.5, 0.8, 0.9].* What is effect of the filter's roll off factor on its impulse and frequency responses?
4. **(Lab Report)** Using Matlab code prepared in advance (section 6.2.2) generate the sequences of root raised cosine pulses with *roll off factors = [0.2, 0.5, 0.9].*
   a. Save the signals in the different files for the future transmission .

7.2.2 Root raised cosine waveform transmission

1. Transmit the first signal - root raised cosine pulses sequence with *roll off factor = [0.2]*. Do the transmission according to section 5 'Method of the transmission and receiving'. Use the following parameters for NI-USRP configuration:
   a. Carrier frequency = 500 MHz
   b. Sampling rate = 1 MHz
   c. TX gain = 10 dB
   d. Rx gain = 0 dB
2. **(Lab Report)** Show the transmitted signal on a spectrum analyzer.
3. **(Lab Report)** Transmit the root raised cosine pulses sequences with *roll off factors = [0.5, 0.9]*, compare these spectrums with the spectrum obtained in paragraph 2.

8 Summary report writing remarks

Your lab report should accomplish the following tasks:

1. Describe in details the result of the all paragraphs marked by note '**(Lab Report)'.**
2. Provide the mathematical / theoretical explanation in all paragraphs where is the explanation is required.

9 References

[1] NI-USRP 2920 specification

[2] R. W. Heath Jr., *Wireless Communications Lab – Lecture notes.*

[3] Oppenheim, A. V., Schafer R.W., Buck J. R. *Discrete-time signal processing.* Vol. 5. Upper Saddle River: Prentice Hall, 1999.