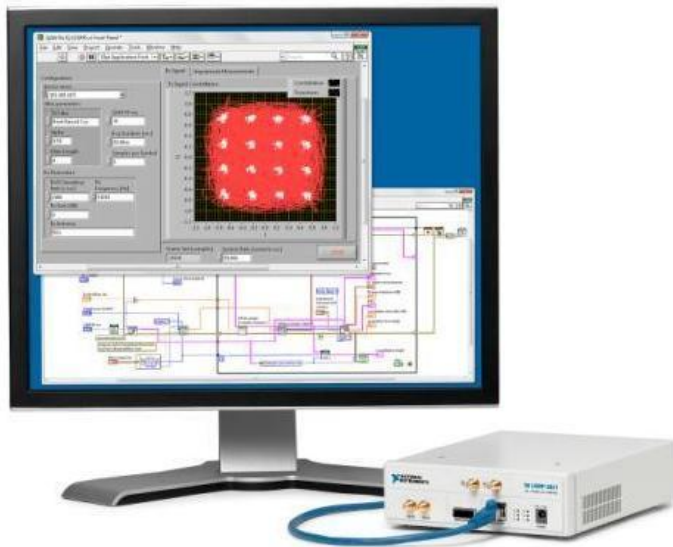


A Rapid Graphical Programming Approach to SDR Design and Prototyping with LabVIEW and the USRP



Filip Langenaken
Academic Program Manager
Benelux & Nordic
National Instruments

NI-USRP: a Platform for SDR Design, Prototyping and Exploration

- Low cost , PC-hosted RF Transceiver for software defined radio prototyping and exploration
- Real-time processing: Gigabit Ethernet link streams live data for real time processing on a Windows-based host computer running LabVIEW
- Hardware and software are easy to install, connect, and learn



**NI-219x
RF Transceiver**

Demo: Packet-based Transceiver

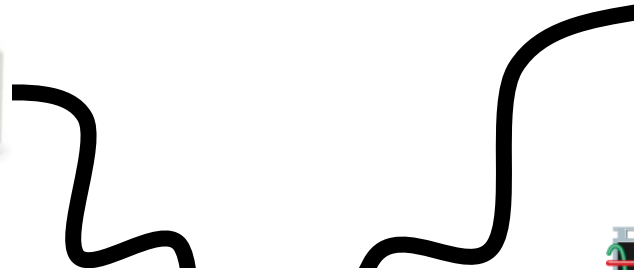
NI USRP-2190
Transmitter



RF Signal

915MHz, PSK packets, 400kbps

NI USRP-2190
Receiver



- USRP control (Tx & Rx)
- Modulate Tx signal
- Demodulate Rx signal
- Reconstruct message

Demo: Packet-based Transceiver

USRP Packet Transmitter.vi Front Panel

File Edit View Project Operate Tools Window Help

15pt Application Font

Packet Transmitter

Specify Message Specify Packet Specify Modulation Tx Parameters Debug

device names
192.168.10.6

Message Text

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth.

Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same.

And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I--
I took the one less traveled by,
And that has made all the difference.

Tx Signal Constellation

USRP Packet Receiver.vi Front Panel

File Edit View Project Operate Tools Window Help

15pt Application Font

Packet Receiver

Rx Display Rx Parameters Specify Modulation Specify Packet Debugging

device names
192.168.10.5

Recovered Message

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth.

Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same.

And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I--
I took the one less traveled by,
And that has made all the difference.

Received Signal

Amplitude

0 0.2 0.4

0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000 22000 24000

sample

Signal and Noise Power Tracking

Amplitude

0 0.02 0.04 0.06 0.08

0 1 2 3 4 5 6 7 8 9

Iteration

Cumulative Packets Recovered

Count

0 20 40 60

0 1 2 3 4 5 6 7 8 9

Iteration

Constellation Graph

Constellation Transitions

1.5 1.0 0.5 0.0 -0.5 -1.0 -1.5

-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5

I

Q

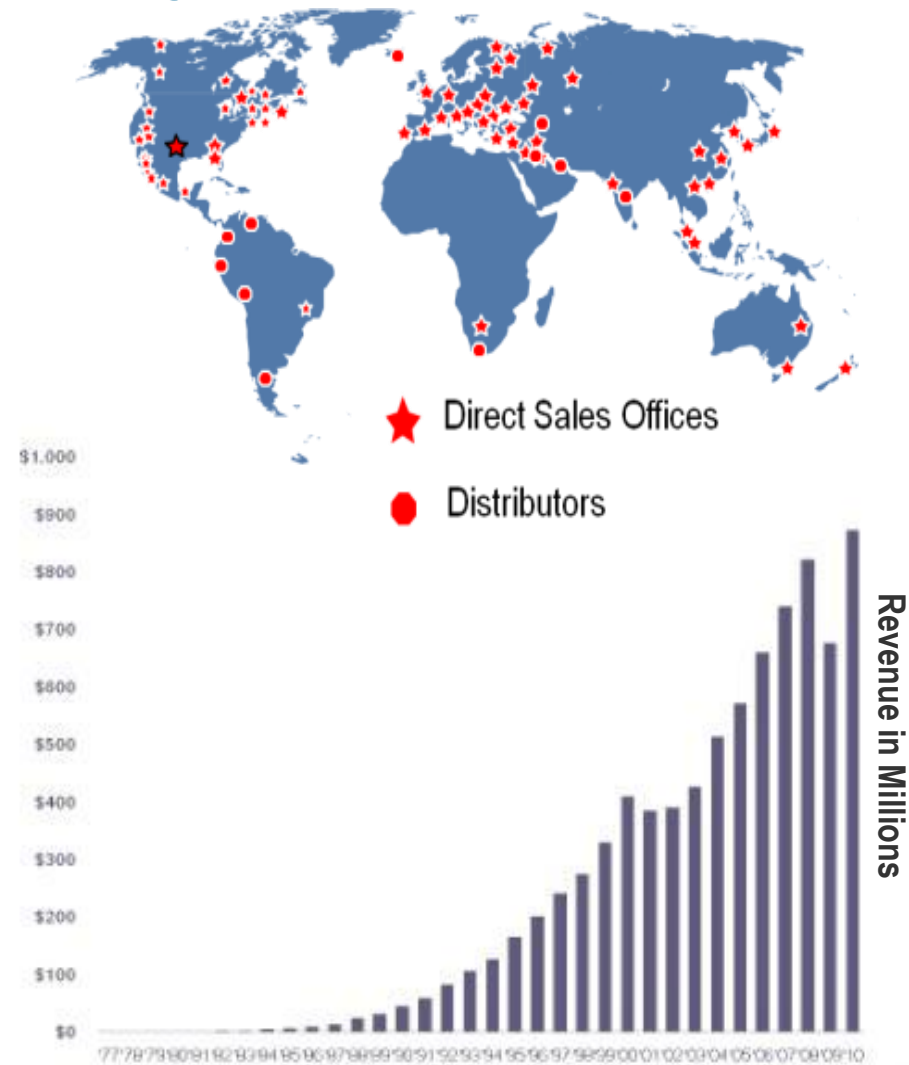
STOP

Agenda

- Background
- NI USRP hardware / software components
- Getting started with NI USRP
- SDR with NI USRP
- Resources

National Instruments: Key Stats

- Founded in 1976, HQ in Austin, TX
- 30+ years growth and profitability
 - \$873M revenue in 2010 (+29% YOY), 17% operating income
 - \$255M revenue in Q3 2011 (+16% YOY)
- 6,000+ employees, Operations in 50+ countries
- *FORTUNE*'s "100 Best Companies to Work For" list for 12 consecutive years
- *FORTUNE*'s "25 Best Multinational Companies to Work For" 2011
- Strong investment in R&D
- Over 30,000 customers, Over 7,000 universities



The National Instruments Vision

Graphical System Design

Test and Measurement

Automated Test
Data Acquisition
Reconfigurable
Instruments

Real-Time Systems

Embedded Monitoring
Hardware-in-the-loop

Industrial & Embedded

Industrial Control (PAC)
Machine Control
Electronic Devices
Software-Defined Radio

**“To do for test and measurement
what the spreadsheet did
for financial analysis.”**

**“To do for embedded what the PC
did for the desktop.”**

NI Platforms for RF/Communications



**NI-USRP for
LabVIEW**



**NI RF VSG,
VSA**



NI FlexRIO



**NI RF 6-GHz
Peer-to-Peer**



RF RIO



NI USRP

Tunable RF Transceiver Front Ends

- Frequency Ranges
50 MHz – 2.2 GHz (NI-2920)
2.4 GHz & 5.5 GHz (NI-2921)

Signal Processing and Synthesis

- NI LabVIEW to develop and explore algorithms
- NI Modulation Toolkit to synthesize and process live signals



Applications

- FM Radio
- TV
- GPS
- GSM
- ZigBee®
- Safety Radio
- OFDM
- Passive Radar
- Dynamic Spectrum Access

Gigabit Ethernet Connectivity

- Plug-and-play capability
- Up to 20 MS/s baseband IQ streaming

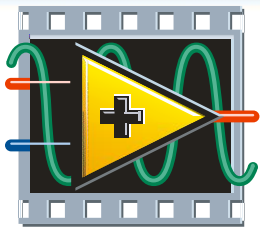
NI USRP enables Host-based Processing

RF
Transceiver

Baseband IQ

Host-based
Processing



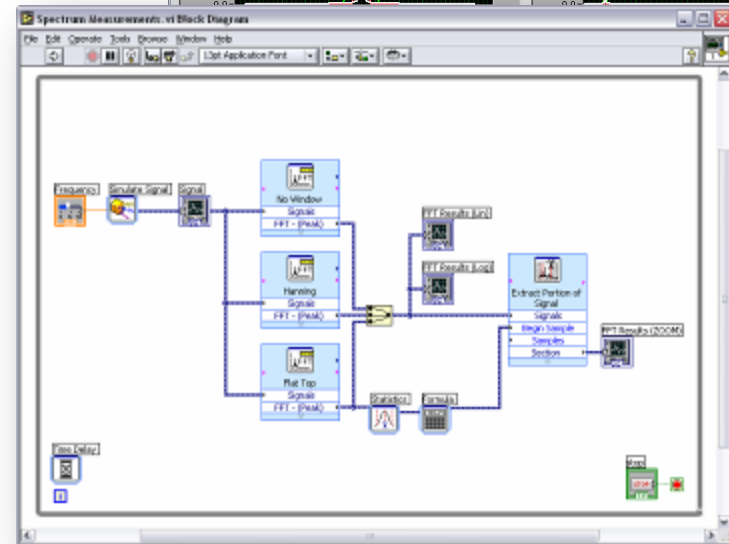
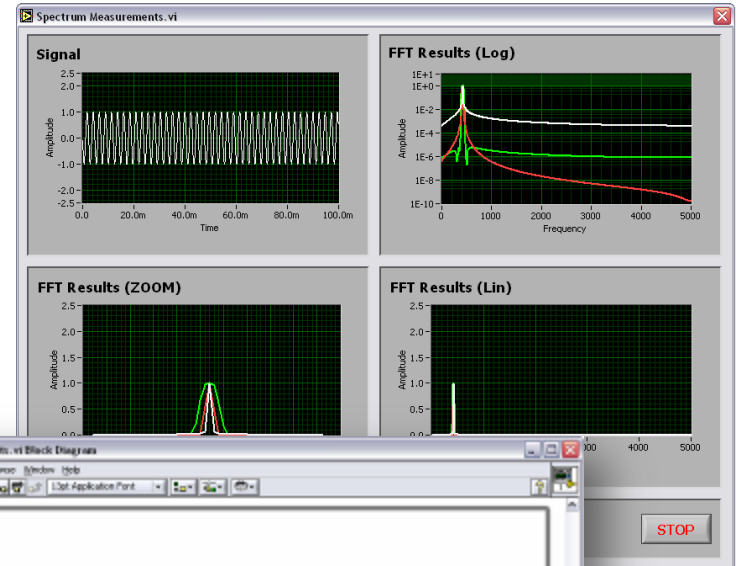


NATIONAL INSTRUMENTS™

LabVIEW™

A Compiled Graphical Development Environment

- Intuitive graphical dataflow programming environment with integrated .m file script textual math
- Functionality tailored for science and engineering
- 750+ functions for signal processing, analysis, and mathematics






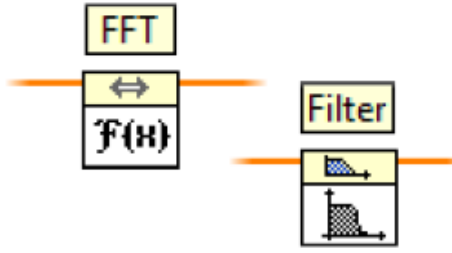
NATIONAL INSTRUMENTS

LabVIEW™

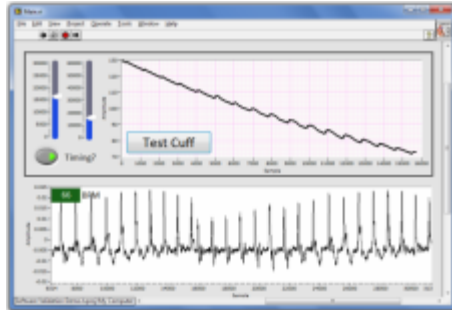
**A Highly Productive Graphical Development Environment
for Engineers and Scientists**



Hardware APIs




Analysis Libraries



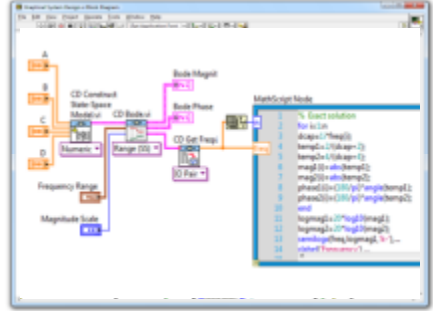
Custom User Interfaces



Deployment Targets

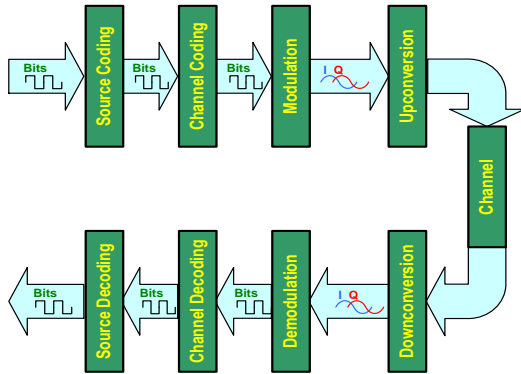


Technology Abstractions

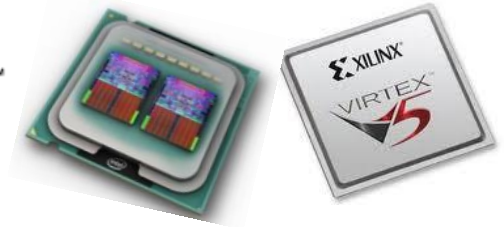


Programming Approaches

From Concept to Prototype ... Rapidly!



NATIONAL INSTRUMENTS
LabVIEW[™]
Graphical System Design



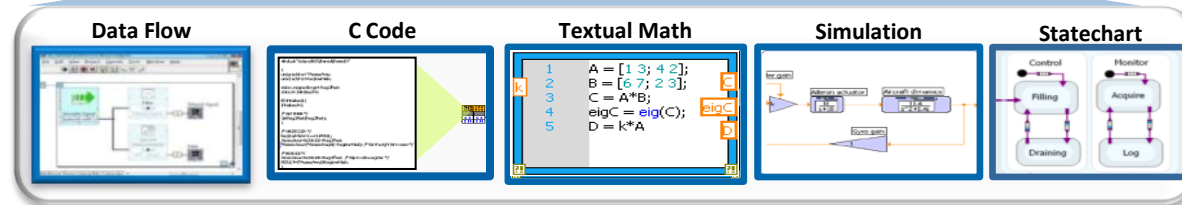
Concept



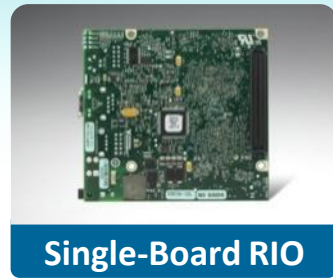
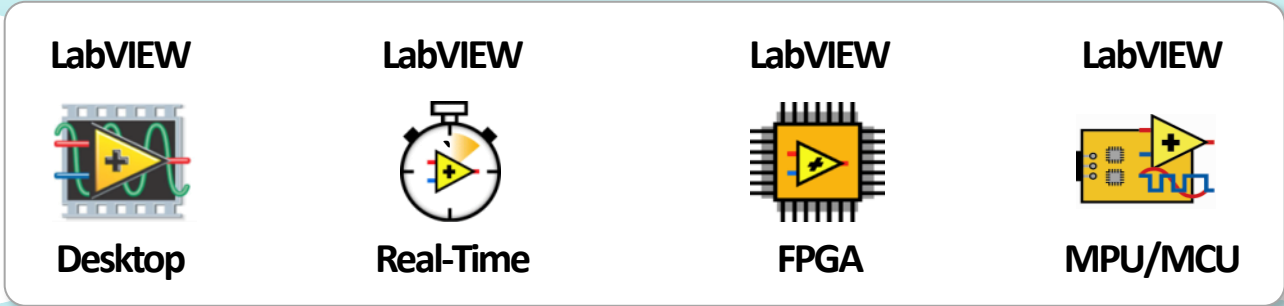
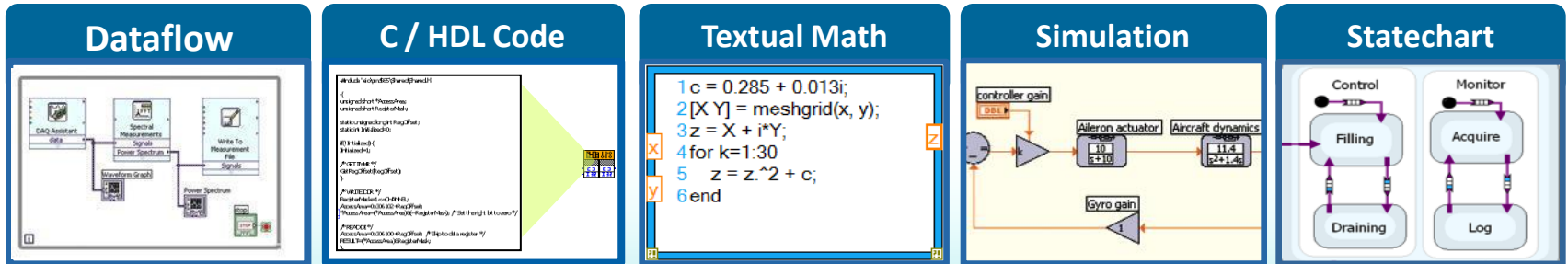
Design Language



Prototype

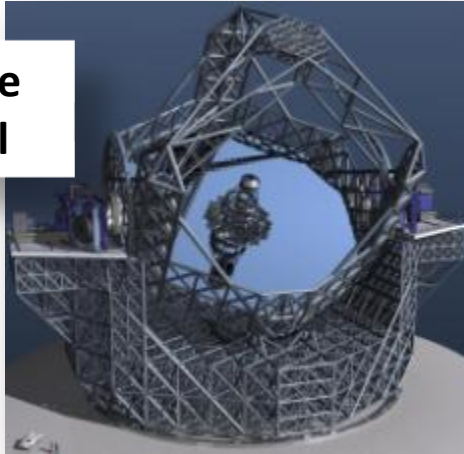


System Design to Deployment

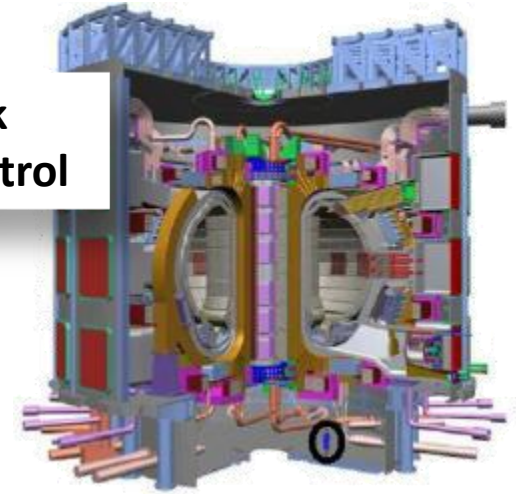


Solving the Toughest Problems on Earth

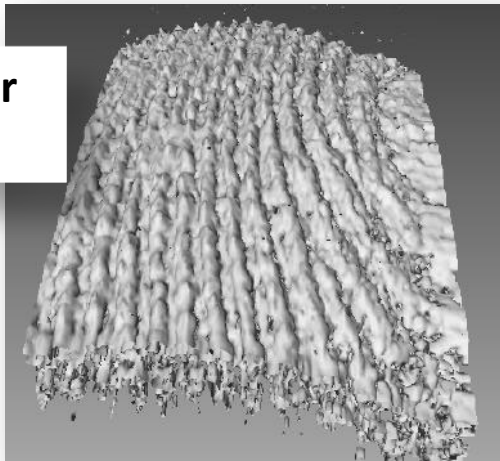
**Large Telescope
Mirror Control**



**Tokamak
Plasma Control**



**Early Cancer
Detection**

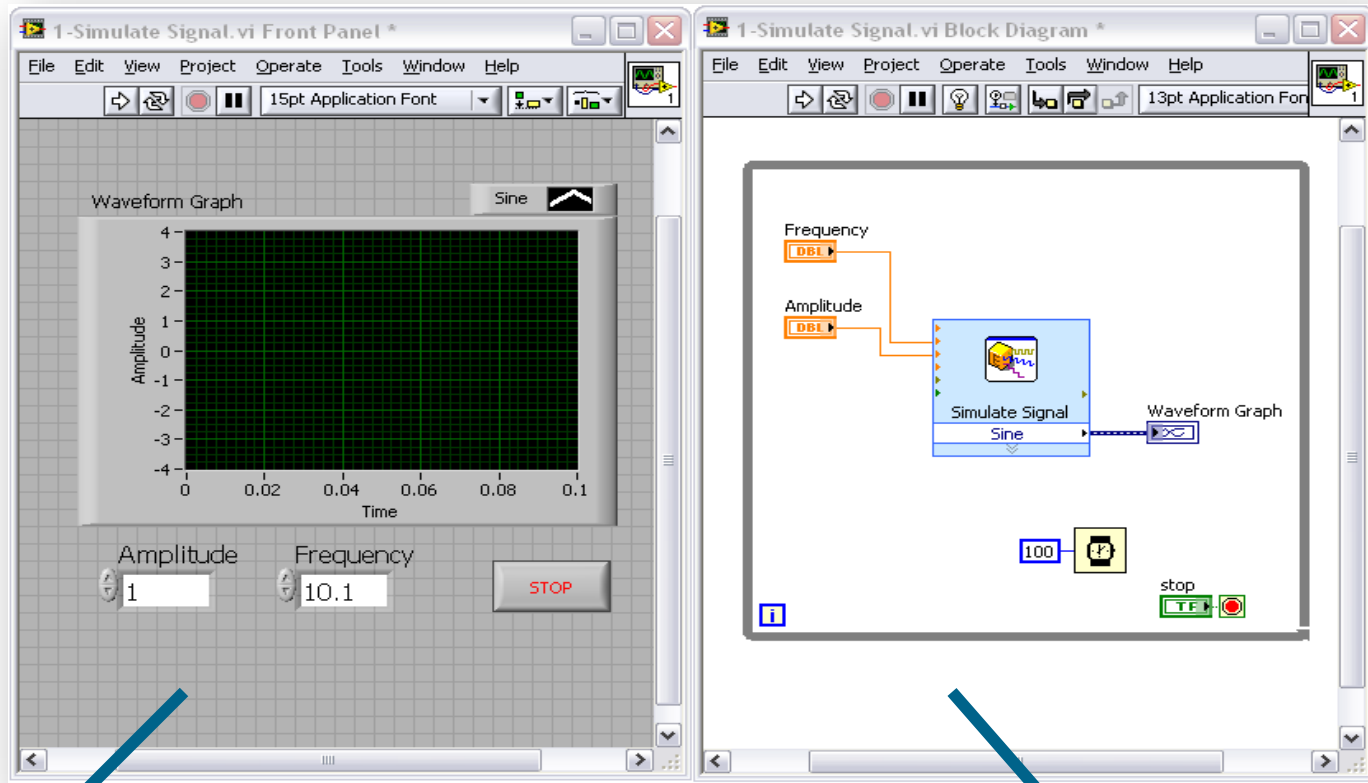


**CERN Large Hadron
Collider**



The LabVIEW Environment

“VI” = program or function

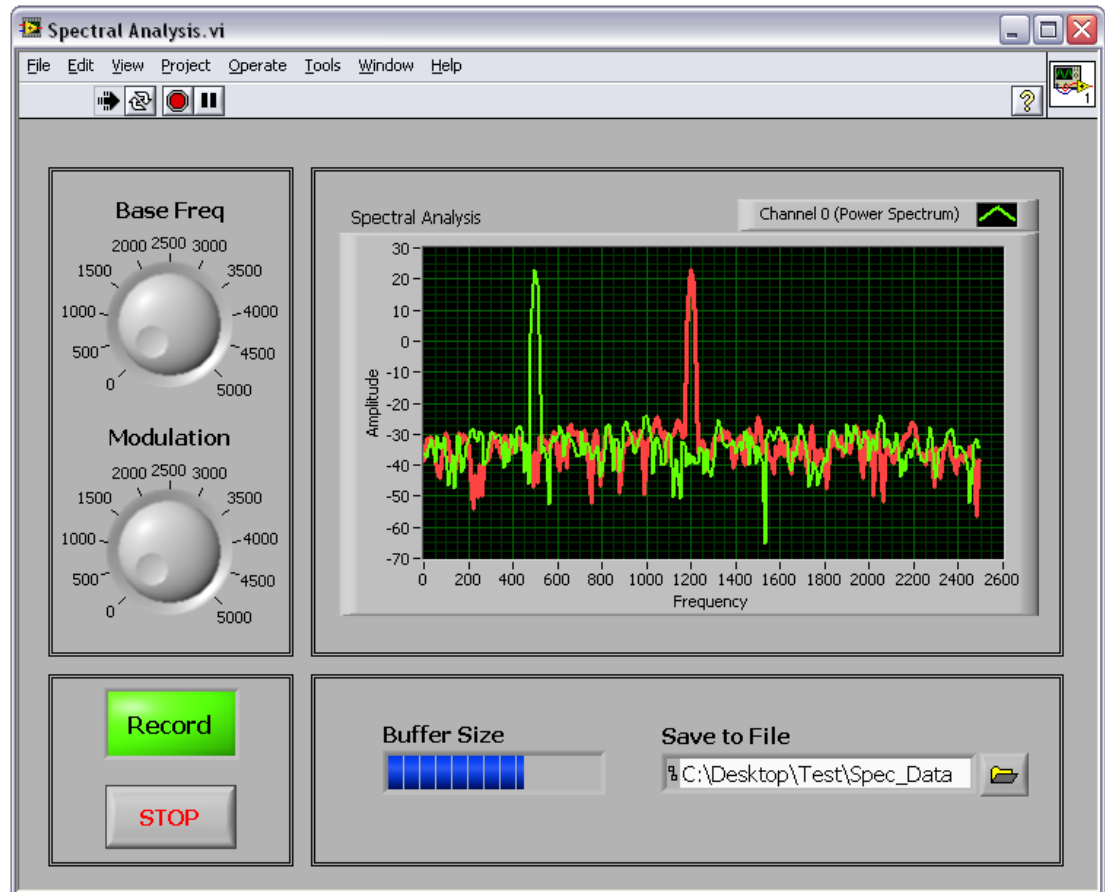


“Front Panel” = user interface

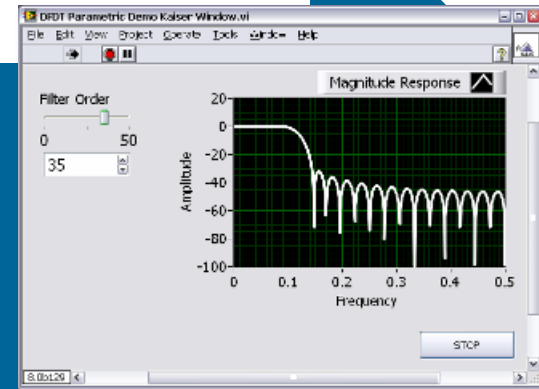
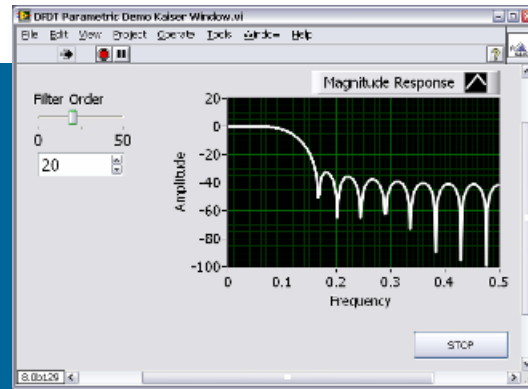
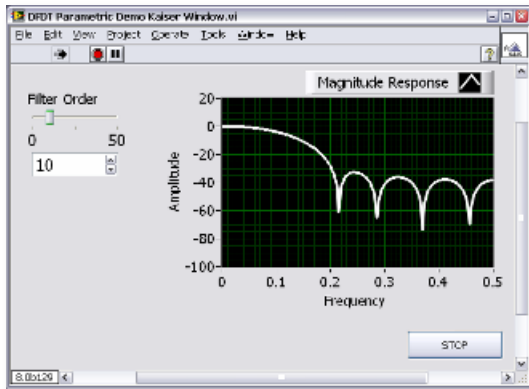
“Block Diagram” = code

Controls & Indicators

- Knobs/Dials
- Graphs/Charts
- Buttons
- Digital Displays
- Sliders
- Thermometers
- Customize and create your own



Interactivity



Problem Definition



Concept Demos



Computational Exploration



Design



Interactive Analysis

Demo: Simple USRP-based Receiver

Gigabit Ethernet
Connection to Host Computer



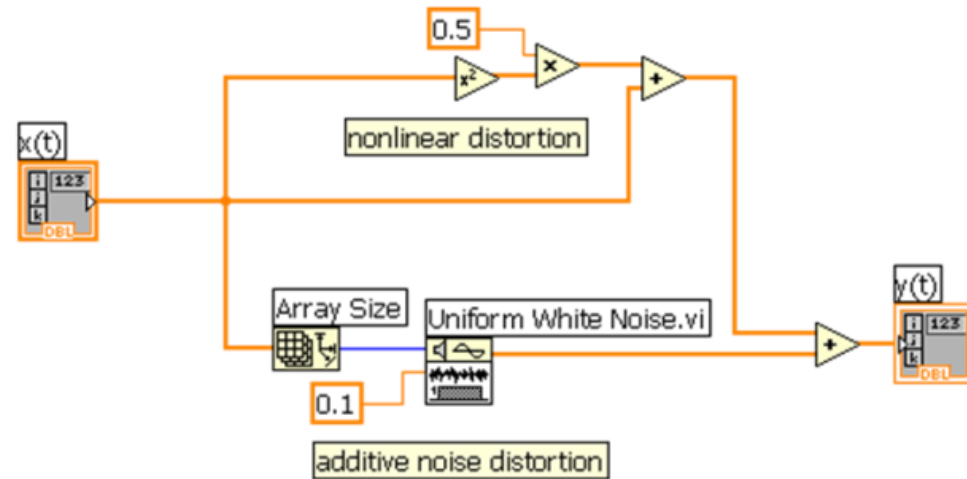
NI USRP-2190
Receiver



- USRP control (Tx & Rx)
- Inline Processing / Display

The G Programming Language

- An intuitive visual representation maps functional blocks to concepts
- Modular and hierarchical
- High-level tools and building blocks
- Reuse external code
- Compiles to machine code
- Directly represents parallel, multithreaded, distributed systems



$$y[n] = 0.5x^2[n] + x[n] + 0.1U_n[n]$$



Functions and Express VIs

The image displays a LabVIEW block diagram window titled "Cont Acq&Graph Voltage-Int Clk.vi Block Diagram". The main diagram shows a sequence of operations: a "Physical Channel" input (I70) is connected to an "AI Voltage" block, which then feeds into a "Sample Rate" block. The output of the "Sample Rate" block is connected to a "Continuous Sample" block. The output of "Continuous Sample" is connected to a "DAQmx" block, which then feeds into a "Sample" block. The output of "Sample" is connected to a "data 2" block (DBI). The output of "data 2" is connected to another "DAQmx" block, which then feeds into a "stop" block (TF).

A "DAQ Assistant" configuration window is overlaid on the diagram. The window has tabs for "Configuration", "Triggering", and "Advanced Timing". The "Configuration" tab is active, showing "Channel Settings" and "Voltage Output Setup". The "Voltage Output Setup" section includes "Signal Output Range" (Max: 10, Min: -10, Scaled Units: Volts) and "Terminal Configuration" (RSE, Custom Scaling: <No Scale>). The "Triggering" section shows "Generation Mode" (N Samples) and "Samples to Write" (100, Rate: 1k).










A callout box labeled "Configuration Based Express VI" points to a "DAQ Assistant" block in the block diagram. The block has three outputs: "data", "stop (T)", and "timeout (s)".

The word "Standard" is partially visible on the left side of the image.

Wires and Data Types

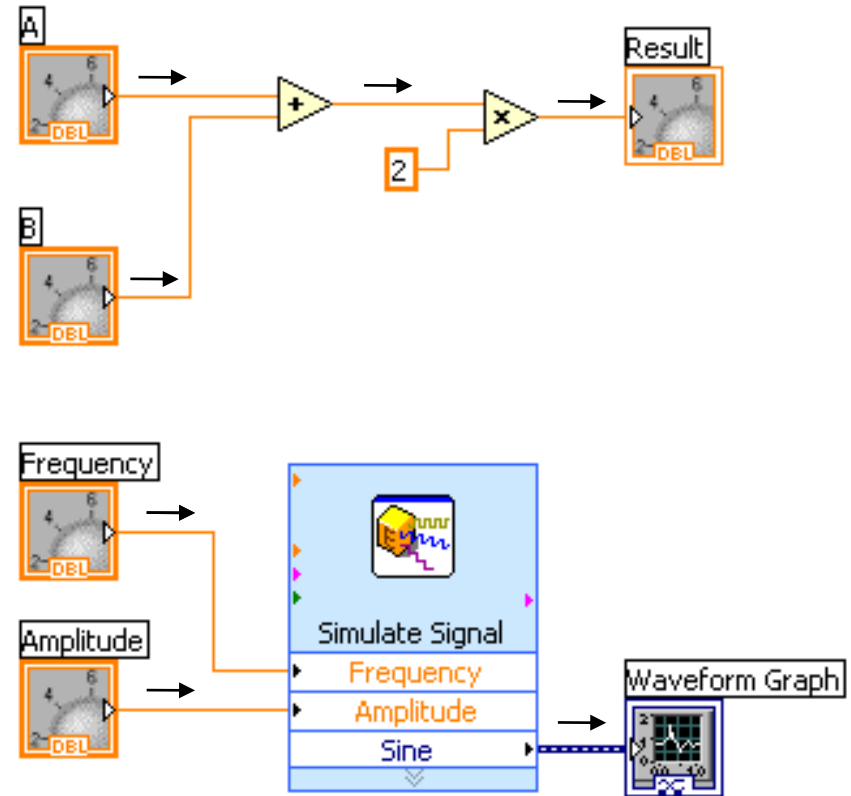
- Transfer data between block diagram objects through wires
- Wires are different colors, styles, and thicknesses, depending on their data types
- A broken wire appears as a dashed black line with a red X in the middle



	DBL Numeric	Integer Numeric	String
Scalar			
1D Array			
2D Array			

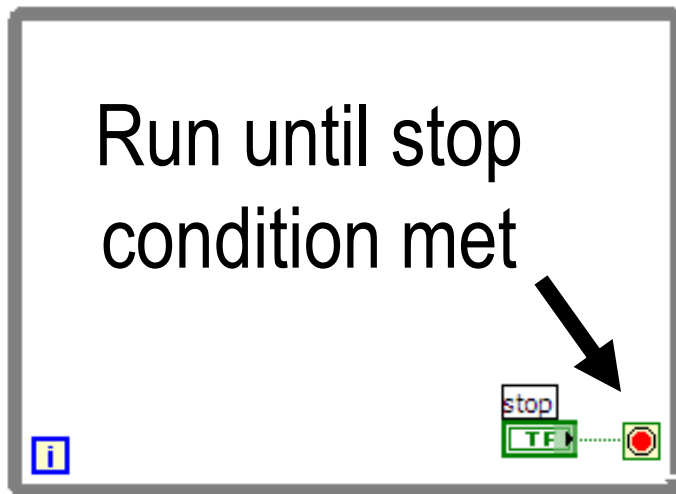
Data Flow Sets Execution Order

- Block diagram execution order depends on the flow of data
- Block diagram does NOT execute left to right
- Nodes execute when data is available to ALL input terminals
- Nodes supply data to all output terminals when done
- If the computer running this code had multiple processors, these two pieces of code could run independently without additional coding

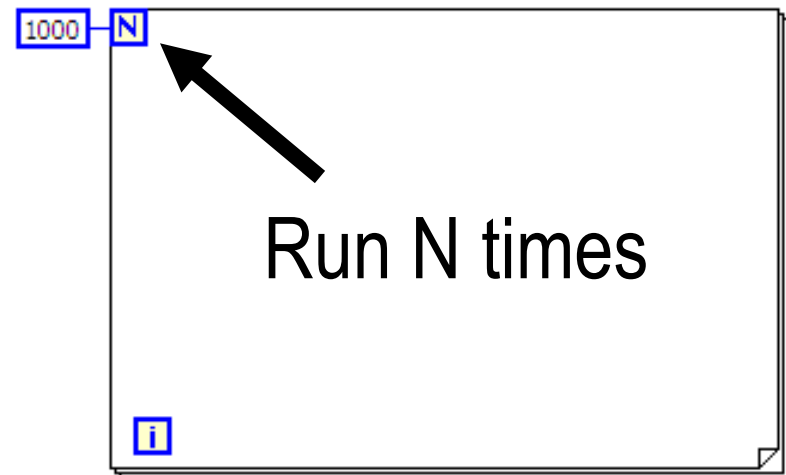


Execution Control Structures

While Loop

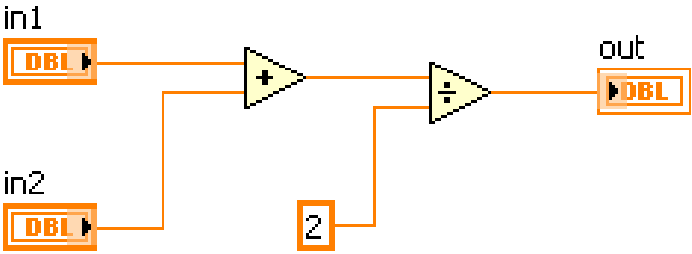
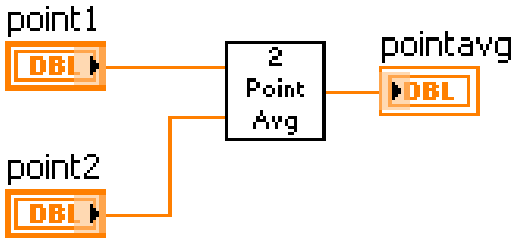


For Loop



- Allow same piece of code to run multiple times
- Exit conditions different for each

Modularity and SubVIs

Function Code	Calling Program Code
<pre>function average (in1, in2, out) { out = (in1 + in2)/2.0; }</pre>	<pre>main { average (point1, point2, pointavg); }</pre>
SubVI Block Diagram	Calling VI Block Diagram
 <p>The SubVI Block Diagram shows two input terminals labeled 'in1' and 'in2', each with a 'DBL' (Double) data type icon. The 'in1' terminal is connected to the left input of an addition block (+). The 'in2' terminal is connected to the right input of the same addition block. The output of the addition block is connected to the left input of a division block (÷). A constant value '2' is connected to the right input of the division block. The output of the division block is connected to an output terminal labeled 'out', which also has a 'DBL' data type icon.</p>	 <p>The Calling VI Block Diagram shows two input terminals labeled 'point1' and 'point2', each with a 'DBL' data type icon. Both 'point1' and 'point2' are connected to the left input of a rectangular block labeled '2 Point Avg'. The output of this block is connected to an output terminal labeled 'pointavg', which also has a 'DBL' data type icon.</p>

Demo: Simple USRP-based Receiver

- with Spectrum Analysis

Gigabit Ethernet
Connection to Host Computer



NI USRP-2190
Receiver



- USRP control (Rx)
- Inline Processing / Display

LabVIEW Signal Processing, Analysis and Math

- **Signal Processing & Analysis**

- Waveform Generation
- Waveform Conditioning
- Waveform Monitoring
- Waveform Measurements
- Signal Generation
- Signal Operations
- Windows
- Digital Filters
- Spectral Analysis
- Transforms
- Point-by-Point

- **Mathematics**

- Numeric
- Elementary and Special Functions
- BLAS/LAPAC-based Linear Algebra
- Curve Fitting
- Interpolation/Extrapolation
- Probability and Statistics
- Optimization
- Ordinary Differential Equations
- Geometry
- Polynomial
- Formula Parsing
- 1D & 2D Evaluation
- Calculus

Using Signal Processing Functions

My Application.vi Block Diagram

File Edit View Project Operate Tools Window Help

20pt Application Font

Configuration Based Express VIs

Spectral Measurements

- Signals
- FFT - (RMS)
- Phase

Programmatic, Low-level VIs

FFT

PSD

Text-based MathScript Node

```
1 %This script generates cosine coordinates
2
3 n=0:length
4 x=cos(2*pi*a*n)
```

Waveform Chart

Demo: Simple USRP-based Receiver

- with Spectrum Analysis
- with live FM radio

Gigabit Ethernet
Connection to Host Computer

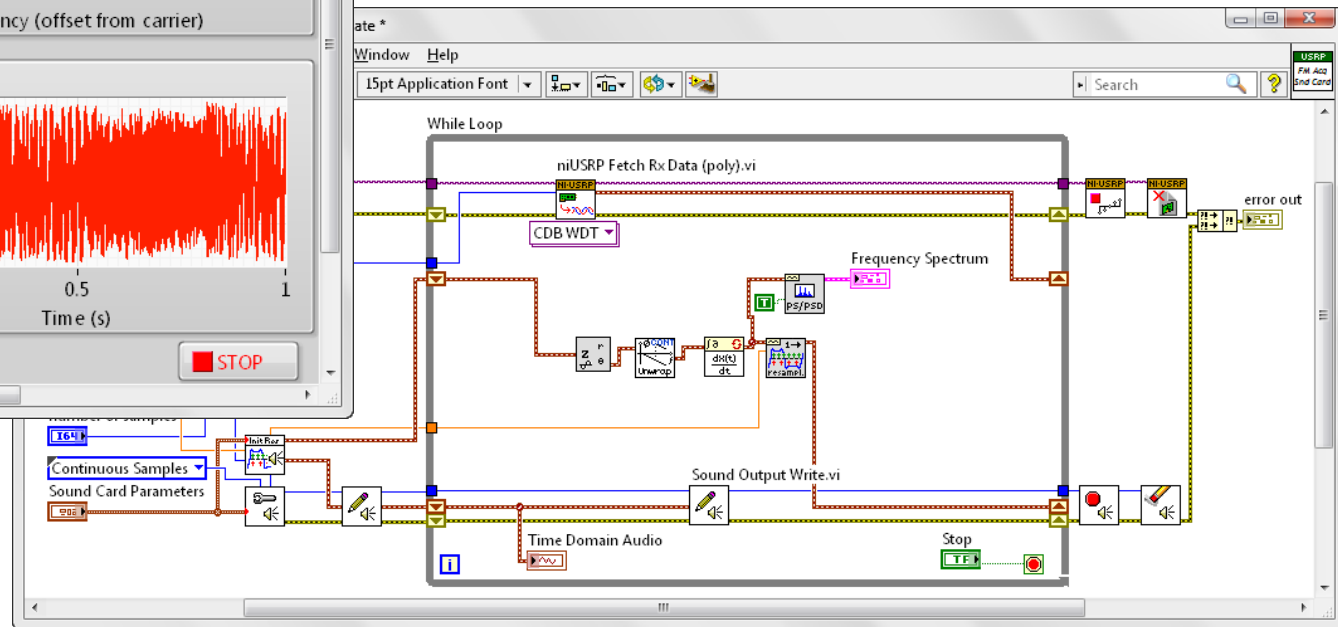
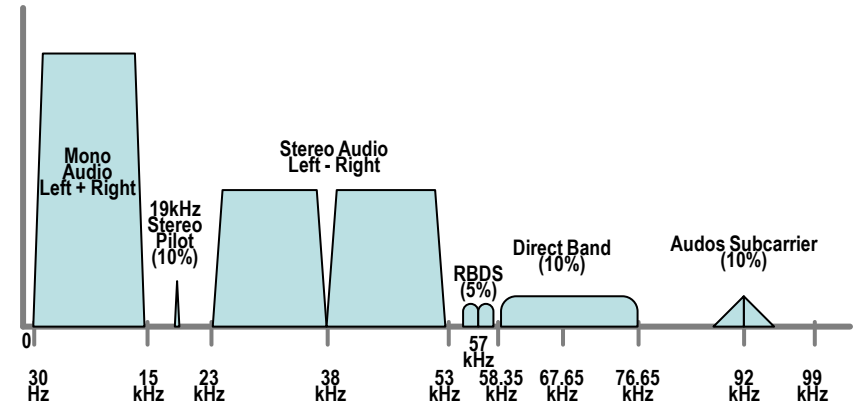
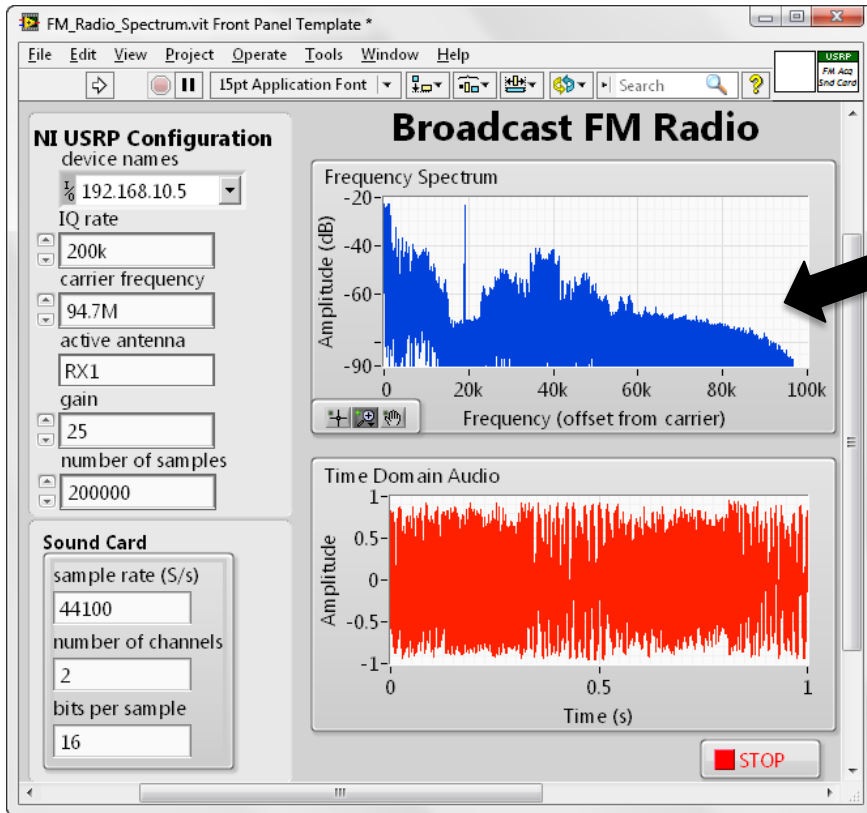


NI USRP-2190
Receiver

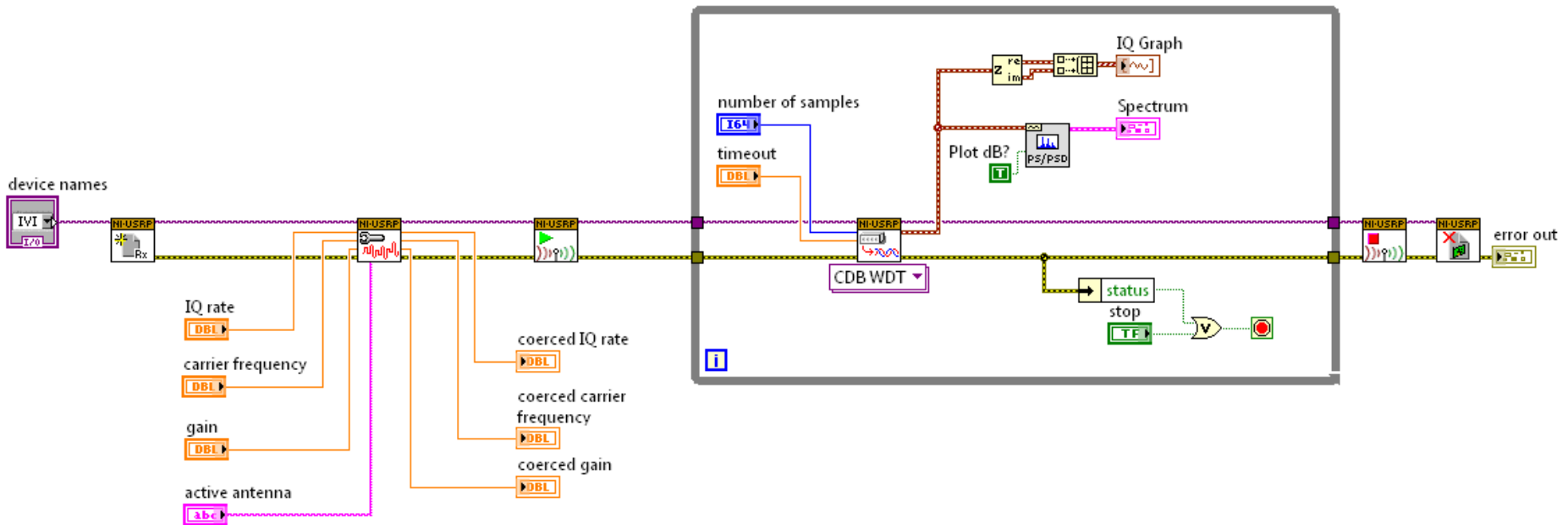
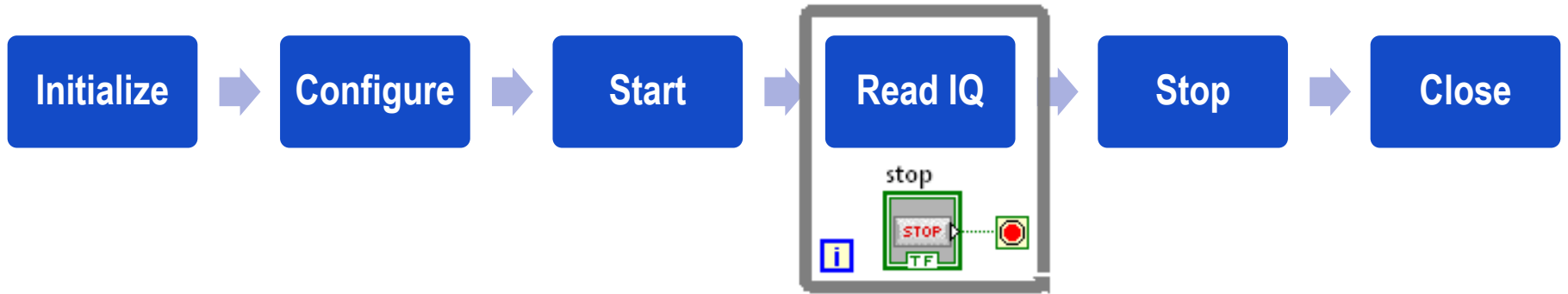


- USRP control (Rx)
- Inline Processing / Display

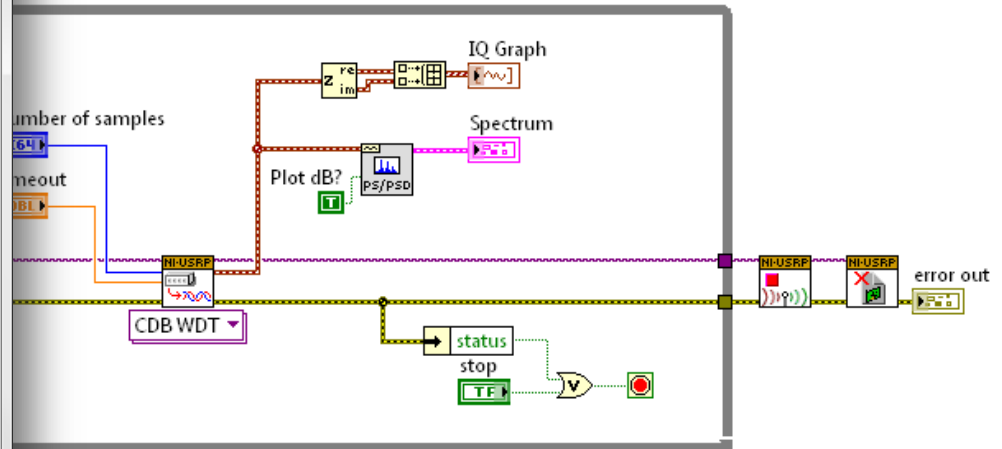
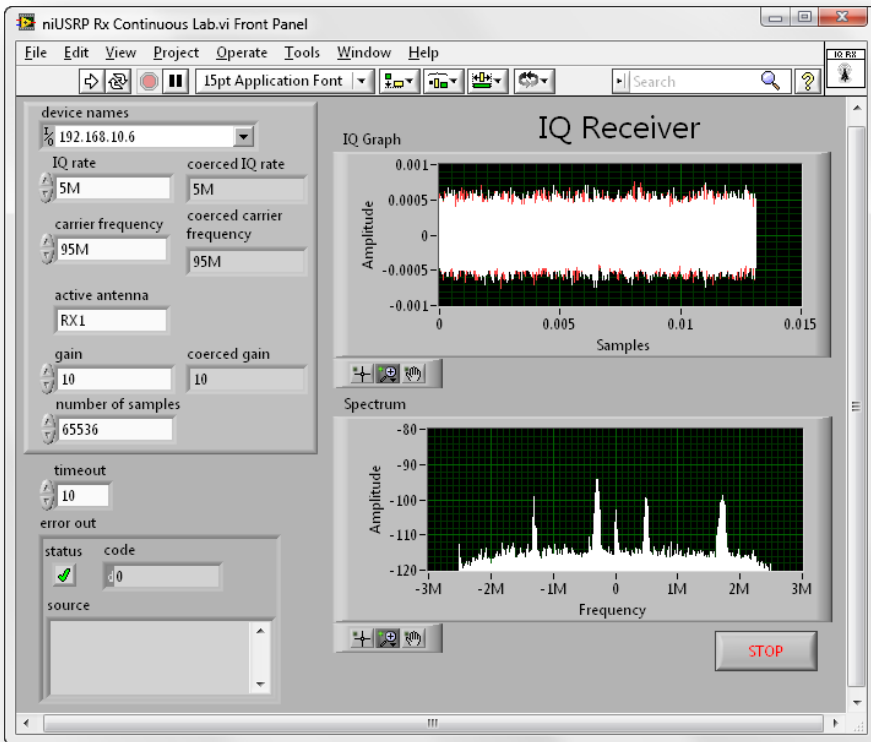
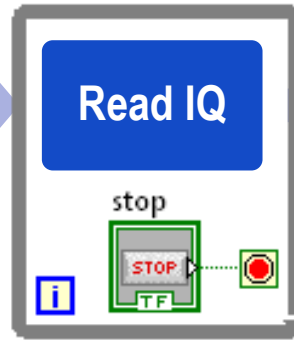
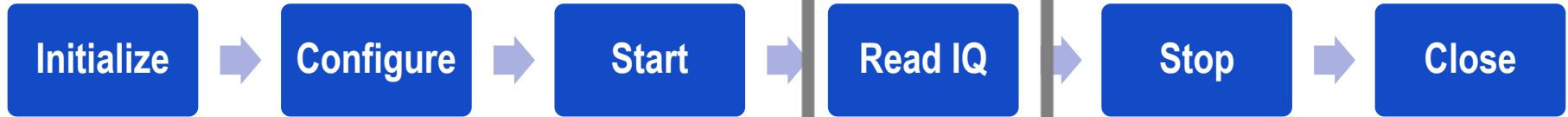
Decode & Hear Live FM Radio



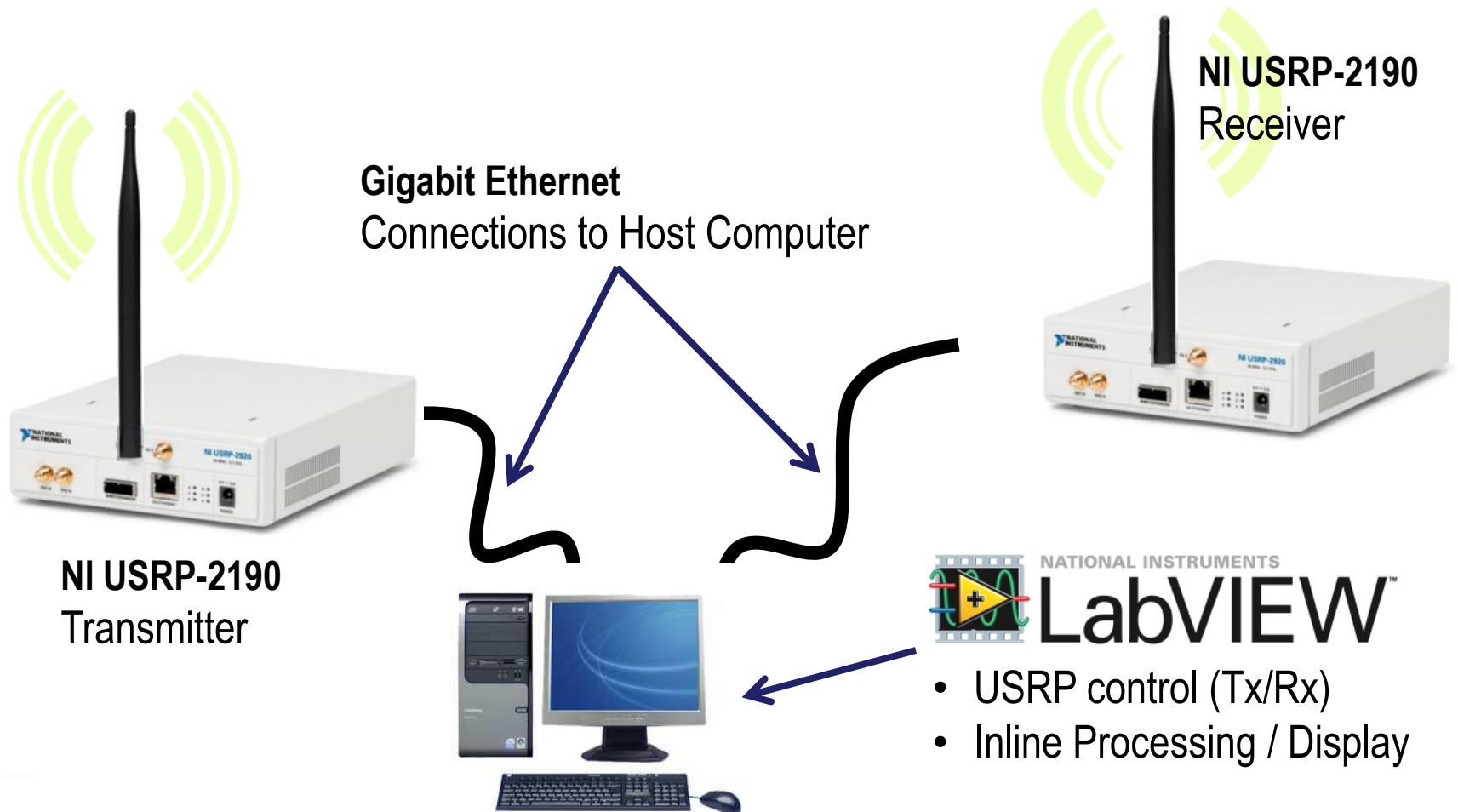
NI-USRP Driver Software



NI-USRP Driver Software



Demo: Simple USRP-based Tx / Rx Pair





NATIONAL INSTRUMENTS

LabVIEW™ MathScript RT Module

Text-based signal processing, analysis, and math within LabVIEW

- 750 built-in functions / user-defined functions
- Reuse many of your .m file scripts created with The MathWorks, Inc. MATLAB® software and others
- Based on original math from NI MATRIXx software

A native LabVIEW solution

- Interactive and programmatic interfaces
- Does not require 3rd-party software
- Enables hybrid programming

The screenshot displays the LabVIEW MathScript RT Module interface. At the top, a 'MathScript Node' block contains the following MATLAB code:

```

1 tic
2 col=30;
3 m=400;
4 cx=0;
5 cy=0;
6 l=1.5;
7 x=linspace(cx-l,cx+l,m);
8 y=linspace(cy-l,cy+l,m);
9 [X,Y]=meshgrid(x,y);
10 c = -.745429;
11 Z=X+i*Y;
12 for k=1:col;
13 Z=Z.^2+c;
14 end
15 W=real(exp(-abs(Z)));
16 time=toc;
  
```

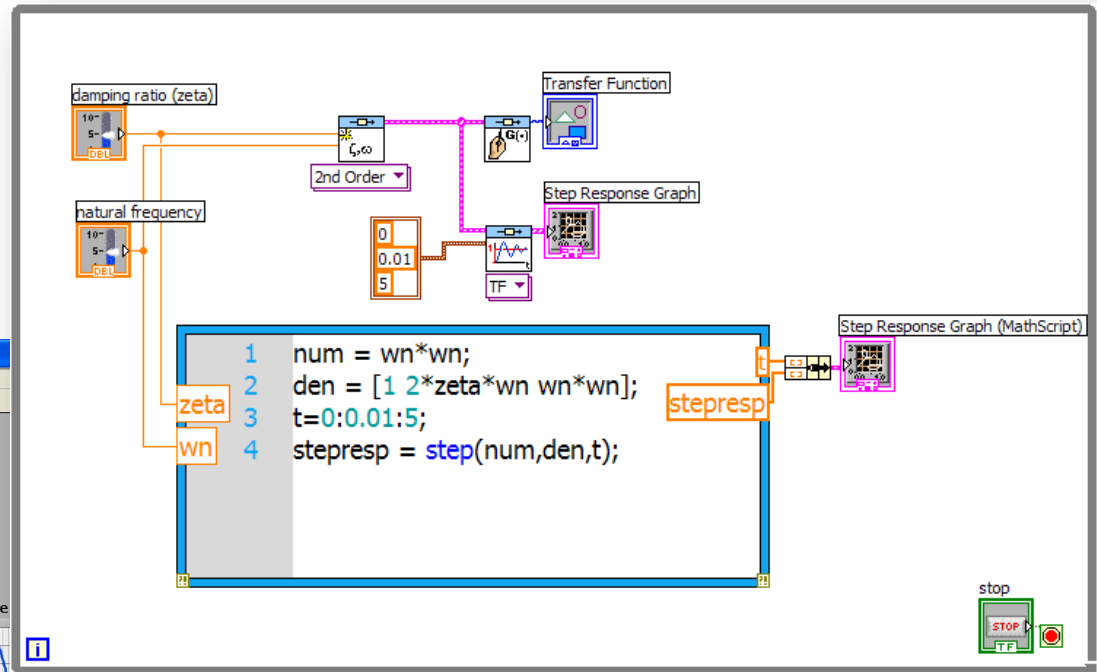
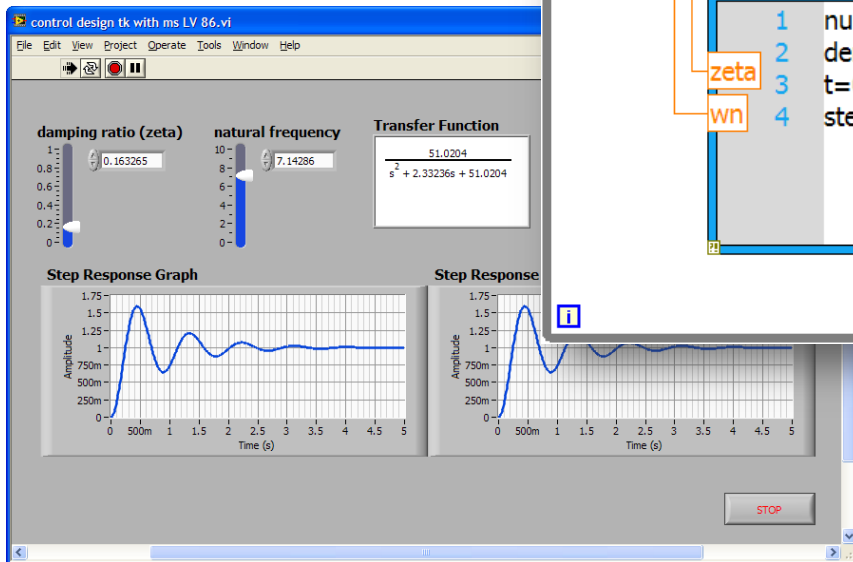
The block diagram shows the code being executed, with a 'time' output terminal and a 'Fractal Plot' block. Below the block diagram, a '3D Graph v Front Panel' displays a 3D surface plot of the fractal function, showing a red, multi-lobed surface. To the left, a 'Picture - W' window shows a 2D plot of the fractal function, displaying a complex, fractal-like pattern. Below the 3D plot, a 'Script Editor' window shows the code being executed. To the right, a list of supported functions is displayed:

- 2D and 3D Plotting / Visualization
- Probability and Statistics
- Digital Signal Processing (DSP)
- Optimization
- Approximation (Curve Fitting / Interpolation)
- Advanced Functions
- Ordinary Differential Equations
- Basic Operations
- Polynomial Operations
- Trigonometric
- Linear Algebra
- Matrix Operations
- Boolean and Bit Operations
- Data Acquisition / Generation
- Vector Operations
- Other

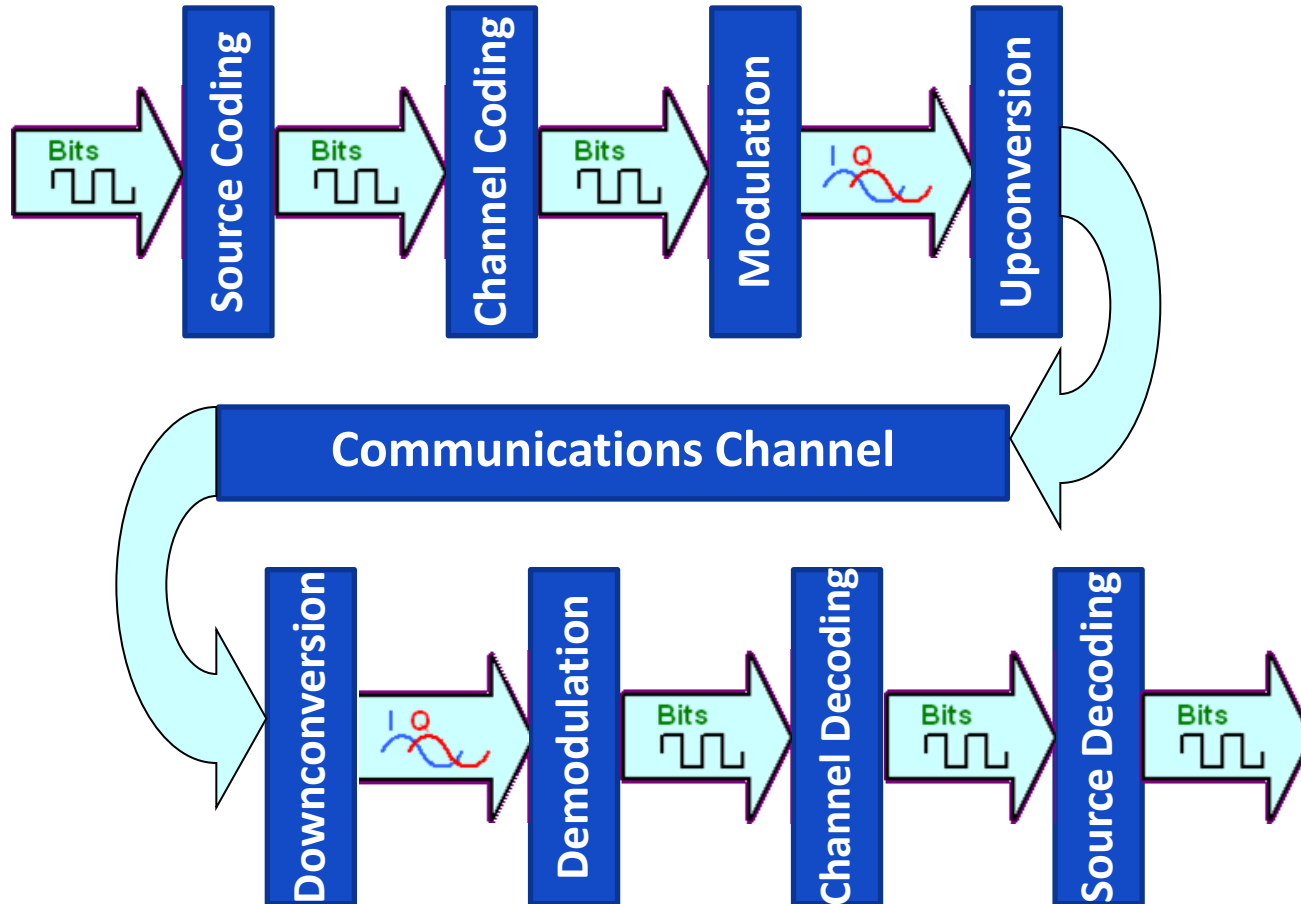
MATLAB® is a registered trademark of The MathWorks, Inc. All other trademarks are the property of their respective owners.

The Hybrid Approach

Combine Graphical / Textual Programming



Digital Communication System

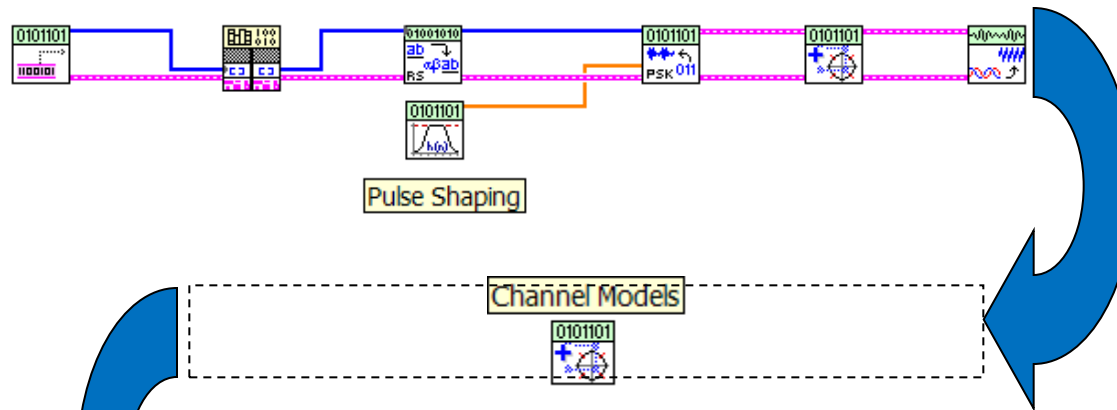


Digital Communication System



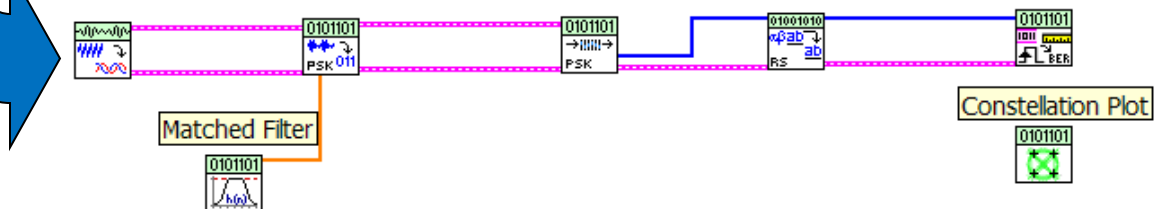
NI Modulation Toolkit

Generate Bits Source Coding Channel Coding Modulation Impairments Upconversion



NI Modulation Toolkit

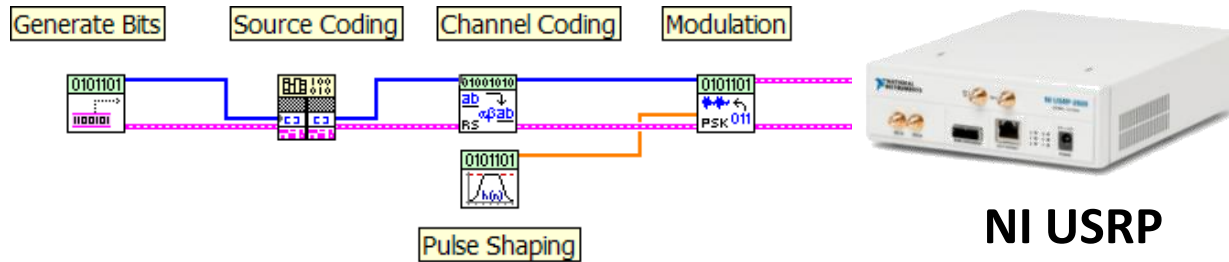
Downconversion Demodulation Equalization Channel Decoding BER Measurement



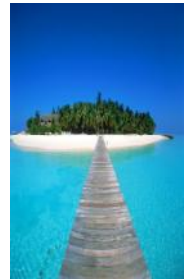
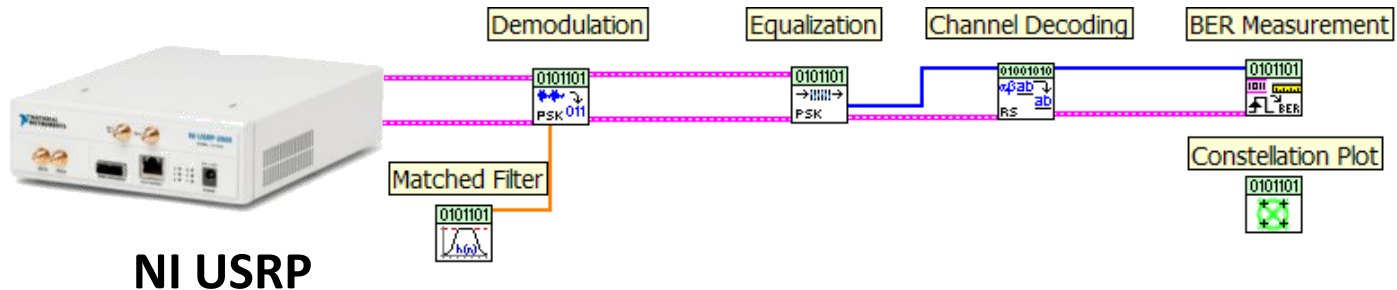
Digital Communication System



NI Modulation Toolkit

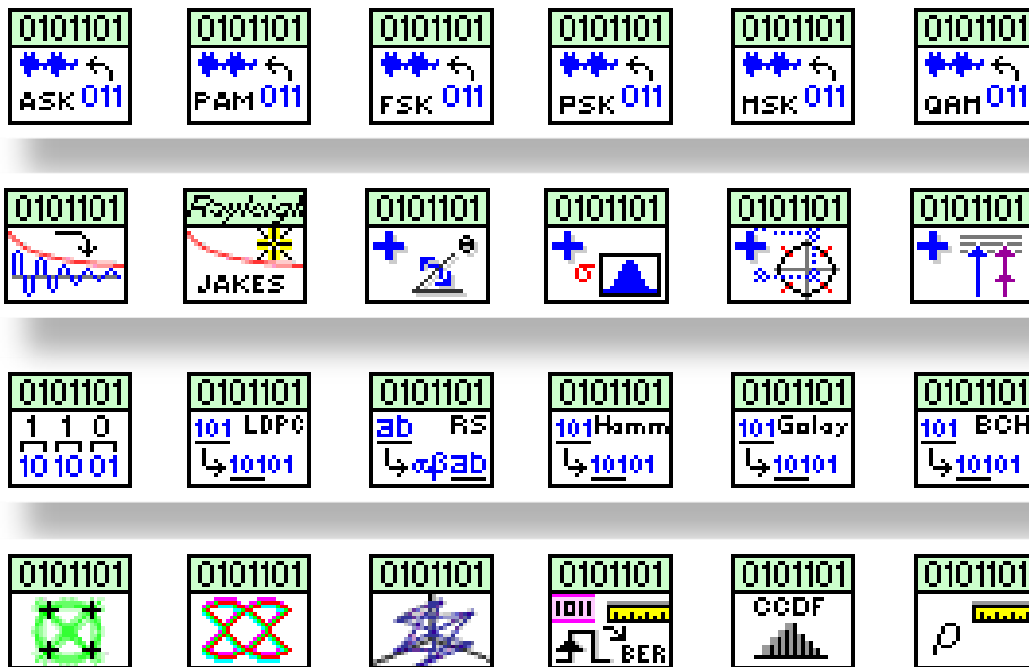
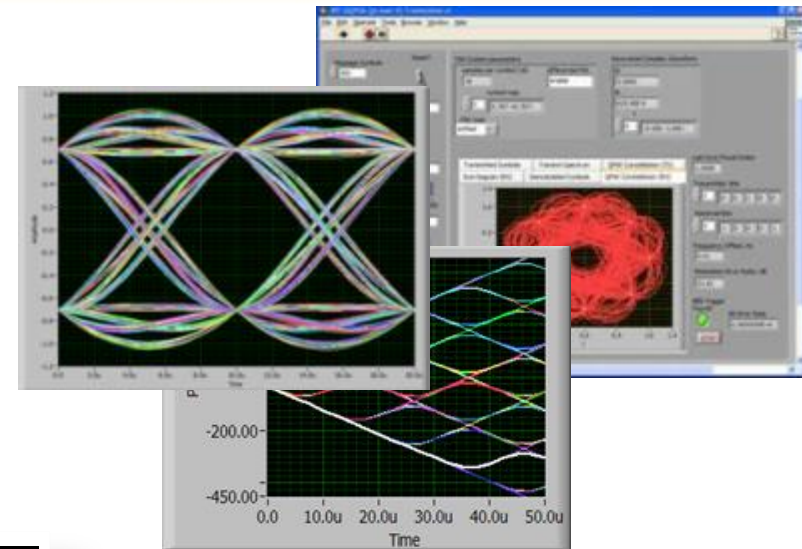


NI Modulation Toolkit



Modulation Toolkit

LabVIEW simulation and modeling tools for communication system design



Modulation & Demodulation

**Channel models /
impairments**

Channel coding

Communication visualization

Demo: QAM Tx / Rx Pair

The image displays a software interface for a QAM Tx/Rx pair, showing the configuration and signal processing parameters for both the transmitter and receiver.

Transmitter (Tx) Configuration:

- device name: 192.168.10.5
- IQ Sampling Rate [S/sec]: 200k
- Carrier Frequency [Hz]: 2.453G
- Gain [dB]: 0
- Active Antenna: TX1
- Pulse Shaping Filter: Root Raised Cos
- Alpha: 0.50
- Filter Length: 6
- QAM M-ary: 16
- Samples per Symbol: 4
- PN Sequence Order: 9
- Frame Length [samples]: 2044
- Symbol Rate [symbols/sec]: 50k

Receiver (Rx) Configuration:

- Carrier Frequency [Hz]: 2.45G
- Gain [dB]: 0
- Active Antenna: RX1
- QAM M-ary: 16
- Samples per Symbol: 8
- Acq Duration [sec]: 10.00m
- Frame Size [samples]: 10000
- Symbol Rate [symbols/sec]: 250.00k
- Reset Demodulator?: False

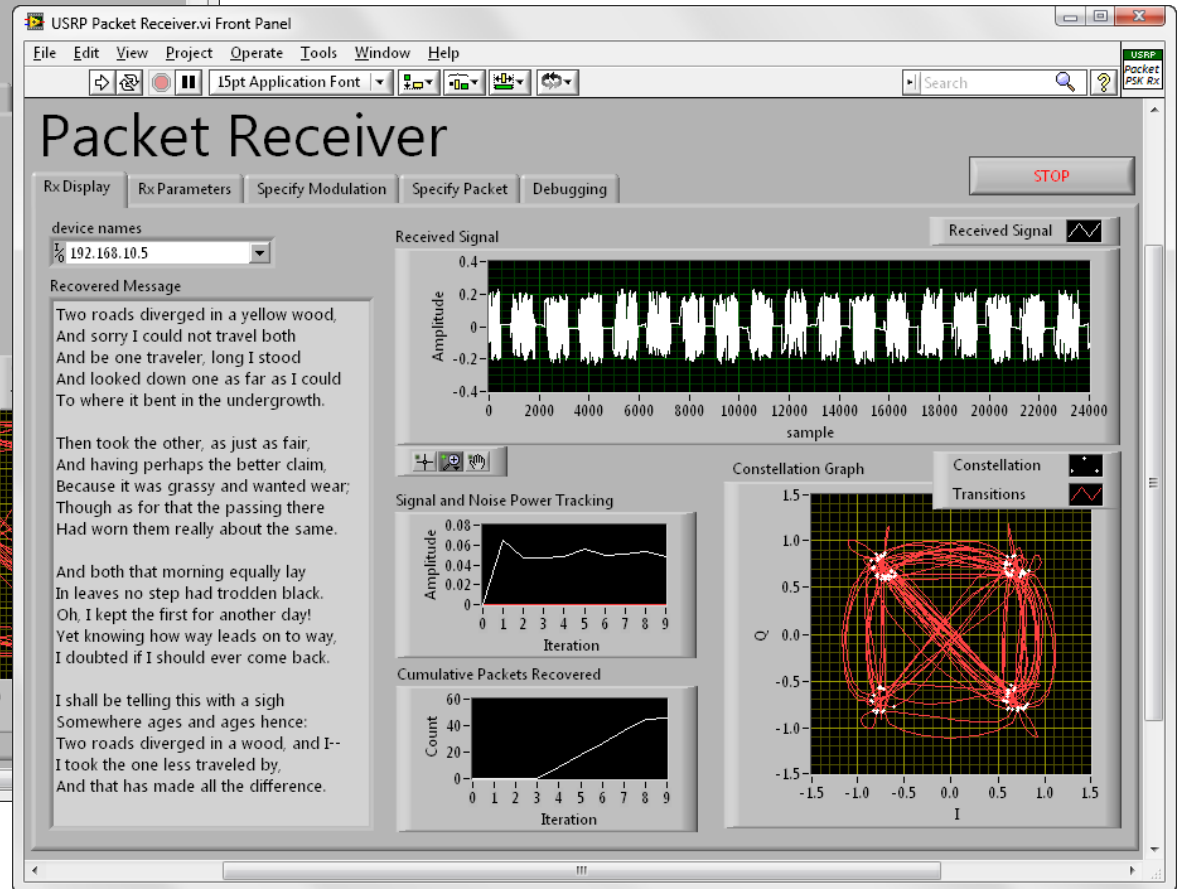
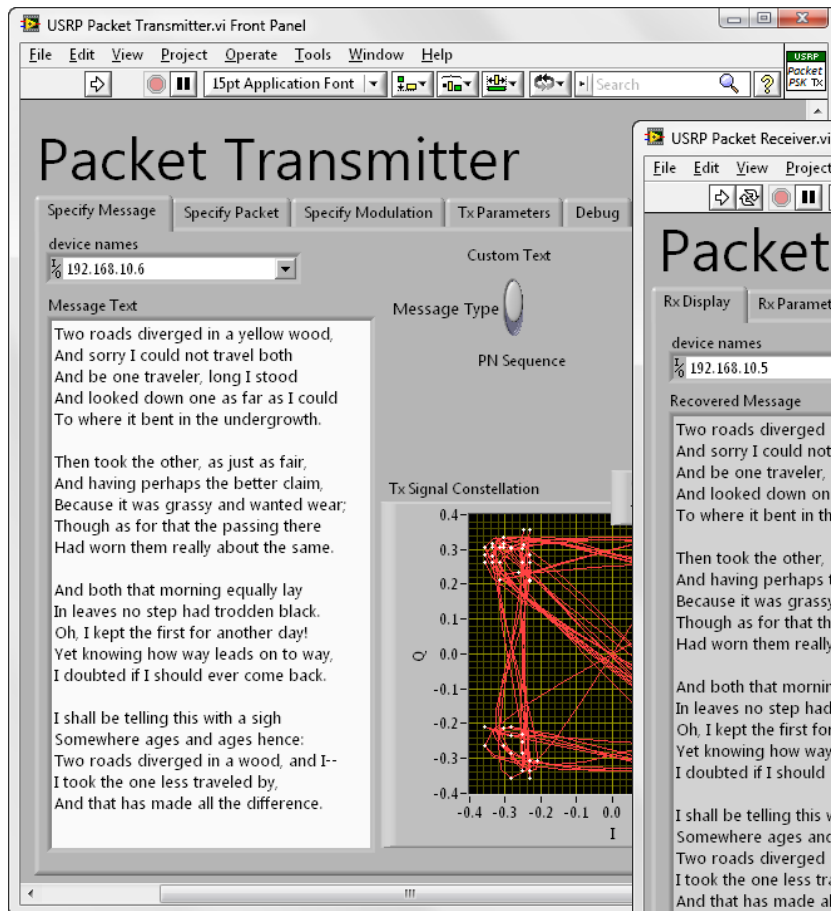
Constellation Diagrams:

- Tx Signal Constellation:** Shows a dense cluster of red points forming a square shape on a grid, indicating the transmitted signal constellation.
- Rx Constellation:** Shows a similar square shape on a grid, indicating the received signal constellation.

Measurements (Rx Constellation):

- frequency offset (Hz): -88.51
- frequency drift (Hz): -1.46
- phase offset: 81.53

Demo: Packet-based Transceiver

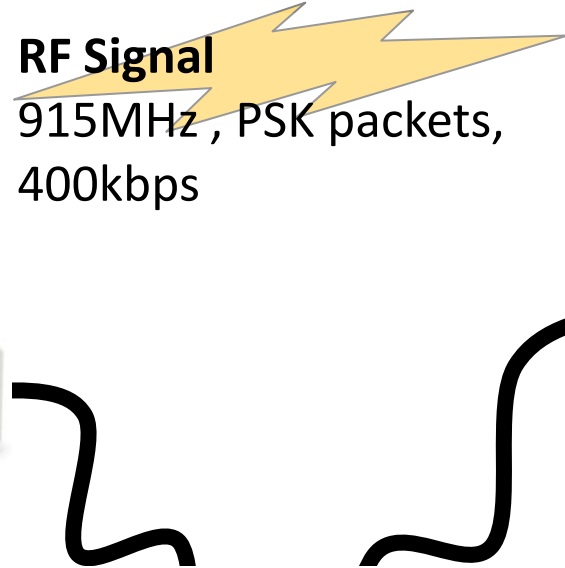


Demo: Packet-based Link

NI USRP-2190
Transmitter



RF Signal
915MHz , PSK packets,
400kbps

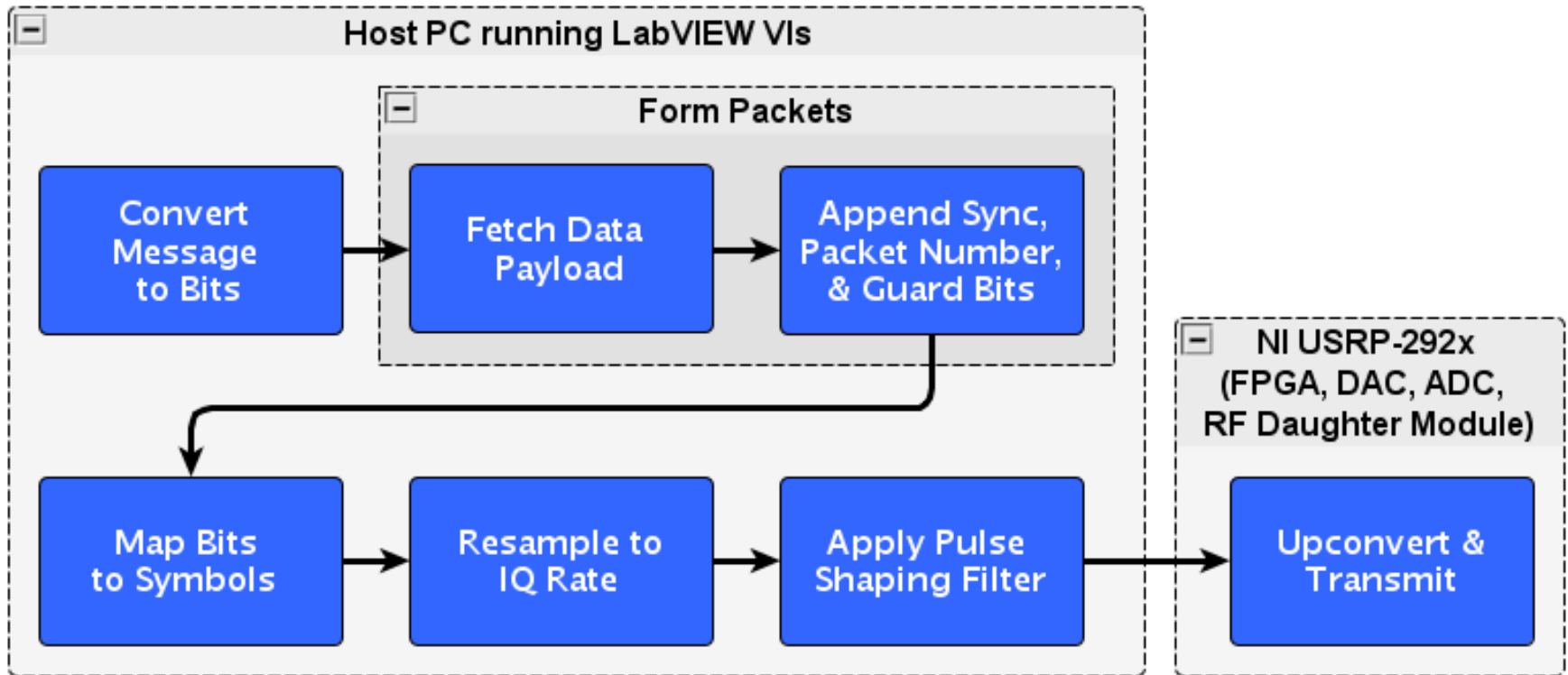


NI USRP-2190
Receiver



- USRP control (Tx & Rx)
- Modulate Tx signal
- Demodulate Rx signal
- Reconstruct message

Transmitter Block Diagram



Packet Structure

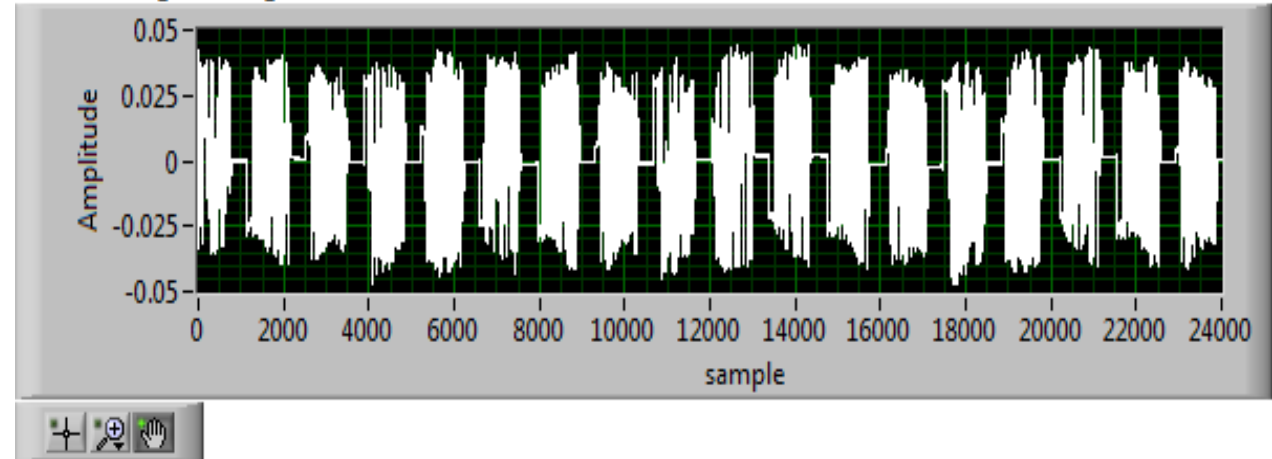


Field	Length [bits]	Description
Guard Band	30	Allow initialization of Rx PLL, filters, etc
Sync Sequence	20	Frame and Symbol Synchronization
Packet Number	8	Range: 0-255 Used for reordering of packets and detection of missing packets
Data	64 - 256	Variable length data field. Length detected dynamically at Rx end
Pad	20	Allows for filter edge effects.

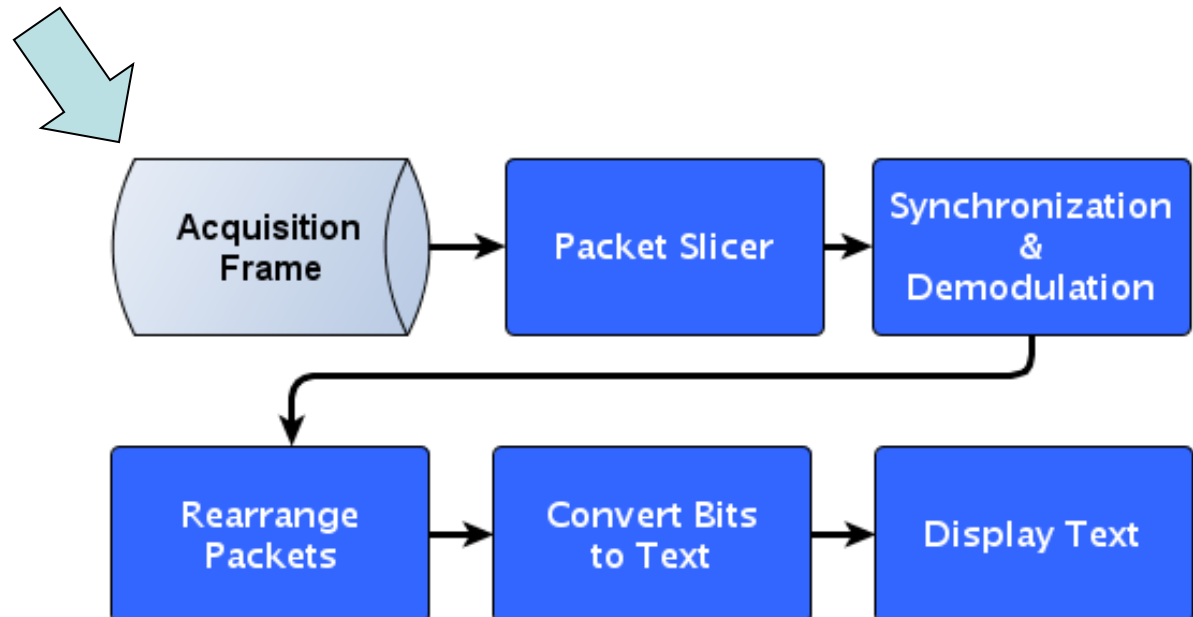
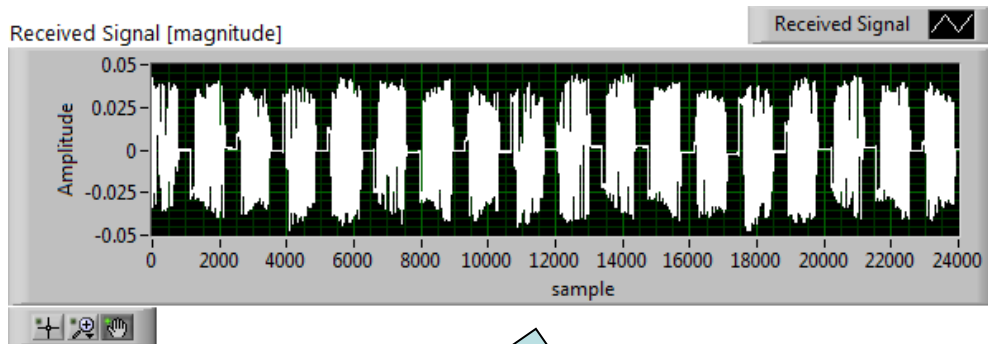
The Received Signal



Received Signal [magnitude]

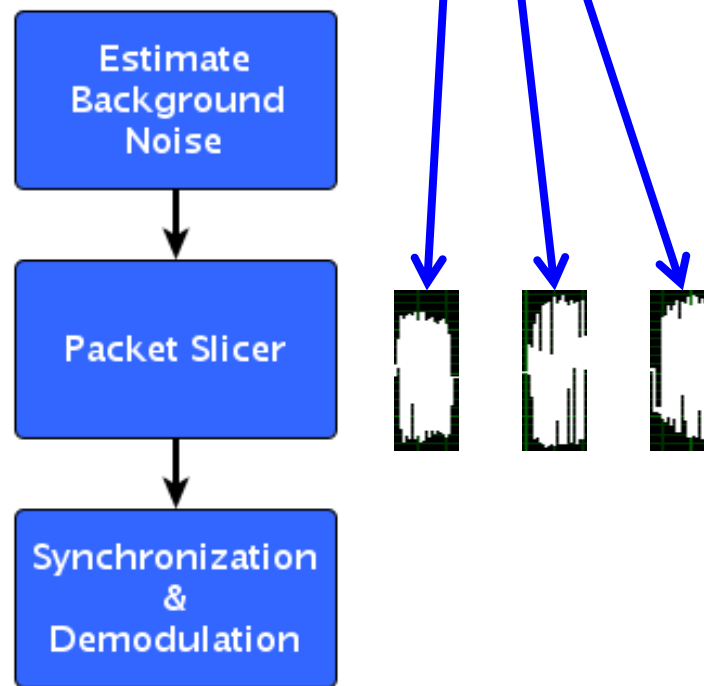
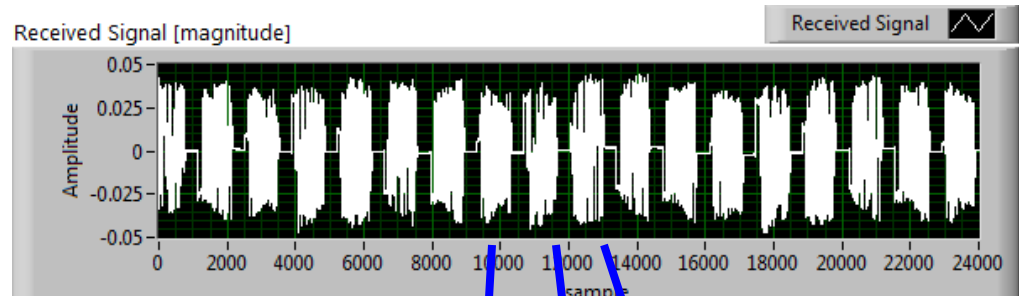


Receiver Block Diagram



Channel Activity Detection

- **Problem:** Inefficient to keep demodulator active for the entire acquisition frame—it needs to be applied only to packets
- **Solution:** Apply a channel activity detector to locate packet boundaries for a packet slicer



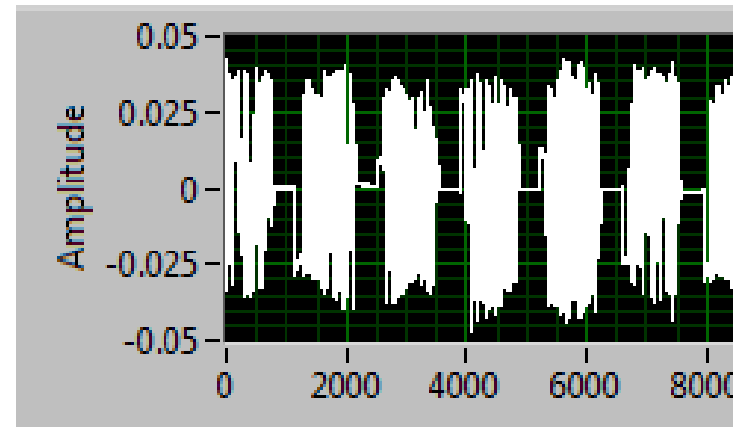
Error Tolerance

Problem: Errors at $\text{SNR} \gg 1$

- Partial packets captured at frame edges
- Improper synchronization

Solution: Repetition Coding

- Repeat each packet n times
- Repeat entire message m times



Error Tolerance

- **Problem:** At $\text{SNR} \gg 1$, errors introduced due to
 - Partial packet captured at frame edge interval
 - Improper synchronization
- **Solution:** Packet Repetition Coding
 - Repeat each packet n times ($n=2$ to 5)
 - Repeat whole message m times ($m = 10$)
- **Proposed Schemes:**
 - CRC Check with two way ACKs
 - Reconstruct packets split across frames

Ideas for Extension

- Improved Error Tolerance
 - CRC check, convolutional coding, interleaving, etc...
- Bi-directional link with ACK messages
- OFDM
- Channel Equalization to improve range
- SW-based Rx gain control to ensure full use of available dynamic range
- Monitor / replicate common links
 - Bluetooth mouse
 - Key fob
- Additional message choices
 - Images, video, etc.



Next Steps

- Learn more about LabVIEW and NI-USRP
 - www.ni.com/usrp
- Find NI-USRP examples & participate in the NI-USRP online community
 - decibel.ni.com/content/groups/ni-usrp-example-labview-vis