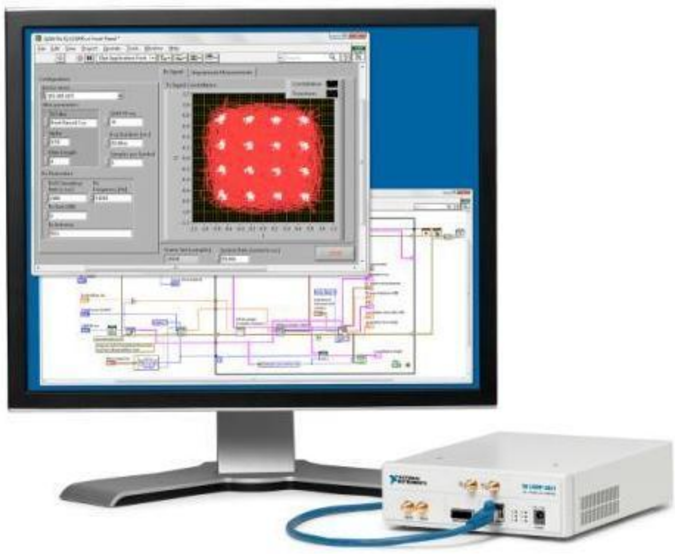
A Rapid Graphical Programming Approach to SDR Design and Prototyping with LabVIEW and the USRP



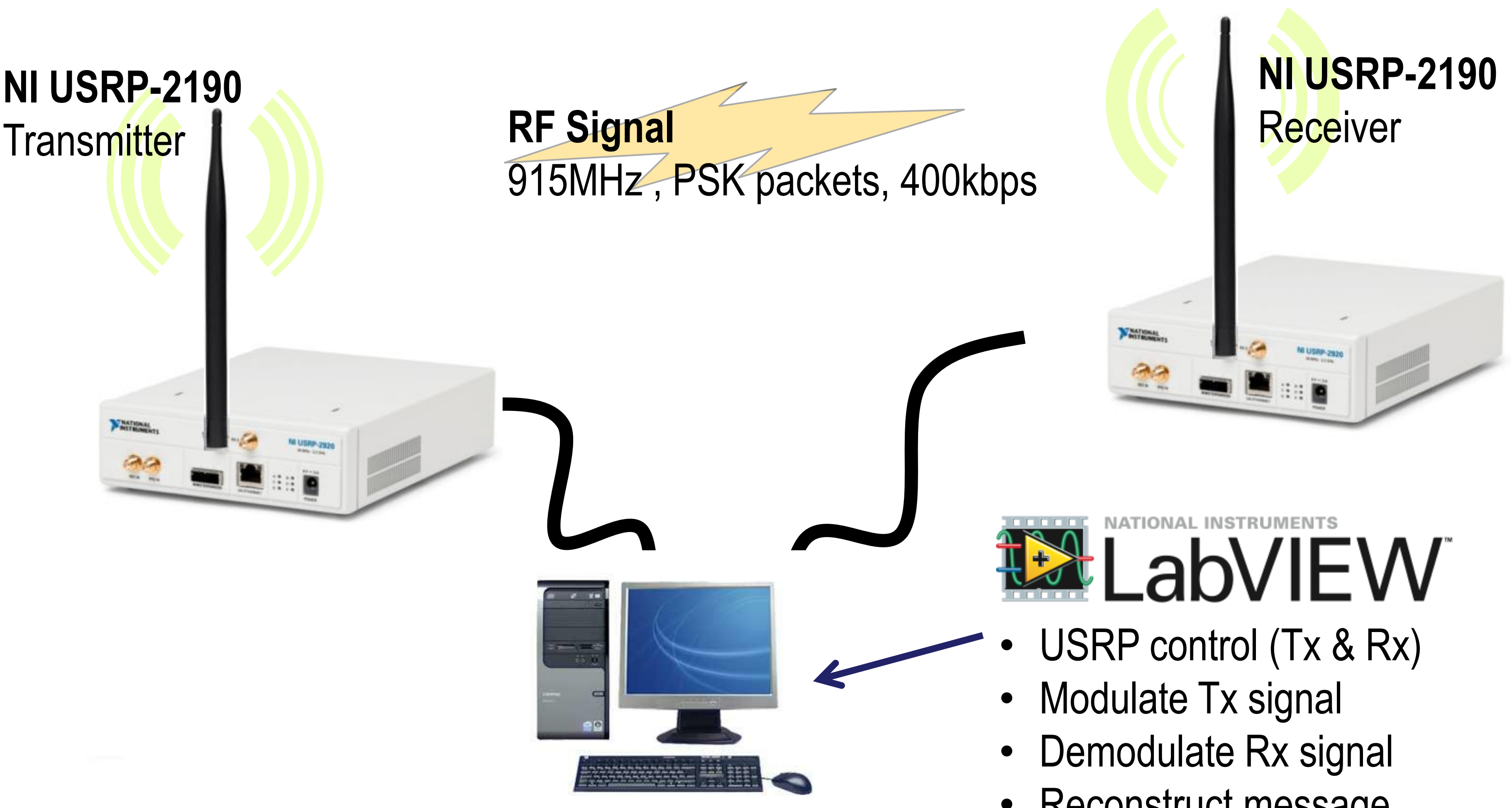
Filip Langenaken
Academic Program Manager
Benelux & Nordic
National Instruments

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

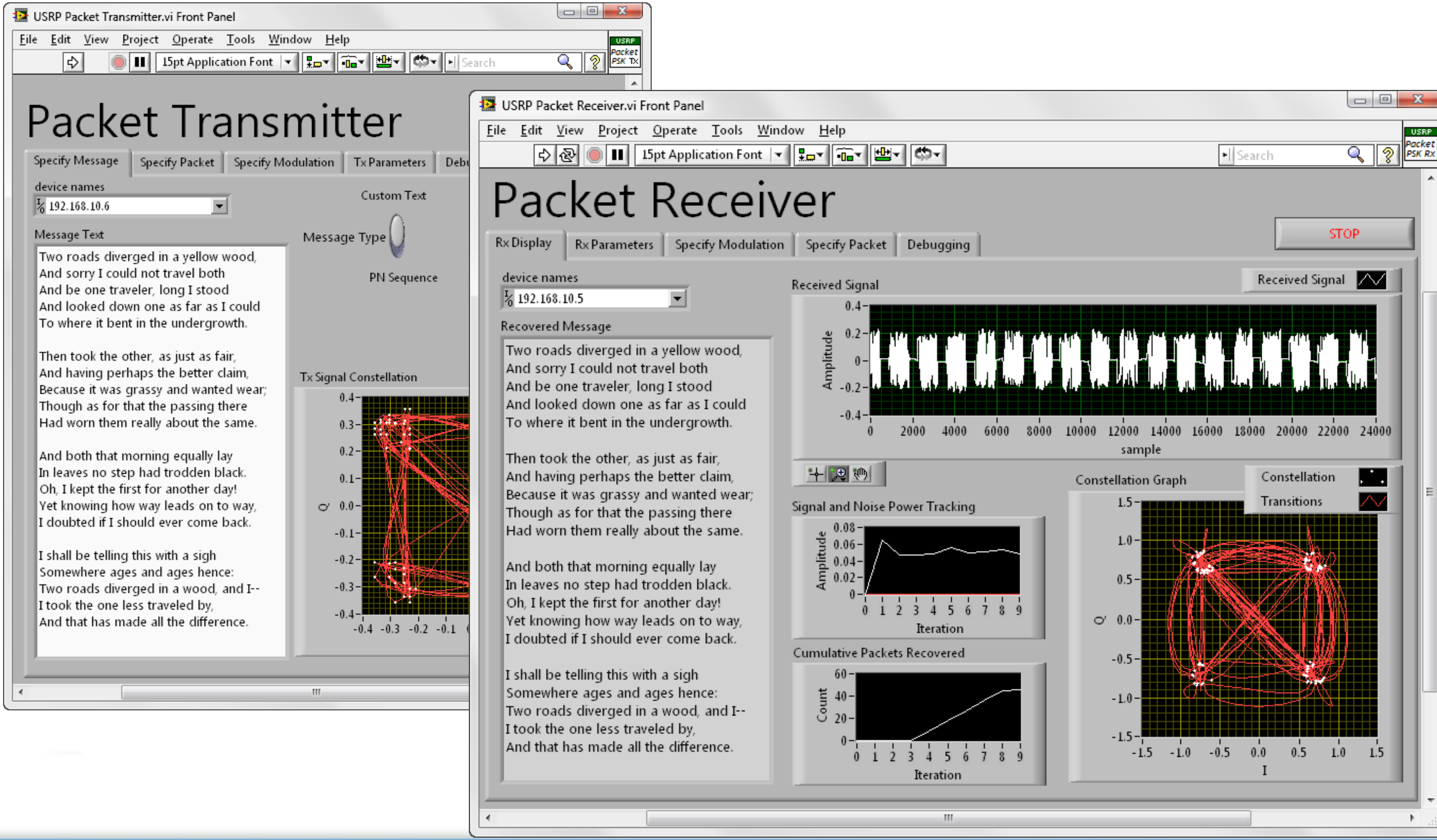
- Low cost , PC-hosted RF Transceiver for software defined radio prototyping and exploration
- Real-time processing: Gigabit Ethernet link streams live data for real time processing on a Windows-based host computer running LabVIEW
- Hardware and software are easy to install, connect, and learn

NI-219x
RF Transceiver

Demo: Packet-based Transceiver



Demo: Packet-based Transceiver

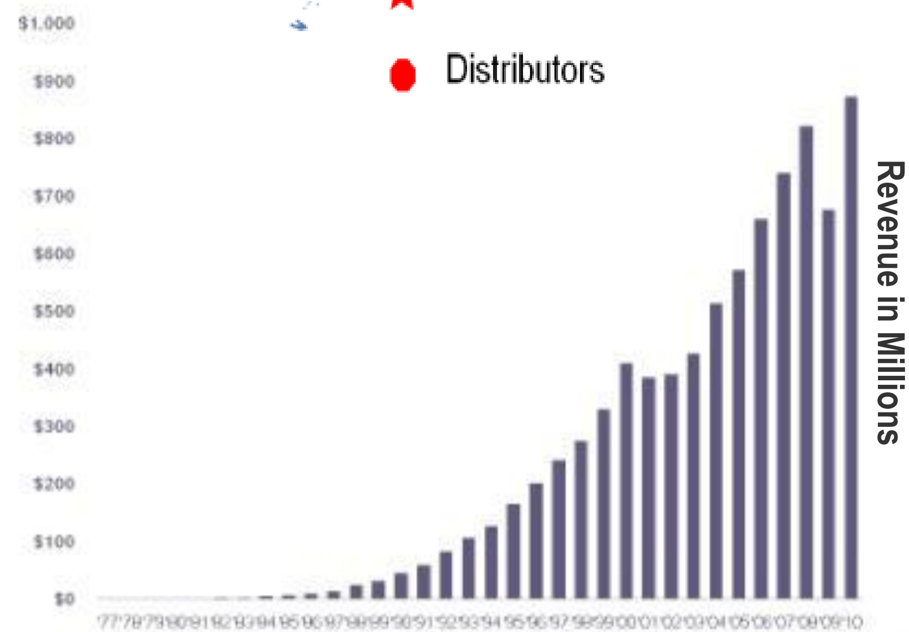


Agenda

- 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



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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."

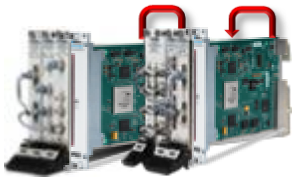
NI Platforms for RF/Communications

NATIONAL INSTRUMENTS LabVIEW™

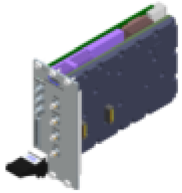
NI-USRP for LabVIEW

NI RF VSG, VSA

NI FlexRIO



NI RF 6-GHz Peer-to-Peer



RF RIO

Host
Embedded, PC

FPGA 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**

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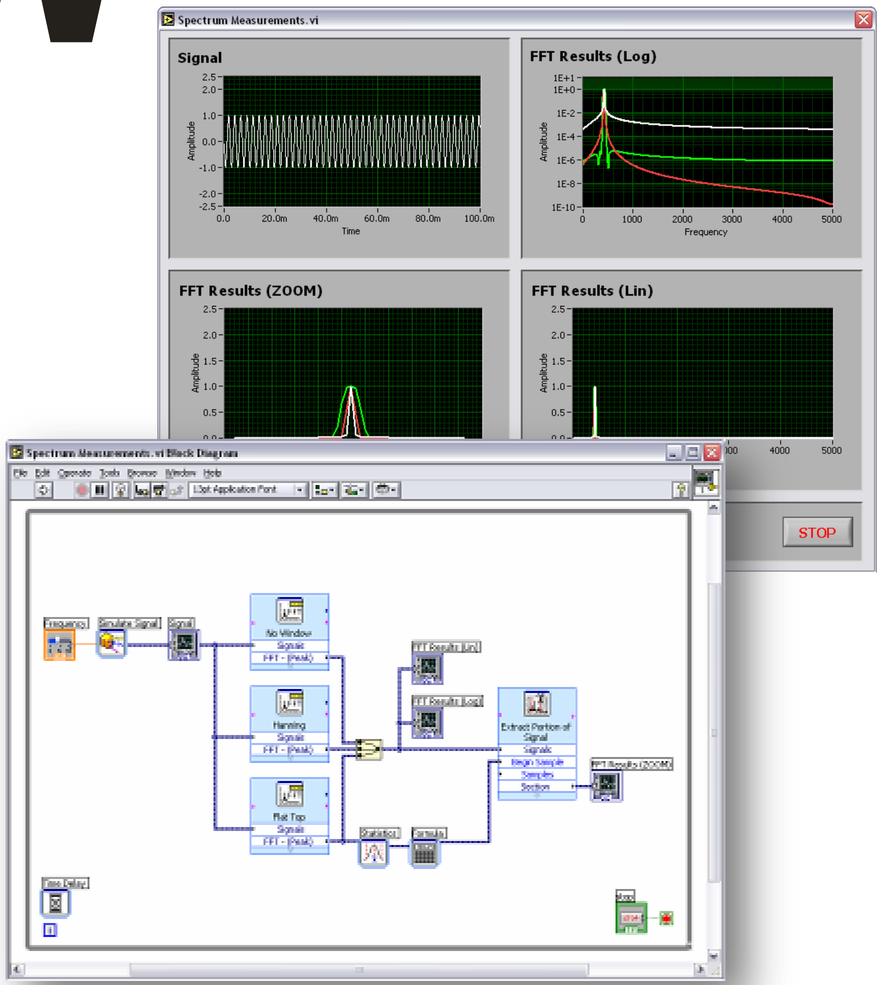
LabVIEW™

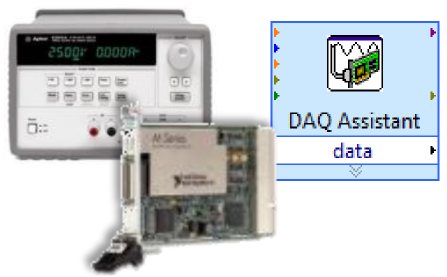
A Compiled Graphical Development Environment

- 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

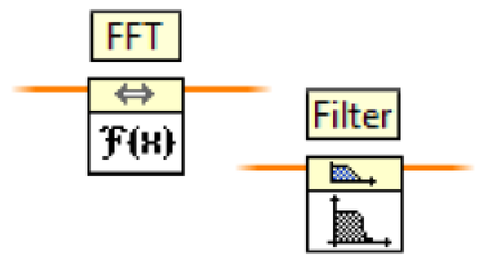


NATIONAL INSTRUMENTS LabVIEW™

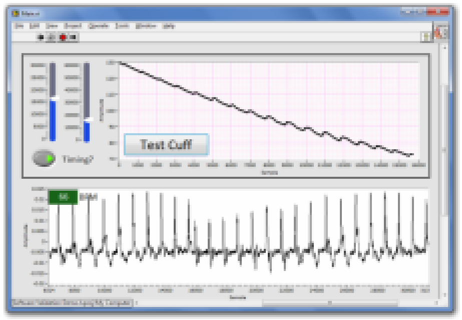
A Highly Productive Graphical Development Environment for Engineers and Scientists



Hardware APIs

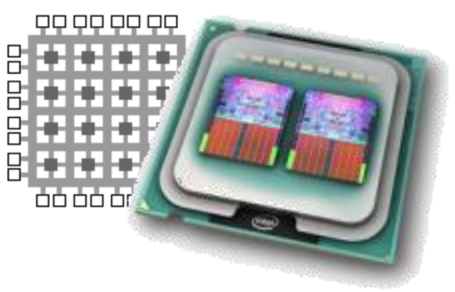


Analysis Libraries

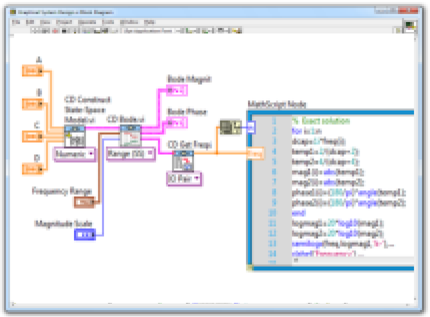


Custom User Interfaces

Deployment Targets

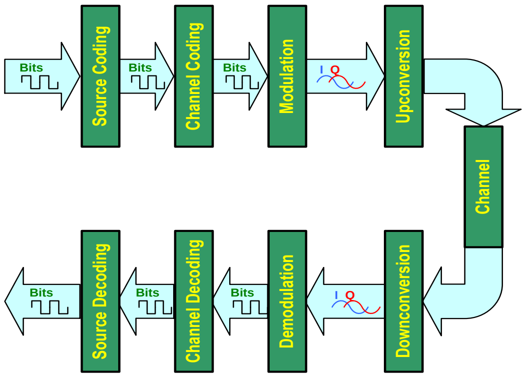


Technology Abstractions



Programming Approaches

From Concept to Prototype … Rapidly!



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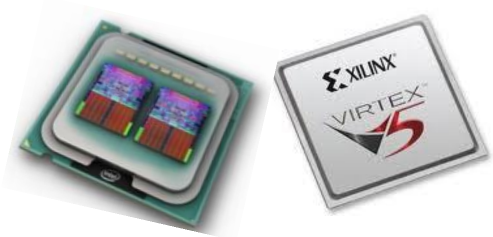
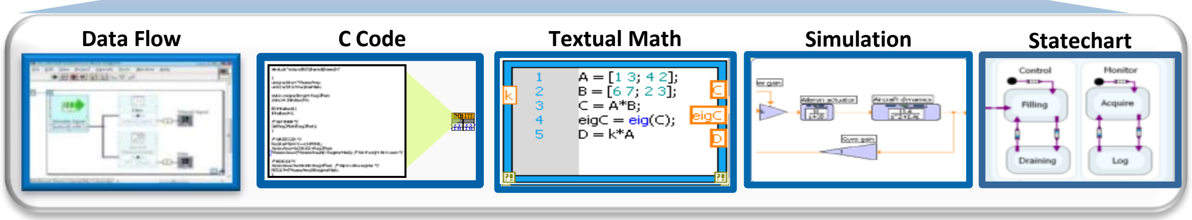
Graphical System Design



Concept → **Design Language** → **Prototype**



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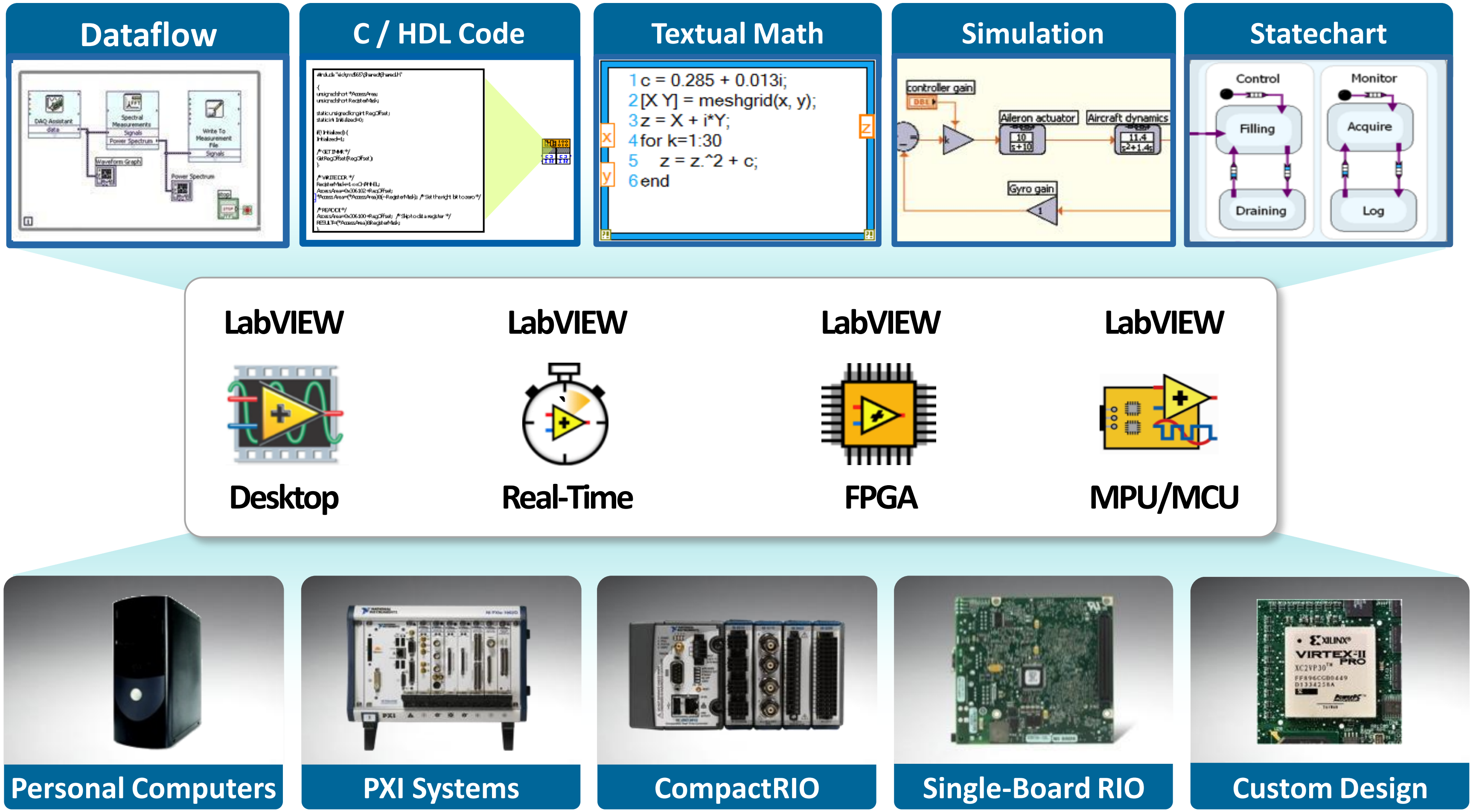
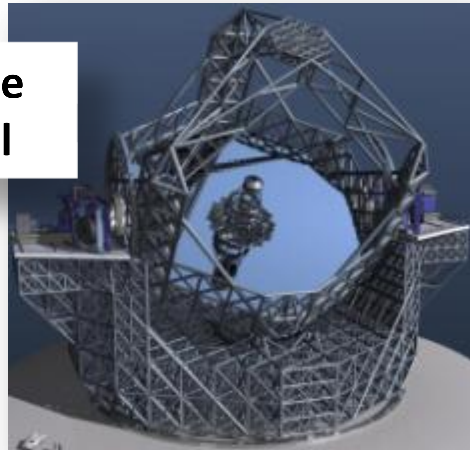
System Design to Deployment

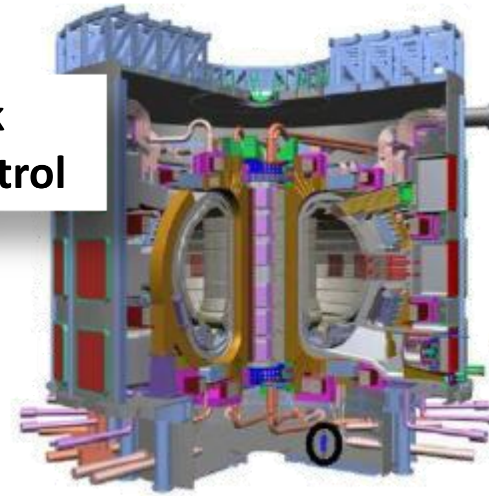


Solving the Toughest Problems on Earth

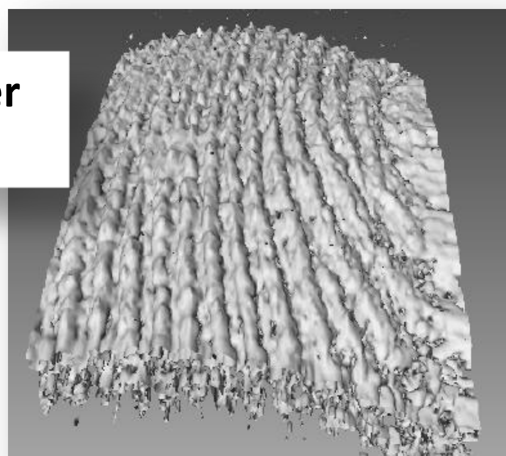
Large Telescope Mirror Control



Tokamak Plasma Control



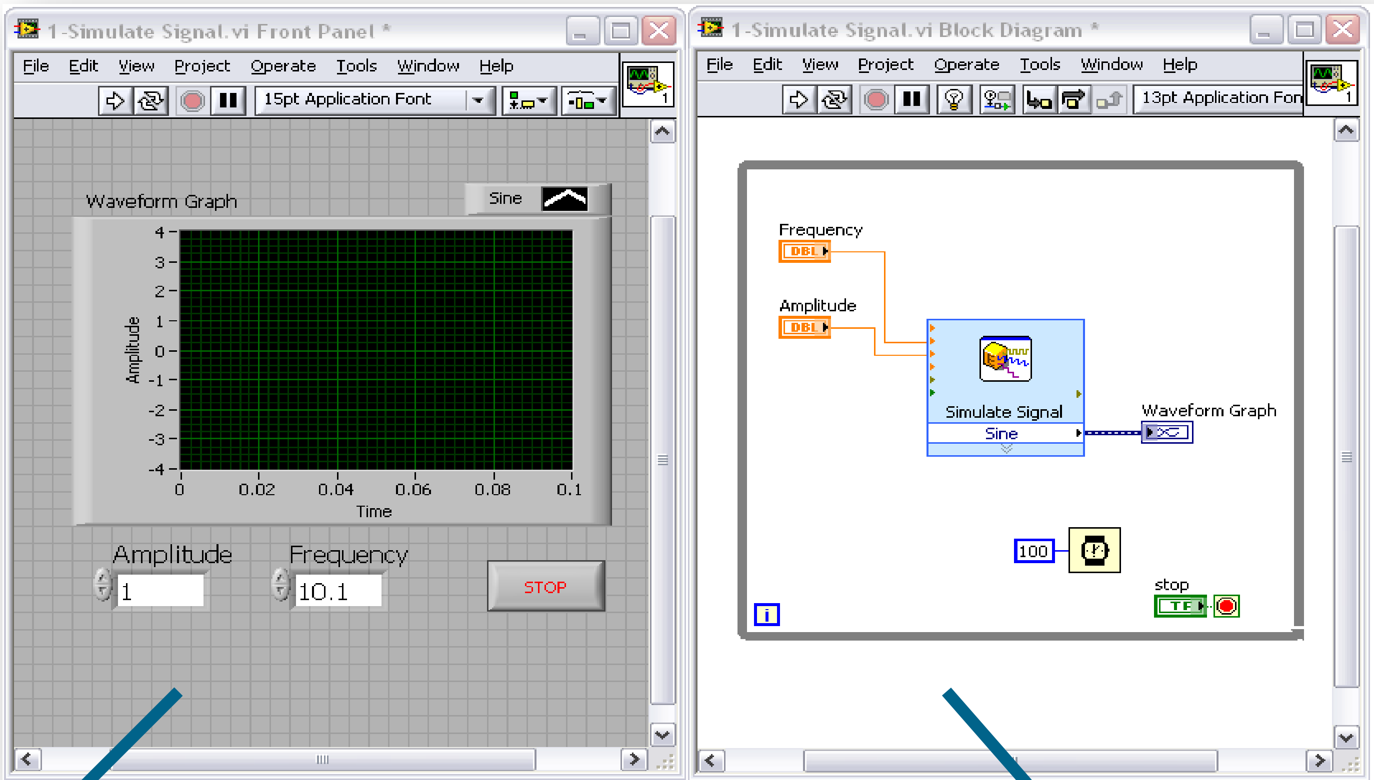
Early Cancer Detection



CERN Large Hadron Collider

The LabVIEW Environment

"VI" = program or function



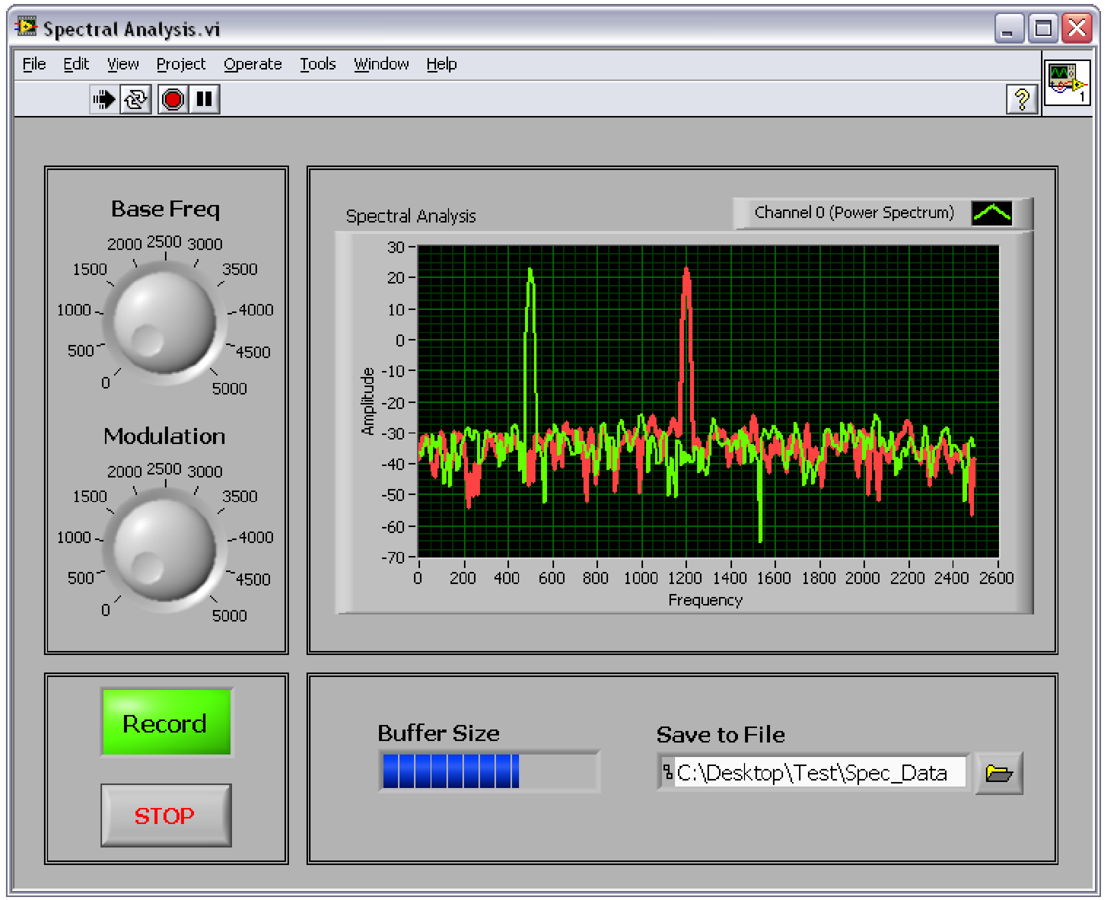
"Front Panel" = user interface

"Block Diagram" = code

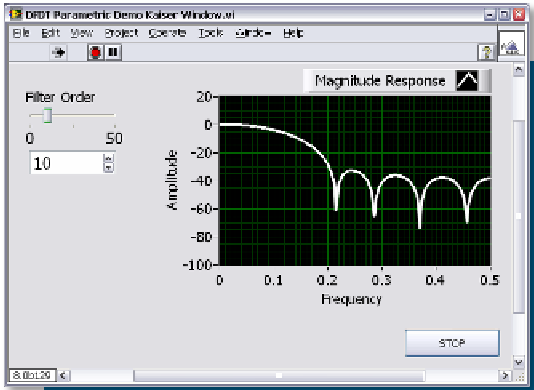
Front Panel

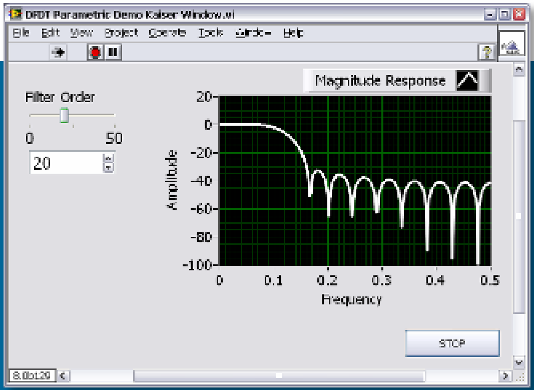
Controls & Indicators

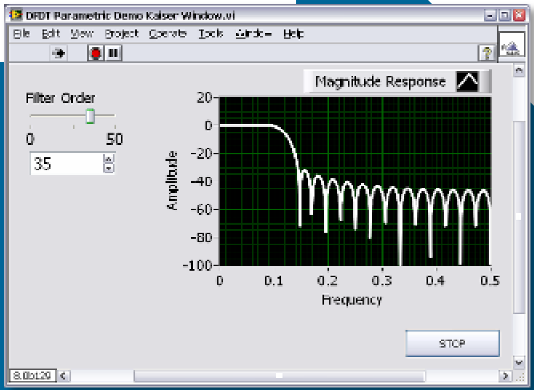
- Knobs/Dials
- Graphs/Charts
- Buttons
- Digital Displays
- Sliders
- Thermometers
- Customize and create your own



Interactivity







- Problem Definition
- Concept Demos
- Computational Exploration
- Design
- Interactive Analysis

Demo: Simple USRP-based Receiver

Gigabit Ethernet
Connection to Host Computer

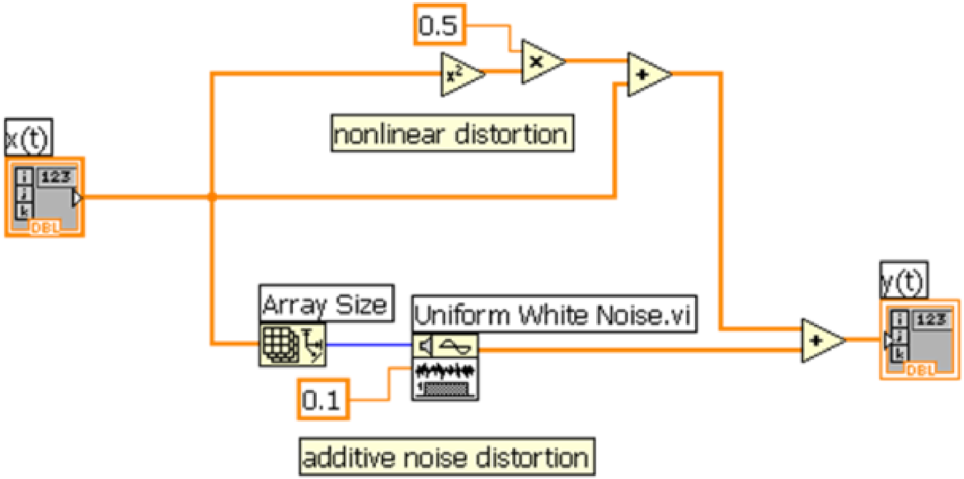
NI USRP-2190
Receiver

NATIONAL INSTRUMENTS LabVIEW™

- 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



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

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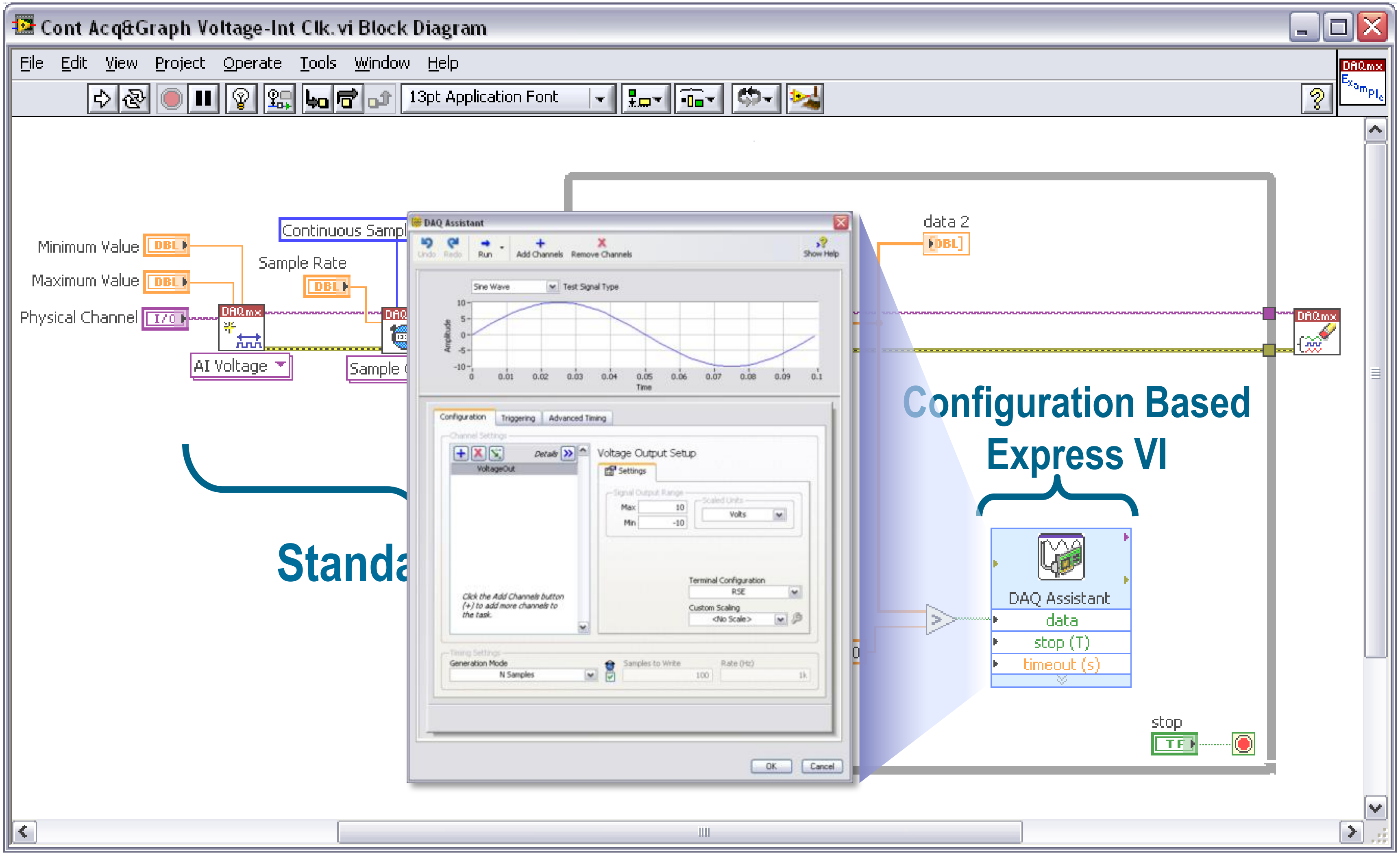
Functions and Express VIs



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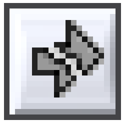
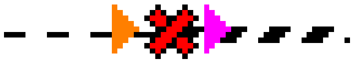
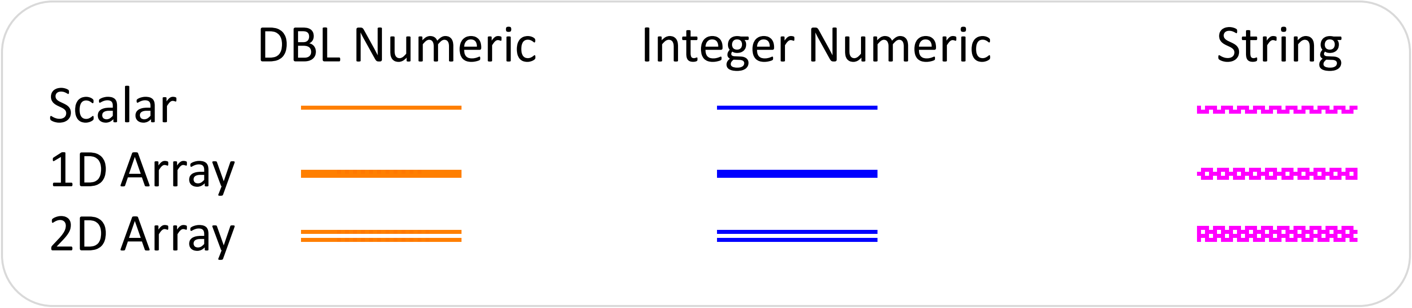
Wires and Data Types

- 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

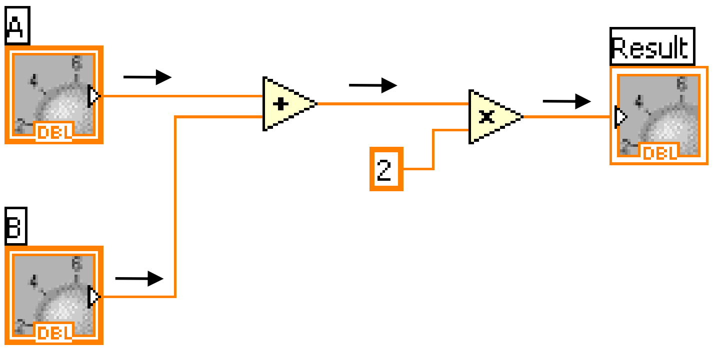


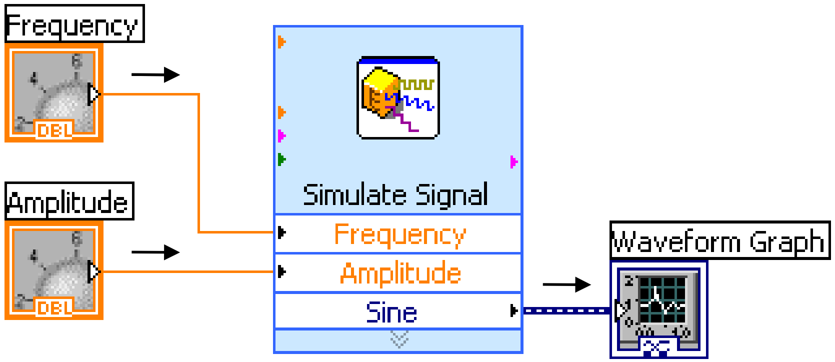




Data Flow Sets Execution Order

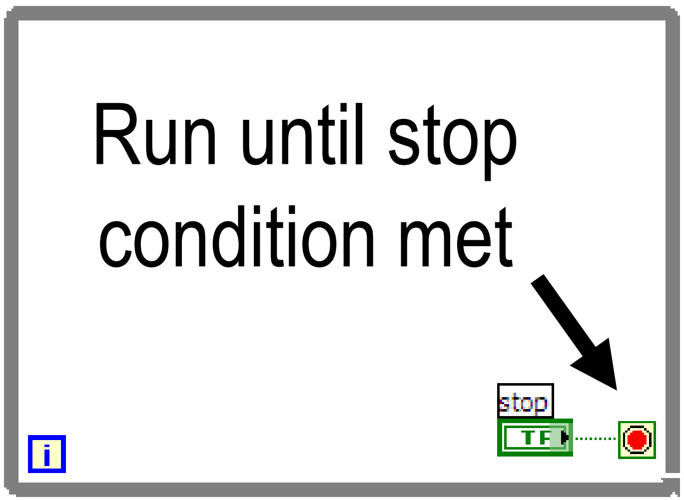
- Block diagram execution order depends on the flow of data
- Block diagram does NOT execute left to right
- Nodes executes when data is available to ALL input terminals
- Nodes supply data to all output terminals when done
- If the computer running this code had multiple processors, these two pieces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



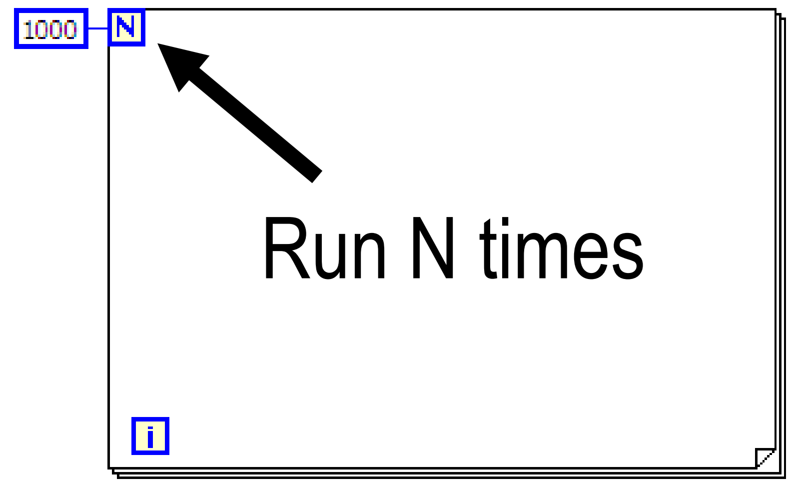


Execution Control Structures

While Loop



For Loop

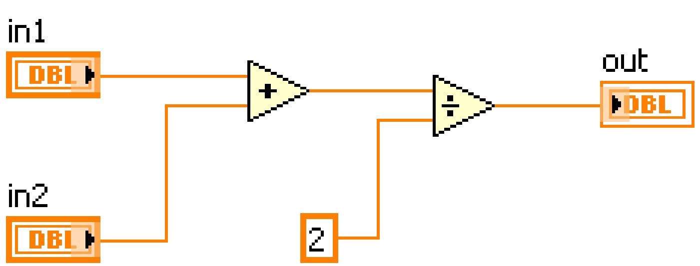
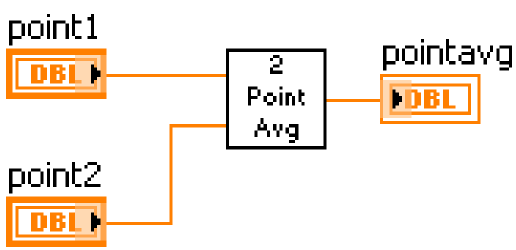


- Allow same piece of code to run multiple times
- Exit conditions different for each

Modularity and SubVIs

Function Code	Calling Program Code

`function average (in1, in2, out)`
`{`
`out = (in1 + in2)/2.0;`
`}`
	`main`
	`{`
	`average (point1, point2, pointavg);`
	`}`

SubVI Block Diagram	**Calling VI Block Diagram**
	

Demo: Simple USRP-based Receiver

- with Spectrum Analysis

NI USRP-2190
Receiver

Gigabit Ethernet
Connection to Host Computer

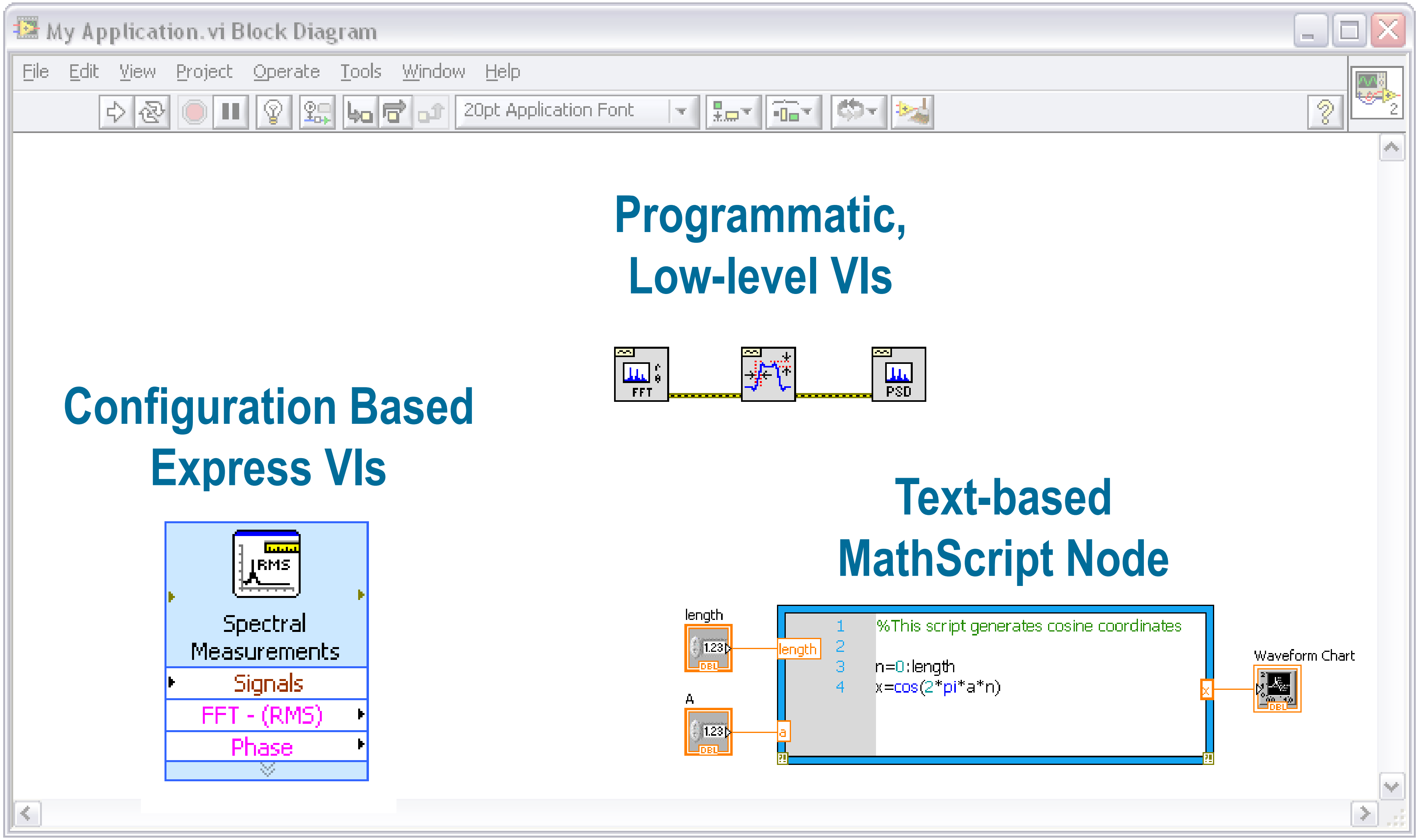
NATIONAL INSTRUMENTS LabVIEW™

- 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



Demo: Simple USRP-based Receiver

- with Spectrum Analysis
- with live FM radio

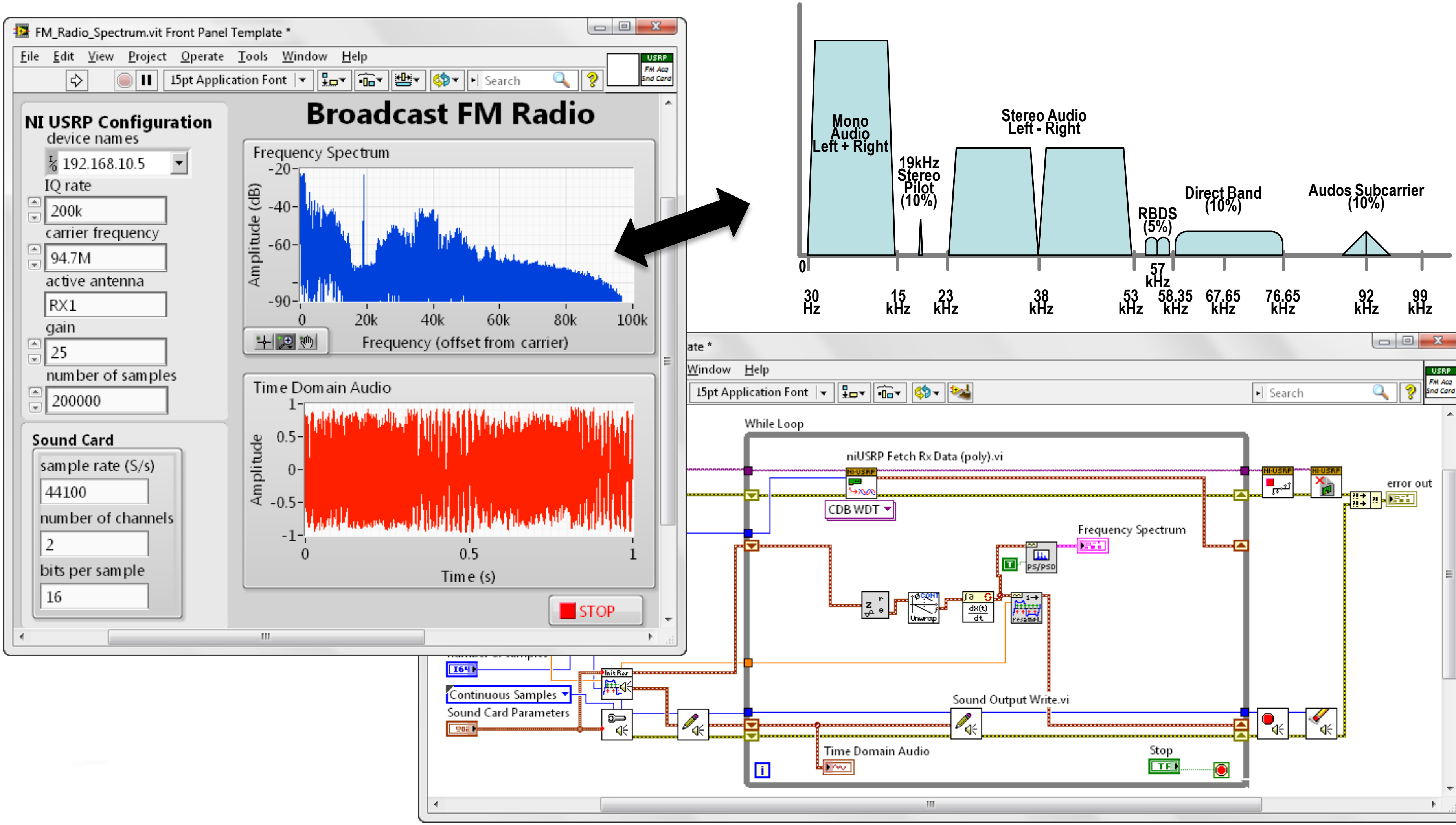
NI USRP-2190
Receiver

Gigabit Ethernet
Connection to Host Computer

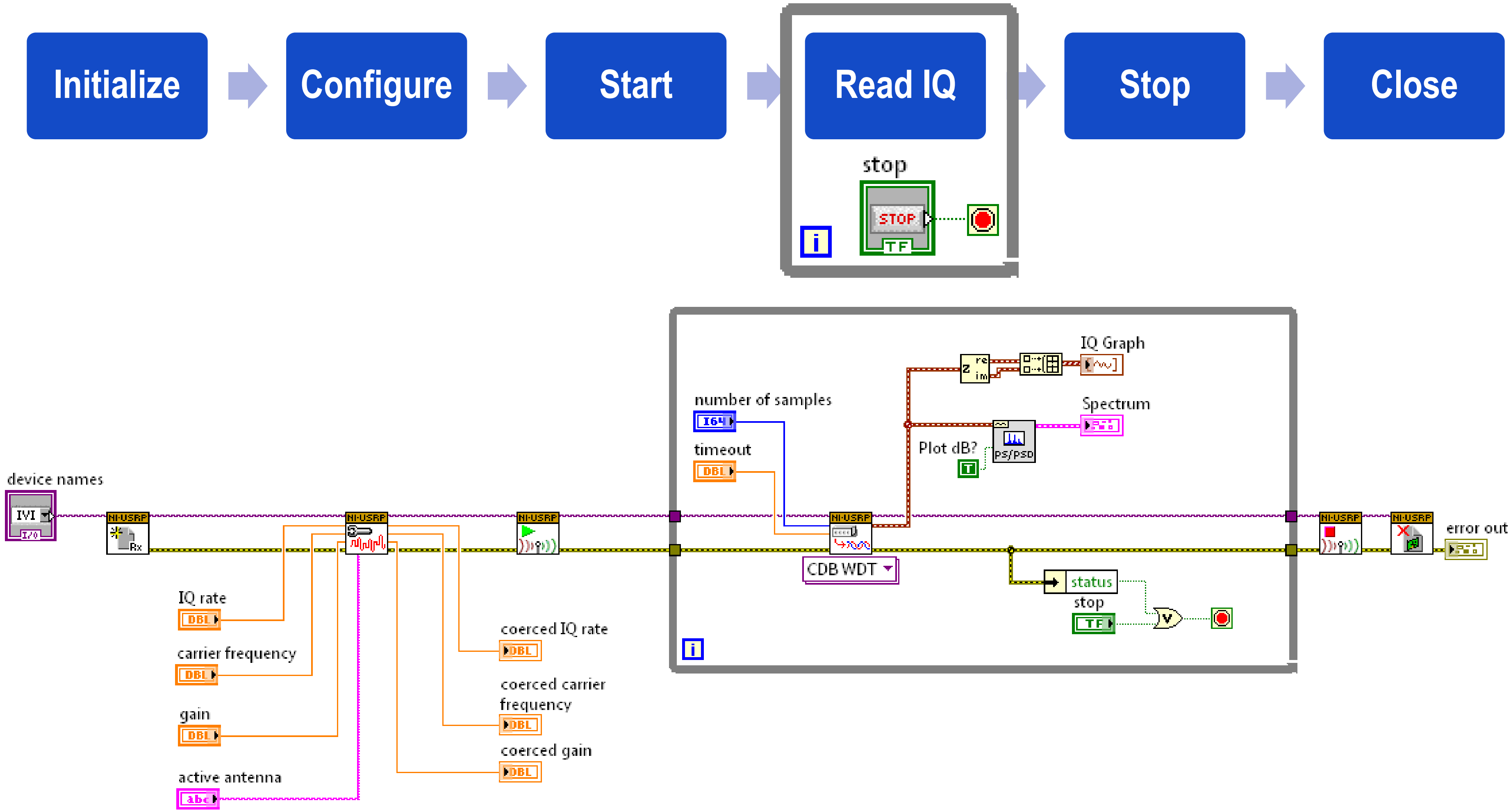
NATIONAL INSTRUMENTS LabVIEW™

- USRP control (Rx)
- Inline Processing / Display

Decode & Hear Live FM Radio

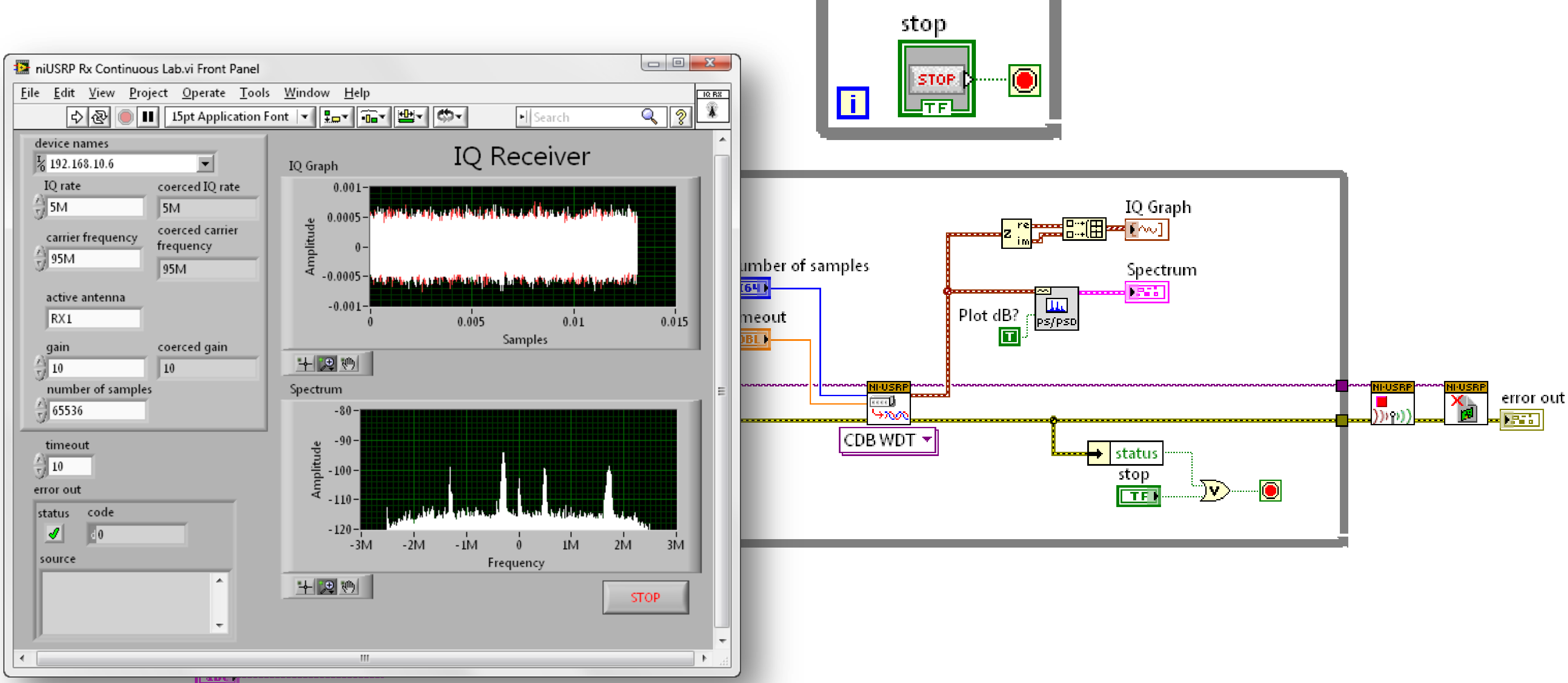


NI-USRP Driver Software



NI-USRP Driver Software

Initialize → Configure → Start → Read IQ → Stop → Close



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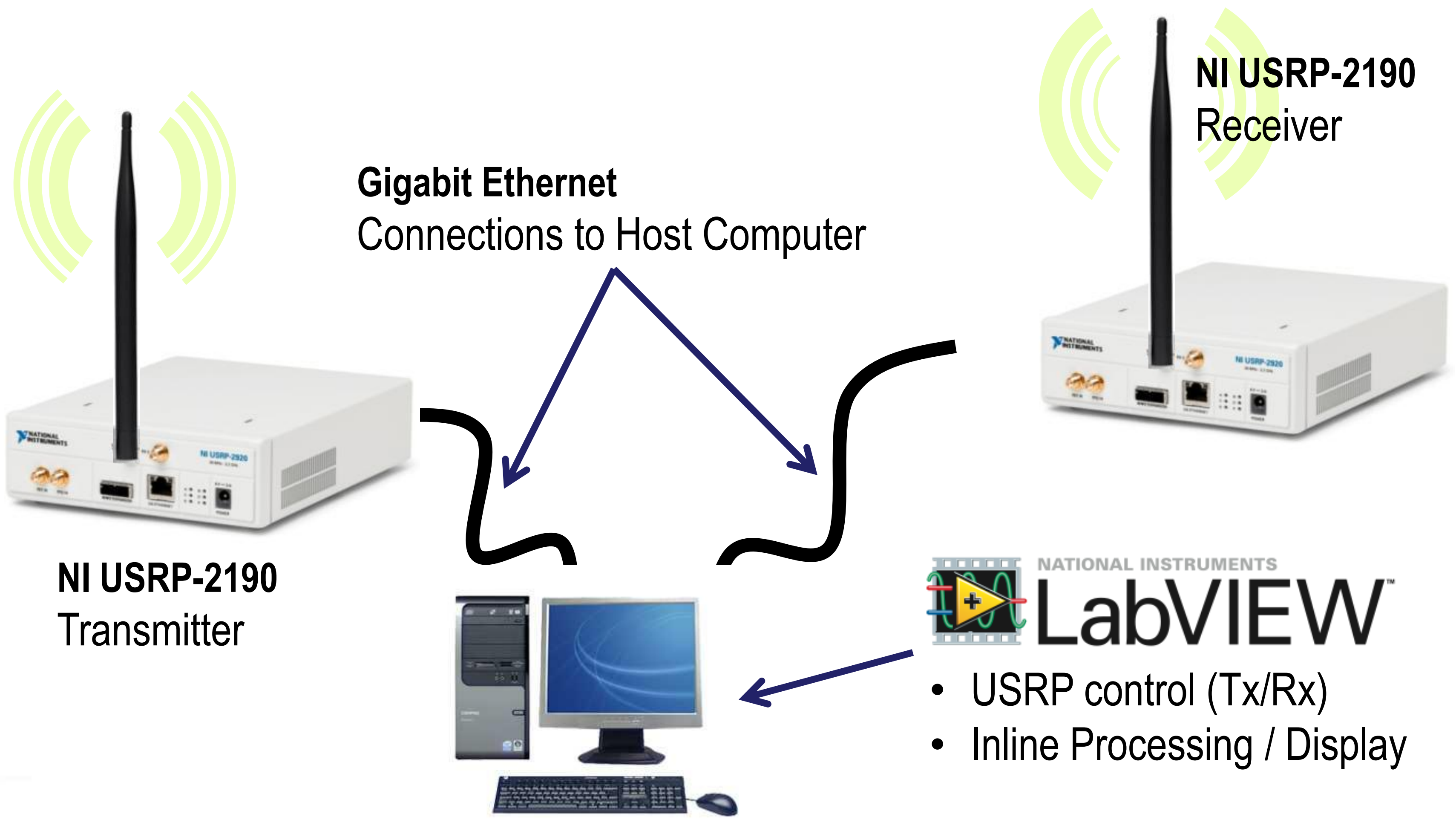
Demo: Simple USRP-based Tx / Rx Pair



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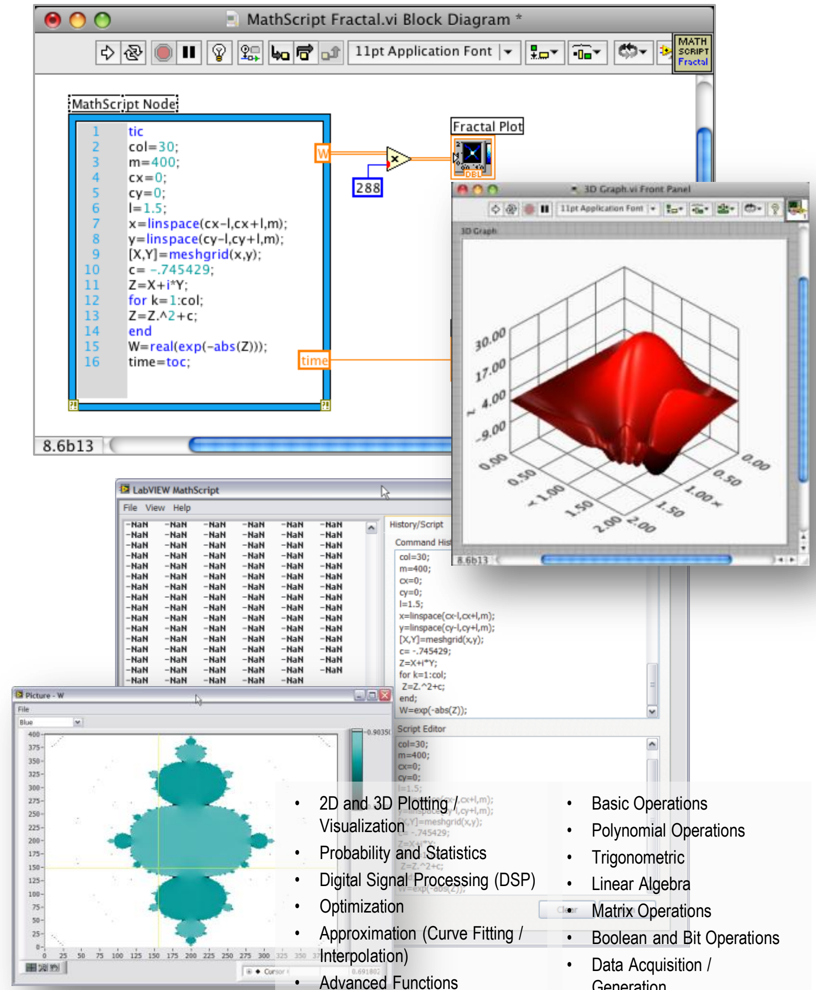
LabVIEW™
MathScript RT Module



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

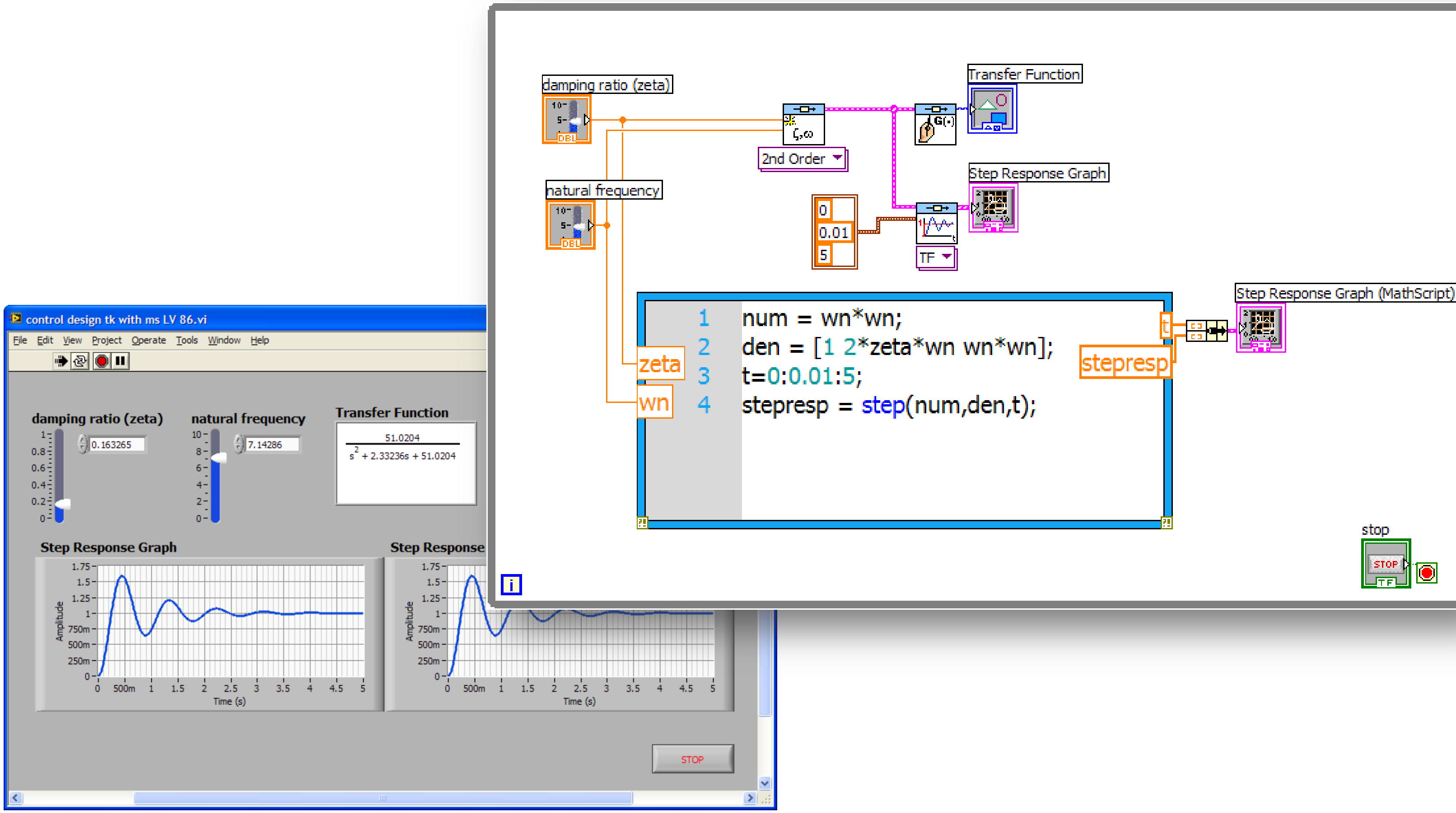
A native LabVIEW solution

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

- 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

The Hybrid Approach

Combine Graphical / Textual Programming



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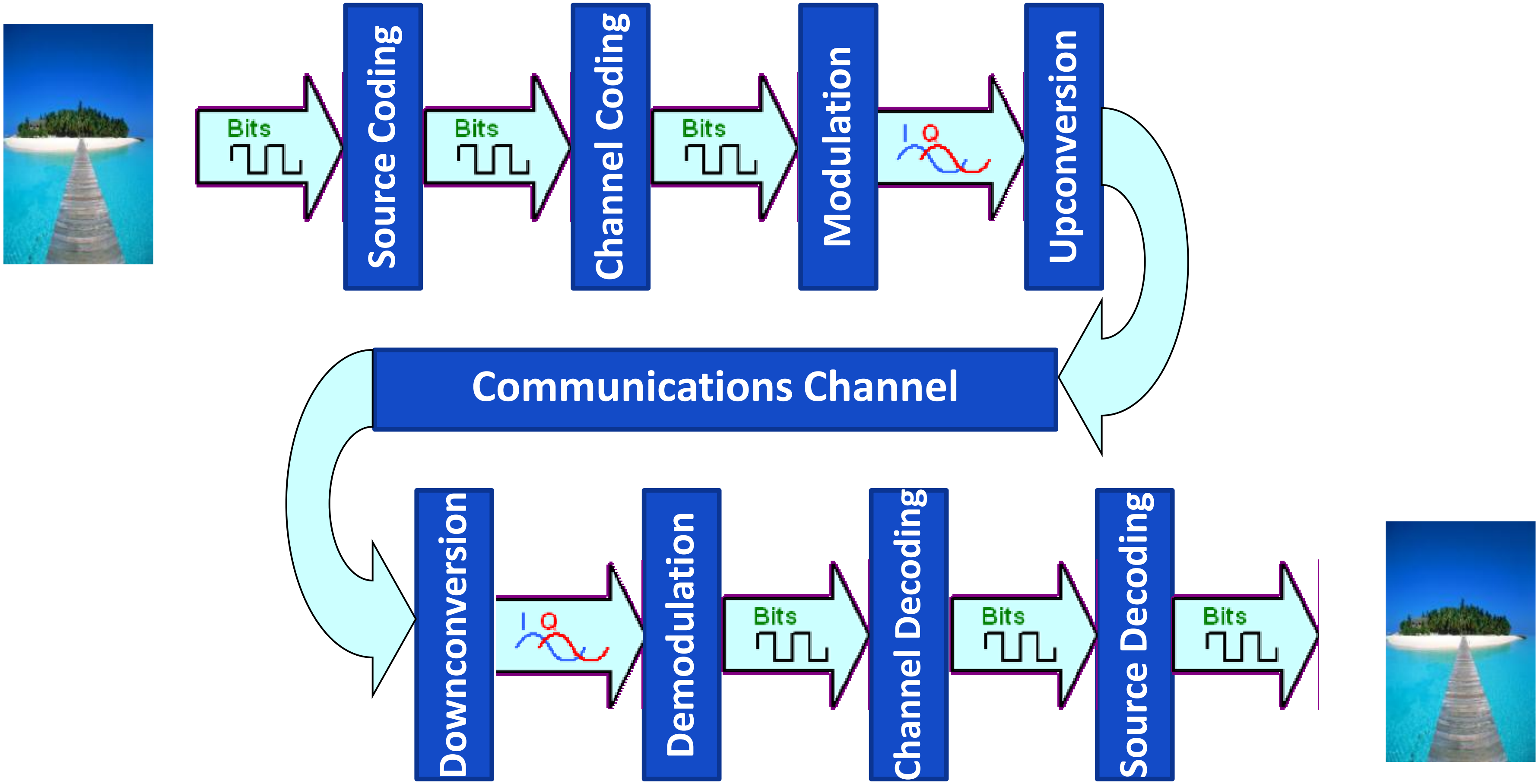
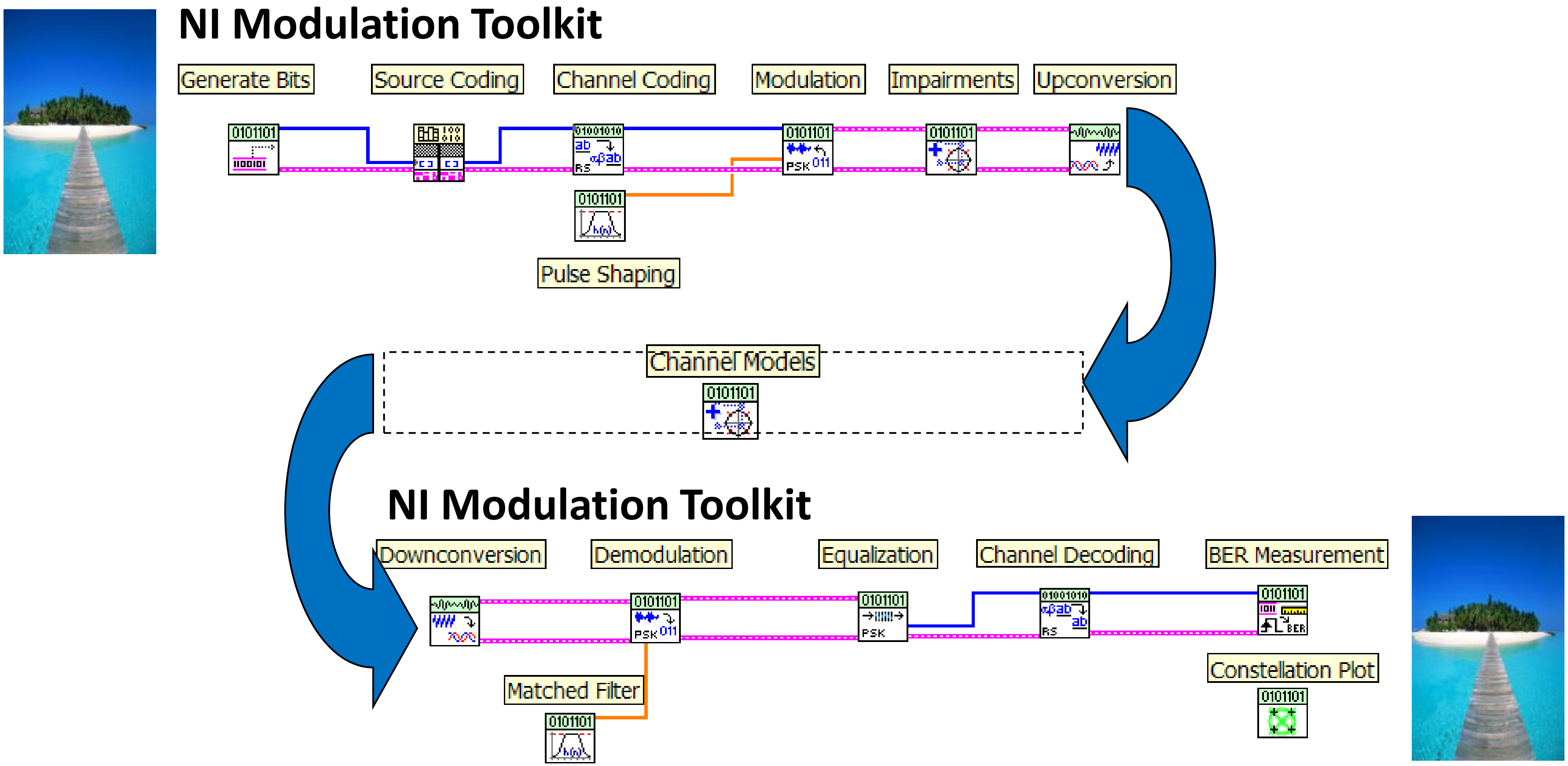
Digital Communication System

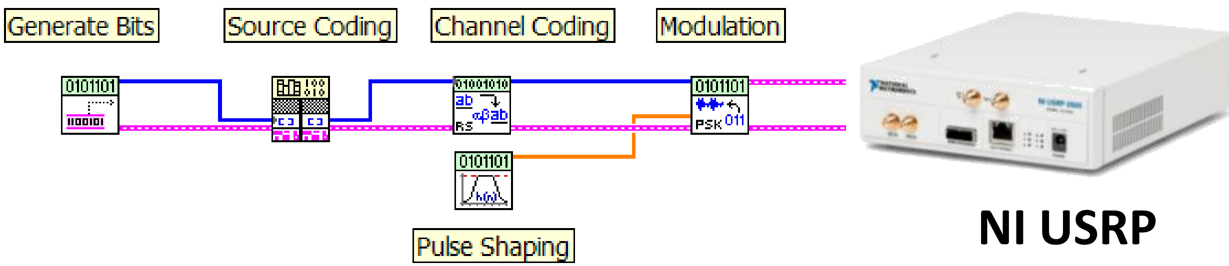


Digital Communication System

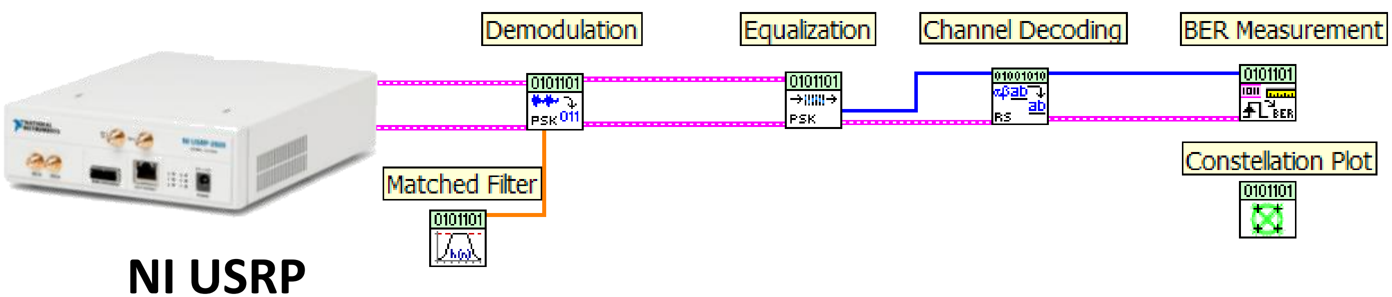


Digital Communication System

NI Modulation Toolkit

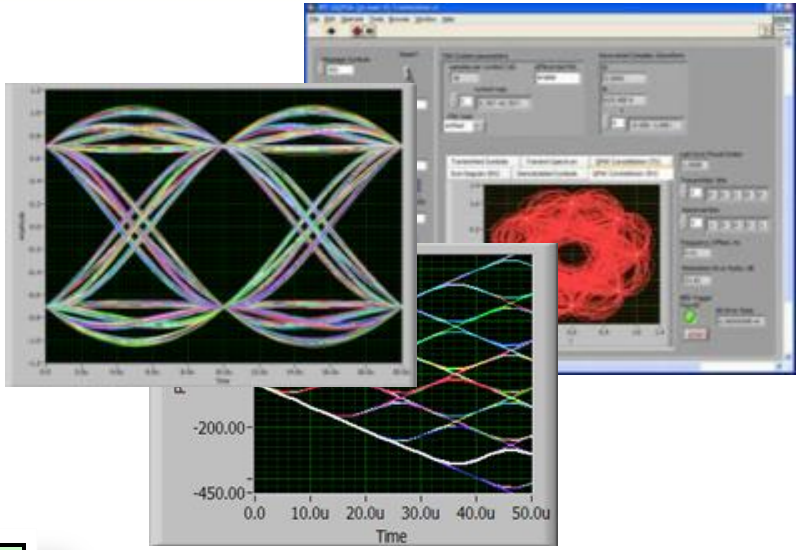


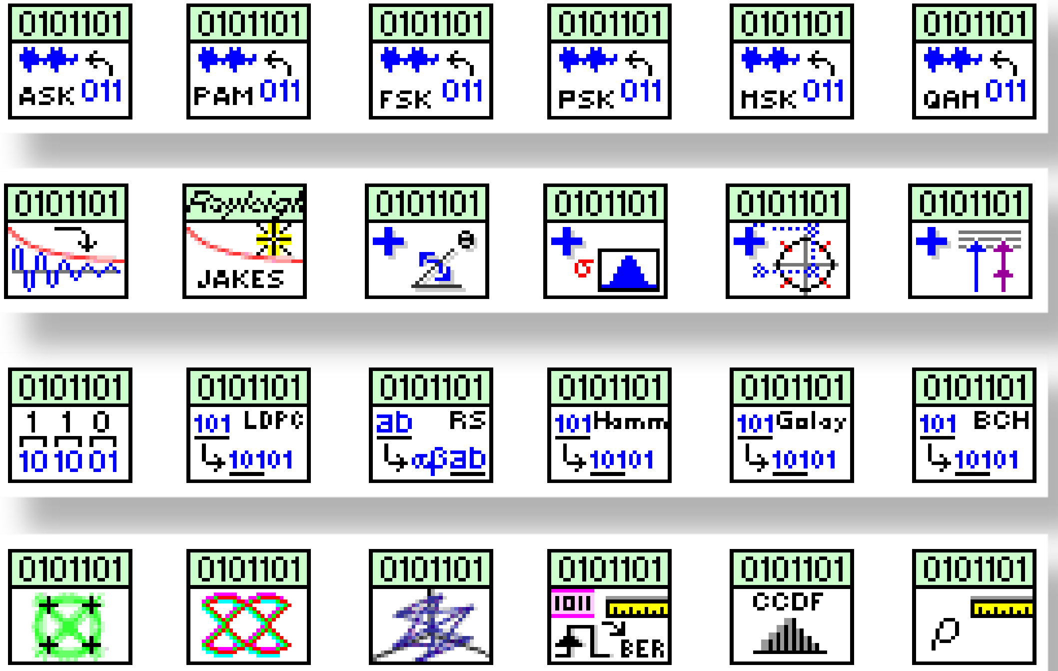
NI Modulation Toolkit



Modulation Toolkit

LabVIEW simulation and modeling tools for communication system design





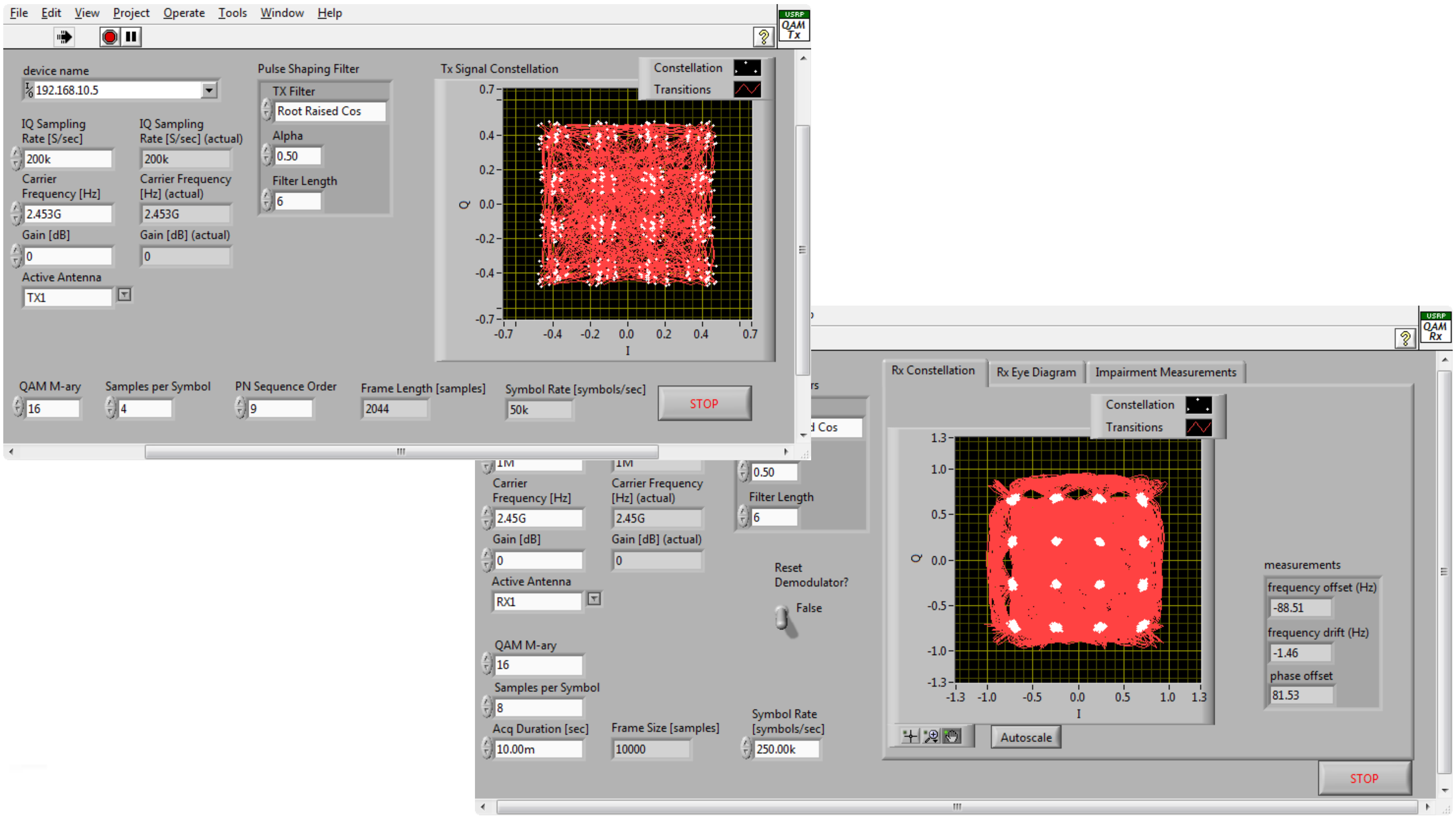
Modulation & Demodulation

Channel models / impairments

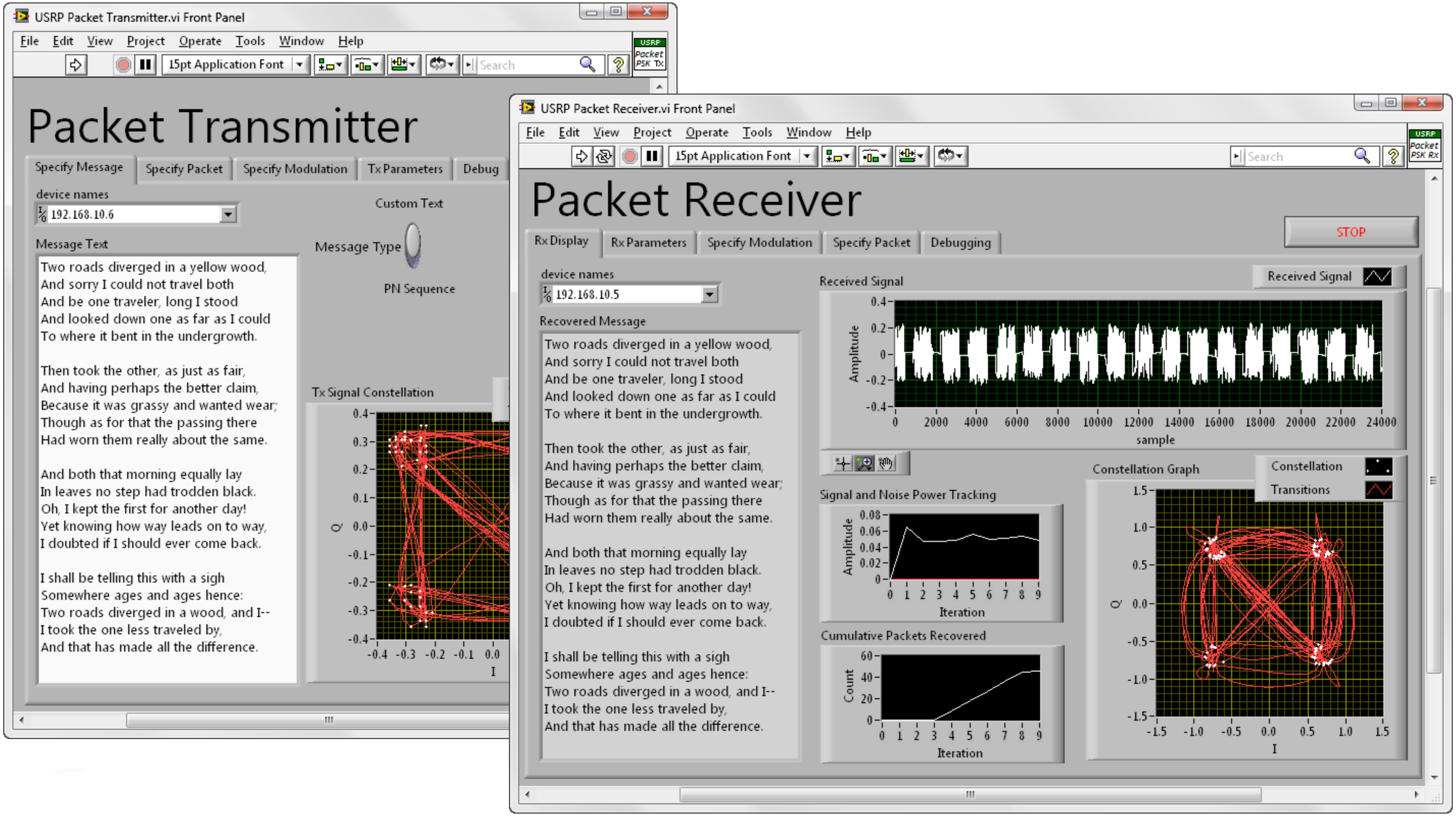
Channel coding

Communication visualization

Demo: QAM Tx / Rx Pair



Demo: Packet-based Transceiver



Demo: Packet-based Link

NI USRP-2190
Transmitter

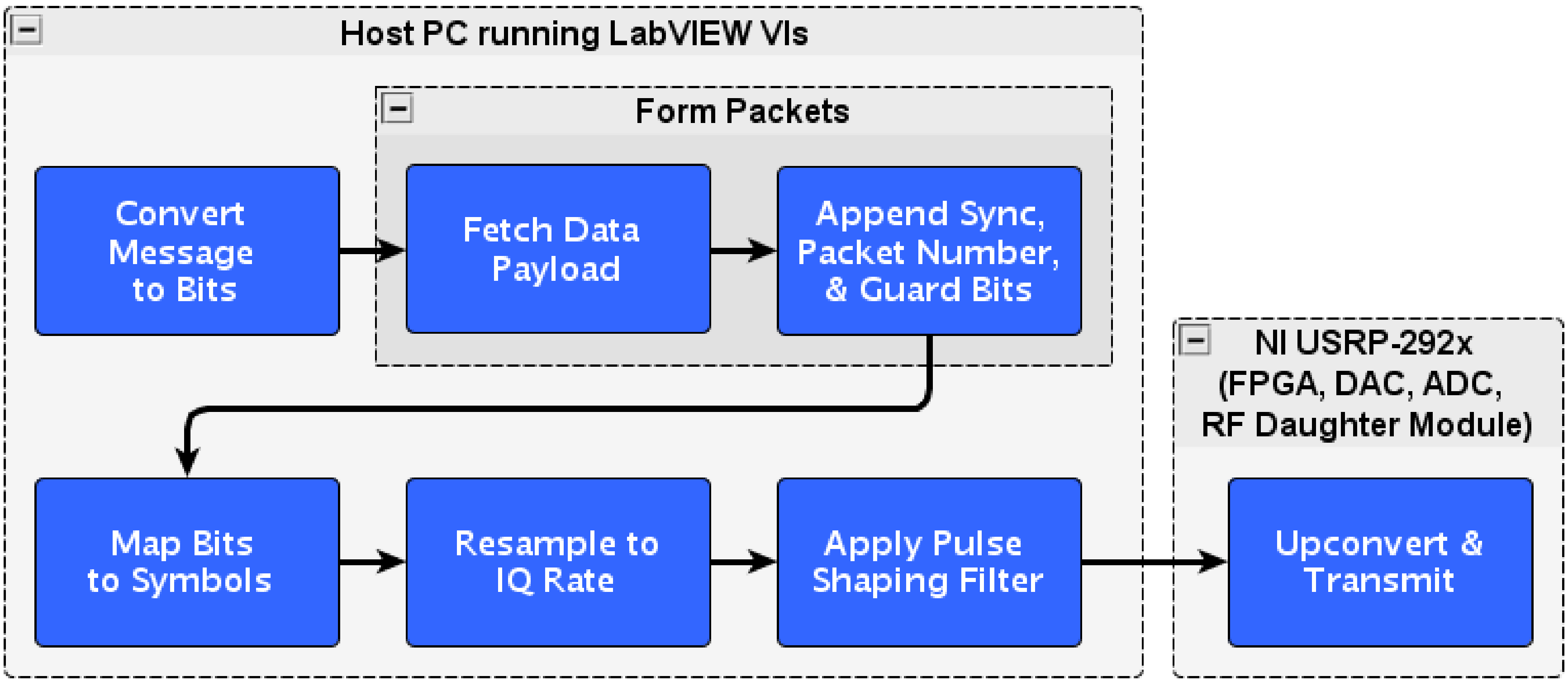
RF Signal
915MHz , PSK packets,
400kbps

NI USRP-2190
Receiver

NATIONAL INSTRUMENTS LabVIEW

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

Transmitter Block Diagram

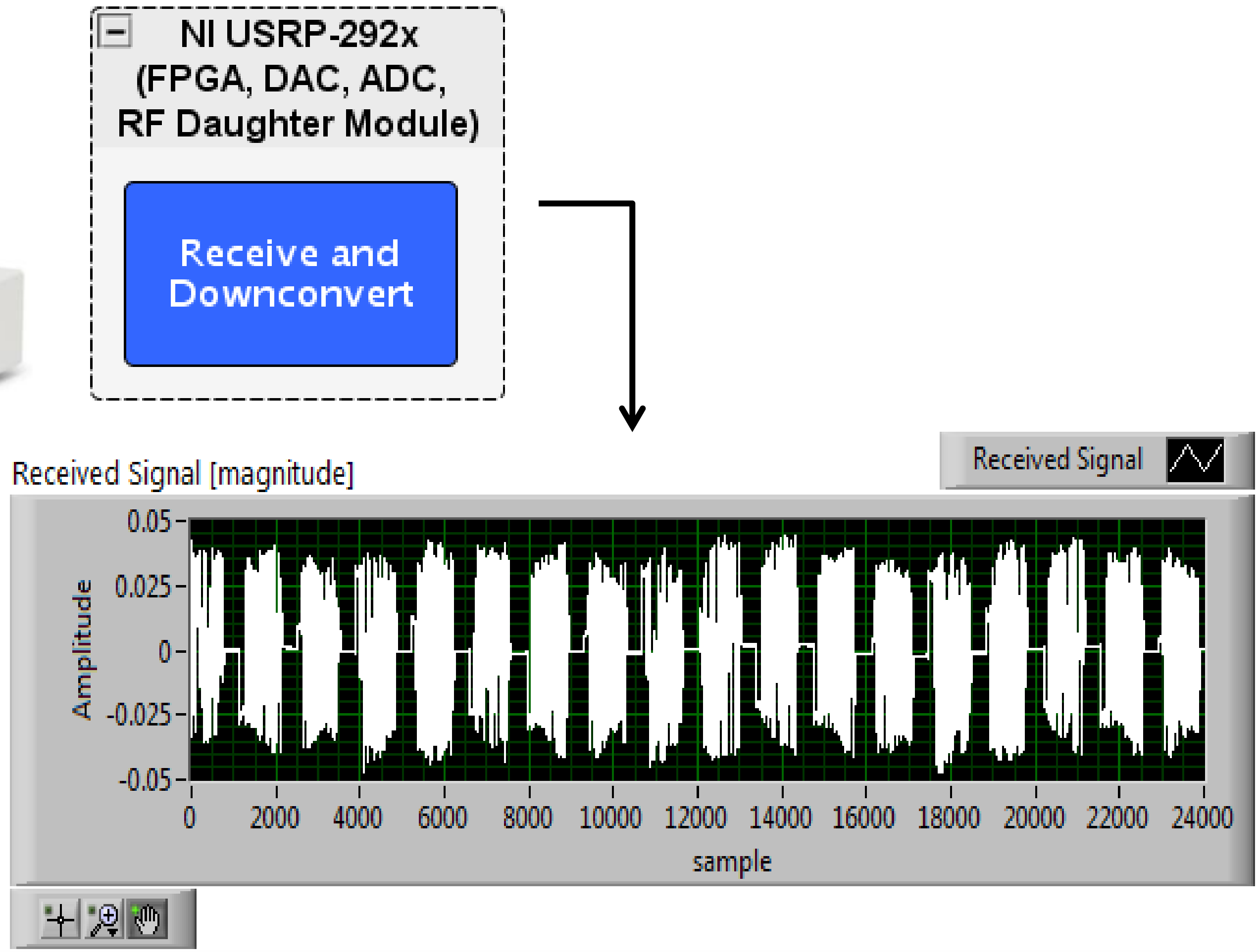


Packet Structure

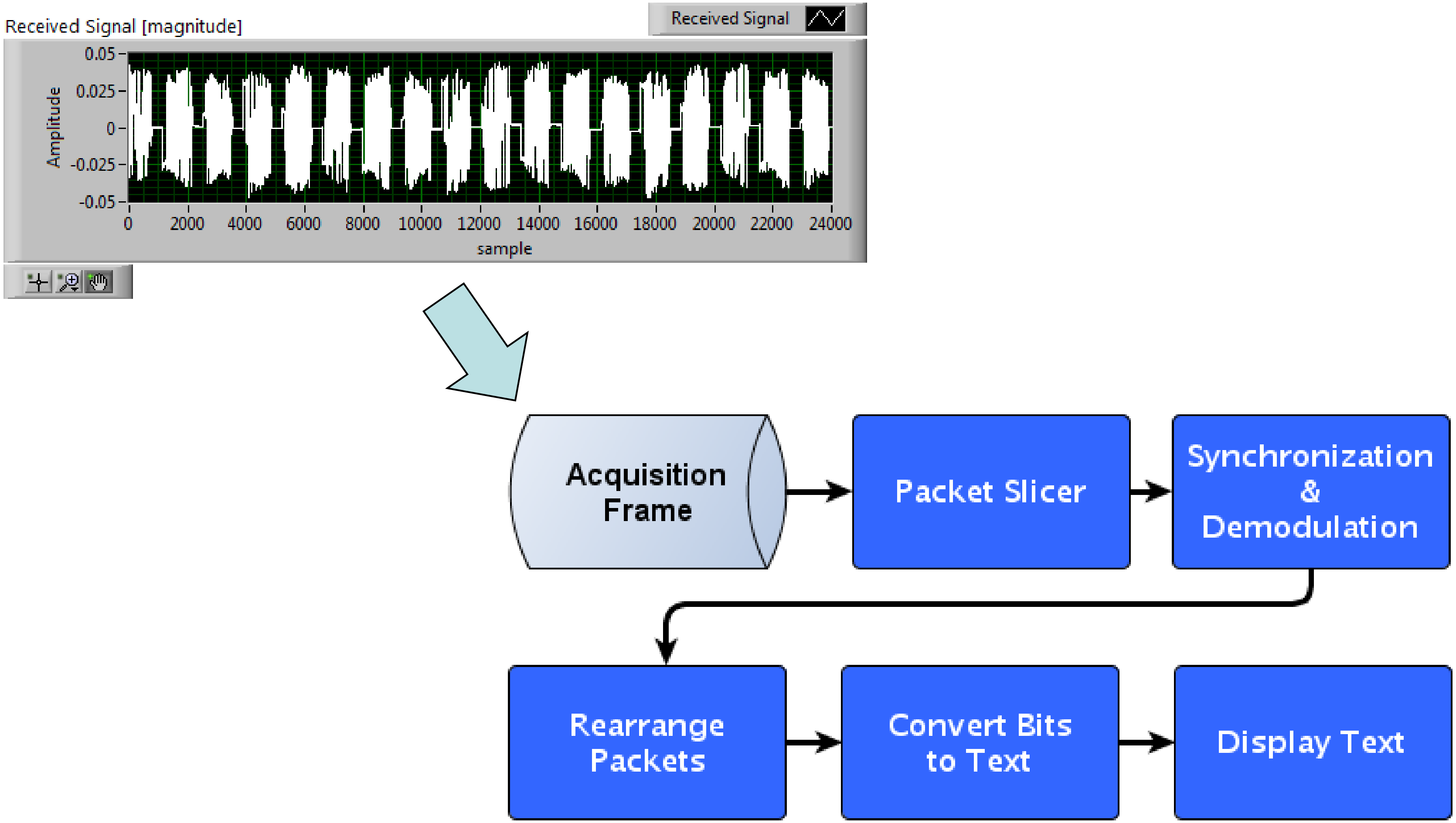
GUARD BAND	SYNC SEQ	PCKT NUM	DATA	PAD

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

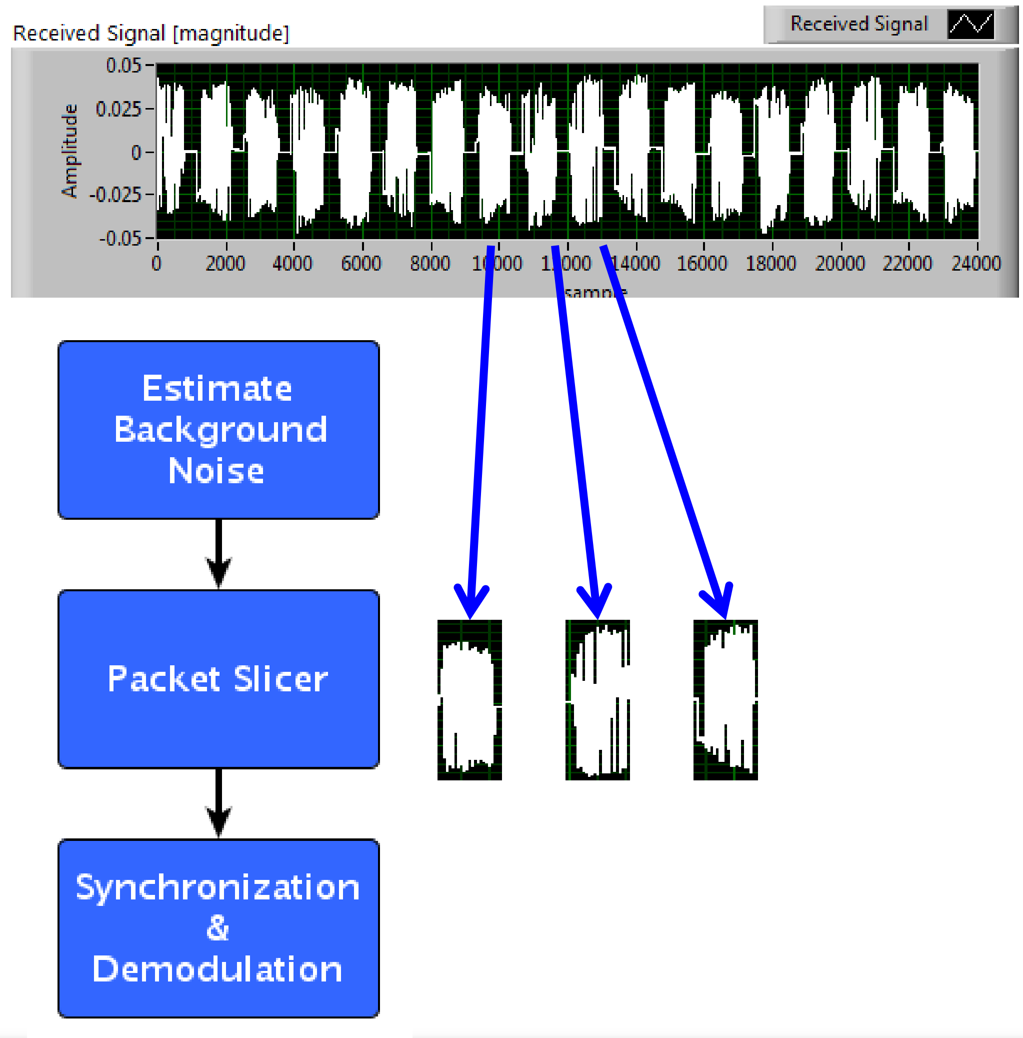


Receiver Block Diagram



Channel Activity Detection

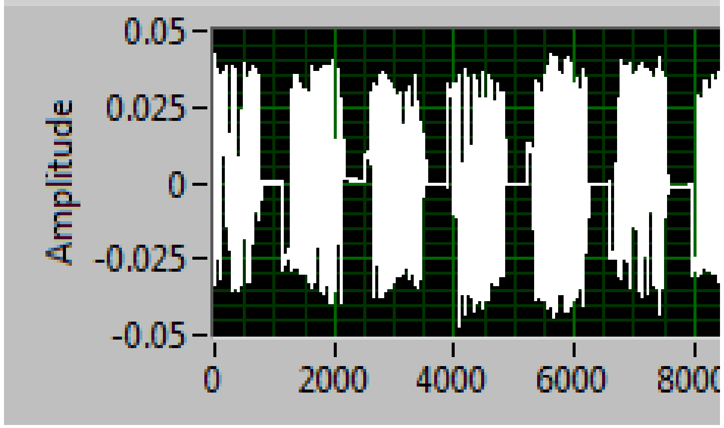
- **Problem:** Inefficient to keep demodulator active for the entire acquisition frame—it needs to be applied only to packets
- **Solution:** Apply a channel activity detector to locate packet boundaries for a packet slicer



Error Tolerance

Problem: Errors at SNR >> 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 SNR >> 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