Introduction to Digital Communication

Ingo Foldvari
Academic Program Manager
National Instruments California

Phone: 760 691 0877
Email: ingo.foldvari@ni.com
Traditional Benchtop Approach
NI USRP and LabVIEW

A Platform for Software Defined Radio Prototyping and Exploration
1. Introduction to RF & Wireless Communications Systems
2. RF and Microwave Spectral Analysis
3. Analog Modulation
4. Digital Modulation
5. Communications Systems
6. Modulation Measurements
7. Communication Standards
8. Understanding RF & Microwave Specifications
9. RF & Communications Terminology and Glossary
10. RF & Communications Resources
11. See Also - RF Fundamentals 3-Day Training Course

RF Handbook

Ideal for learning or refreshing your knowledge of RF & Comm.
• Practical information, theoretical foundation
Demonstrations and lab exercises based on
• NI LabVIEW
• LabVIEW Modulation Toolkit
• NI IF & RF Communications Hardware Platform

Full Color Version
• Orderable Book: http://www.lulu.com/content/1133250

Black&White (low cost) Version
• Orderable Book: http://www.lulu.com/content/1193352
• Free PDF Download: http://www.lulu.com/product/file-download/rf-communications-handbook-(bw)/1714760

LabVIEW VIs (free download): http://www.lulu.com/content/1302357
# Online Community

https://decibel.ni.com/content/groups/ni-usrp-example-labview-vis

<table>
<thead>
<tr>
<th>Subject</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>USRP Transmit Phase Modulated Signal</td>
<td>Wireless Video Link</td>
</tr>
<tr>
<td>USRP Transmit Frequency Modulated (FM) Signal</td>
<td>MIMO Spectrum Monitoring</td>
</tr>
<tr>
<td>AM-DSB/SC Tx Example</td>
<td>Decode 802.11b SSID with NI USRP</td>
</tr>
<tr>
<td>Wideband Spectrum Monitoring</td>
<td>2x2 MIMO QAM with Alamouti Coding</td>
</tr>
<tr>
<td>TDM Transmit VI for NI USRP</td>
<td>RF Record and Playback with NI USRP</td>
</tr>
<tr>
<td>Automatic Modulation Classification using Cyclic Feature Detection with NI USRP</td>
<td>GPS Simulation with NI USRP and LabVIEW</td>
</tr>
<tr>
<td>6x6 MIMO-OFDM System with NI USRP</td>
<td>NI USRP Examples (Chinese Translation) version 1</td>
</tr>
<tr>
<td>POCSAG Alpha Numeric Pages with the USRP</td>
<td>Packet-based Digital Link</td>
</tr>
<tr>
<td>Forward Powerpoint Slides with Your Car Keyfob</td>
<td>PSK Phase Shift Demo</td>
</tr>
<tr>
<td>Demodulate and Listen to FM Radio with NI USRP</td>
<td>Software Trigger and Gate on Continuous Rx IQ Frames</td>
</tr>
<tr>
<td>ADS-B Decoder (Airplane Tracker)</td>
<td></td>
</tr>
</tbody>
</table>
Wireless Digital Communication

IQ waveform modulated

analog
digital

User

00100100

00100100
digital

User
Basics of Frequency Spectrum

Wavelength Calculation

\[
\frac{\text{Speed of Light (meters/sec)}}{\text{Frequency (Hz)}} = \text{Wavelength (meters)}
\]

FM Radio Example

\[
\frac{299,792,458 \text{ m/s}}{100 \text{ MHz}} \approx \frac{300 \text{ M m/s}}{100 \text{ MHz}} = 3 \text{ m wavelength}
\]

\(\frac{1}{4}\) wave antenna = .75 m = 2.5 feet
NI USRP and LabVIEW
A Platform for Software Defined Radio Prototyping and Exploration
A Highly Productive Graphical Development Environment for Engineers and Scientists

Hardware APIs

Analysis Libraries

Custom User Interfaces

Deployment Targets

Technology Abstractions

Models of Computation
Models of Computation

Dataflow
C / HDL Code
Textual Math
Simulation
Statechart

LabVIEW
Desktop
Real-Time
FPGA
MPU/MCU

Personal Computers
PXI Systems
CompactRIO
Single-Board RIO
Custom Design

ni.com
Review: Creating a Virtual Instrument

- LabVIEW programs are called Virtual Instruments or VIs.
- Each VI has two windows
  - Front Panel → User Interface (UI)
    - Controls = User Inputs
    - Indicators = Outputs
  - Block Diagram → Program Code
    - Data travels on wires from controls through functions to indicators
    - Blocks execute by Dataflow
Review: Front Panel Controls Palette (Controls & Indicators)

**Control:** Numeric

**Indicator:** Gauge

Front Panel

Indicator: Gauge
Review: Block Diagram Functions Palettes

Structure: While Loop
Review: Block Diagram – Wires

- 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
Review: Block Diagram Terminals

Front Panel Window

Block Diagram Window

Numeric Controls

Numeric Indicator
Review: Tools Palette

- Recommended: Automatic Selection Tool
- Tools to operate and modify both front panel and block diagram objects

Automatic Selection Tool

Automatically chooses among the following tools:

- Operating Tool
- Positioning/Resizing Tool
- Labeling Tool
- Wiring Tool
Review: Status Toolbar

Run Button
Continuous Run Button
Abort Execution

Additional Buttons on the Diagram Toolbar

Execution Highlighting Button
Retain Wire Values Button
Step Function Buttons
Review: Dataflow Programming

• Block diagram execution
  – Dependent on the flow of data
  – Block diagram does NOT execute left to right
• Node executes when data is available to ALL input terminals
• Nodes supply data to all output terminals when done
Review: Context Help Window

- Help » Show Context Help, press the <Ctrl+H> keys
- Hover cursor over object to update window

Additional Help

- Right-Click on the VI icon and choose Help, or
- Choose “Detailed Help.” on the context help window
Review: Textual Math with the MathScript Node

- Implement equations and algorithms textually
- Input and Output variables created at the border
- Generally compatible with popular m-file script language
- Terminate statements with a semicolon to disable immediate output

Prototype your equations in the interactive MathScript Window.
Review: The Interactive MathScript Window

- Rapidly develop and test algorithms
- Share Scripts and Variables with the Node
- View /Modify Variable content in 1D, 2D, and 3D

(LabVIEW » Tools » MathScript Window)
Programming Demo

DATA VS. WAVEFORMS
NI USRP Under the Hood

RF Transceiver

Baseband IQ

Software Processing
System Setup

NI USRP-2920 Transmitter

NI USRP-2920 Receiver

LabVIEW

- USRP control (Tx & Rx)
- Modulate Tx signal
- Demodulate Rx signal
- Reconstruct message
NI USRP-2920 Hardware Diagram

Analog RF Transceiver

Fixed Function FPGA

PC
NI USRP

Tunable RF Transceiver Front Ends
- Frequency Range
  - 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 and LabVIEW add-ons to simulate or process live signals

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

1 Gigabit Ethernet Connectivity
- Plug-and-play capability
- Up to 25 MS/s baseband IQ streaming
Graphical Implementations and MathScript RT

NI USRP-2920 Transmitter

NI USRP-2920 Receiver
NI-USRP Driver Software
Communications Design Topics

- **Education**
  - Introductory Communications
  - Digital Communications
  - Antenna Theory

- **Research**
  - Physical layer research (SISO & MIMO)
  - Cognitive Radio & Dynamic Spectrum Access
  - RF transmit or receive applications

- **Defense**
  - Spectral Monitoring
  - Prototyping Communications Systems
Programming Demo

TRANSMIT WAVEFORM
Programming Demo

TRANSMIT WAVEFORM WITH COERCED HW SETTINGS
Why IQ?

• It is difficult to vary precisely the phase of a high-frequency carrier sine wave in a hardware circuit according to an input message signal.

• A hardware signal modulator that manipulates the amplitude and phase of a carrier sine wave would therefore be expensive and difficult to design and build.

• HW circuit that uses I and Q waveforms are more flexible.
Quadrature Modulation

\[ A_c \cos(2\pi f_c t + \phi) \]

Amplitude  Frequency  Phase

Angle
(Frequency = Rate of change of Angle)

\[ I(t) \cos(2\pi f_c t) - Q(t) \sin(2\pi f_c t) \]

Note: I and Q capture magnitude and phase information
I refers to in-phase data (because the carrier is in phase)
Q refers to quadrature data (because the carrier is offset by 90 degrees).
IQ Modulator

IQ is the Cartesian representation of a vector from a Polar Coordinate System.

\[ I(t) = M(t) \cos(\phi(t)) \]
\[ Q(t) = M(t) \sin(\phi(t)) \]

Figure 11. Hardware Diagram of an I/Q Modulator
Programming Demo

PHASOR PLOT
TRANSMIT COMPLEX IQ WAVEFORM
Modulation Basics

- RF communication systems use advanced forms of modulation to increase the amount of data that can be transmitted in a given amount of frequency spectrum.

- Signal modulation can be divided into two broad categories:
  - analog modulation (*analog audio data is modulated onto a carrier sine wave*)
  - digital modulation (digital bits modulated onto a carrier sine wave)
Modulation Basics

- Carrier sine wave needs to change in amplitude, frequency, and phase in order to encode information.
Modulation Example – AM Radio

Audio Signal
20Hz – 20kHz

Baseband IQ

AM Radio Signal

LabVIEW Software

NI USRP Hardware
More than just the message: Packet Structure

<table>
<thead>
<tr>
<th>Field</th>
<th>Length [bits]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guard Band</td>
<td>30</td>
<td>Allow initialization of Rx PLL, filters, etc</td>
</tr>
<tr>
<td>Sync Sequence</td>
<td>20</td>
<td>Frame and Symbol Synchronization</td>
</tr>
<tr>
<td>Packet Number</td>
<td>8</td>
<td>Range: 0-255 Used for reordering of packets and detection of missing packets</td>
</tr>
<tr>
<td>Data</td>
<td>64 - 256</td>
<td>Variable length data field. Length detected dynamically at Rx end</td>
</tr>
<tr>
<td>Pad</td>
<td>20</td>
<td>Allows for filter edge effects</td>
</tr>
</tbody>
</table>
Modulation Basics - Digital Modulation
the “how one sends” of “what” one sends

Bit Stream (32 Bits)

Symbol Stream (4-QAM)
(2 bits/symbol → 16 IQ symbols)

IQ Baseband Data

To RF Amplifier

ni.com
Mapping Bits to Symbols

In digital modulation, the number of bits sent per second is called Bit Rate - the higher the bit rate, the faster the communication speed. One way for digital communication systems to support a higher bit rate is to encode multiple bits of information in the variations of the carrier signal.

Symbol maps for 4-ASK modulation (left) and 4-PSK modulation (right)
4-QAM Symbol Map

- Four-QAM uses four combinations of phase and amplitude.
- Each combination is assigned a 2-bit digital pattern.

Example
- generate the bit stream (1,0,0,1,1,1)
- each symbol has a unique 2-bit pattern
- bits are grouped in two’s so that they can be mapped to the corresponding symbols
- (1,0,0,1,1,1) is grouped into the three symbols (10,01,11).
Pulse-Shaping Filter

In communications systems, two important requirements of a wireless communications channel demand the use of a pulse shaping filter.

- Generating bandlimited channels (reduce bandwidth)
- Reducing inter symbol interference (ISI) from multi-path signal reflections

Both requirements can be accomplished by a pulse shaping filter which is applied to each symbol

A sync pulse meets both of these requirements because it efficiently utilizes the frequency domain to utilize a smaller portion of the frequency domain, and because of the windowing affect that it has on each symbol period of a modulated signal.

Pulse-Shape Filtering in Communications Systems
Pulse-Shaping Filter

Sharp transitions from one symbol to the next occur when filtering is not applied. Sharp transitions in any signal result in high-frequency components in the frequency domain resulting in significant channel power outside of the defined bandwidth. Applying a pulse-shaping filter to the modulated sinusoid, the sharp transitions are smoothed and the resulting signal is limited to a specific frequency band.
Programming Demo

AM MODULATION
4-QAM SYMBOL MAPPING
PSK PULSE-SHAPING FILTER
NI-USRP Driver Software

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

device names

IQ rate
carrier frequency
gain
active antenna

coerced IQ rate
coerced carrier frequency
coerced gain

number of samples
timeout

IQ Graph
Spectrum

error out

ni.com
NI-USRP Driver Software

- Initialize
- Configure
- Start
- Read IQ
- Stop
- Close
Programming Demo

RECEIVE COMPLEX IQ
Digital Communication System

NI Modulation Toolkit

- Generate Bits
- Source Coding
- Channel Coding
- Modulation

NI USRP

Pulse Shaping

NI USRP

NI Modulation Toolkit

- Downconversion
- Demodulation
- Equalization
- Channel Decoding
- BER Measurement

Matched Filter

Constellation Plot

ni.com
Communications Design in LabVIEW
LabVIEW Modulation Toolkit

- Analog and Digital modulation formats
  - AM, FM, PM
  - ASK, FSK, MSK, GMSK, PAM, PSK, QAM
  - Custom
- Visualization
  - 2D and 3D Eye, Trellis, Constellation
- Modulation Analysis
  - BER, MER, EVM, burst timing, frequency deviation, ρ (rho)
- Impairments
  - Additive White Gaussian Noise (AWGN)
  - DC offset, Quadrature skew, IQ gain imbalance, phase noise
- Equalization, Channel Coding, Channel Models
Programming Demo

PSK PHASE SHIFT
RECEIVE AND DECODE COMPLEX IQ
ADDITIONAL DEMOS
DEMO

FM RADIO
Decode & Hear Live FM Radio
DEMO

PACKET BASED TRANSCEIVER
Packet Based Transceiver

Packet Transmitter

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, 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.

Packet Receiver

Received 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, 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.
NI PXI RF & NI USRP

Case Studies and User Solutions
NI PXI RF
NI RF and Communications Market

Communications Design
- Low Cost
- Flexible
- Portable
- Radio

RF Test & Measurement
- Calibration
- Low Phase Noise
- Precise measurement
- Real-time
- High Bandwidth

ni.com
The networking and connectivity subsidiary of Qualcomm, Inc.

Leading provider of wired and wireless technologies

Serving mobile, computing, consumer electronics and networking channels

802.11ac Device Block Diagram

- 11ac Radio Front End
- WLAN RF
- CPU and Memory SOC, MAC and PHY
- Synthesizer
- Power Management
- GPIO
- PCIE
- 3.3 V
- REF CLK/Crystal

2.4/5 GHz
RF Standards—Increasing Complexity

802.11a + b + g
- Over 30 Channels
- 20 Modulations
- 1 Filter Width
- 1 Spatial Stream

100+ Combinations

+ 802.11n
- Over 50 Channels
- 28 Modulations
- 2 Filter Widths
- 4 Spatial Streams

1,000+ Combinations

+ 802.11ac
- Over 100 Channels
- 38 Modulations
- 4 Filter Widths
- 8 Spatial Streams

10,000+ Combinations
Software – Designed Approach

Traditional Approach:
The majority of the time is spent communicating to instruments.

- Communicate to VSG to Generate Stimulus
- Settling Time
- Acquire Data
- Query VSA for Measurement Results

FPGA-Based Approach:
Instrument communication time is negligible.

- Communicate to VSG to Generate Stimulus
- Settling Time
- Acquire Data
- Query VSA for Measurement Results

Elapsed Time (Repeat 5-7 Times)
NI PXIe-5644R Hardware Front Panel

**RF Input**
- 65 MHz – 6 GHz
- 80 MHz BW

**RF Output**
- 65 MHz – 6 GHz
- 80 MHz BW

**Reference In/Out**
- Always keep the calibration cable connected

**Trigger**

**Digital I/O**
- 24 channels
- Up to 250 Mbps
- Additional triggering

**LOs In/Out**
- Independent
- In & Out
- MIMO Support
Vector Signal Transceiver/Device Under Test Integration

Qualcomm Atheros 802.11ac Device Under Test

Digital Device Control

VSA
VSG
Digital I/O

ni.com
EVM* (dB) vs. Average Output Power

Traditional Instrumentation

NI PXI Vector Signal Transceiver

“At Qualcomm Atheros, instrumentation flexibility and to-the-pin control are critical for keeping our RF test process as efficient as possible, and we're pleased with the performance gains we've seen when testing with NI's new vector signal transceiver.”

Doug Johnson, Director of Engineering at Qualcomm Atheros
### Digital Communications Labs
by Dr. Robert Heath, UT Austin

1. AWGN Simulator
2.1 Modulation / Demodulation
2.2 Pulse Shaping
3. Energy Detection
4. Equalization
5. Frame Detection
6. Intro to OFDM
7. Frequency Correction & Sync
8. OFDM Channel Coding

(Ships in Bundle)

### Communications Systems Labs
by Dr. Sachin Katti, Stanford

1. Source Coding
2. Packet Communication, Sync, and Channel Correction
3. Modulation
4. Demodulation
5. Design Challenge: Packet based Transceiver

(FREE: ni.com/courseware)
NI USRP at Stanford University

Student Course Feedback:

“Awesome class! I really enjoyed the lectures, where I learned a lot, and the labs were really cool because we got to use the hardware. … I am glad that I took this class!”

Source: Stanford EE 49: Teaching Evaluations (Spring Quarter 2011)
Needs:
• Exposure to real-world signals
• Recruit students to RF/Communications early
• Prepare students for research

Solution:
• SDR Platform
• Lower learning curve
• Maintainable
• Affordable

“The course evaluations for our class was fantastic. Students rated the class 4.94/5.0, likely one of the highest ratings among all classes in the School of Engineering at Stanford.”

Dr. Sachin Katti, ECE

Stanford, CA
NI USRP Research Case Study:
Cognitive Radio & Whitespace

LabVIEW Graphical System Design
• Spectral sensing with blind detection
• GPS geographic localization
• Adaptive spectrum utilization

“LabVIEW software and the NI USRP hardware are key components of this research project, allowing the team to rapidly prototype and successfully deploy the first cognitive radio test bed of this kind.” Dr. Paulo Marques, COGEU

Aveiro, Portugal
MIMO Radio Prototyping

- Plug and play 2x2 MIMO
- Driver based synchronization
- Reference designs available
  - Maximal Ratio Combining
  - Alamouti Coding
6x6 MIMO Testbed
NI USRP Research Case Study: NI USRP 8x8 MIMO Testbed

- Adaptable from 2x2 to 8x8
- Algorithm design in MathScript RT
- 128 subcarrier OFDM, 4 QAM, spatial diversity
- Independently clocked, phase coherent Tx & Rx

Dr. Robert Heath
Director WNCG
University of Texas at Austin
 NI USRP Research Case Study: Physical Layer Prototyping

- Continuously monitoring multiple wifi channels
- Demodulation and descrambling of 802.11b beacon signals
- Identification of hotspots, tracking relative power levels

802.11b SSID Decoding

- Carrier Detection
- Frequency Offset Estimation & Correction
- Demodulation & Descrambling
- Interpret the frame for SSID
NI USRP Research Case Study: Algorithm Research

Cleaning Up “Dirty RF”

Established a live, over-the-air communication OFDM link

- 1024 subcarriers
- 256-QAM modulation per subcarrier
- bit rate of about 1.4 Mbps on laptop

LabVIEW host-based VIs

- Imported m-file scripts
- Extensive use of Mathscript RT
- ~2 month timeframe
- reducing project time by 2/3

ni.com
256-QAM, 1024 Subcarrier OFDM using USRP

TU-Dresden
Vodafone Chair Mobile Communications Systems
jan.dohl@ifn.et.tu-dresden.de

XY Graph

USRP Rx IP
192.168.10.7

Rx Parameters:
Rx IQ Sampling Rate (s/sec) Rx Frequency [Hz]
2000000000

25 MHz

Rx Gain [dB]
0 dB

Rx Antenna
RX1
NI USRP Research Case Study: Position Detection & Localization

- Testing MUSIC direction finding algorithm
- Rapid prototyping in LabVIEW with MathScript RT
- Synchronized up to 12 USRP devices
- Reference provides continuous phase alignment compensation

Direction Finding (uniform linear array)
Research: Downloadable Reference Designs

8x8 MIMO - OFDM

RF Record & Playback

ni.com/usrp

RF Direction Finding & Localization

ni.com