Analysis and Evaluation of Register Transfer Logic Software Defined Radio Performance

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MQP Final Presentation

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Software-Defined Radio (SDR)

• Modern radio with some hardware controlled by software
  – Software implementations of filters, modulators, amplifiers, etc.

• Easily reprogrammable to adjust parameters
  – Center frequency, input gain, modulation, etc.

• Can be used for various purposes
  – Communication systems
  – Signal transmission
  – Message reception

Image Sources:
http://wwwrtl-sdr.com/
https://www.ettus.com/
http://www.nooelec.com/
http://www.sqdeal.com/
SDR Aircraft Application

- Aircraft Transmissions
- Electronic Surveillance
- Software-Defined Radio Receiver
- Geolocation
- Software-Defined Radio Receivers
# Software-Defined Radio Comparison

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Focus of this brief
Outline

• Introduction
• Background
  – The USRP and the RTL-SDR
  – USRP and RTL-SDR Comparison
  – Multi-Channel RTL-SDR System
• Standalone SDR Performance Testing
• Multi-Channel RTL-SDR System
• Conclusion
## The USRP and the RTL-SDR

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<tr>
<td>• Commercial grade SDR</td>
<td>• DVB-T television tuner and other hardware on USB dongle</td>
</tr>
<tr>
<td>• Supported by Ettus Research and National Instruments</td>
<td>• SDR receiver supported by open-source community</td>
</tr>
<tr>
<td>• Relatively expensive compared to RTL-SDR</td>
<td>• Inexpensive alternative for hobbyist radio users</td>
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![Ettus USRP](image1.png)  
![RTL-SDR](image2.png)
# USRP and RTL-SDR Comparison

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The hobbyist RTL-SDR was compared against the commercial USRP.
Multi-Channel RTL-SDR System

- Implement clock-synchronized RTL-SDRs in multi-tuner system
  - System clock oscillators physically connected
  - Increases possible reception bandwidth
  - Allows for simultaneous signal analysis through multiple channels

Image Source: https://ptrkrysik.github.io/
Outline

- Introduction
- Background
- Standalone SDR Performance Testing
  - Received Sample Ratio
  - Noise Floor
  - Frequency Coverage
  - Frequency Response
- Multi-channel RTL-SDR System
- Conclusion
Performance Testing

• Compare RTL-SDR performance with commercial SDR
  – Hobbyist: NooElec, SQdeal, and RTL-SDR Blog RTL-SDRs
  – Commercial: Ettus USRP X310 with UBX-160 daughterboard

• Test performance characteristics
  – Received sample ratio
  – Noise floor
  – Frequency coverage
  – Frequency response
Received Sample Ratio Test

- Run RTL and USRP test scripts on RTL-SDRs and USRP
  - Test at various sample rates from 2.0 MHz to 3.2 MHz
  - Record number of dropped samples per number of total samples

- Perform calculations and plotting in MATLAB
  - Calculate received sample ratio
  - Plot received sample ratio of SDRs across sample rate range
Received Sample Ratio Results

- All RTL-SDRs have nearly identical performance
- RTL-SDRs maintain perfect performance through 2.85 MHz
- USRP maintains perfect received sample ratio performance through sample rate of 2.85 MHz.
Noise Floor Test

- Collect magnitude data from SDRs through GNU Radio
  - Collect CW input from signal generator
  - Test at constant sample rate of 2.0 MHz and frequency of 895 MHz
  - Store calibration data to file at amplitudes from -105-10 dBm

- Perform calculations and plotting in MATLAB
  - Calculate mean recorded magnitude from each data file in dBm
  - Plot mean recorded magnitude from SDRs versus input magnitude
Noise Floor Results

- RTL-SDRs noise floors about -60 dBm
- USRP noise floor lower at about -85 dBm
- Theoretical noise floor $N = kTB = -111$ dBm
  - Recorded noise floors much higher due to lack of LNA

RTL-SDR has noise floor about 25 dB higher than noise floor of USRP.
Frequency Coverage Test

• Collect magnitude data from SDRs through GNU Radio
  – Collect CW input from signal generator
  – Test at constant sample rate of 2.0 MHz and amplitude of -20 dBm
  – Store data to file at frequencies from 24 MHz to 1766 MHz

• Perform calculations and plotting in MATLAB
  – Calculate mean recorded magnitude from each data file in dBm
  – Plot mean recorded magnitude of SDRs across frequency range
Frequency Coverage Results

- RTL-SDR signal always above noise floor from 50-1600 MHz
- USRP signal well above noise floor across frequency range
- RTL-SDR SNR about 30-40 dB, USRP SNR about 55-65 dB

RTL-SDR can reliably match USRP frequency coverage performance between 50-1600 MHz.
Frequency Response Test

- Collect IQ data from SDRs through GNU Radio
  - Collect 50-kHz-bandwidth input from signal generator
  - Test at constant sample rate of 2.0 MHz and amplitude of -20 dBm
  - Store data to file at frequencies from 24 MHz to 1766 MHz

- Perform calculations and plotting in MATLAB
  - Plot Welch periodogram power spectrum estimate of signal
  - Determine 3-dB bandwidth
Frequency Response Results

- ADS-B: carrier frequency of 1090 MHz, bandwidth of 50 kHz
- RTL-SDR 3-dB bandwidth of 49.359 kHz
- USRP 3-dB bandwidth of 49.293 kHz

RTL-SDR frequency response performance comparable to USRP.
Outline

- Introduction
- Background
- Standalone SDR Performance Testing
- Multi-Channel RTL-SDR System
  - Multi-Channel Hardware Implementation
  - Rise Time Testing
  - Two-Channel Phase Testing
- Conclusion
Multi-Channel Hardware Implementation

- Successfully built two-channel and three-channel RTL-SDR
- System clock oscillators connected physically
- Verified to work and collect samples
Two-Channel Rise Time

- Two-channel RTL-SDR system used
  - Each RTL-SDR identically configured
  - RTL-SDRs turned on to capture data
  - Signal generator turned on and then off after 1-2 seconds

![Multi RTL-SDR]

**Magnitude**

**Time (μsec)**

- RTL-SDR Channel 1
- RTL-SDR Channel 2
Two-Channel Rise Time Correction

- Record timestamp when first sample was received over USB
- Shift lagging dataset by the time difference (images below)
- Improved results but still inconsistent (.175 ms -> 4.26 ns) (avg: 40 ns)
  - Most likely caused by USB

In order for a multi-channel system to work, a method of synchronization must be used to correlate the two signals.
Two-Channel Phase Testing

- Identical configuration of two-channels
  - Center Frequency: 895 MHz
  - Sample Rate: 2 MHz
  - Turned on at same time
  - Each collect 5 seconds worth of samples

- Signal Generator
  - Output a 895.05 MHz sine wave (50 kHz sine wave at baseband)
  - Amplitude of -10 dBm

- Find beginning of 50 kHz sine wave in each
  - Band-pass filter w/ Interpolation
  - Find the peaks and see the difference between locations in two signals
Two-Channel Phase Results

- Two-Channel RTL-SDR was within 350 ns for 50 ms
- Standard deviation consistently near 300 ns
- Our peak algorithm was inconsistent at aligning peaks
- Sub-sample standard deviation (interpolated x10)
  - Green bars correspond to one sample
Outline

- Introduction
- Background
- Standalone SDR Performance Testing
- Multi-Channel RTL-SDR System
- Conclusion
  - ADS-B Reception Example
  - Summary
  - Future Work
ADS-B Reception Example

- Idealized Radar Range Equation for SDR Receiver
  - \[ SNR = 10 \cdot \log_{10}(\frac{(P_T \cdot c^2)}{((4\pi)^2 \cdot f_0^2 \cdot R^2 \cdot k \cdot T_0 \cdot B \cdot F_n)}) \] dB
  - \[ C = 3 \times 10^8 \text{ m/s}, \ k = 1.38 \times 10^{-23} \text{ J/K}, \ T_0 = 290 \text{ K} \]
  - \( f_0 \) is ADS-B signal carrier frequency (1090 MHz)
  - \( B \) is bandwidth of receiver (2 MHz)
  - \( F_n \) is receiver noise figure (8 dB for USRP, 13.6-17 dB for RTL-SDR)
  - \( R \) is radar range, \( SNR \) is signal-to-noise ratio at receiver
Summary

- Tested standalone performance of RTL-SDR Vs. USRP

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<td>2.0-3.2 MHz, at Least</td>
<td>2.0-2.85 MHz</td>
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<tr>
<td>Sample Ratio</td>
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<td></td>
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<tr>
<td>Noise Floor</td>
<td>~85 dBm</td>
<td>~60 dBm</td>
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<td>Frequency Coverage</td>
<td>24-1766 MHz</td>
<td>50-1600 MHz</td>
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<td>Frequency Response</td>
<td>Accurate Bandwidth</td>
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- Developed and tested multi-channel RTL-SDR systems
  - Built two-channel and three-channel clock-synchronized systems
  - Developed rise time delay correction procedure
  - Determined phase delay deviation between channels
Future Work

• More advanced signal processing for phase testing
• Wideband reception through multi-channel RTL-SDR system
• Over-the-air reception through multi-channel RTL-SDR system
• Geolocation with three-channel RTL-SDR system
• Implementation of larger multi-channel RTL-SDR system
Acknowledgements

• Group 108
  – Lisa Basile
  – Matt Beals
  – James Burke
  – Sarah Curry
  – Andrew Daigle
  – Josh Erling
  – Bob Giovannucci
  – Chris Massa
  – Dave McQueen
  – Vito Mecca
  – John Palmer
  – Michael Stillwell
  – Jeremy VanSchalkwyk

• Lincoln Lab MQP Program
  – Emily Anesta, Sarah Curry, Seth Hunter and Katie Haas
  – Professor Clancy
Thank You

Questions?
Clock Stability Testing

• Tested NooElec RTL-SDR and SQdeal Mini USB RTL-SDR
  – Found time interval error
  – Analyzed frequency of oscillator

• NooElec showed better performance due to temperature controlled oscillator
  – For time interval test the time variance was around half of SQdeal
  – Frequency yielded NooElec’s range was around half of SQdeal

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<th>Std Dev</th>
<th>Max Lag</th>
<th>Max Lead</th>
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<tbody>
<tr>
<td>NooElec NESDR Mini 2+</td>
<td>56.00ps</td>
<td>193.33ps</td>
<td>180.00ps</td>
</tr>
<tr>
<td>SQdeal Mini USB RTL-SDR</td>
<td>98.71ps</td>
<td>315.00ps</td>
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NooElec oscillator chosen as source for three-channel RTL-SDR system.
Three-Channel Time Histogram

Three-Channel Time Error

Interpolated Time Error (ns)

Occurrences
Two-Channel RTL-SDR System