# PERFORMANCE CHARACTERIZATION OF USRPs

Gayathri Ramasubramanian (Virginia Tech, USA, gramasub@vt.edu),
Carl B. Dietrich (Virginia Tech, USA, cdietric@vt.edu)

***Abstract*—This paper presents transmitter and receiver characterization and calibration results for software defined radio systems designed using the combination of RF front end hardware like USRPs (from Ettus Research) and software interfaces like GNU Radio. The main motivation for this study was the lack of useful references pertaining to calibration of such SDR systems, confining them to proof of concept experimentation. Measurements were taken using an SDR system designed using the USRP N210 with WBX daughterboard, GNU Radio utilities, and laboratory instruments. The main aim was to determine the differences between the values obtained on the GNU Radio spectrum analyzer software GUI utility and a laboratory spectrum analyzer. One-dB compression point, Third order Input Intercept point, and transmitted power variation with gain were measured to determine calibration factors and offsets. Experiments were conducted over sample set of USRP N210 devices to get standardized values. The calibration factors thus obtained were used in indoor path-loss modeling and position location estimation using the CORNET nodes at Virginia Tech to determine their effectiveness. As expected the root mean square deviations from expected values were lower when calibration factors were used to correct the power measurement readings from the GNU Radio utilities.**

***Index Terms*—Calibration, Characterization, USRP N210.**

## I. INTRODUCTION

Software Defined Radios (SDRs) have brought many advantages to wireless communications such as improved interoperability, technology adaptation capability as well as the potential for future proof hardware and programming flexibility through use of multiple processing devices like GPP and FPGA.

SDR systems have successfully shifted much of radio signal processing from the analog to the digital domain. Laboratory friendly RF front end hardware such as the Ettus Research Universal Software Radio Peripherals (USRPs) devices, used in combination with PCs and with software interfaces such as GNU Radio, provide a researchers with the ability to design and prototype SDR systems. However, a major limitation of use of these devices is that they are un-calibrated in terms of power or voltage and hence give the results in relative terms/counts, rather than in standard units such as milliwatts, dBm, and/or millivolts. Characterization of SDR RF front end performance, including variability among multiple devices of the same model, is necessary to ensure that these devices are not confined to proof of concept implementation and demonstrations, and to realize more fully their potential utility for experimentation. **[1]**

USRP and GNU Radio tutorials and wiki links **[2] [3]** proved useful in understanding the working of hardware and software signal processing utilities and experimenting with them. Previous research work in this area done by Terrence J. Brisebois [**4**] and Michael Maxwell Hill [**5**] provided insight into performance and capability measures of the GNU Radio - USRP combination, but one of the major drawbacks evident from the literature review seemed to be the lack of information on effective calibration of the USRP devices, creating an inability for the results to be related and understood in terms of real world metrics **[6]**. This limits their utility for rigorous experimentation.

Many questions appeared to be unanswered but are very much a requisite in case USRPs are to be used as standard radio front ends for software defined radio systems. Some are: Can USRPs be characterized using any standard methods? Is there a significant variation among the USRPs units of the same model and daughter board combination? Is there any variation between different USRP models and daughter board combinations? Is there a possibility to derive standard factors or look up tables for the calibration of each USRP- daughterboard combination? Is the calibration specific to the software utility used or would it be standard across different utilities and different software packages? Practical applications like position location estimation based on received signal strength (RSS), e.g., triangulation and received signal strength difference of arrival techniques, would require precise received power measurement so as to be able to characterize the channel correctly, model the path loss accurately and reduce the error in position estimation.

The main aim of this experimentation was to obtain a relation between the readings obtained on a spectrum analyzer utility provided as part of the GNU Radio Companion (GRC) development environment with the real world metrics like dBm for power **[6]**. A software-defined radio was implemented using the USRP N210 with the GNU Radio software. The RF daughter boards used for the tests were mainly WBX transceiver boards with a broad frequency range from 50 MHz to 2.2 GHz. Characterization tests like the received power stability test, the transmitted power and frequency stability tests were done and the values obtained were studied in order to understand the difference in the value on UHD_FFT.grc graph and the dBm metric value obtained on the Tektronix spectrum analyzer, when the same experiments were conducted with it. Next the correction factors for various parameters like power, frequency were utilized in an application like position location estimation and indoor multi-floor path loss modeling in order to check if there was any improvement in the estimated values with regard to expected results. **[1]**

In Section II we detail the main idea behind this research and its methodology while in Section III we describe the experimental configurations and procedures, test background and parameters used for the pivotal TX and RX characterization tests resulting in calibration metrics. In Section IV we describe the experimentation procedure for indoor path-loss modeling on Virginia Tech's cognitive radio network (CORNET) test bed **[7]** and consider position estimation as a direct application for the power calibration metrics along with the results, wherein the results obtained are compared with the actual expected results and conclusions are drawn. In Section V we conclude by summarizing the overall intent along with the outcomes.

## II. Hardware and Software Requirements

The SDR system used in these measurements was built out of commonly used hardware and software. The device under test was the USRP N210 with WBX boards **[8]**. This allowed obtaining calibration factors for the highest performing USRP hardware available to us at the time of the measurements. The sample set consisted of 10 such USRP N210 units. Since the WBX Daughter boards were used with the USRP N210(s) for the experiments (which allow operation in 50 MHz to 2.2 GHz range **[9]**) the experiments were performed at 400 MHz, 900 MHz and 1.8GHz so as to enable learning and generation of calibration factors in 3 ranges – low, mid and high frequencies. A Linux based system with Ubuntu 12.10, 64 bit operating system operated as the Host system. A Debian based system was preferred as it has been used extensively with the GNU Radio software. GNU Radio software downloadable files are available from the GNU Radio website **[2]**. They usually provide software releases supported by LINUX distribution system. The GNU Radio / GNU Radio Companion version used was 3.6.4.1 with GNU C++ version of 4.4.3. UHD Firmware or the "USRP Hardware Driver" that provides driver interface and API for ETTUS Research products was installed. The version used was UHD_003.005 compatible with GNU radio version 3.6.4.1 and Ubuntu 12.10 **[10]**.

Since a set 10 similar USRP N210(s) were available and therefore were used as a sample set, the values obtained per USRP per test could be easily averaged over assuming uniform behavior. But for the purpose of comparisons, the same tests were performed on a USRP 2 with WBX board and USRP N210 with SBX board.

However the calibration factors thus obtained needed to be verified through practical applicative experiments. Path-loss modeling and Position Estimation using RSS were taken up for this purpose **[11] [14]**.

For receiver characterization, the GNU Radio GUI spectrum plot utility UHD_FFT.py was used; the USRP was studied across different units and the variation, if any, was noted. Similarly for the transmitter side, the UHD_SIGGEN.py utility was used along with a standard laboratory spectrum analyzer.

The USRP N210 was operated under the recommended power specifications i.e. under +20 dBm when used as a transmitter (TX) and maximum received power of -10 dBm at any of the ports (RF1/RF2) when operated as a receiver (RX) **[12]**.

## III. Main RX and TX characterization tests for Calibration

A system block diagram of the experimental setup is shown Figure 1 along with photo of the laboratory setup for RX characterization in Figure 2. The main devices consist of the spectrum analyzer for output signal measurement, Agilent signal generator as a standard signal source. The host system connects to USRP and enables it to either perform transmit or receive operations by executing the in-built application programs like UHD_SIGGEN.py, UHD_FFT.grc or the custom flow-graphs of GNU radio.

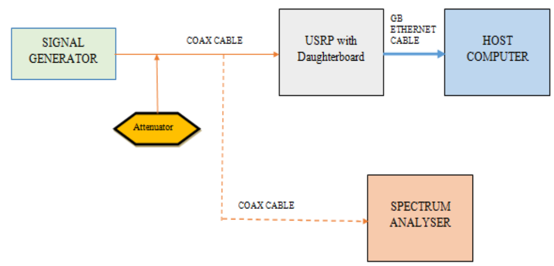


Figure 1. Block diagram of for Receiver characterization tests

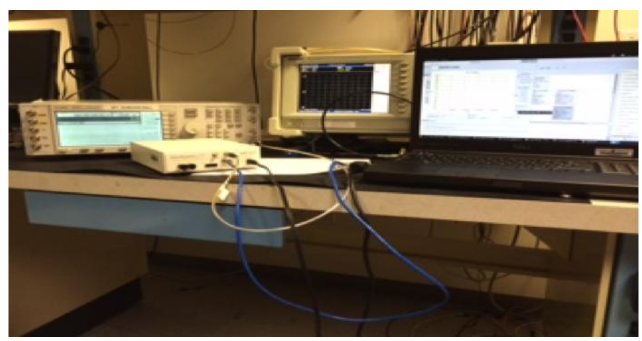

Figure 2. Laboratory set-up for Receiver Characterization tests

### a. The 1-dB Compression Point Test

Usually a power amplifier's linearity, efficiency and quality can be judged well by two key measurements which are 1 dB Compression point (1-dB CP): and third-order Input Intercept point (IIP3).

The 1-dB compression point of a device is a measure of its linear range. The output of the device driven with a good input signal first increases as its input signal increases. However, for sufficiently powerful input signals, the output signal will not increase proportional to the input signal increase. At this stage the device output is said to start compressing and the gain decreases; the output approaches a limit that is not exceeded regardless of further increases in input signal power. The point when the decrease in output signal gain equals 1 dB with increase in input signal is called the 1 dB compression point, generally denoted as 1-dBC or 1-dB CP **[16][17]**.

This point has a major significance in the behavior of the device and the expected output. As long as the device is operated below the 1-dBC point, the output of the device would be approximately proportional to the input factoring in the external gain and attenuation applied. However, when the 1-dBC point is passed, the output signal would be distorted and further increase in input would lead to spurious signals or inter-modulation products. In general, spurious signals could result in interference of the transmitted signal with other signals and hence the device is best operated well below the 1 dB compression point. Thus the knowledge of this metric greatly helps in avoiding any undesired/unexpected behavior from a device. The 1-dBC point is generally seen to be 10 dB below the 3rd order intercept point of the device **[16] [17]**.

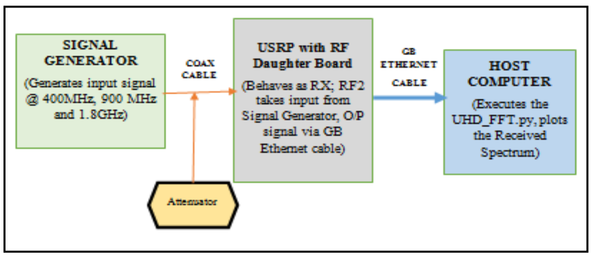


Figure 3. Block Diagram of 1-dB Compression Point Test

The variation of output power Pout measured on UHD_FFT against the input power from signal generator was linear until this point (Pin= -10 dBm) for all the devices.

Table 1. Average Offset to be subtracted from UHD_FFT.grc power reading to obtain actual power in dBm as measured with a spectrum Analyzer

| USRP Type | Average Received Power offset b/w UHD_FFT and Spectrum Analyzer | | |
|---|---|---|---|
| | 400 MHz | 900 MHz | 1800 MHz |
| | | | |
| USRPN210 + WBX board | 35.54 | 31.24 | 23.57 |
| | | | |
| USRPN210 + SBX board | 32.19 | 24.43 | 20.54 |
| | | | |
| USRP2 + WBX Board | 32.90 | 32.04 | 26.67 |

### b. The IIP3 test

The IIP3 point or the third order input intercept point is the theoretical point at which the inter-modulation products and the fundamental tones meet and are at the same output power level. Thus the IIP3 is a good measure of the linearity of the USRP. The higher the IIP3, more liner is the device. Or in other words the device is linear over a longer range of amplitude of the input signal if it has a higher IIP3 value **[18].**

Analytically the IIP3 point can be calculated using the formula **[16] [18]**:

$$IIP3 = P_{in} + \frac{PF1 - PIMD}{2} \qquad (3.1)$$

As Pin and $P_{F1}$ / $P_{F2}$ are 1:1 proportional, it could also be written as:

$$IIP3 = P_{F2} + \frac{PF1 - PIMD}{2} \qquad (3.2)$$

$P_{F1}$ and $P_{F2}$ are interchangeable provided they show equal amplitudes. It applies for IMD products 2 F2 - F1 and 2 F1 - F2 frequencies as well.

The $OIP3$ point is simply given as:

$$OIP3 = IIP3 + Gain \qquad (3.3)$$

Another important thing to note is that point of convergence of fundamental and inter-modulation products' power level is purely theoretical, as the device is never pushed to that point. It would get severely damaged if done so, and moreover there would be internal system breaks placed to avoid this i.e. the device would saturate **[16].**

One more important relation is that of $1 - dBCP$ and $IIP3$. It is as given below **[17]**:

$$IP3 = 9.6\,dB + 1 - dBCP \qquad (3.4)$$

where $IP3$ is the Third Order Intercept Point. So generally the 3rd order intercept point should be ~10 dB higher than the 1 dB compression point of the device. The basic block diagram of the hardware setup is as shown below.

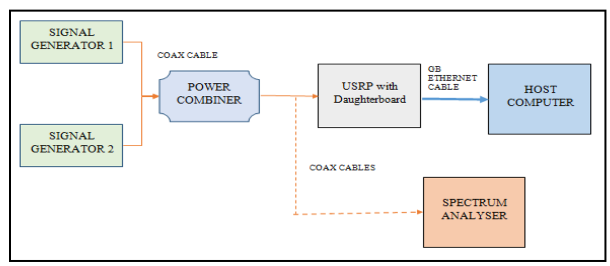


Figure 4. Block Diagram for IIP3 test

The OIP3 point of the device (USRP N210+WBX) was found to be around 1.96 dBm while the IIP3 was found to be ~ 2.3dBm graphically at 400 MHz. This was using the calibration value found using the 1 dB compression point (1 dB CP or 1dBC point) test of 35.5 as the difference between the UHD_FFT.grc plot reading and the actual spectrum analyzer reading for a given input power from the Agilent Signal source at 400 MHz. However in this test the power combiner apparatus leads to a loss of ~ 4dBm and hence the effective gain or calibration factor used is = -35.5 +4 = -31.5 dBm. This was for test conducted at 400 MHz. The readings of IMD @ 400.7 MHz were calibrated with just the loss of 4 dBm as other correction factor of 35.5 is valid only in linear range.

Using the relation that IP3 needs to be around 10 dBm higher than 1 dB CP, we can now estimate the I-dBC point at 400 MHz. At 400 MHz, IIP3 is 2.8 dBm , this implies 1 dB CP has to be approx 2.3- 10 = - 7.7 dBm, which seems a likely value as the USRP N210 displays linear characteristics until -10 dBm. Using the OIP3 value at 400 MHz of 1.96 dBm we get the 1 dBC point as 1.96-10 = -8.04. dBm which again close to the estimate and predicted value. Similarly at 900 MHz the IIP3 was found to be 5.6 dBm. Hence the 1 dBC point can be estimated to be around 5.6 - 10 = -4.4 dBm.

Analytically also, the average IP3 found for 8 devices is found to be ~ 0.25 @ 400 MHz and 3.95 dBm at 900 MHz. There were large deviations in readings of certain USRP N210 devices, which may be attributed to the individualistic conditions of the device and to the fact that readings were prone to human error. At 1800 MHz for USRP N210 device with WBX board, the IIP3 point was found to be ~ -2.46 dBm analytically, and hence 1 dB CP can be estimated to be around -2.46-10 = -12.46 dBm

### c. Transmitted Signal Variation with Tx Gain Test

The gain range of a daughter board is the maximum allowable gain for the transmitted signal. This in turns affects the maximum power that can be transmitted by the device under the given set of conditions. Observing the variation of the output power with respect to the transmitter gain would help understand the transmitted power from these USRP devices which by fact are said to be un-calibrated devices undergoing various stages of amplification before being fed to the DAC. This would also enable learning of the linear range of the device when behaving as a transmitter.

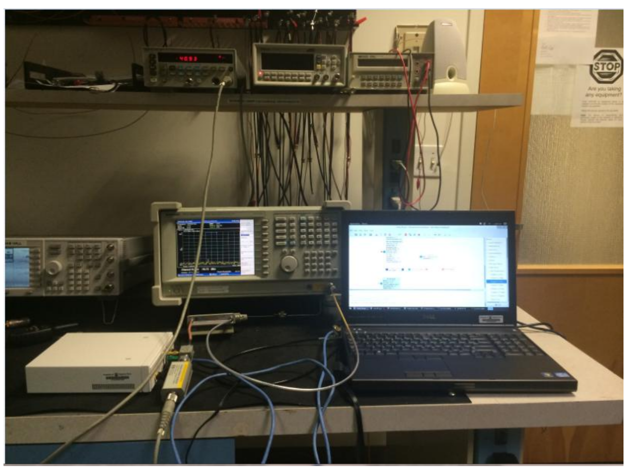

Figure 5. Laboratory set-up for TX characterization

The setup for this test is similar to most of the Transmitter characterizations test. The device is connected to the host laptop using a gigabit Ethernet connection. The Tx (RF1) port's output is fed to a power splitter. One output port of the power splitter fed the spectrum analyzer while the second output port was connected to a power meter. A power meter enables more accurate reading of the power as it measures the power over the entire signal bandwidth. The measured readings were tabulated and studied to understand the effect of gain on the output power and linearity of the device. Single tone and two tone tests were conducted for this purpose on the USRP N210 device with WBX board and USRP N210 device with SBX board as this is mainly dependent on the gain of the daughter board.

## IV. Impact of Obtained Calibration Factors

The prevalence of wireless protocols standards like Wi-Fi and Bluetooth has increased interest in indoor path loss modeling and propagation characterization. Intra-vehicular propagation modeling and channel characterization using 5 GHz band **[13]** is also an active research area.

Path loss modeling allows study of methods to estimate and minimize effects of path loss and enables the design of systems for robust communication in most anticipated operating environments.

Another application causing much interest in wireless communication is position location estimation. Though there are different methods of determining the position of a transmitter using metrics like transmitted signal's Angle of Arrival, Time of arrival etc, and Position location using Received Signal Strength (RSS) is one of the simplest methods, with low receiver end processing, and is also applicable to indoor wireless systems. Algorithmic approaches like RF fingerprinting have led to more deterministic evaluations of the sensor positions with low error coefficient **[19]**.

Here, the CORNET test bed at Virginia Tech was used to perform path loss measurements across multi-floors to determine the path-loss exponent best suited for such signal propagation. The basis of the methodology was the research done on 914 MHz and 2.4GHz bands previously for indoor propagation [**14] [15]**.

The position location experiment was performed using the Received Signal Strength (RSS) and Combined Differential Received Signal Strength (CDRSS) methodology **[11] [20]**. The main aim amongst these experiments was to show that the calibration factors obtained from the characterization experiments helped to gain closeness to real-world practical values, while the values taken directly from the UHD_FFT.grc GUI plot do not give any meaningful results.

It is important to understand that the multi-floor path loss calculation on the CORNET Test bed and the Position location experiments were conducted indoors. Hence the received power would not be affected as in the typical free space manner and would need to be handled differently. In both the experiments the Received Signal Strength is the important measure for the calculation and the correction factors were mainly applied to that.

### a. Path Loss Modeling Test

The CORNET nodes were used to conduct the path loss tests. On the HOST PC, two terminals were opened for remote logging into the CORNET. One of the nodes connected was chosen as the transmitter. The UHD_SIGGEN.py with the following parameters was run at this terminal: -f 460e6, -x 1e3, -s 1e6, amplitude=0.707.The second terminal was used to establish a secure shell (ssh) connection to another node, which was the receiver node, which ran the UHD_FFT.grc, flow graph. The center frequency of UHD_FFT was tuned to 460 MHz to avoid phase noise error. The value of power was noted down for this pair of TX-RX. Next the receiver node connection was closed and the terminal was used to ssh into another one of the remaining nodes. The steps were repeated for every working node in CORNET keeping the transmitter node constant across the floors. For each TX-RX node pair, the actual path loss was calculated using simple power subtraction. Using this path loss value, the path loss exponent was calculated using the log-distance path loss formula. PL (@ 1m) was taken to be 25 dB. The theoretical path loss was calculated using the ITU model **[14] [15]**.

$$PL = 10*\log(f) + 10*n*\log(d) - 28 \quad (4.1)$$

Keeping the path loss exponent ‘n’ unknown, using trial and error different values (starting from 2 to 5) were substituted so as to get the theoretical PL close to practical PL. This was done for the value of the received power from UHD_FFT.grc with and without the correction factor (taken as 35.5 for 450 MHz). It was seen that path loss exponent came to a value ~ 5 (close to and as expected from the multi-floor indoor path loss exponent calculated at 914 MHZ and 2.4 GHz) **[14] [15]**. When received power was used without correction factor, the path loss exponent came to a value between 1 and 2 (for same and one floor above). This is not as per expectations. Hence through this experiment it was seen that calibration factor helps to get values closer to expected real world metrics. The floor attenuation factor that was calculated as a part of the path loss experiment also gave values similar to those obtained in **[14] [15].** The FAF is given by:

FAF = PL_c – PL (same floor);

Where: PL_c is calculated path loss and

PL (same floor) = PL (d0) + 10*n (same floor)*log (d).

Path loss can be calculated at a distance using either multi-floor exponent value or the FAF in an indoor multi-floor environment, E.g.

PL (30 m) = 25.2 + 10* 6.25*log (30) = 117.5 dBm: multi-floor exponent value used

PL (30 m) = 25.2 + 10*5*log (30) +13.88 = 112.94 dBm: same floor exponent used with FAF (1 floor above) used.

Table 2. Path Loss Calculation with Calibrated Power using CORNET

| Txd Node | Rx node | Power Transmitted (dBm) | Power Received on UHD_FTT (dB) | RX Gain (dB) | Power Received-Correction Factor-Gain (dBm) | Calculated PL (dB) | 20log10(f) (dB) | 10nlog(d) (dB) | K value for the ITU Model (dB) | Theoretical PL (dB) | Path Loss exponent using ITU Model | Path Loss exponent using log-Distance Model |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | |
| **Floor1** | **Floor 1** | | | | | | | | | | | |
| 7001 | 7002 | 15.5 | -7.79 | 15 | -54.99 | 70.49 | 53.06 | 45.25 | -28.00 | 70.31 | 5.37 | 5.37 |
| | 7004 | 15.5 | -35.16 | 15 | -82.36 | 97.86 | 53.26 | 72.06 | -28.00 | 97.31 | 5.75 | 5.80 |
| | 7005 | 15.5 | -28.00 | 15 | -75.20 | 90.70 | 53.26 | 65.02 | -28.00 | 90.27 | 4.80 | 4.83 |
| | 7006 | 15.5 | -37.72 | 15 | -84.92 | 100.42 | 53.26 | 75.02 | -28.00 | 100.28 | 5.10 | 5.11 |
| | 7007 | 15.5 | -30.56 | 15 | -77.76 | 93.26 | 53.26 | 67.58 | -28.00 | 92.83 | 4.25 | 4.28 |
| | 7011 | 15.5 | -45.51 | 15 | -92.71 | 108.21 | 53.26 | 82.78 | -28.00 | 108.03 | 4.60 | 4.61 |
| | | Average n (same floor) | | | | | | | | | 4.98 | 5.00 |
| **Floor1** | **Floor 2** | | | | | | | | | | | |
| 7001 | 7013 | 15.5 | -18.74 | 15 | -65.94 | 81.44 | 53.26 | 55.61 | -28.00 | 80.87 | 6.60 | 6.67 |
| | 7014 | 15.5 | -28.84 | 15 | -76.04 | 91.54 | 53.26 | 65.55 | -28.00 | 90.80 | 6.60 | 6.68 |
| | 7024 | 15.5 | -65.59 | 15 | -112.79 | 128.29 | 53.26 | 102.38 | -28.00 | 127.64 | 5.55 | 5.59 |
| | | Average n (1 floor above) | | | | | | | | | 6.25 | 6.31 |
| **Floor1** | **Floor 3** | | | | | | | | | | | |
| 7001 | 7035 | 15.5 | -73.05 | 15 | -120.25 | 135.75 | 53.26 | 110.25 | -28.00 | 135.50 | 6.10 | 6.12 |
| | 7036 | 15.5 | -66.74 | 15 | -113.94 | 129.44 | 53.26 | 103.46 | -28.00 | 128.71 | 5.60 | 5.64 |
| | | Average n (2 floors above) | | | | | | | | | 5.85 | 5.88 |

Table 3: Floor Attenuation Factor Calculation with Calibrated Power

| Txd Node | Rx node | Power Transmitted (dBm) | Power Received on UHD_FTT (dB) | RX Gain (dB) | Power Received-Correction Factor-Gain (dBm) | Calculated PL (dB) | FAF Model [PL(d0)+10*n(same floor)*log(d)] (dB) | Floor Attenuation Factor (dB) |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| **Floor1** | **Floor 1** | | | | | | **n (same floor) = 5** | |
| 7001 | 7002 | 15.5 | -7.79 | 15 | -54.99 | 70.49 | 67.33 | 3.16 |
| | 7004 | 15.5 | -35.16 | 15 | -82.36 | 97.86 | 87.86 | 10.00 |
| | 7005 | 15.5 | -28.00 | 15 | -75.20 | 90.70 | 92.92 | -2.22 |
| | 7006 | 15.5 | -37.72 | 15 | -84.92 | 100.42 | 98.75 | 1.67 |
| | 7007 | 15.5 | -30.56 | 15 | -77.76 | 93.26 | 104.70 | -11.45 |
| | 7011 | 15.5 | -45.51 | 15 | -92.71 | 108.21 | 115.18 | -6.97 |
| | | Average FAF (same floor) | | | | | | -0.97 |
| | | | | | | | | |
| **Floor1** | **Floor 2** | | | | | | **n (same floor) = 5** | |
| 7001 | 7013 | 15.5 | -18.74 | 15 | -65.94 | 81.44 | 67.33 | 14.11 |
| | 7014 | 15.5 | -28.84 | 15 | -76.04 | 91.54 | 74.86 | 16.69 |
| | 7024 | 15.5 | -65.59 | 15 | -112.79 | 128.29 | 117.44 | 10.86 |
| | | Average FAF (1 floor above) | | | | | | 13.88 |
| | | | | | | | | |
| **Floor1** | **Floor 3** | | | | | | **n (same floor) = 5** | |
| 7001 | 7035 | 15.5 | -73.05 | 15 | -120.25 | 135.75 | 115.57 | 20.19 |
| | 7036 | 15.5 | -66.74 | 15 | -113.94 | 129.44 | 117.57 | 11.86 |
| | | Average FAF (2 floors above) | | | | | | 16.03 |

## b. Position Location Estimation

For position location using RSS, 3 nodes were placed at 3 positions around a standardized transmitter (a signal generator). The position coordinates of the transmitter were assumed to be (0, 0) and the coordinates of the receiver nodes were calculated w.r.t the (0, 0) location **[11]**. The SMA 703 antennas used for the transmitter and receiver nodes. The transmitter was set at -20 dBm, 450 MHz. Executing the UHD_FFT.grc at each of the node terminals and noting down the readings from this graph at each of the nodes measured the power received at the 3 nodes. The received power value from UHD_FFT was used with and without the correction factor and using the least squares method **[21] [22]**. It was seen that the root mean square error value was less when calculated with the calibrated power value than when calculated with the un-calibrated power value, when the experiment was conducted in a semi open area like a big room.

Figure 6. Layout of Room Used for Position Location Experiment

Figure 7. Layout of Corridor used for Position Location Experiment

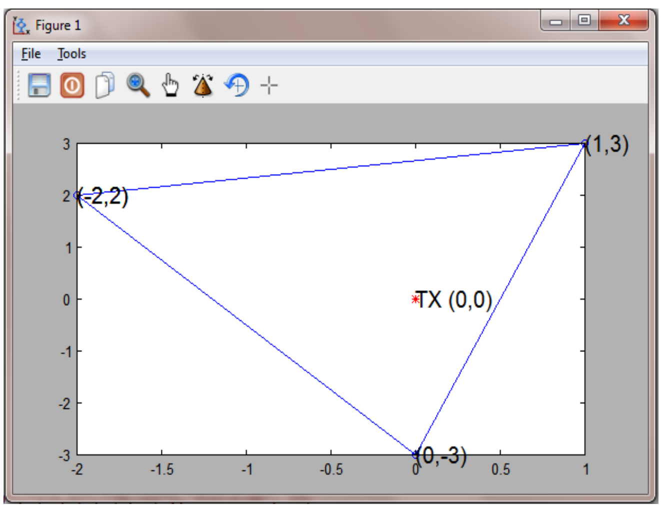


Figure 8. Position of the Receiver Nodes w.r.t Transmitter in Large Room

Table 4. Mean Square Error: Position Estimate in Large Room

| | Root Mean Square Error | |
|---|---|---|
| Number of nodes/ Power | Calibrated Received Power (dBm) | Un-Calibrated Received Power (dB) |
| 3 Receiver Nodes | 0.34 | 0.44 |

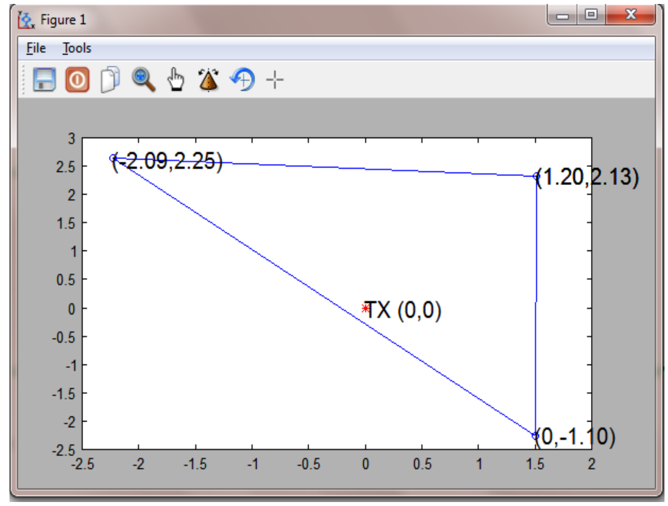


Figure 9. Position of Receiver Nodes w.r.t TX in Corridor, Exp 1

This experiment was also conducted with 5 nodes instead of 3 and it was observed that the root mean square error value is lesser when calculated with 5 nodes than when calculated with 3 nodes by almost 40 %. Hence the accuracy increases with the number of receiver (reference) nodes used in the calculation. This is in line with the basis of the least mean square algorithm.

Table 5. Root Mean Square Error: Position Estimate. in Corridor

| | Root Mean Square Error | |
|---|---|---|
| Number of nodes/ Power | Calibrated Received Power (dBm) | Un-Calibrated Received Power (dB) |
| 3 Receiver Nodes | 0.55 | 0.53 |
| 5 Receiver Nodes | 0.26 | 0.27 |

Since the UHD_FFT.grc does not give the correct power measurement in dBm, this experiment was also again conducted with the QT Frequency Sink GUI utility as this flow graph with QT Sink enables power measurement directly in dBm and hence is more user-friendly. For this experiment the only change was that instead of UHD_FFT.grc, the power_measure_QT_Sink.grc flow graph was executed at the receiver nodes terminals.

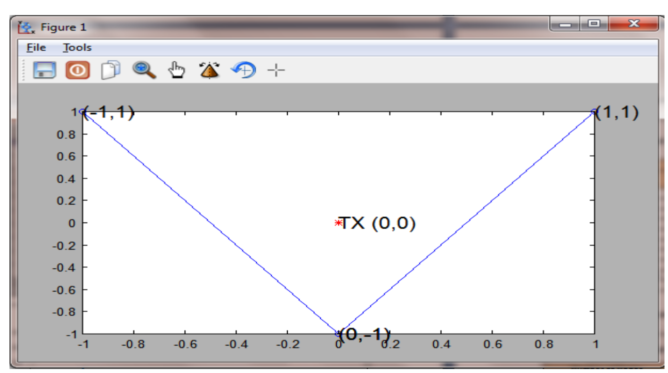


Figure 10. Position of Receiver Nodes w.r.t TX in Corridor, Exp 2

The values measured at the receiver nodes in this experiment were used in Simple RSS based Position Location Algorithm and also in Combined Differential RSS Based Position Location Algorithm **[11] [20].**

Table 6. Root Mean Square Error: Pos. Est. in Corridor (3 nodes, QT Flow Graph)

| Using power_measure_QT_Sink.grc and n = 3.5 | Simple RSS Based Algorithm | | CDRSS Based Algorithm | |
|---|---|---|---|---|
| Number of Nodes | RMSE (m) | | RMSE (m) | |
| | Calibrated | Un-Calibrated | Calibrated | Un-Calibrated |
| 3.00 | 0.26 | 0.46 | 0.68 | 0.68 |
| 3.00 | 0.56 | 0.62 | 0.39 | 0.39 |
| 3.00 | 0.72 | 0.78 | 0.51 | 0.51 |
| 3.00 | 0.70 | 0.70 | 1.50 | 1.50 |
| 3.00 | 1.06 | 1.12 | 1.02 | 1.02 |
| | | | | |
| Average | 0.66 | 0.73 | 0.82 | 0.82 |
| Standard Deviation | 0.29 | 0.25 | 0.45 | 0.45 |
| 95 % Confidence Interval | 0.26 | 0.22 | 0.51 | 0.51 |
| | | | | |

Table 7. Root Mean Square Error: Pos. Est. in Corridor (5 nodes, QT Flow Graph)

| Using power_measure_QT_Sink.grc and n=3.5 | Simple RSS Based Algorithm | | CDRSS Based Algorithm | |
|---|---|---|---|---|
| Number of Nodes | RMSE (m) | | RMSE (m) | |
| | Calibrated | Un-Calibrated | Calibrated | Un-Calibrated |
| 5.00 | 0.54 | 0.57 | 0.23 | 0.23 |
| 5.00 | 0.19 | 0.22 | 0.48 | 0.48 |
| 5.00 | 0.52 | 0.57 | 0.68 | 0.68 |
| | | | | |
| Average | 0.42 | 0.45 | 0.46 | 0.46 |
| Standard Deviation | 0.20 | 0.20 | 0.23 | 0.23 |
| 95 % Confidence Interval | 0.17 | 0.18 | 0.26 | 0.26 |

It was seen that this flow graph was able to provide better results than the UHD_FFT.grc both with and without the respective calibration factors.

It was seen that Simple RSS based algorithm was able to estimate the coordinates of the transmitter more accurately and with less error than CDRSS based algorithm with n = 3.5 value, though this is not as per expectations.

With increasing exponent value it can be seen that error decreases and the difference between the calibrated and un-calibrated RMSE also seems to decrease. This may be due to fact that the circumcenter of the triangle created by the receiver nodes around the transmitter node is shifted closer to actual transmitter position when the exponent value is closer to the actual value. When the path loss exponent is near 3.5 to 4 ('n' tends to this range of values when calculated using different reference nodes positions assuming a log normal distribution for the path loss) the Simple RSS method is seen to give less error and more accurate localization.

With respect to calibration, the Simple RSS based method showed considerable difference (RMSE was lesser for calibrated power readings), while the calibration factor had no impact on the CDRSS based method since they are based on differential power measurements. This is also in a way contradicting to the UHD_FFT.grc based measurements and hence it can be seen that the second flow graph is better for such power measurement dependent applications.

It was also seen that the between 3 and 5 nodes, the CDRSS based algorithm lent better accuracy to the results and closer x and y estimates than simple RSS based algorithm for the same set of measurements. The error seemed to drop by almost 45 %. This was not the case with Simple RSS based algorithm for a set of 5 receiver nodes.

## V. Conclusion

Characterization and Calibration is just one step closer to making the SDR systems designed using laboratory friendly devices like USRPs and GNU Radio utilities a wider platform for real world applications. Extensive documentation in terms of useful reference metrics is lacking and experiments that explore the performance abilities would help provide a good reference for researchers. Experiments were conducted to derive calibration factors that would help relate the test results to real world metrics and make the result-set more easily and clearly understandable. These experiments were conducted specific to some SDR software interfaces and with some specific laboratory equipment like spectrum analyzers and hence may not be applicable to all the USRP devices uniformly. However, these experiments have helped understand the basis of derivation of such calibration metrics and provide a platform for future work to obtain more uniformly and globally acceptable results.

## References


[1] G.Ramasubramanian,"Performance Characterization of USRPs," Bradley Dept of ECE, Virginia Tech, M.S Thesis November 2014

[2] Jean-Philippe Lang. (2013) GNU Radio – The Free and Open Software Ecosystem. [Online]. http://www.gnu.org/software/gnuradio

[3] (2014) Ettus Research – A national Instruments Company. [Online]. https://www.ettus.com/product

[4] Terrence J. Brisebois, "Wideband RF Front End Daughterboard Based on the Motorola RFIC," Electrical Engineering, Virginia Tech, Blacksburg, M.S Thesis 2009

[5] Michael Hills, "Developing a Generic Software Defined Radar Transmitter using GNU Radio," School of Electrical and Electronics Engineering, The University of Adelaide, Adelaide, M.S Thesis November 2012

[6] Jean-Philippe Lang. (2013) GNU Radio - The Free and Open Software Radio Ecosystem. [Online]. http://gnuradio.org/redmine/projects/gnuradio/wiki/FAQ#How-do-I-know-the-exact-voltagepower-of-my-received-input-signal

[7] (2010) CORNET – Cognitive Radio Network Testbed. [Online]. http://cornet.wireless.vt.edu/

[8] (2014) Ettus Research – A National Instruments Company. [Online].https://www.ettus.com/content/files/07495_Ettus_N200-210_DS_Flyer_HR_1.pdf

[9] (2014) Ettus Research – A National Instruments Company. [Online].http://www.ettus.com/content/files/kb/Selecting_an_RF_Daughterboard.pdf

[10] (2014) Ettus Research – A National Instruments Company. [Online].http://www.ettusresearch.com/content/files/kb/application_note_uhd_examples.pdf

[11] Ayad M. H. Khalel, "Position Location Techniques in Wireless Communication Systems,"Department of Electrical

Engineering, Blekinge Institute of Technology, Karlskrona, SWEDEN, M.S Thesis 2010.
[12] (2014) GNU Radio Archive. [Online]. http://lists.gnu.org/archive/html/discuss-gnuradio/2010-11/msg00542.html
[13] Arvind Chandrasekaran, "Intra-Vehicle Channel Characterization in the 5 GHz Band,"Department of Electrical and Computer Science, Ohio University, Athens OH, M.S Thesis 2011.
[14] Scott Y Seidel and Theodore S. Rappaport, "914 MHz Path Loss Predeiction Models for Indoor Wireless Communications in Multifloored Buildings." *IEEE Transactions on Antennas and Propagation*, vol. 40,no. 2, February 1992
[15] T. R. Sontakke B. R. Jadhavar, "2.4 GHz Propagation Prediction Models for Indoor Wireless Communications Within Building," International Journal of Soft Computing and Engineering (IJSCE), vol. 2, no. 3, July 2012.
[16] Lou Frenzel. (2013, October) Electronic Design. [Online]. http://electronicdesign.com/what-s-difference-between/what-s-difference-between-third-order-intercept-and-1-db-compression-point
[17] (2009) Signal Processing Group Inc., Website - Wireless and Analog ASICs and Modules.[Online]. http://www.signalpro.biz/pointsf1.pdf
[18] William Domino and Nooshin Vakilian Darioush Agahi. (2002, March) Microwave Journal. [Online]. http://www.microwavejournal.com/articles/3411-two-tone-vs-single-tone-measurement-of-second-order-nonlinearity
[19] J.R. Casar, P. Tarrio A.M. Bernardos, "Real time calibration for RSS indoor positioning systems," in Indoor Positioning and Indoor Navigation (IPIN), 2010.
[20] Islam Alyafawi, Desislava Dimitrova, and Torsten Ingo Braun, "SDR-based Passive Indoor Localization System for GSM," in SIGCOMM Software Radio Implementation Forum (SRIF), Chicago IL, 2014.
[21] Yung-Fa Huang and You-Ting Jheng. Chaoyang University ofTechnolgy.[Online].http://ir.lib.cyut.edu.tw:8080/bitstream/310901800/12095/1/C08.pdf
[22] Songfeng Zheng. (2010) Missouri State University. [Online].http://people.missouristate.edu/songfengzheng/Teaching/MTH541/Lecture%20notes/evaluation.pdf