Northeastern University

Private Automated Contact Tracing (PACT) Technical Report

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Revision History

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Summary

The PACT, or Private Automated Contact Tracing, concept provides a possible method to track human exposure to contagions using everyday devices such as phones, smart watches, cars, and potentially vast amounts of IoT devices. Using Bluetooth LE (BTLE) "Chirps" that are uniquely traceable and that are sent and received by almost all devices, the exposure level of an uninfected person to an infected person can be accurately tracked. The timestamps of each chirp provides a way to determine contact time and the signal strength of each chirp received by a device provides a measure of distance. The image below depicts the overall concept.

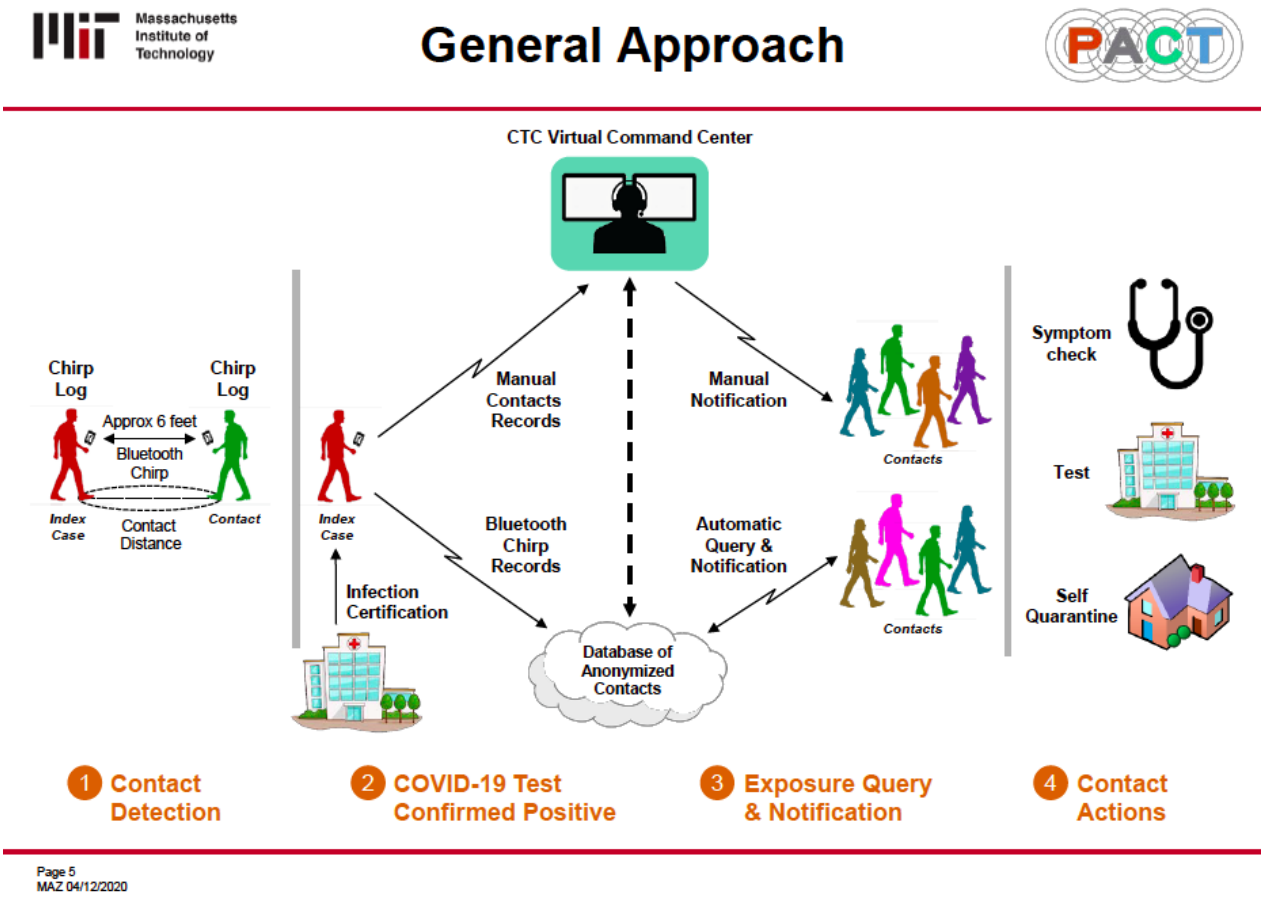


Figure 1: PACT Concept

Research Objective

In order to prove that the PACT method works, key research questions surrounding the RF phenomenology must be answered. BTLE is a short range communications protocol with range between 1m and 100m depending on the class of the transmitter; see Table 1. Early testing has shown that there is a high amount of variability in the RSSI (Received Signal Strength Indicator) reported by a BTLE device but it is theorized that a contact detector can be design that provides alerting with a high degree of accuracy.

BTLE Device Class	Tx Power (max)	Expected Range
3	1mW	1m
2	2.5mW	10m
1	100mW	100m

Table 1: BTLE Transmitter Classes

In order to determine contact range of an infected person to an uninfected person the probability distribution of the RSSI reported by a phone needs to be characterized in different environments and at different poses without any additional interference or signal modification. The unimpeded probability distribution must be measured in an anechoic chamber for different phone makes/models. This will then inform the multi-organization PACT team that seeks to better understand the channel model and how phone position impacts ability to estimate range from transmitter to receiver; the data can then be used for developing a detector that can determine contact that is too close for too long.

The ECUAS Lab anechoic chamber offers the perfect testbed for capturing required data to fully document the performance of BTLE signals at the most basic level from a variety of devices and phones. The chamber provides >100dB of isolation and better than -50dB of reflectivity at 2.4GHz. The chamber has an integrated 2-axis antennas positioner that can be used to automate the capture of RSSI reports at different angles and poses of a transmitting or receiving phone.

Research Plan

The following tasks have been identified in order to build a repeatable testbed for BTLE data collection and analysis at the ECUAS Lab Anechoic Chamber:

Table 2: Research Tasks and Status

Task Number	Description	Status
1	Design and Build Hardware Testbed - Identify phones of interest - Background Research on BTLE RSSI reported by BTLE chips - Identify BTLE Sensors for collecting RSSI data - Test rig for mounting hardware in anechoic chamber	**Completed**
2	Design and Implement Software for capturing RSSI - Passive BTLE packet capture - Real-time data plot - PACT data capture format/metadata format - Live data statistics - RSSI capture automation	**Completed**
3	Design and Implement Software for Antenna Positioner Tests - Control the ETS-Lindgren EMCenter Controller for 2-Axis Multiaxis Antenna Positioner - Test automation for capturing multiple angle offsets between transmit and receive	**Completed**

Task Number	Description	Status
4	Collect and Analyze Data - Collect fixed 0-degree offset data (transmitter facing directly at receiver) - Collect stepped 0-360 degree offset data on both Azimuth and Elevation axes - Collect continuous motion data from 0-360 degrees on Azimuth and Elevation axes	Completed
5	Participate in weekly PACT collaboration meetings and engage with other researchers	Ongoing
6	Analyze PACT Data	Ongoing

BTLE RSSI Background

Understanding how the BTLE RSSI varies without any other external interference is critical in developing detectors that can determine when two BTLE devices have been in close contact for too long. Therefore, an initial background study was done on how BTLE RSSI is measured on different devices.

The RSSI, or Received Signal Strength Indicator, is potential link quality indicator built in to the physical layer interface for BTLE. It is an indicator of the channel quality between the transmitting device and receiving device. A low RSSI value indicates that the channel may not be reliable and can be caused by a number of factors, one being distance from the transmitter to receiver and others being interference from other devices, multipath, objects place between the transmitter and receiver (e.g. a wall or a person), and even orientation differences between two devices that places either one in what is known as a "null" or area of high attenuation due to the geometric antenna pattern. If two devices are in close proximity but there is a large RF reflecting or absorbing object between them than the RSSI can be very low making it appear as though the two devices could be far away; when considering phones, a common problem that is discussed on the PACT project is the case where a phone is place in a pocket or purse next to a person's body.

The BTLE standard specifies that RSSI is to be measured on 3 of the available channels in the 2.4GHz band. These 3 channels are known as the advertising channels and are fixed and cannot be changed, as shown in Figure 2[1]; all other channels using frequency hopping while the advertising channels do not so that device pairing and discovery can function. The 3 channels number are 37, 38, and 39 and the BTLE physical layer samples each one on a round-robin type schedule in order to measure possible interference at the low-end, mid-range, and high-end of the band. The exact method of sampling RSSI is chip-vendor dependent, so consideration should be given to account

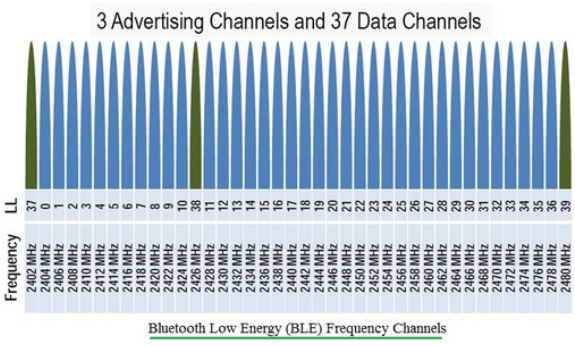


Figure 2: BTLE RSSI Measurement Channels[1]

[1] https://www.rfwireless-world.com/images/BLE-frequency-channels.jpg

for differences in how sampling is done[2]. Additionally, device vendors may also average multiple RSSI samples in order to filter out noise and combine RSSI from the low, mid and high points of the band.

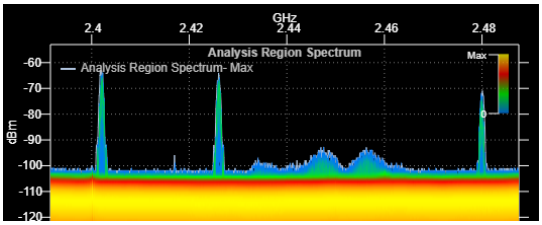


Figure 3: BTLE RF Capture (Samsung Galaxy S7)

Using an advanced RF capture device and antenna we verified the presence of the 3 channels from a test device along with expected RSSI levels as shown in Figure 3. Based on this plot, the expected RSSI levels at a 6ft range are between -60dBm to -70dBm with a 0-degree offset in pointing angle to the sensor, i.e. the front face of the phone pointed directly at the sensor. The differences in RSSI at the three frequencies are a distinct quality of the both the transmitter and receiver characteristics; for example, the BTLE transmit antenna and RF front end may perform slightly better or worse at different frequencies, this also can be said for the receiving antenna and receiver circuits. These variabilities are often due to chip-to-chip or board-to-board variations across the same family of devices.

Testbed

The block diagram of the testbed for collecting BTLE RSSI data within the Anechoic Chamber is shown below. It consists 7 main components: (1) the Turntable/Mast that is controlled by the (2) antenna positioner and (3) position controller for aligning the (4) Transmit BTLE device with the (5) BTLE sniffer. The sniffer connects to the (6) data capture network for sending BTLE packets to the (5) data capture laptop, which runs the main visualization and capture software. All hardware is off-the-shelf equipment to minimize cost and development time for setting up the testbed.

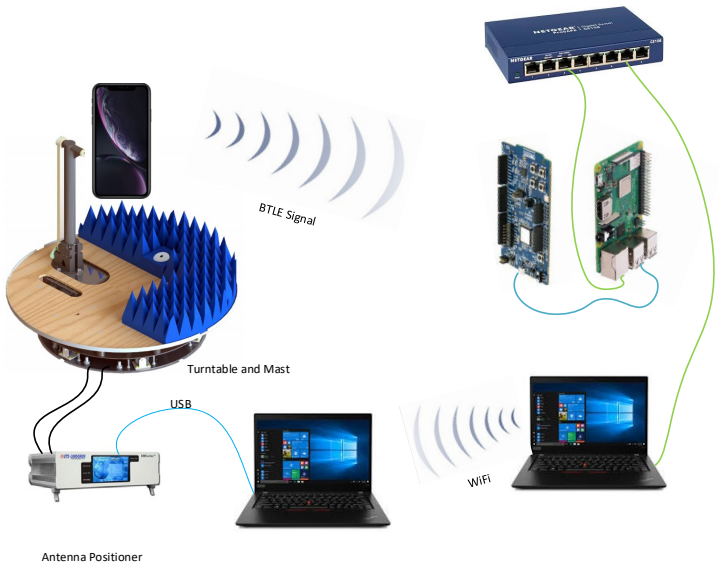


Figure 4: Block Diagram

[2] https://www.bluetooth.com/blog/proximity-and-rssi/

The implemented testbed within the Anechoic Chamber is shown in the following figure. The support structure used to hold the BTLE Sniffer and data capture network devices was made of a lightweight fiberglass, non-RF reflective, frame the is typically used for electro-magnetic pulse testing. This frame helped to minimize the amount of metallic, RF reflective surfaces, within the chamber to minimize multipath signal interference that could alter the RSSI measurements. The data capture network devices are shielded using a large section of RF absorbing foam to minimize reflections from them. Additionally, the Anechoic Chamber is configured as fully-anechoic, i.e. all surfaces covered with RF absorbing foam to eliminate unwanted reflections

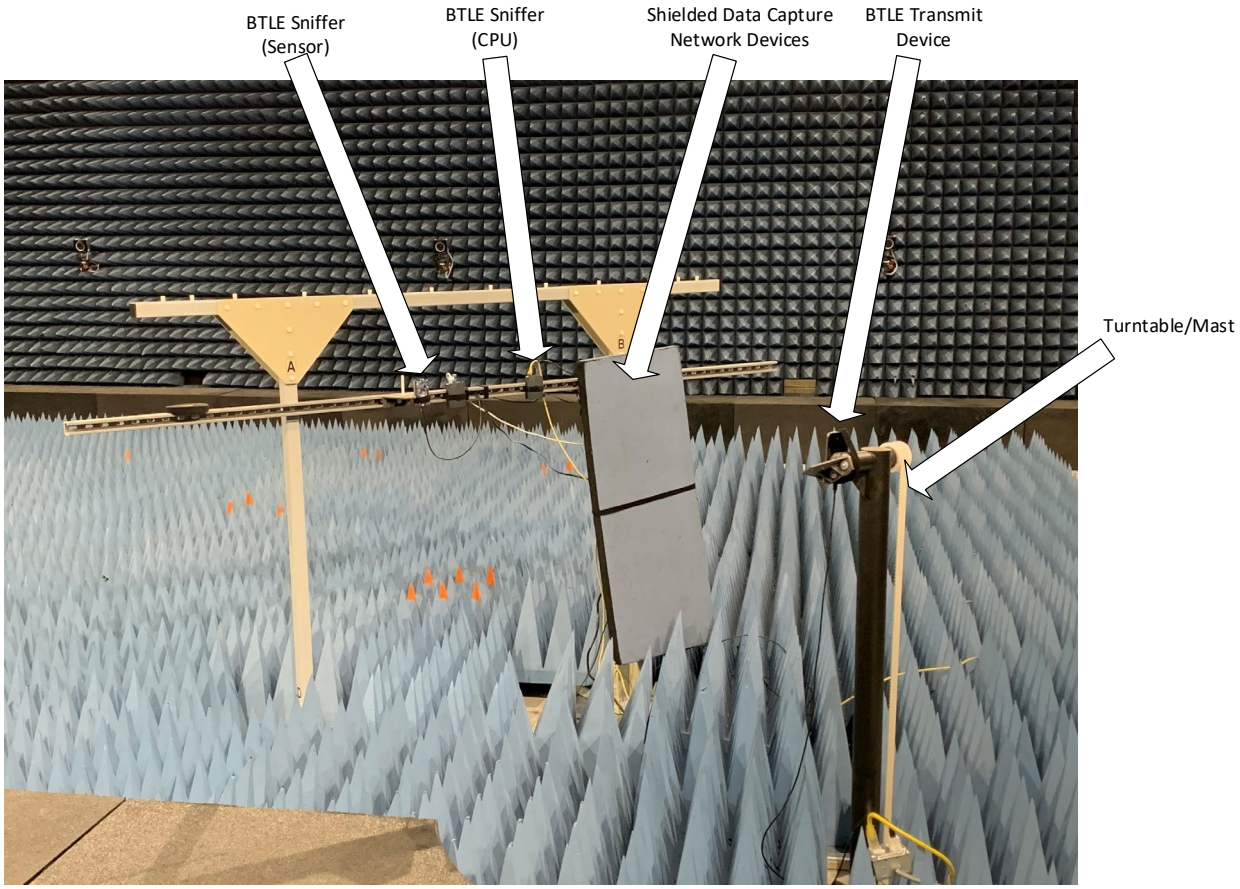


Figure 5: Anechoic Chamber Testbed

Turntable/Mast

We use the ETS-Lindgren model 2117 Multi-axis Antenna Positioner (MAPS) for positioning the transmit BTLE device relative to the BTLE sniffer. The MAPS has both horizontal (elevation) and vertical (azimuth) rotation axes with a maximum device under test (DUT) capacity of 25lbs.

Antenna Positioner

To control the Turntable/Mast unit we use the ETS-Lindgren EMCenter positioner. This is “a modular RF platform consisting of an integrated micro-controller, modular chassis, and a selection of optional plug-in card modules. It can be used to perform a variety of RF measurement applications and is controlled with TILE!™, EMQuest™ and other PC compatible RF software packages, including custom designed

applications that use the published EMCenter Serial I/O API. To conduct the BTLE related measurement we use a custom built application that allows the BTLE capture software to directly control the turntable/mast system and automate all of the measurements (see Antenna Positioner Software).

Position Controller

The Position Controller consists of a computer connected to the EMCenter positioner via USB. The computer runs a Python server application that allows any other system connected to the lab network to control the mast/turntable (see Antenna Positioner Software)

Transmit BTLE Device

The transmit BTLE devices consist of commonly used mobile phones. The following phones were selected and acquired for testing:

1. iPhone 11 (MWKM2LL/A)
2. Samsung Galaxy S7
3. Samsung Galaxy S10 SMG973U1ZKAX

These phones were chosen due to the popularity of the devices. The iPhone 11 and Samsung Galaxy S10 are both the newest phone models available from both manufacturers and represent the latest in BTLE technology (chips and antennas). The Samsung Galaxy S7 is a 3 generation old phone model but was chosen for comparison of an older phone to newer ones.

BTLE Sniffer

The BTLE Sniffer device consists of two components. The actual BTLE sensor is the Nordic Semi nRF52-DK (or development kit) that can run the Nordic Semi BTLE sniffer firmware. The sniffer firmware implements a passive capture utility for recording live BTLE traffic from all devices within proximity. The capture utility is integrated with the widely used Wireshark network capture and analysis tool. According to Nordic Semi[3]: "The nRF52 DK is a single-board development kit (DK) for Bluetooth Low Energy, Bluetooth mesh, ANT and 2.4 GHz proprietary applications using the nRF52810 and nRF52832 SoCs."

The BTLE Sniffer sensor (nRF52-DK) connects to a RaspPI 4 via USB for control and data links. The RaspPI runs the Ubuntu Linux OS and provides the driver level interface to the nRF52-DK as well as a network layer interface via the data capture network to the data capture laptop, which runs the main application for receiving and processes BTLE packets in real-time.

Note that the nRF52-DK was chosen as the preferred BTLE capture device after an extensive experimental analysis to judge the performance of it and other devices. Other options included the nRF51, and several phones running the nRFConnect app to log RSSI data. In the end the nRF52-DK provided the best overall solution due to its accuracy in measuring RSSI as well as the ability to create highly customized programs around it.

Data Capture Network

The data capture network is a dedicated Local Area Network (LAN) for all sensor and capture hardware. The LAN uses a 1Gbps Netgear Ethernet switch to connect all devices.

[3] https://www.nordicsemi.com/Software-and-tools/Development-Kits/nRF52-DK

Data Capture Laptop

The data capture laptop runs the Ubuntu Linux OS and a custom design/developed Python program to control the nRF52-DK sensor via the RaspPI and capture the stream of BTLE packets using the recommended PACT project capture format.

RSSI Capture Software

The BTLE RSSI Capture Software was developed to enable use of the nRF52-DK as a BTLE capture device using the available Nordic Semi sniffer firmware[4]. This firmware is meant to run alongside the Wireshark network packet capture and analysis software tool, which acts as the user interface for controlling the sensor as well as viewing captured data. In order to automate data capture for characterizing RSSI data, the custom built application has to operate under the constraints of the Nordic Semi Wireshark driver and nRF52-DK firmware, which presents some significant challenges.

The first challenge is that the nRF52-DK sniffer firmware interface or source code are not published, so without full reverse engineering and significant effort the provided Wireshark driver has to be used. This driver only works with the graphical user interface (GUI) based Wireshark program and not its console based counterpart "tshark", which can be used for automated "headless" (no GUI) scenarios. Therefore, a complex method of running the GUI-based Wireshark alongside a custom built GUI for live RSSI visualization was devised. This method uses multiple threads running on the data capture laptop that interface with the RaspPI and the instance of Wireshark running remotely on it to interface with the nRF52-DK. It works as follows:

1) Locally, the BTLE RSSI Capture software application executes a command to launch Wireshark on the RaspPI and pipes the display to the local machine. The remote instance of Wireshark is commanded to output its capture stream to a file.
2) Another remote process is then started on the RaspPI to read the output file from Wireshark using tshark. This process is configured to stream its output to a pipe that is redirected to another local process.
3) A local tshark process is started that reads the input of the redirected pipe. As packets are received by the local tshark process they are also written to a local temporary file for any further local post-processing.

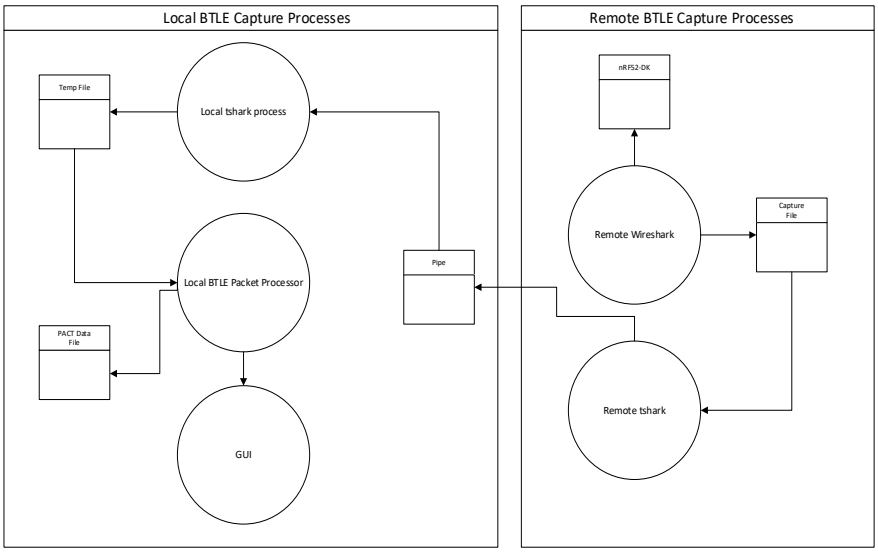


Figure 6: Software Process Diagram

[4] https://www.nordicsemi.com/Software-and-tools/Development-Tools/nRF-Sniffer-for-Bluetooth-LE

4) The BTLE Capture Software application reads all packets from the temporary file and parses them to extract the required fields for both live display and creating a capture file in the agreed upon PACT file format.

The graphical user interface for the software application is shown in the figure below. It contains three plots that are generated using the PySimpleGUI[5] Python library. Each plot corresponds to one of the BTLE advertising channels (37, 38, and 39) in order to display the RSSI data independently. During the early phase of the PACT project many questions arose about RSSI data from different sensors and understanding the underlying trends; some researchers found that the RSSI data they were collecting had a bi-modal or tri-modal distribution because they neglected to separate out the three channels that each have their own independent distributions. The GUI also has a real-time statistics display for each channel as well as several control widgets for filtering or data display options. Displayed statistics are: min, max, mean median, mode, standard deviation, and mode.

Figure 7: BTLE Capture GUI

The final stage of BTLE data processing is parsing and formatting to comply with the PACT data format, which is shown in Figure 8. All entries begin with a date/timestamp as shown. At the beginning of the file there are metadata fields for (1) Environment, (2) Device, (3) Range, (4) Angle, (5) TxPower, and (6) GPS coordinates; these are static values for the entire capture so only occur once. The remaining fields consists of the RSSI logs and contain "date/timestamp, field type = Bluetooth, Unique ID, RSSI, TX Power Level, Time since Epoch, and BTLE Channel".

[5] https://pysimplegui.readthedocs.io/en/latest/

```
2020-05-01 14:14:48.497962,Environment,Anechoic Chamber
2020-05-01 14:14:48.497974,Device,Samsung Galaxy S7
2020-05-01 14:14:48.497979,Range,6
2020-05-01 14:14:48.497982,Angle,0
2020-05-01 14:14:48.497985,TxPower,-1
2020-05-01 14:14:48.497988,GPS,NA
2020-05-01 14:14:16.141625,Bluetooth,55:cc:be:9c:85:dd,-56,-1,1588356856.141625,39
2020-05-01 14:14:16.145332,Bluetooth,55:cc:be:9c:85:dd,-67,-1,1588356856.145332,37
2020-05-01 14:14:16.147332,Bluetooth,55:cc:be:9c:85:dd,-58,-1,1588356856.147332,38
2020-05-01 14:14:16.149738,Bluetooth,55:cc:be:9c:85:dd,-59,-1,1588356856.149738,39
2020-05-01 14:14:16.151620,Bluetooth,55:cc:be:9c:85:dd,-67,-1,1588356856.15162,37
2020-05-01 14:14:16.153487,Bluetooth,55:cc:be:9c:85:dd,-58,-1,1588356856.153487,38
2020-05-01 14:14:16.155551,Bluetooth,55:cc:be:9c:85:dd,-59,-1,1588356856.155551,39
2020-05-01 14:14:16.157319,Bluetooth,55:cc:be:9c:85:dd,-67,-1,1588356856.157319,37
```

Figure 8: PACT Data File Example

Coupled with each of the previously mentioned application features is an automation engine that enables correlated movement of the Transmit BTLE device and data capture in order to understand the impact of device orientation and movement on RSSI measurements. The automation engine allows for repeatable testing of different devices with exactly the same physical orientations of devices.

All software developed was made open source and shared with other researchers participating in the PACT project. Source code, associated use instruction, and all data collected are posted to:

https://github.com/klingm/btle_sniffer

Antenna Positioner Software

The Antenna Positioner Software application was developed to allow remote control of the Turntable/Mast using a computer connect to the EMCenter positioner controller. It is a client/server application that implements the command/response Serial I/O driver interface for the EMCenter positioner. The client connects over a network connection and the server acts as a proxy to send commands to the locally USB connected EMCenter device. The details of the API for controlling the turntable and mast are documented in an Appendix in the EMCenter Manuals[6]. Only the subset of commands and responses required to move and stop both the horizontal (mast) and vertical (turntable) axes were implemented. Figure 9 shows the user interface.

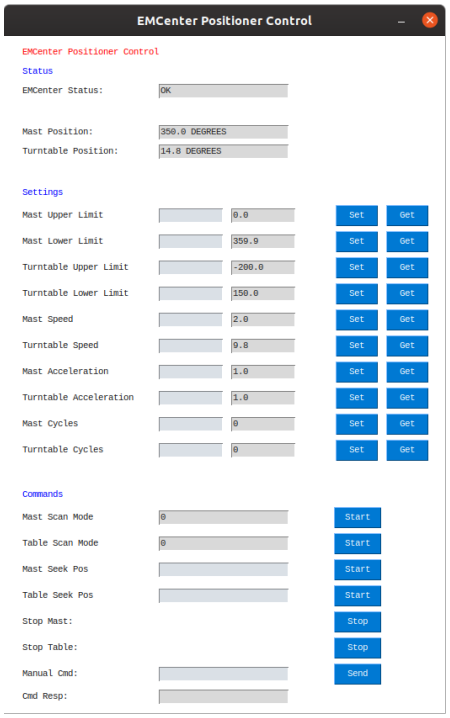


Figure 9: Antenna Positioner Software GUI

The program consists of two executable scripts. The first script(tcp_serial_redirect.py) implements a TCP to serial "pipe" to allow an arbitrary remote computer to send commands and receive status from the EMCenter controller hardware. This executable must be run on a computer that is physically connected to the controller via USB and also that is physically connected to an accessible network. The second script (emcenter_ctrl.py) implements the user interface and all control logic. This program can be run on an

[6] http://www.ets-lindgren.com/sites/etsauthor/ProductsManuals/Test_Systems/399342%20C%20EMCenter.pdf
http://www.ets-lindgren.com/sites/etsauthor/SiteCollectionDocuments/Manuals/Positioners/EMControl%20399348%20C.pdf

arbitrary computer system that is connected to the same network as previous system. It then sends and receives network commands/status to control the antenna positioner. For reference, the figure below provides a reference for the rotation axes controlled by this program.

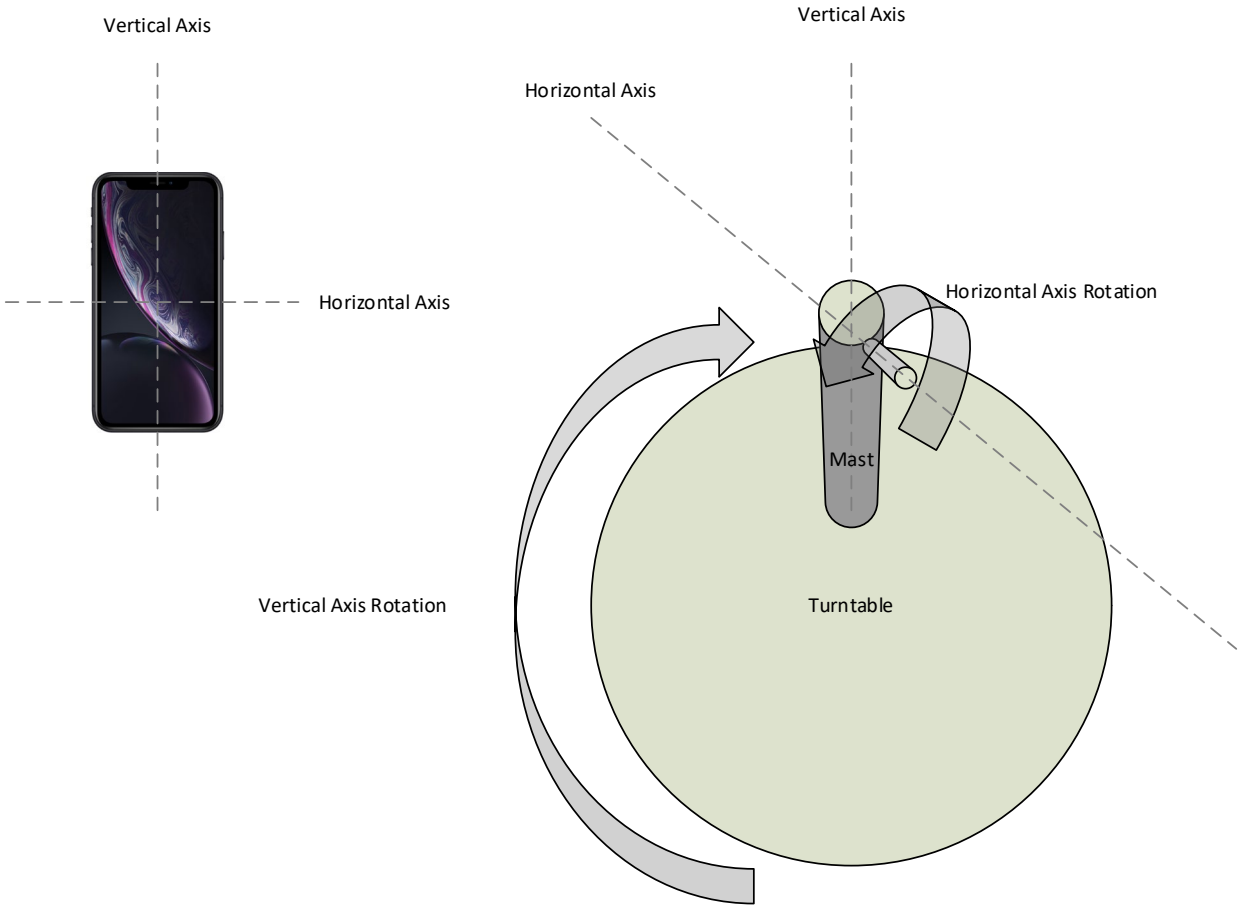


Figure 10: Antenna Positioner Rotation Axes

This software was also published as open source and posted to Github at the following site as a part of the overall PACT data collection software suite.

https://github.com/klingm/EMCenter-Controller

Data Collection and Analysis

Data collection was performed using the developed software and associated testbed with the scenarios in Table 3 in order to characterize BTLE RSSI behavior in a shielded environment, with little to no interference and multipath. The following sub-sections provide snapshots of each dataset collected.

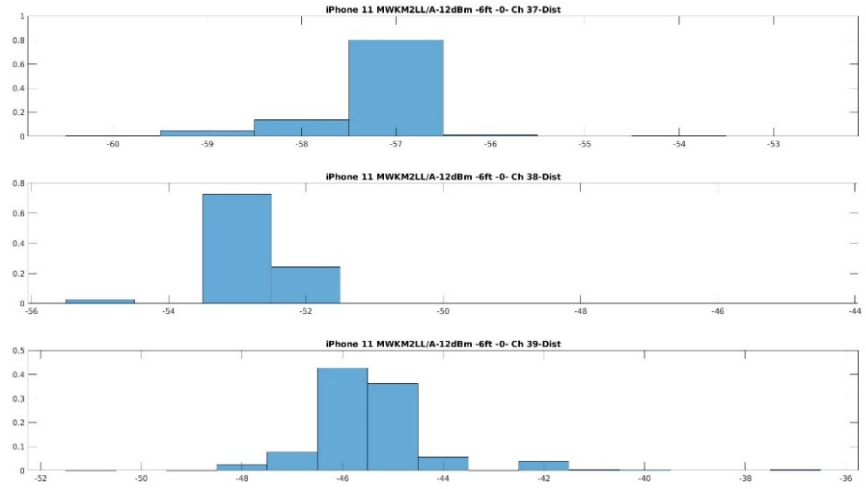
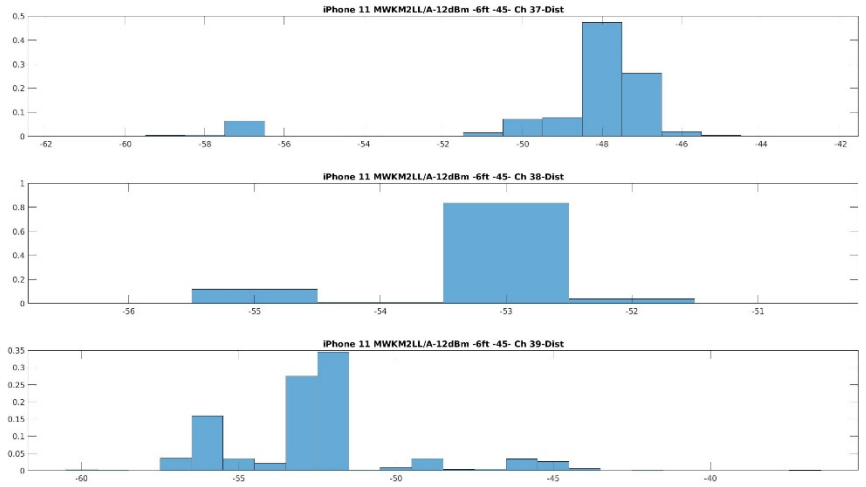
Table 3: Data Collection Scenarios

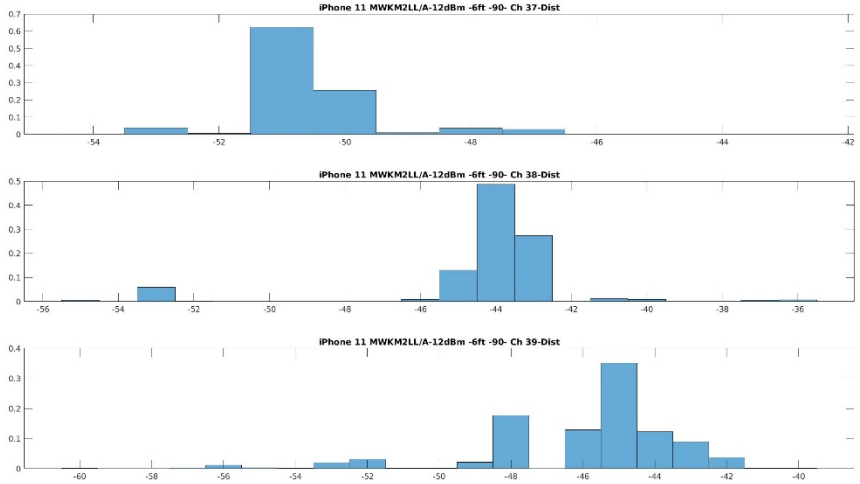
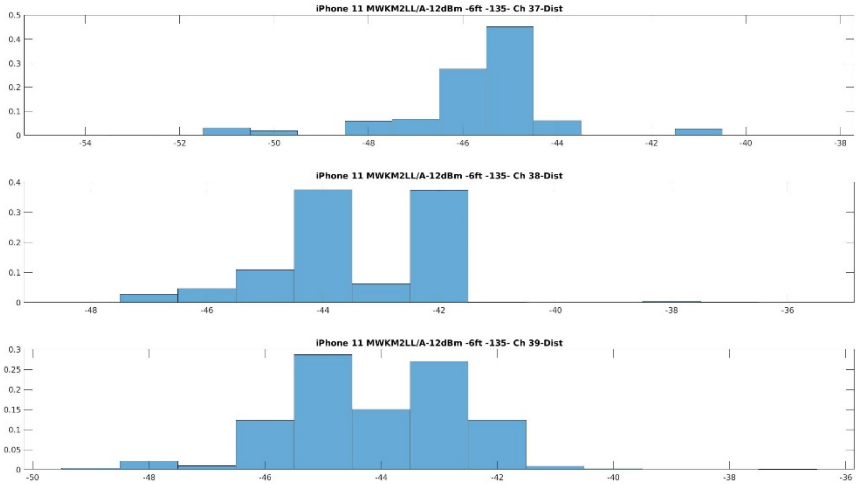
Scenario Number	Scenario Name	Description
1	0 Degree Horizontal Axis	Phone in upright position, face point directly at BTLE sensor. Data captured for >2 minutes then halted before movement to next position.
2	45 Degree Horizontal Axis	Phone tilted 45 degrees on horizontal axis. Data captured for >2 minutes then halted before movement to next position.
3	90 Degree Horizontal Axis	Phone tilted 90 degrees on horizontal axis. Data captured for >2 minutes then halted before movement to next position.
4	135 Degree Horizontal Axis	Phone tilted 135 degrees on horizontal axis. Data captured for >2 minutes then halted before movement to next position.
5	180 Degree Horizontal Axis	Phone tilted 180 degrees on horizontal axis. Data captured for >2 minutes then halted before movement to next position.
6	225 Degree Horizontal Axis	Phone tilted 225 degrees on horizontal axis. Data captured for >2 minutes then halted before movement to next position.
7	270 Degree Horizontal Axis	Phone tilted 270 degrees on horizontal axis. Data captured for >2 minutes then halted before movement to next position.
8	315 Degree Horizontal Axis	Phone tilted 315 degrees on horizontal axis. Data captured for >2 minutes then halted before movement to next position.
9	Horizontal Axis In Motion	Phone continuously rotated from 0-359 and then back again on horizontal axis. Data captured continuously until movement completed.
10	Vertical Axis In Motion	Phone continuously rotated from 0-350* and then back again on vertical axis. Data captured continuously until movement completed.

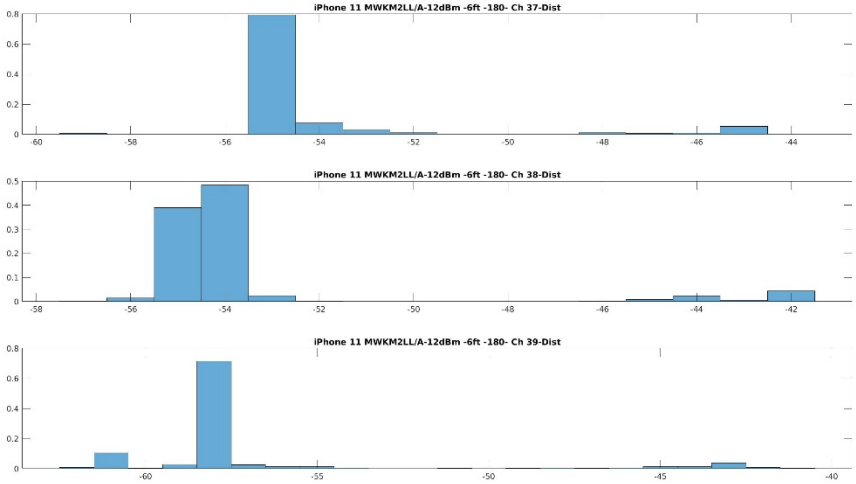
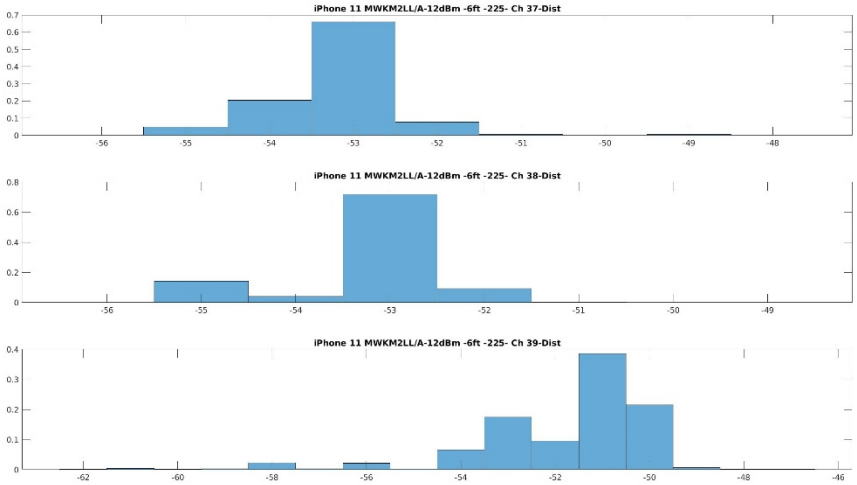
*Table rotation has a hard limit that prevents full rotation

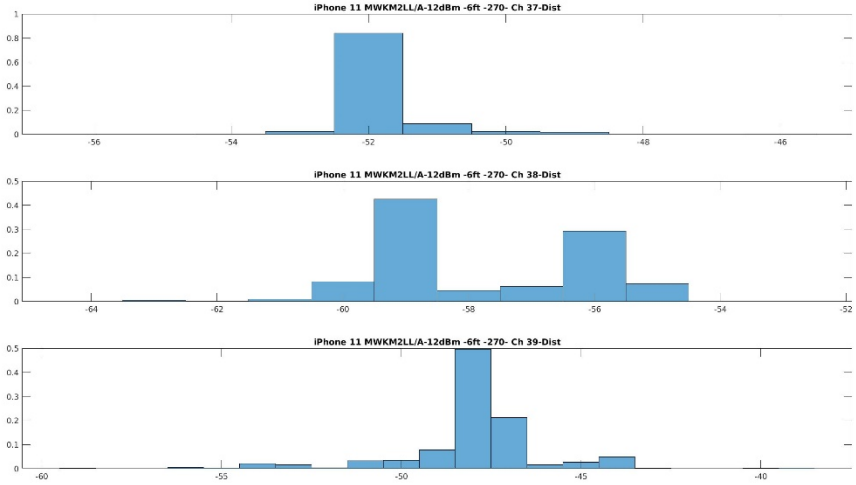
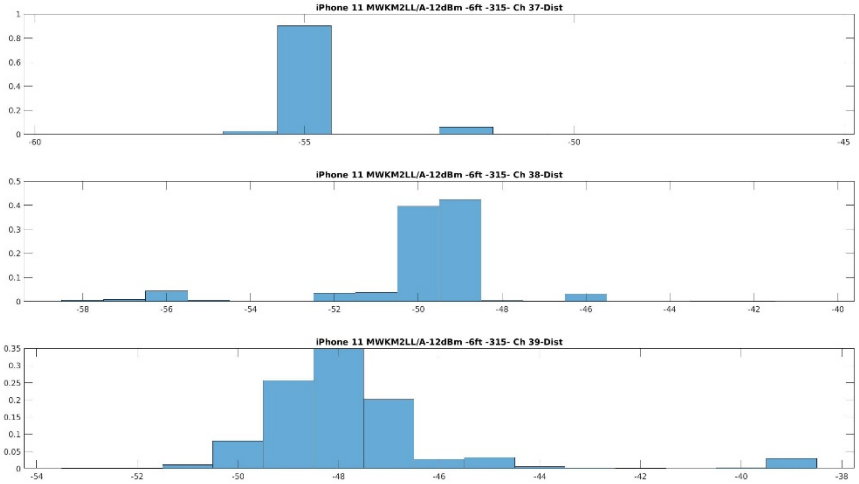
The data distributions for scenarios 1-8 are shown first for each dataset; the titles of each plot contain the relevant parameters and are formatted as "*phone type-TX Power-range-angle-btle channel-dist*". Following the data distributions for the fixed positions are raw RSSI plots for live motion on each axis and each BTLE channel.

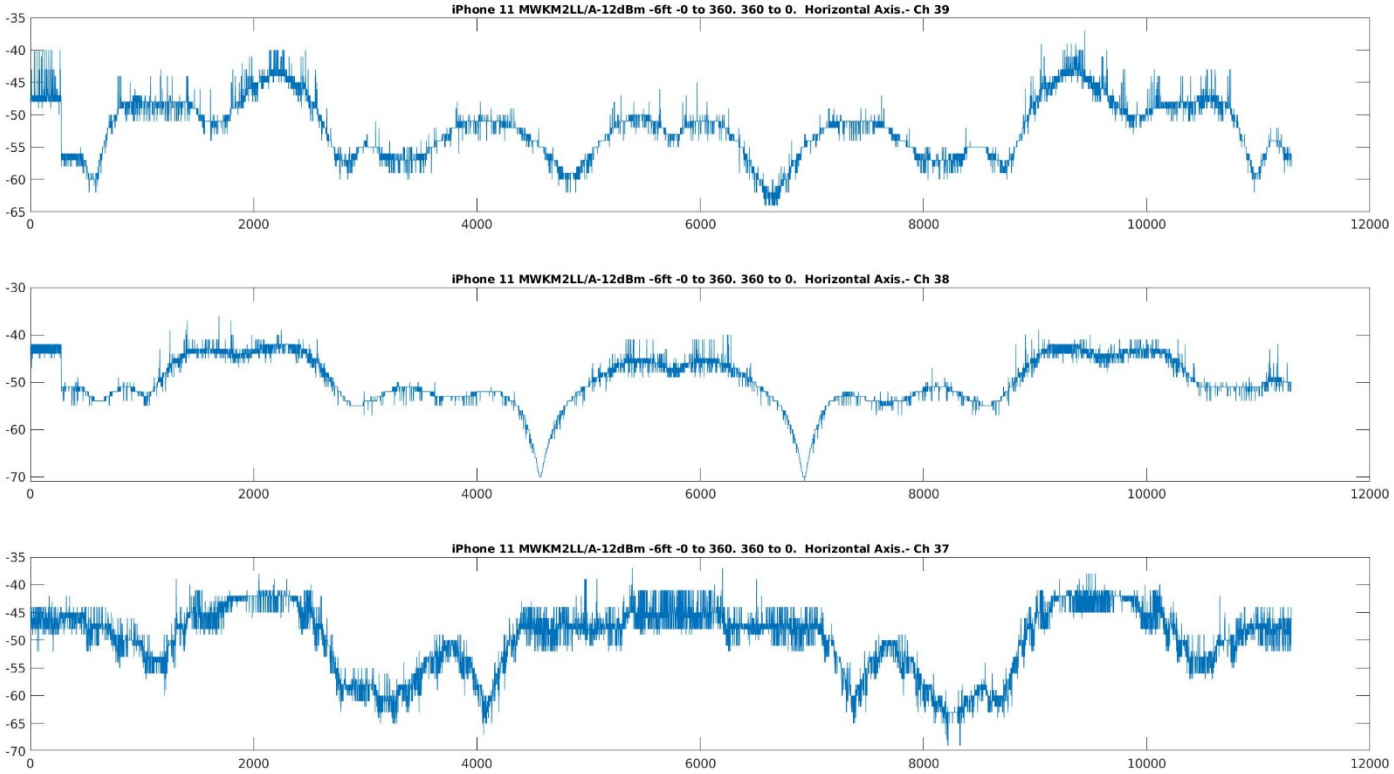
Dataset – iPhone11 (6ft)

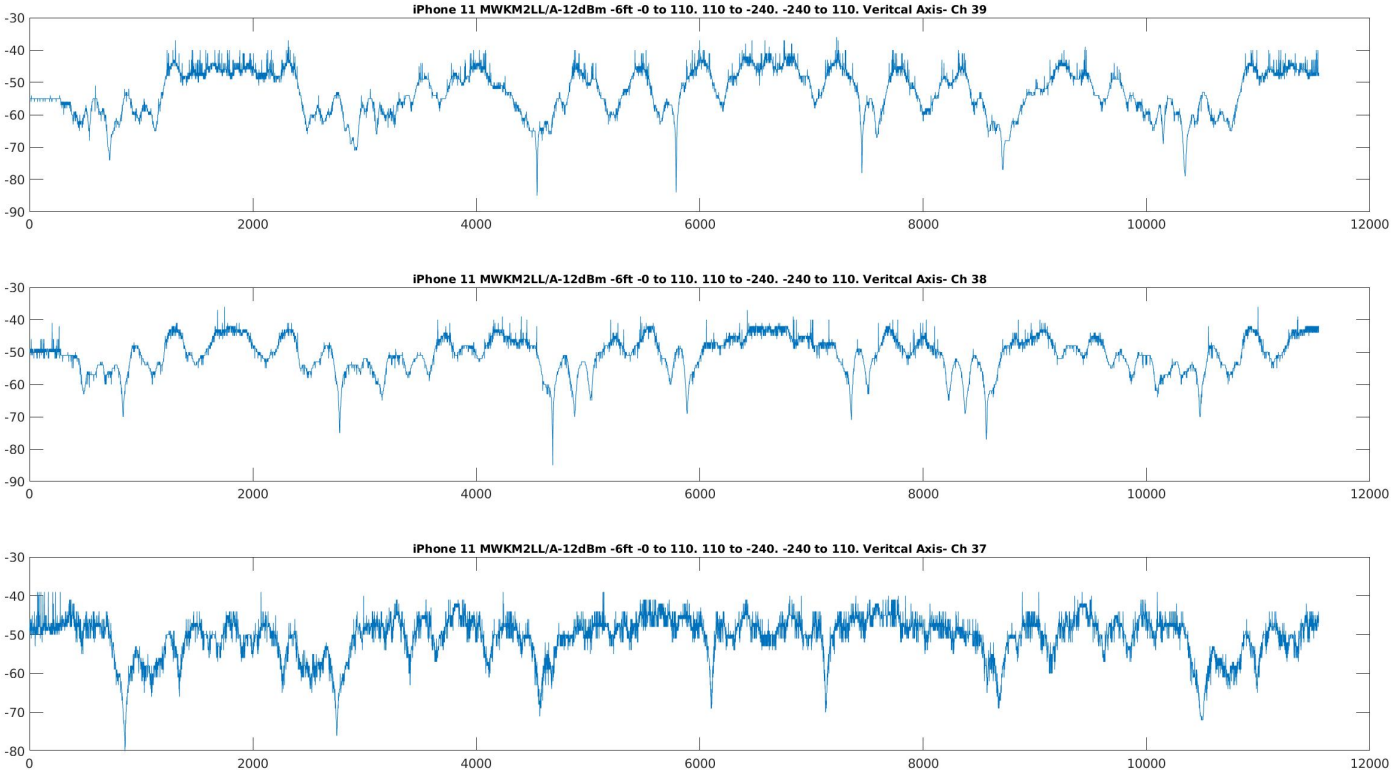
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -60.0 max = -53.0 mean = -57.215 median = -57.0 mode = -57.0 std = 0.586 range = 7.0	**Ch 38 Stats:** min = -55.0 max = -45.0 mean = -52.805 median = -53.0 mode = -53.0 std = 0.580 range = 10.0	**Ch 39 Stats:** min = -51.0 max = -37.0 mean = -45.421 median = -46.0 mode = -46.0 std = 1.271 range = 14.0
	**Ch 37 Stats:** min = -61.0 max = -43.0 mean = -48.663 median = -48.0 mode = -48.0 std = 2.647 range = 18.0	**Ch 38 Stats:** min = -56.0 max = -51.0 mean = -53.202 median = -53.0 mode = -53.0 std = 0.695 range = 5.0	**Ch 39 Stats:** min = -60.0 max = -37.0 mean = -52.646 median = -53.0 mode = -52.0 std = 2.766 range = 23.0

RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -54.0 max = -43.0 mean = -50.577 median = -51.0 mode = -51.0 std = 1.075 range = 11.0	**Ch 38 Stats:** min = -55.0 max = -36.0 mean = -44.345 median = -44.0 mode = -44.0 std = 2.630 range = 19.0	**Ch 39 Stats:** min = -60.0 max = -40.0 mean = -45.904 median = -45.0 mode = -45.0 std = 2.656 range = 20.0
	**Ch 37 Stats:** min = -54.0 max = -39.0 mean = -45.732 median = -45.0 mode = -45.0 std = 1.709 range = 15.0	**Ch 38 Stats:** min = -48.0 max = -36.0 mean = -43.432 median = -44.0 mode = -44.0 std = 1.416 range = 12.0	**Ch 39 Stats:** min = -49.0 max = -37.0 mean = -44.114 median = -44.0 mode = -45.0 std = 1.481 range = 12.0

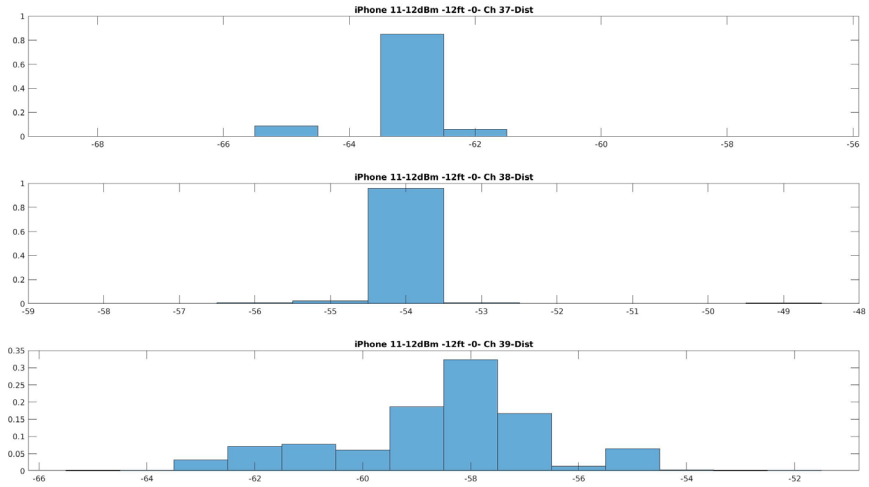
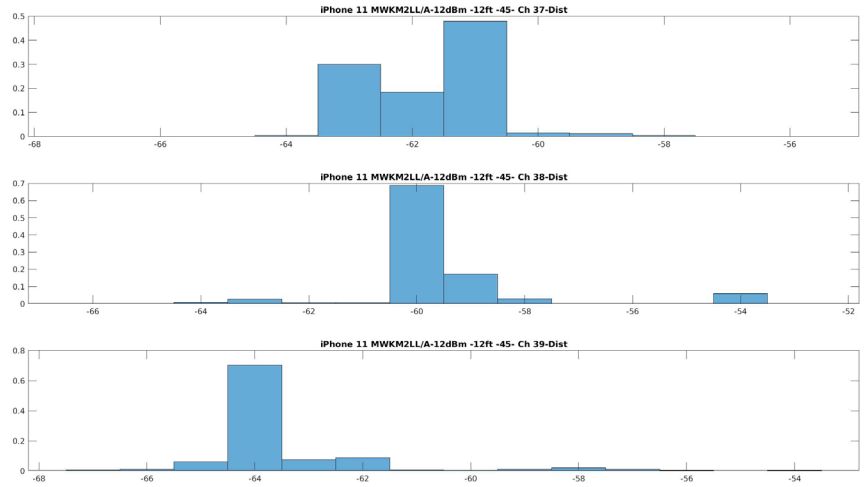
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -59.0 max = -44.0 mean = -54.091 median = -55.0 mode = -55.0 std = 2.594 range = 15.0	**Ch 38 Stats:** min = -57.0 max = -42.0 mean = -53.486 median = -54.0 mode = -54.0 std = 3.222 range = 15.0	**Ch 39 Stats:** min = -62.0 max = -41.0 mean = -57.087 median = -58.0 mode = -58.0 std = 4.205 range = 21.0
	**Ch 37 Stats:** min = -56.0 max = -48.0 mean = -53.193 median = -53.0 mode = -53.0 std = 0.737 range = 8.0	**Ch 38 Stats:** min = -56.0 max = -49.0 mean = -53.225 median = -53.0 mode = -53.0 std = 0.817 range = 7.0	**Ch 39 Stats:** min = -62.0 max = -47.0 mean = -51.771 median = -51.0 mode = -51.0 std = 1.859 range = 15.0

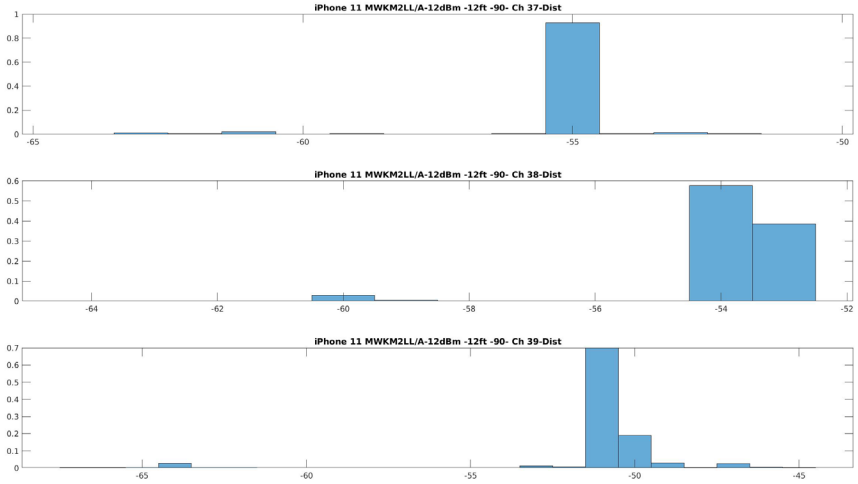
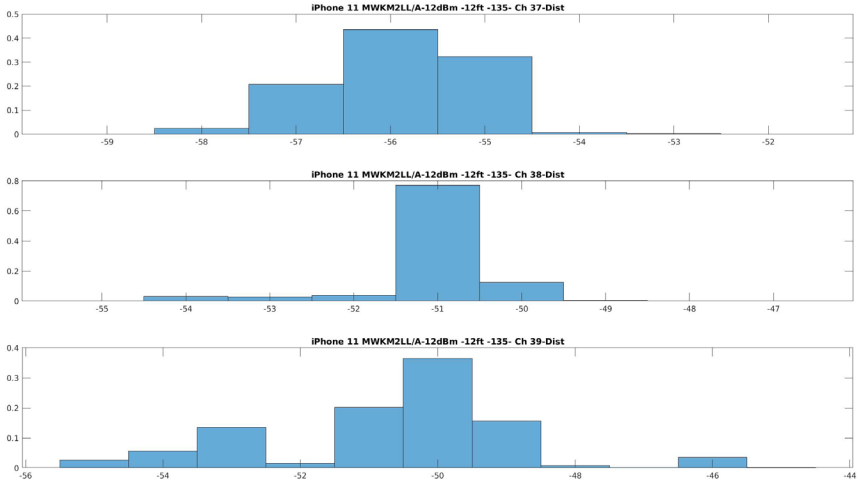
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -56.0 max = -46.0 mean = -51.823 median = -52.0 mode = -52.0 std = 0.705 range = 10.0	**Ch 38 Stats:** min = -64.0 max = -53.0 mean = -57.794 median = -59.0 mode = -59.0 std = 1.703 range = 11.0	**Ch 39 Stats:** min = -59.0 max = -39.0 mean = -47.985 median = -48.0 mode = -48.0 std = 1.954 range = 20.0
	**Ch 37 Stats:** min = -59.0 max = -46.0 mean = -54.805 median = -55.0 mode = -55.0 std = 0.863 range = 13.0	**Ch 38 Stats:** min = -58.0 max = -41.0 mean = -49.894 median = -50.0 mode = -49.0 std = 1.991 range = 17.0	**Ch 39 Stats:** min = -53.0 max = -39.0 mean = -47.776 median = -48.0 mode = -48.0 std = 1.993 range = 14.0

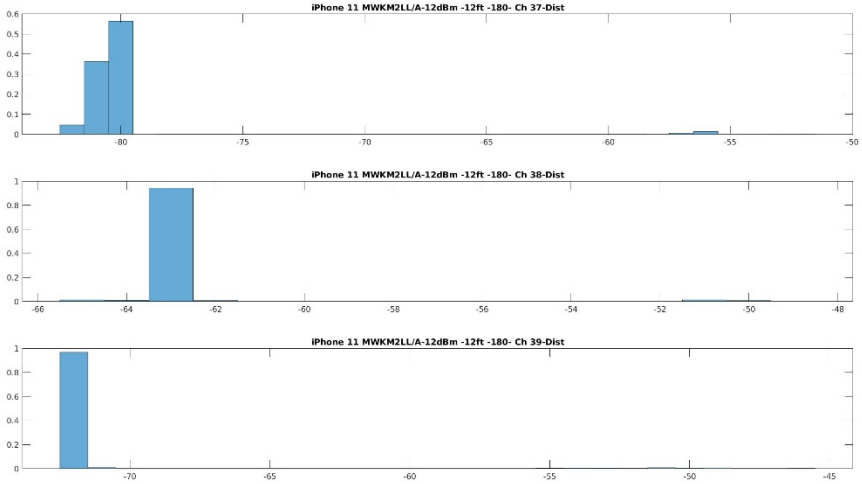
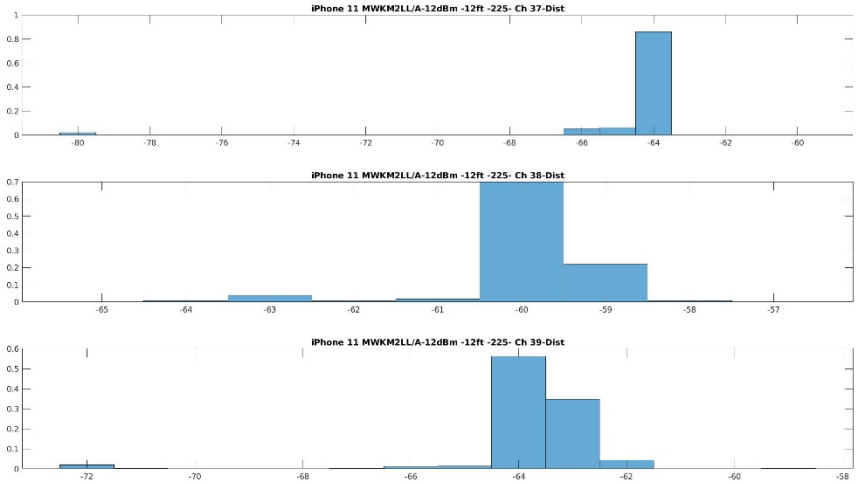

iPhone 11 MWKM2LL/A-12dBm -6ft -0 to 360. 360 to 0. Horizontal Axis.- Ch 39
-35
-40
-45
-50
-55
-60
-65
0
2000
4000
6000
8000
10000
12000
iPhone 11 MWKM2LL/A-12dBm -6ft -0 to 360. 360 to 0. Horizontal Axis.- Ch 38
-30
-40
-50
-60
-70
0
2000
4000
6000
8000
10000
12000
iPhone 11 MWKM2LL/A-12dBm -6ft -0 to 360. 360 to 0. Horizontal Axis.- Ch 37
-35
-40
-45
-50
-55
-60
-65
-70
0
2000
4000
6000
8000
10000
12000

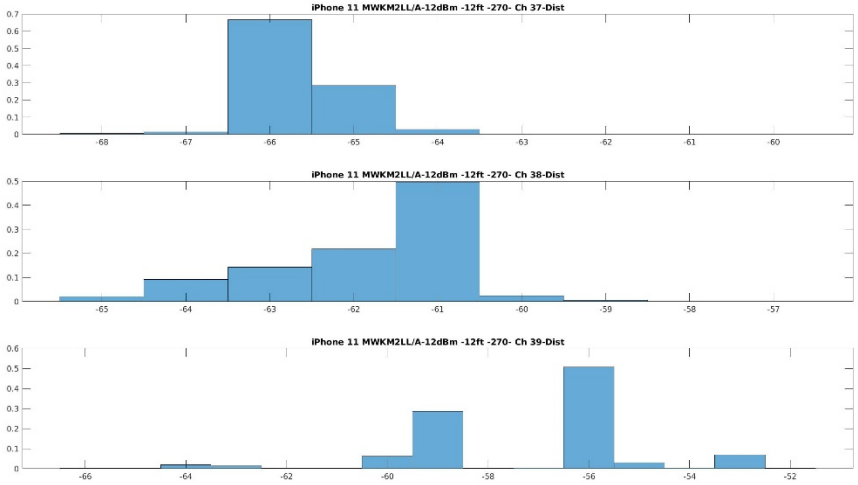
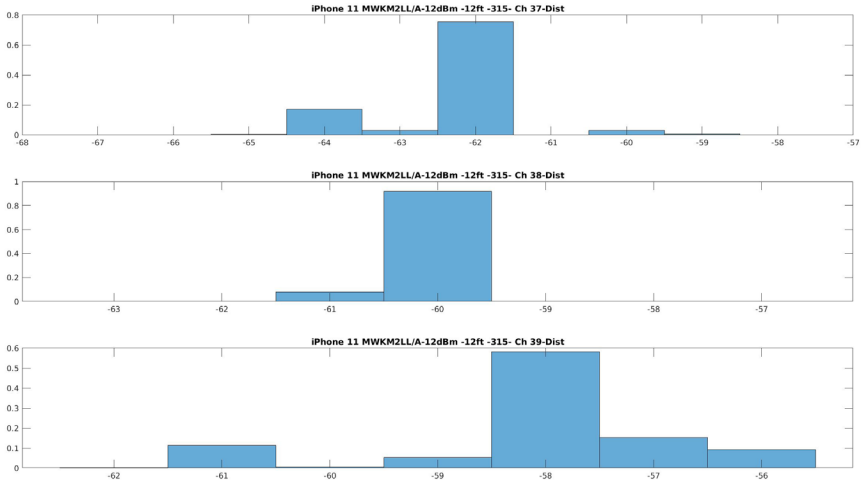

iPhone 11 MWKM2LL/A-12dBm -6ft -0 to 110. 110 to -240. -240 to 110. Veritcal Axis- Ch 39
iPhone 11 MWKM2LL/A-12dBm -6ft -0 to 110. 110 to -240. -240 to 110. Veritcal Axis- Ch 38
iPhone 11 MWKM2LL/A-12dBm -6ft -0 to 110. 110 to -240. -240 to 110. Veritcal Axis- Ch 37
-30
-40
-50
-60
-70
-80
-90
0
2000
4000
6000
8000
10000
12000

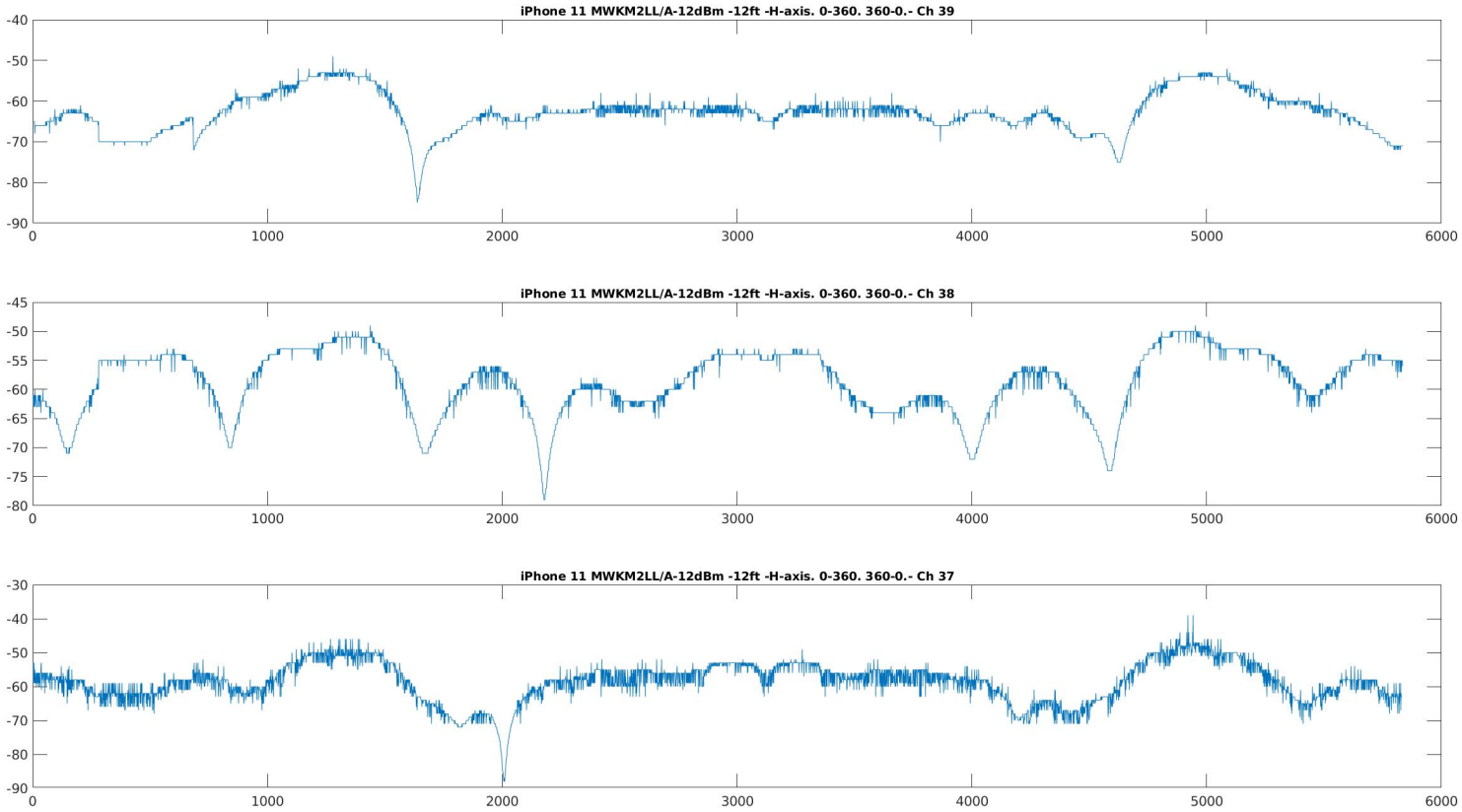
Dataset – iPhone11 (12ft)

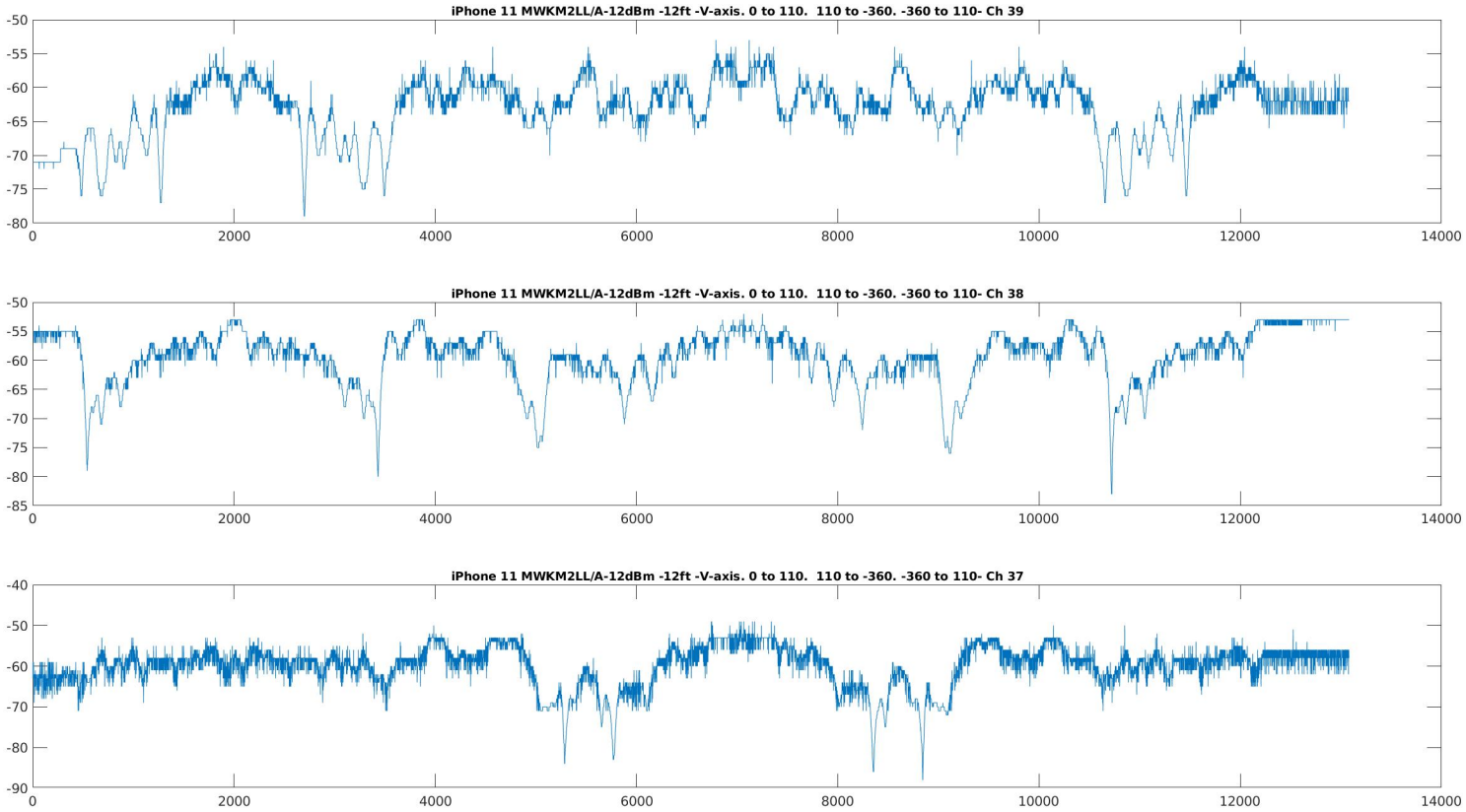
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -68.0 max = -57.0 mean = -63.118 median = -63.0 mode = -63.0 std = 0.645 range = 11.0	**Ch 38 Stats:** min = -58.0 max = -49.0 mean = -54.040 median = -54.0 mode = -54.0 std = 0.313 range = 9.0	**Ch 39 Stats:** min = -65.0 max = -52.0 mean = -58.580 median = -58.0 mode = -58.0 std = 1.914 range = 13.0
	**Ch 37 Stats:** min = -67.0 max = -56.0 mean = -61.746 median = -61.0 mode = -61.0 std = 1.011 range = 11.0	**Ch 38 Stats:** min = -66.0 max = -53.0 mean = -59.522 median = -60.0 mode = -60.0 std = 1.642 range = 13.0	**Ch 39 Stats:** min = -67.0 max = -54.0 mean = -63.535 median = -64.0 mode = -64.0 std = 1.483 range = 13.0

RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -64.0 max = -51.0 mean = -55.214 median = -55.0 mode = -55.0 std = 1.366 range = 13.0	**Ch 38 Stats:** min = -64.0 max = -53.0 mean = -53.833 median = -54.0 mode = -54.0 std = 1.295 range = 11.0	**Ch 39 Stats:** min = -67.0 max = -45.0 mean = -51.132 median = -51.0 mode = -51.0 std = 2.620 range = 22.0
	**Ch 37 Stats:** min = -59.0 max = -52.0 mean = -55.912 median = -56.0 mode = -56.0 std = 0.831 range = 7.0	**Ch 38 Stats:** min = -55.0 max = -47.0 mean = -51.057 median = -51.0 mode = -51.0 std = 0.771 range = 8.0	**Ch 39 Stats:** min = -55.0 max = -45.0 mean = -50.675 median = -50.0 mode = -50.0 std = 1.833 range = 10.0

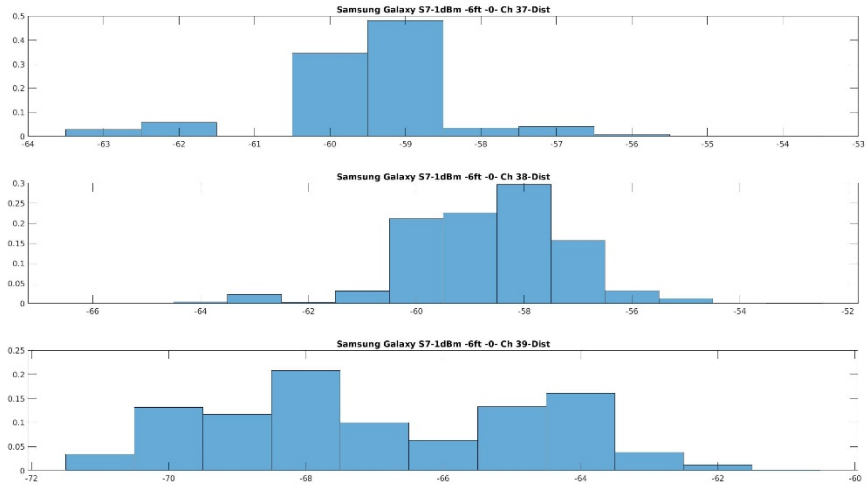
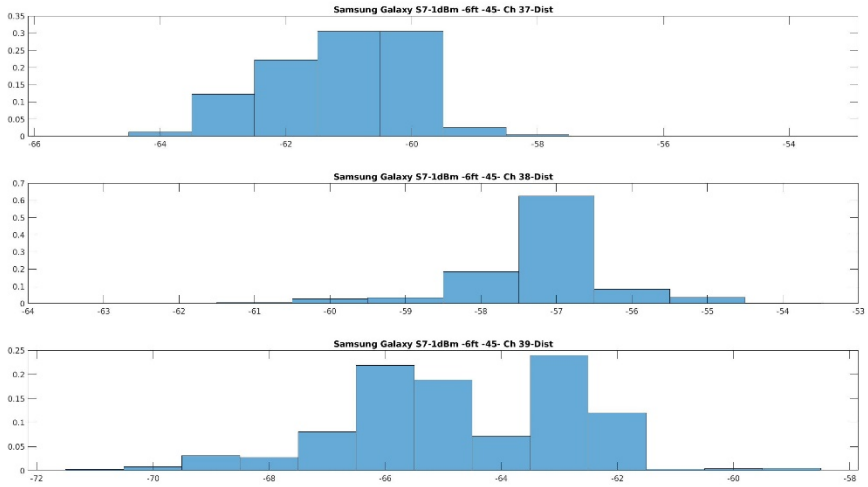
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -82.0 max = -52.0 mean = -79.870 median = -80.0 mode = -80.0 std = 3.809 range = 30.0	**Ch 38 Stats:** min = -65.0 max = -49.0 mean = -62.7253 median = -63.0 mode = -63.0 std = 1.928 range = 16.0	**Ch 39 Stats:** min = -72.0 max = -46.0 mean = -71.478 median = -72.0 mode = -72.0 std = 3.254 range = 26.0
	**Ch 37 Stats:** min = -80.0 max = -60.0 mean = -64.497 median = -64.0 mode = -64.0 std = 2.302 range = 20.0	**Ch 38 Stats:** min = -65.0 max = -57.0 mean = -59.950 median = -60.0 mode = -60.0 std = 0.889 range = 8.0	**Ch 39 Stats:** min = -72.0 max = -59.0 mean = -63.768 median = -64.0 mode = -64.0 std = 1.358 range = 13.0

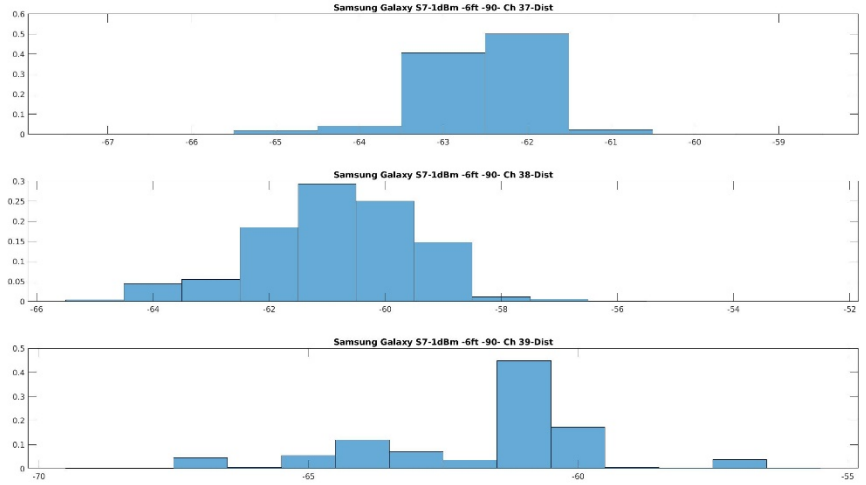
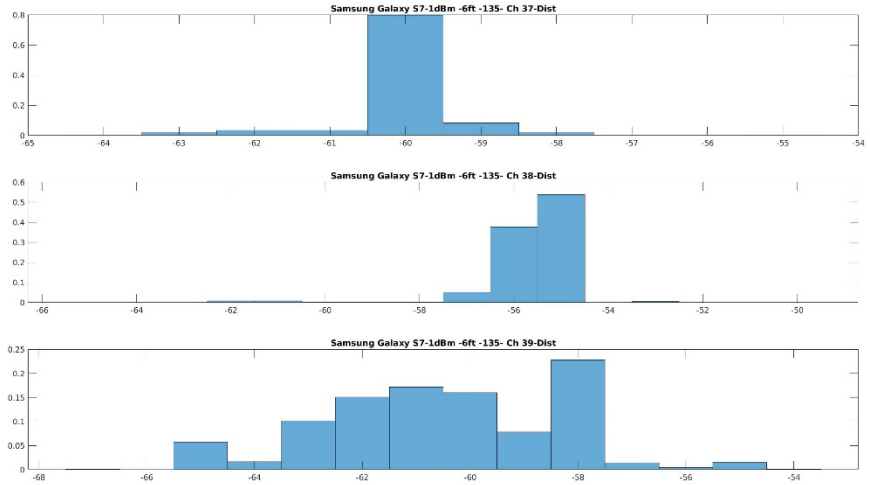
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -68.0 max = -60.0 mean = -65.677 median = -66.0 mode = -66.0 std = 0.589 range = 8.0	**Ch 38 Stats:** min = -65.0 max = -57.0 mean = -61.823 median = -61.0 mode = -61.0 std = 1.147 range = 8.0	**Ch 39 Stats:** min = -66.0 max = -52.0 mean = -57.142 median = -56.0 mode = -56.0 std = 2.254 range = 14.0
	**Ch 37 Stats:** min = -67.0 max = -58.0 mean = -62.303 median = -62.0 mode = -62.0 std = 0.934 range = 9.0	**Ch 38 Stats:** min = -63.0 max = -57.0 mean = -60.083 median = -60.0 mode = -60.0 std = 0.290 range = 6.0	**Ch 39 Stats:** min = -62.0 max = -56.0 mean = -58.070 median = -58.0 mode = -58.0 std = 1.275 range = 6.0

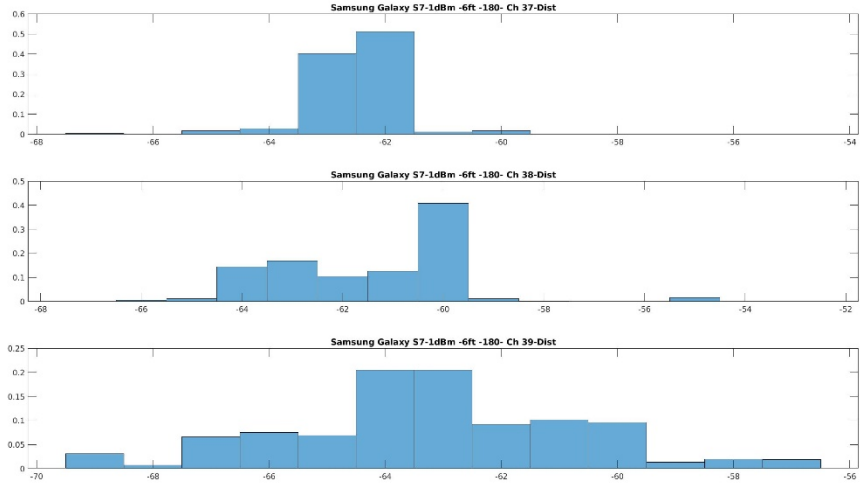
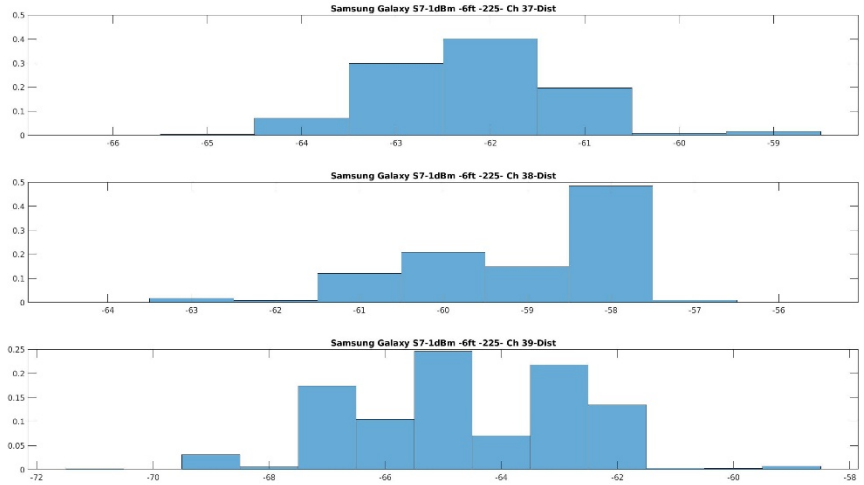

iPhone 11 MWKM2LL/A-12dBm -12ft -H-axis. 0-360. 360-0.- Ch 39
-40
-50
-60
-70
-80
-90
0
1000
2000
3000
4000
5000
6000
iPhone 11 MWKM2LL/A-12dBm -12ft -H-axis. 0-360. 360-0.- Ch 38
-45
-50
-55
-60
-65
-70
-75
-80
0
1000
2000
3000
4000
5000
6000
iPhone 11 MWKM2LL/A-12dBm -12ft -H-axis. 0-360. 360-0.- Ch 37
-30
-40
-50
-60
-70
-80
-90
0
1000
2000
3000
4000
5000
6000

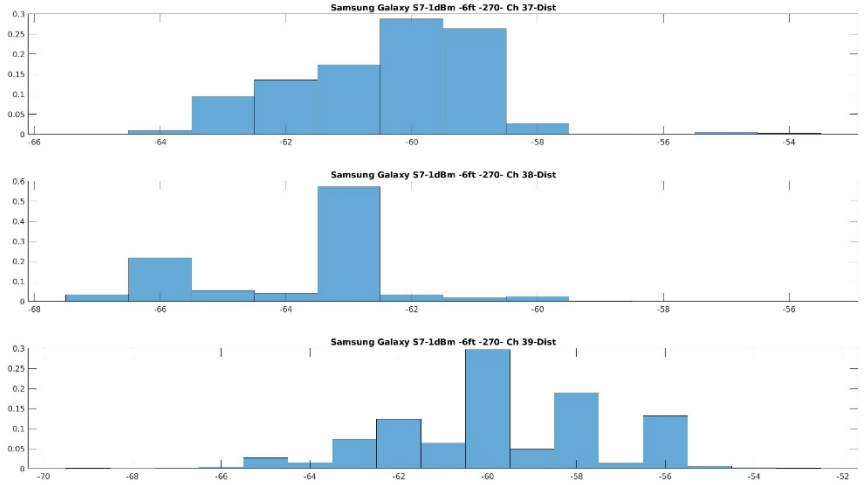
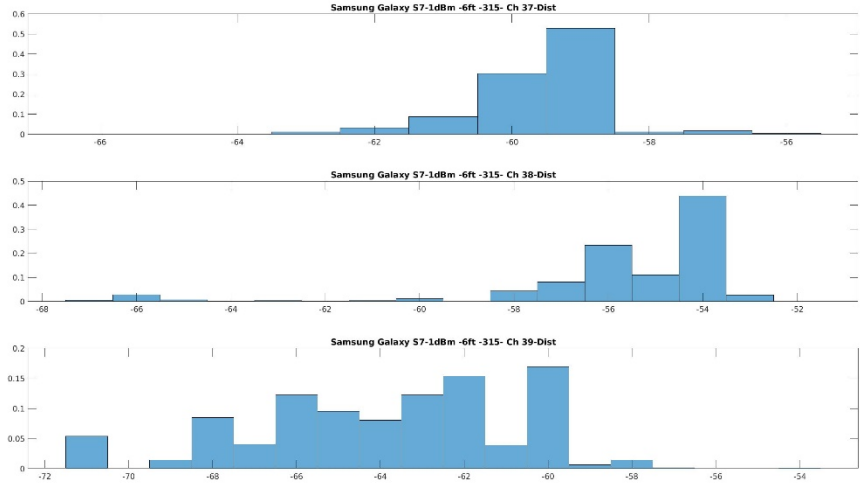

iPhone 11 MWKM2LL/A-12dBm -12ft -V-axis. 0 to 110. 110 to -360. -360 to 110- Ch 39
-50
-55
-60
-65
-70
-75
-80
0
2000
4000
6000
8000
10000
12000
14000
iPhone 11 MWKM2LL/A-12dBm -12ft -V-axis. 0 to 110. 110 to -360. -360 to 110- Ch 38
-50
-55
-60
-65
-70
-75
-80
-85
0
2000
4000
6000
8000
10000
12000
14000
iPhone 11 MWKM2LL/A-12dBm -12ft -V-axis. 0 to 110. 110 to -360. -360 to 110- Ch 37
-40
-50
-60
-70
-80
-90
0
2000
4000
6000
8000
10000
12000
14000

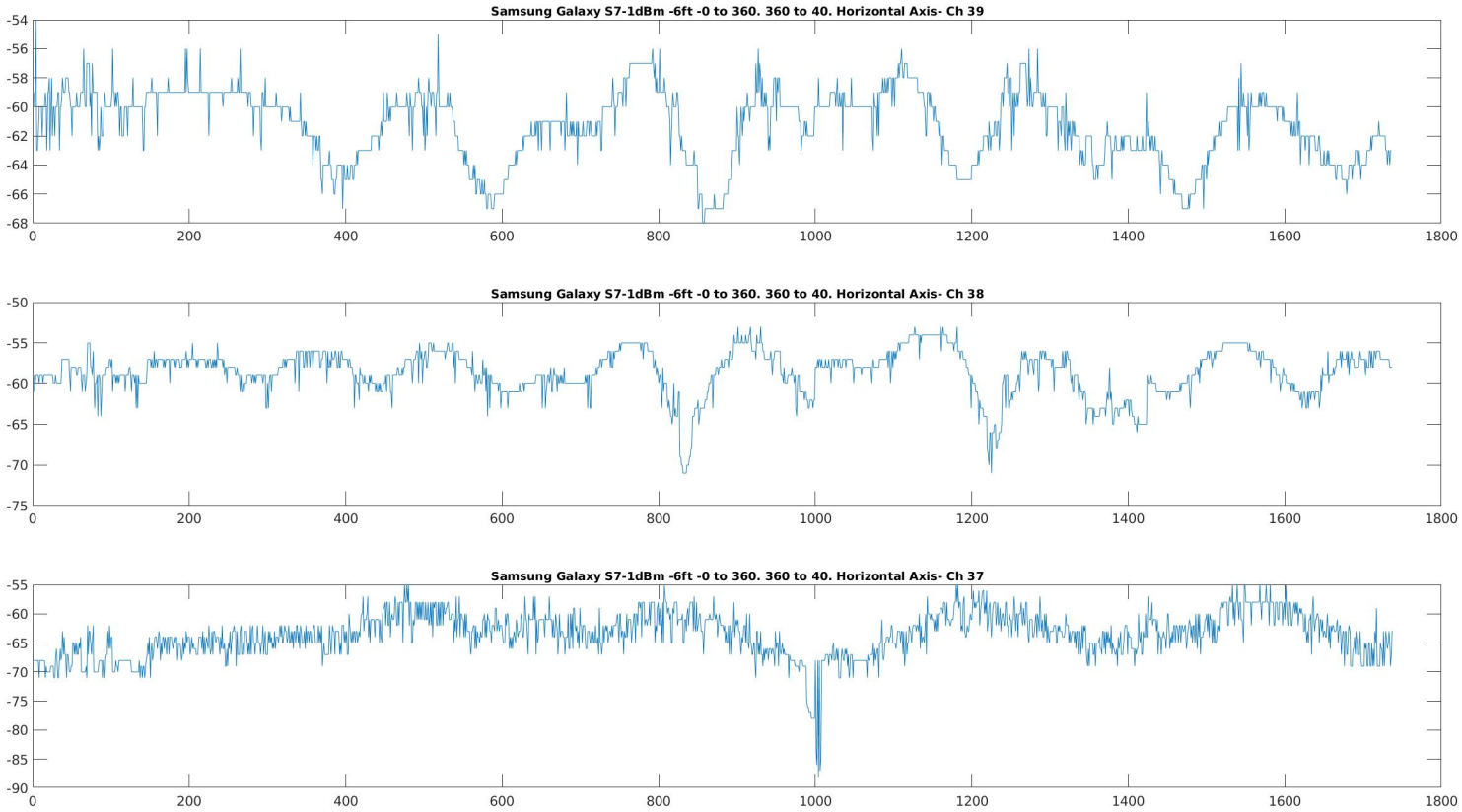
Dataset – Samsung Galaxy S7 (6ft)

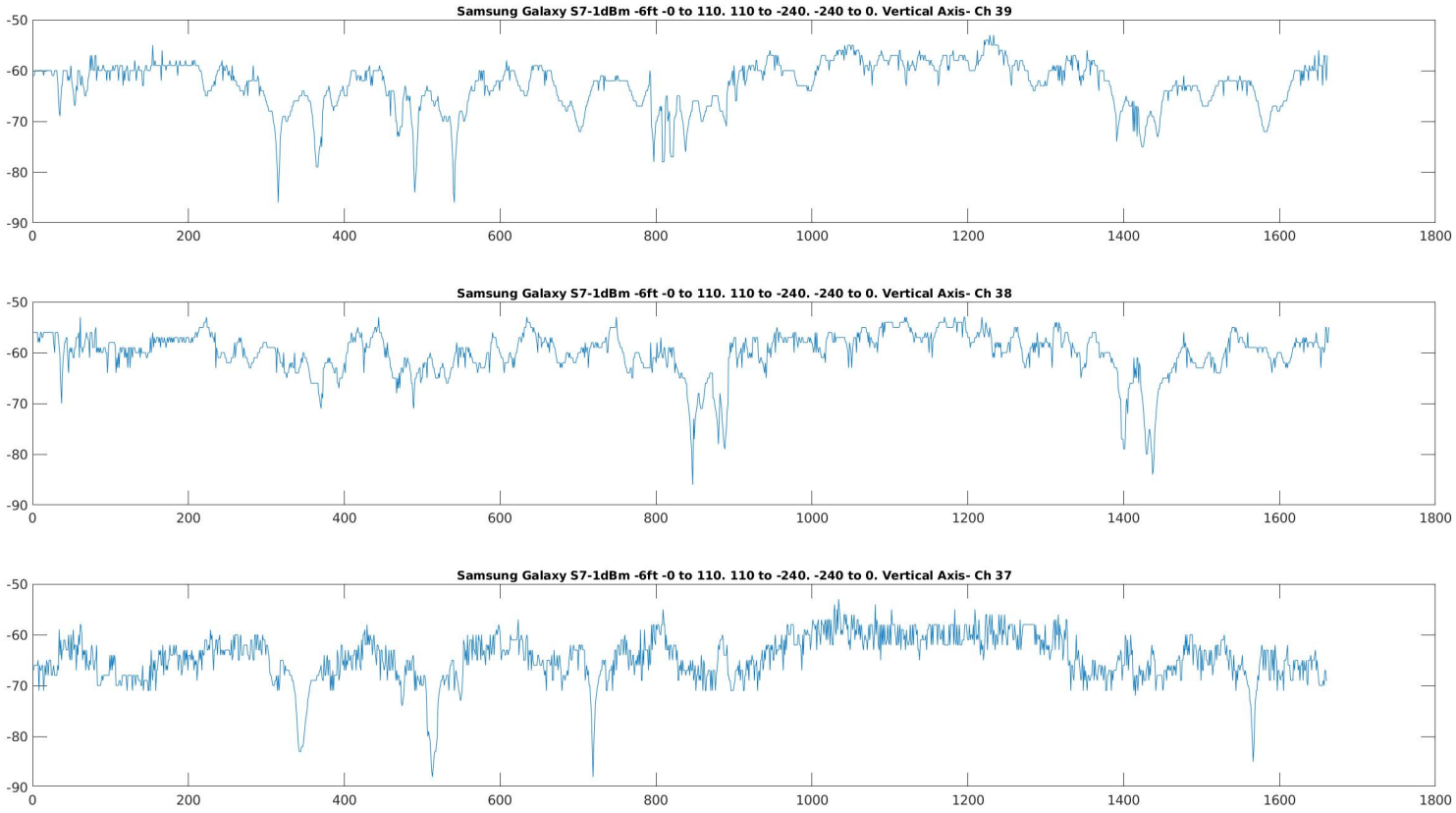
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -63.0 max = -54.0 mean = -59.473 median = -59.0 mode = -59.0 std = 1.215 range = 9.0	**Ch 38 Stats:** min = -66.0 max = -53.0 mean = -58.630 median = -58.0 mode = -58.0 std = 1.484 range = 13.0	**Ch 39 Stats:** min = -71.0 max = -61.0 mean = -66.942 median = -67.0 mode = -68.0 std = 2.327 range = 10.0
	**Ch 37 Stats:** min = -65.0 max = -54.0 mean = -61.124 median = -61.0 mode = -61.0 std = 1.158 range = 11.0	**Ch 38 Stats:** min = -63.0 max = -54.0 mean = -57.210 median = -57.0 mode = -57.0 std = 0.969 range = 9.0	**Ch 39 Stats:** min = -71.0 max = -59.0 mean = -64.668 median = -65.0 mode = -63.0 std = 1.974 range = 12.0

RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	Ch 37 Stats: min = -67.0 max = -59.0 mean = -62.529 median = -62.0 mode = -62.0 std = 0.767 range = 8.0	Ch 38 Stats: min = -65.0 max = -53.0 mean = -60.822 median = -61.0 mode = -61.0 std = 1.405 range = 12.0	Ch 39 Stats: min = -69.0 max = -56.0 mean = -61.712 median = -61.0 mode = -61.0 std = 2.118 range = 13.0
	**Ch 37 Stats:** min = -64.0 max = -55.0 mean = -60.033 median = -60.0 mode = -60.0 std = 0.806 range = 9.0	**Ch 38 Stats:** min = -65.0 max = -50.0 mean = -55.620 median = -55.0 mode = -55.0 std = 1.106 range = 15.0	**Ch 39 Stats:** min = -67.0 max = -54.0 mean = -60.459 median = -60.0 mode = -58.0 std = 2.190 range = 13.0

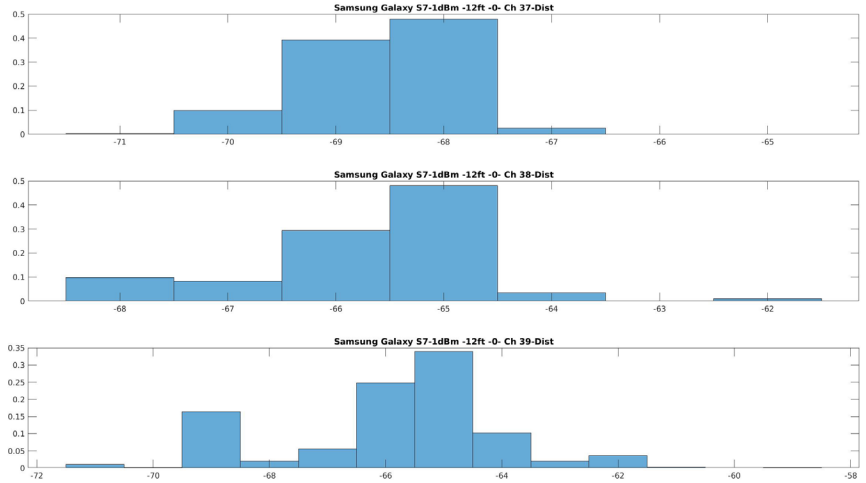
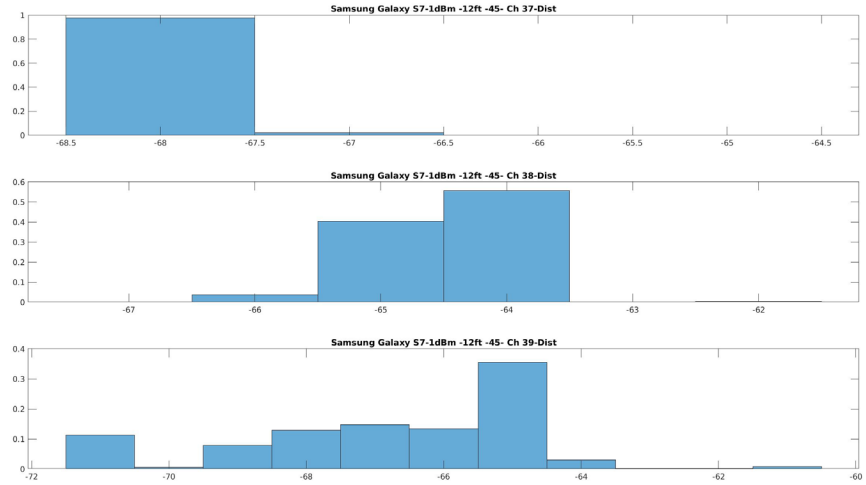
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -67.0 max = -55.0 mean = -62.477 median = -62.0 mode = -62.0 std = 0.853 range = 12.0	**Ch 38 Stats:** min = -67.0 max = -53.0 mean = -61.402 median = -61.0 mode = -60.0 std = 1.840 range = 14.0	**Ch 39 Stats:** min = -69.0 max = -57.0 mean = -63.208 median = -63.0 mode = -64.0 std = 2.500 range = 12.0
	**Ch 37 Stats:** min = -66.0 max = -59.0 mean = -62.194 median = -62.0 mode = -62.0 std = 0.990 range = 7.0	**Ch 38 Stats:** min = -64.0 max = -56.0 mean = -59.047 median = -59.0 mode = -58.0 std = 1.272 range = 8.0	**Ch 39 Stats:** min = -71.0 max = -59.0 mean = -64.622 median = -65.0 mode = -65.0 std = 1.954 range = 12.0

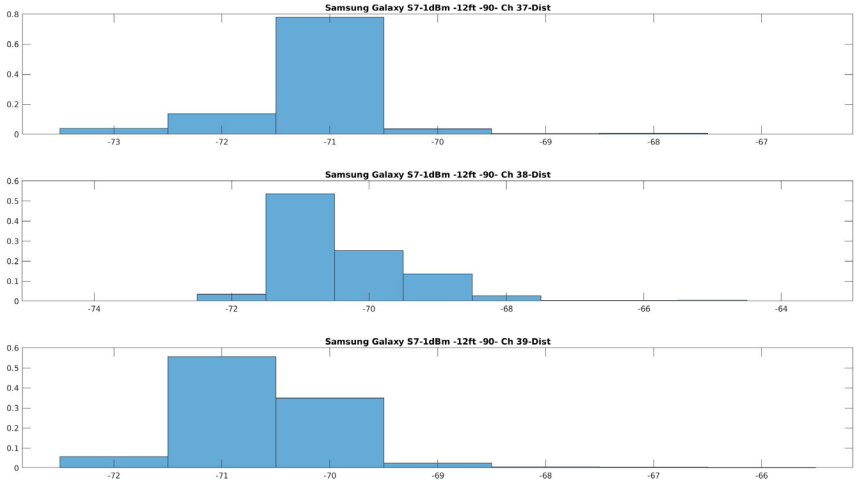
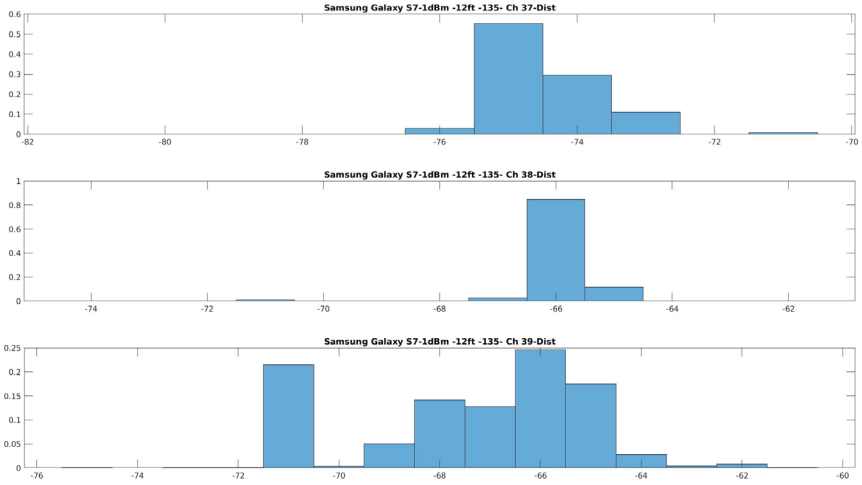
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -65.0 max = -54.0 mean = -60.420 median = -60.0 mode = -60.0 std = 1.460 range = 11.0	**Ch 38 Stats:** min = -67.0 max = -56.0 mean = -63.780 median = -63.0 mode = -63.0 std = 1.609 range = 11.0	**Ch 39 Stats:** min = -69.0 max = -53.0 mean = -59.732 median = -60.0 mode = -60.0 std = 2.380 range = 16.0
	**Ch 37 Stats:** min = -66.0 max = -56.0 mean = -59.579 median = -59.0 mode = -59.0 std = 1.014 range = 10.0	**Ch 38 Stats:** min = -67.0 max = -52.0 mean = -55.639 median = -55.0 mode = -54.0 std = 2.670 range = 15.0	**Ch 39 Stats:** min = -71.0 max = -54.0 mean = -63.886 median = -63.0 mode = -60.0 std = 3.154 range = 17.0

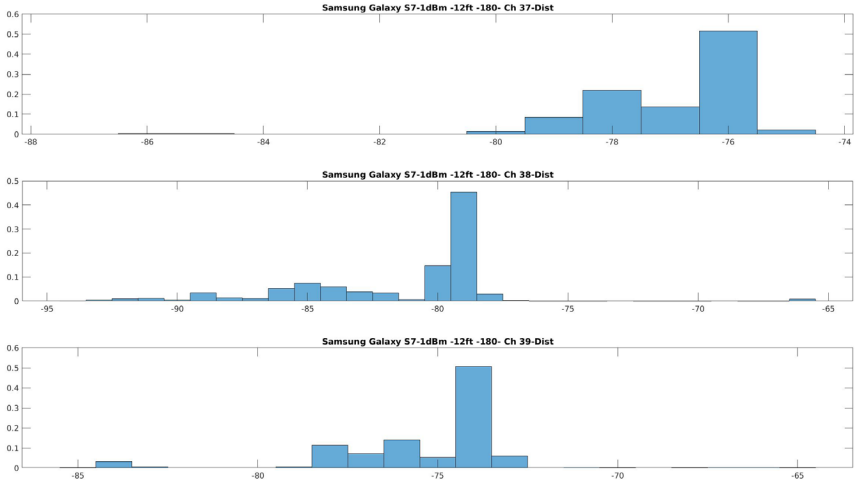
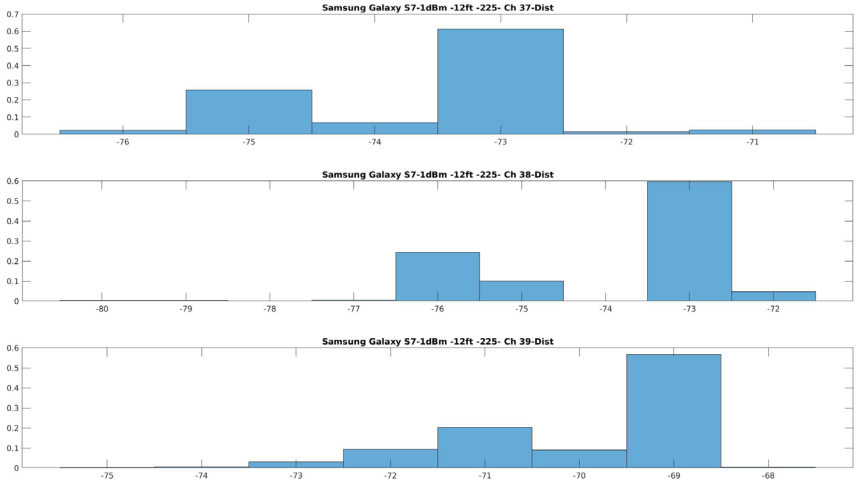

Samsung Galaxy S7-1dBm -6ft -0 to 360. 360 to 40. Horizontal Axis- Ch 39
-54
-56
-58
-60
-62
-64
-66
-68
0
200
400
600
800
1000
1200
1400
1600
1800
Samsung Galaxy S7-1dBm -6ft -0 to 360. 360 to 40. Horizontal Axis- Ch 38
-50
-55
-60
-65
-70
-75
0
200
400
600
800
1000
1200
1400
1600
1800
Samsung Galaxy S7-1dBm -6ft -0 to 360. 360 to 40. Horizontal Axis- Ch 37
-55
-60
-65
-70
-75
-80
-85
-90
0
200
400
600
800
1000
1200
1400
1600
1800

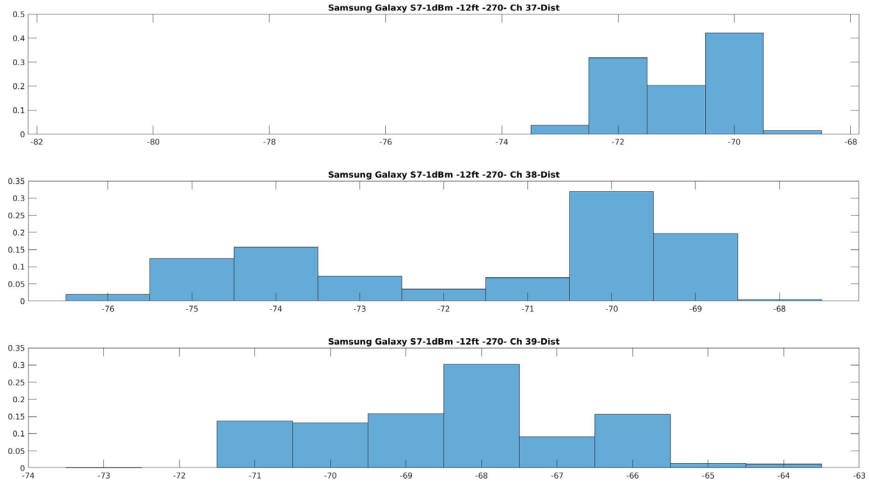
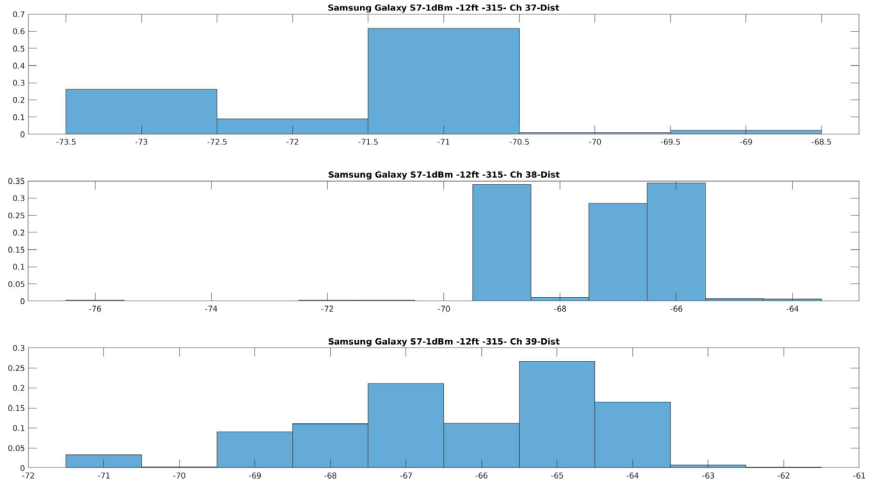

Samsung Galaxy S7-1dBm -6ft -0 to 110. 110 to -240. -240 to 0. Vertical Axis- Ch 39
Samsung Galaxy S7-1dBm -6ft -0 to 110. 110 to -240. -240 to 0. Vertical Axis- Ch 38
Samsung Galaxy S7-1dBm -6ft -0 to 110. 110 to -240. -240 to 0. Vertical Axis- Ch 37
-50
-60
-70
-80
-90
0
200
400
600
800
1000
1200
1400
1600
1800

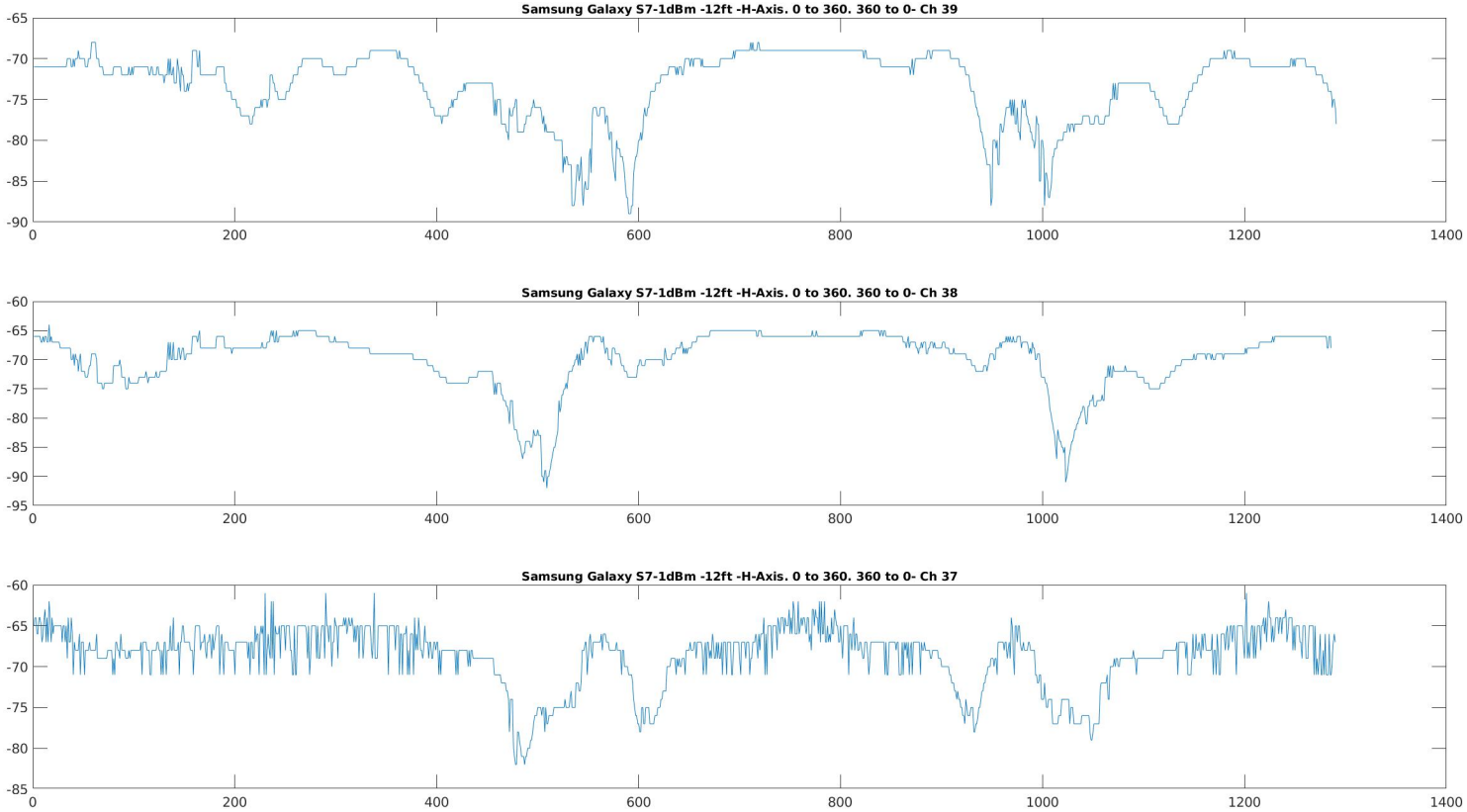
Dataset – Samsung Galaxy S7 (12ft)

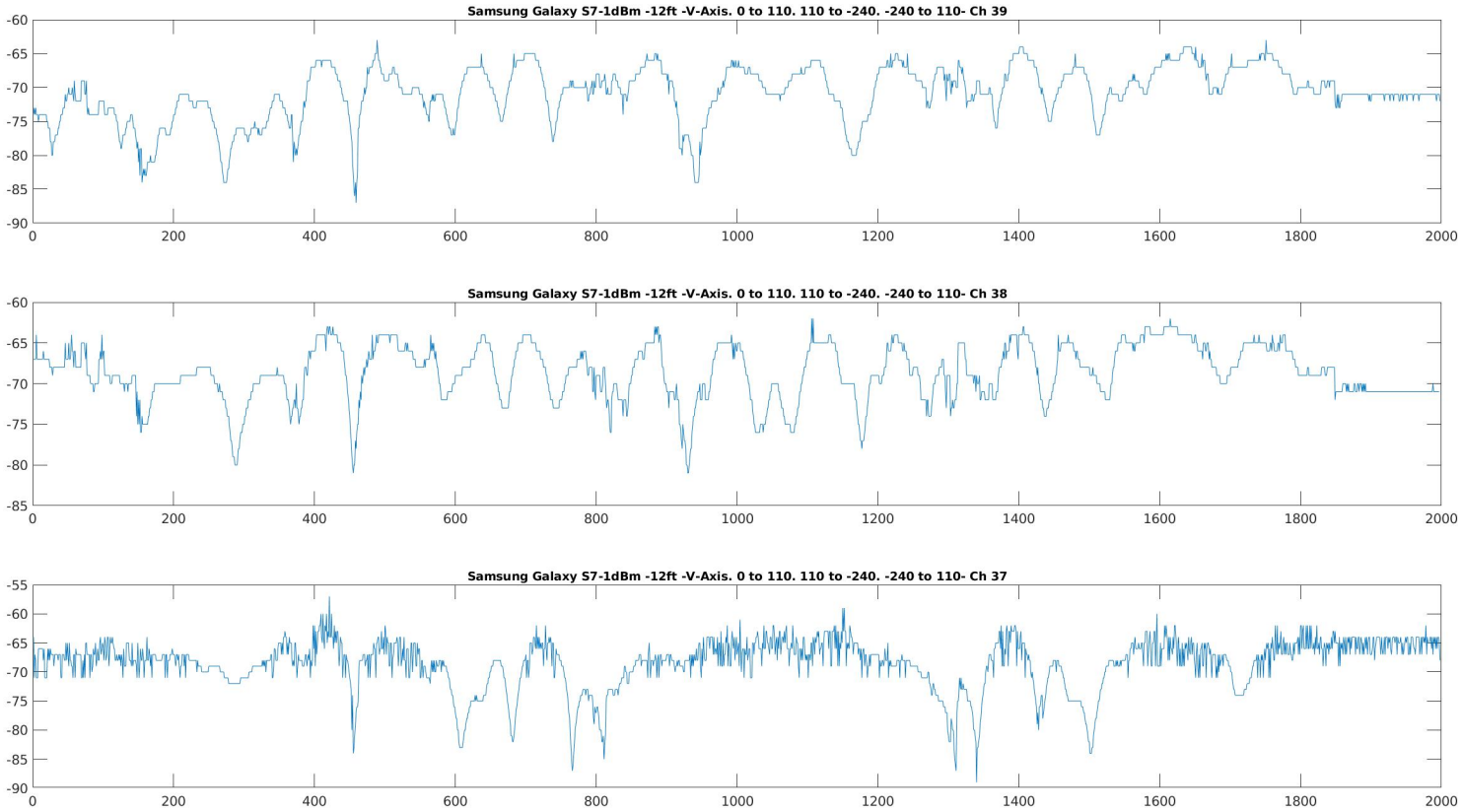
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -71.0 max = -65.0 mean = -68.570 median = -68.0 mode = -68.0 std = 0.716 range = 6.0	**Ch 38 Stats:** min = -68.0 max = -62.0 mean = -65.685 median = -65.0 mode = -65.0 std = 1.079 range = 6.0	**Ch 39 Stats:** min = -71.0 max = -59.0 mean = -65.869 median = -65.0 mode = -65.0 std = 1.860 range = 12.0
	**Ch 37 Stats:** min = -68.0 max = -65.0 mean = -67.976 median = -68.0 mode = -68.0 std = 0.174 range = 3.0	**Ch 38 Stats:** min = -67.0 max = -62.0 mean = -64.470 median = -64.0 mode = -64.0 std = 0.587 range = 5.0	**Ch 39 Stats:** min = -71.0 max = -61.0 mean = -66.767 median = -66.0 mode = -65.0 std = 2.089 range = 10.0

RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -73.0 max = -67.0 mean = -71.151 median = -71.0 mode = -71.0 std = 0.620 range = 6.0	**Ch 38 Stats:** min = -74.0 max = -64.0 mean = -70.365 median = -71.0 mode = -71.0 std = 1.029 range = 10.0	**Ch 39 Stats:** min = -72.0 max = -66.0 mean = -70.618 median = -71.0 mode = -71.0 std = 0.714 range = 6.0
	**Ch 37 Stats:** min = -81.0 max = -71.0 mean = -74.482 median = -75.0 mode = -75.0 std = 0.821 range = 10.0	**Ch 38 Stats:** min = -74.0 max = -62.0 mean = -65.967 median = -66.0 mode = -66.0 std = 0.693 range = 12.0	**Ch 39 Stats:** min = -75.0 max = -61.0 mean = -67.380 median = -67.0 mode = -66.0 std = 2.287 range = 14.0

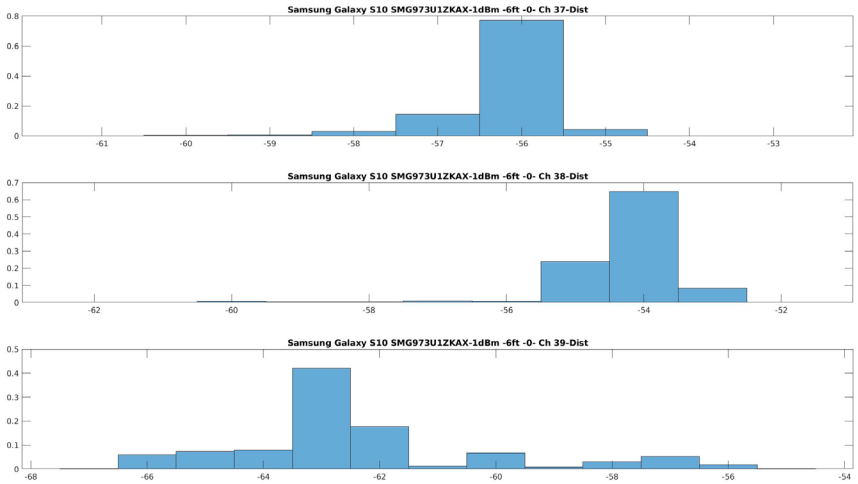
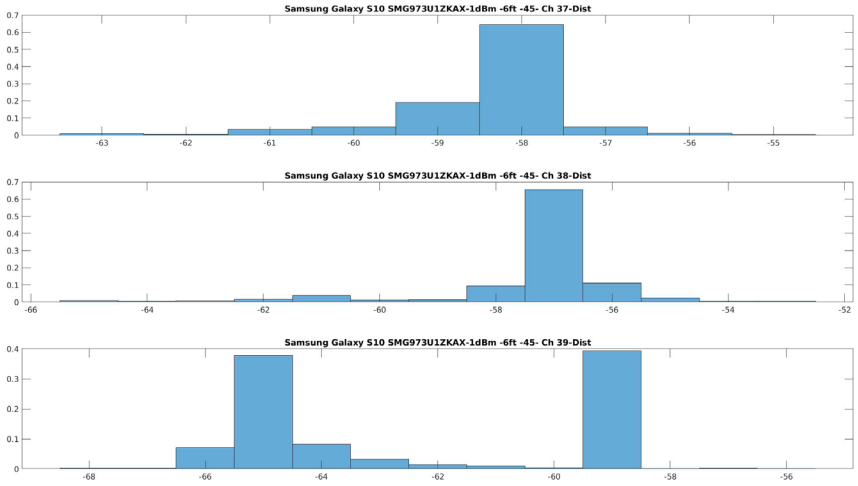
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -87.0 max = -75.0 mean = -76.928 median = -76.0 mode = -76.0 std = 1.324 range = 12.0	**Ch 38 Stats:** min = -94.0 max = -66.0 mean = -81.317 median = -80.0 mode = -79.0 std = 3.771 range = 28.0	**Ch 39 Stats:** min = -85.0 max = -65.0 mean = -75.316 median = -74.0 mode = -74.0 std = 2.434 range = 20.0
	**Ch 37 Stats:** min = -76.0 max = -71.0 mean = -73.587 median = -73.0 mode = -73.0 std = 1.032 range = 5.0	**Ch 38 Stats:** min = -80.0 max = -72.0 mean = -73.944 median = -73.0 mode = -73.0 std = 1.445 range = 8.0	**Ch 39 Stats:** min = -75.0 max = -68.0 mean = -69.934 median = -69.0 mode = -69.0 std = 1.251 range = 7.0

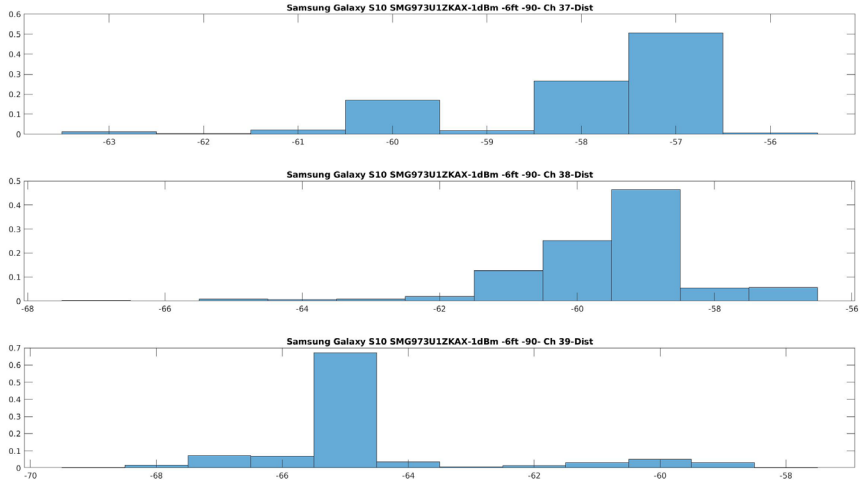
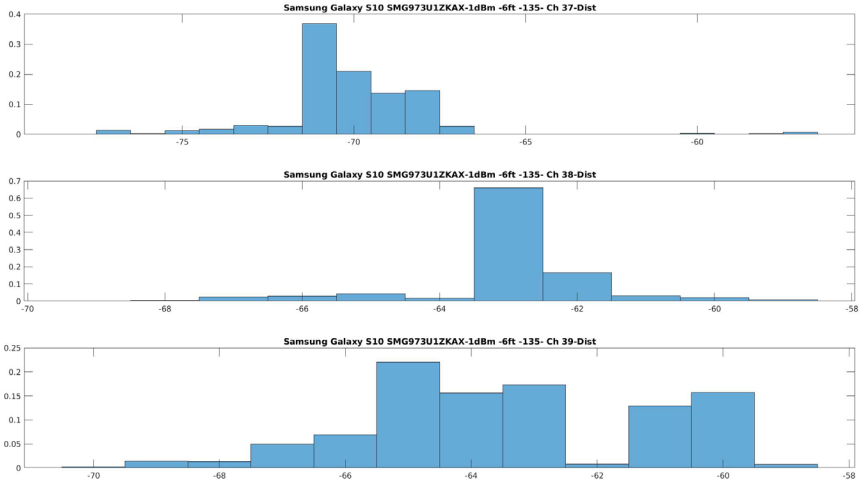
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -81.0 max = -69.0 mean = -70.962 median = -71.0 mode = -70.0 std = 1.036 range = 12.0	**Ch 38 Stats:** min = -76.0 max = -68.0 mean = -71.517 median = -70.0 mode = -70.0 std = 2.259 range = 8.0	**Ch 39 Stats:** min = -73.0 max = -64.0 mean = -68.344 median = -68.0 mode = -68.0 std = 1.680 range = 9.0
	**Ch 37 Stats:** min = -73.0 max = -69.0 mean = -71.556 median = -71.0 mode = -71.0 std = 0.965 range = 4.0	**Ch 38 Stats:** min = -76.0 max = -64.0 mean = -67.368 median = -67.0 mode = -66.0 std = 1.421 range = 12.0	**Ch 39 Stats:** min = -71.0 max = -62.0 mean = -66.250 median = -66.0 mode = -65.0 std = 1.817 range = 9.0

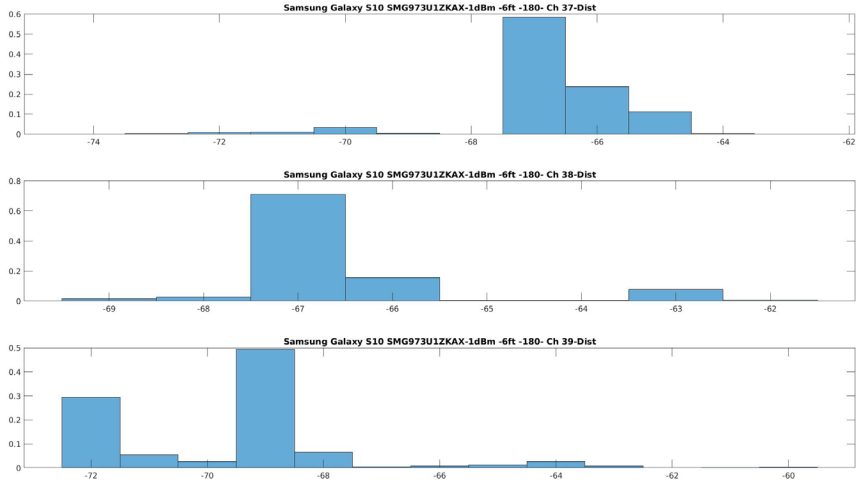
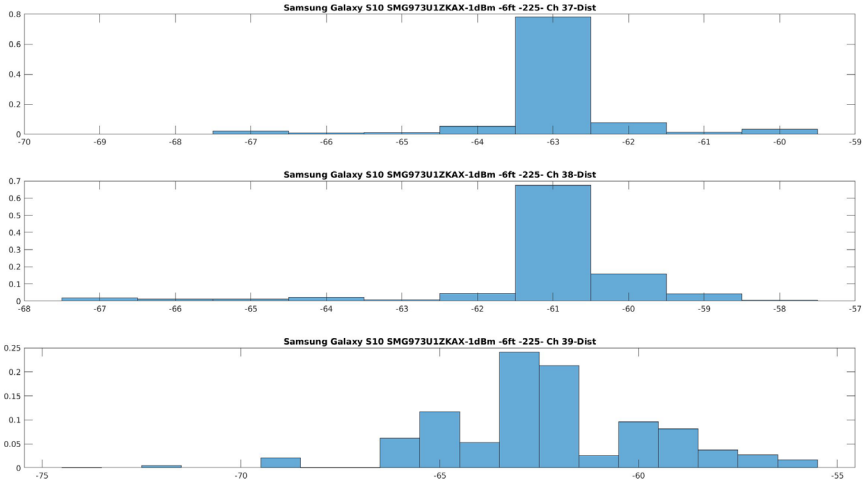

Samsung Galaxy S7-1dBm -12ft -H-Axis. 0 to 360. 360 to 0- Ch 39
-65
-70
-75
-80
-85
-90
0
200
400
600
800
1000
1200
1400
Samsung Galaxy S7-1dBm -12ft -H-Axis. 0 to 360. 360 to 0- Ch 38
-60
-65
-70
-75
-80
-85
-90
-95
0
200
400
600
800
1000
1200
1400
Samsung Galaxy S7-1dBm -12ft -H-Axis. 0 to 360. 360 to 0- Ch 37
-60
-65
-70
-75
-80
-85
0
200
400
600
800
1000
1200
1400

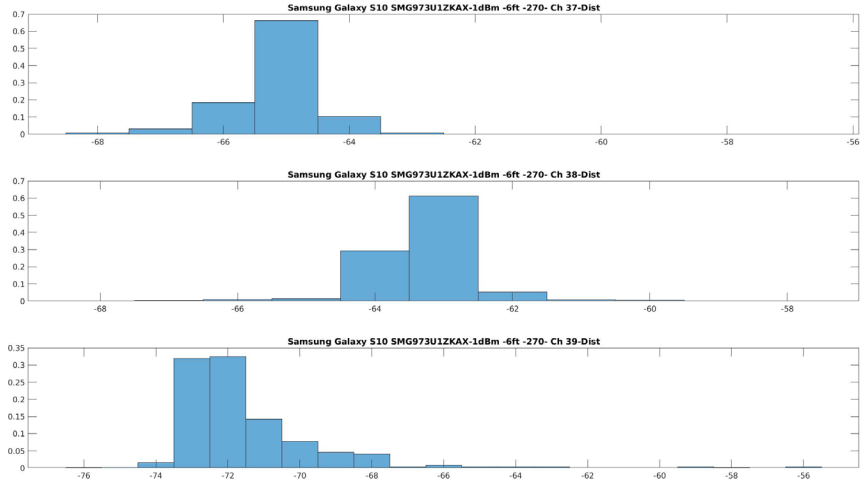
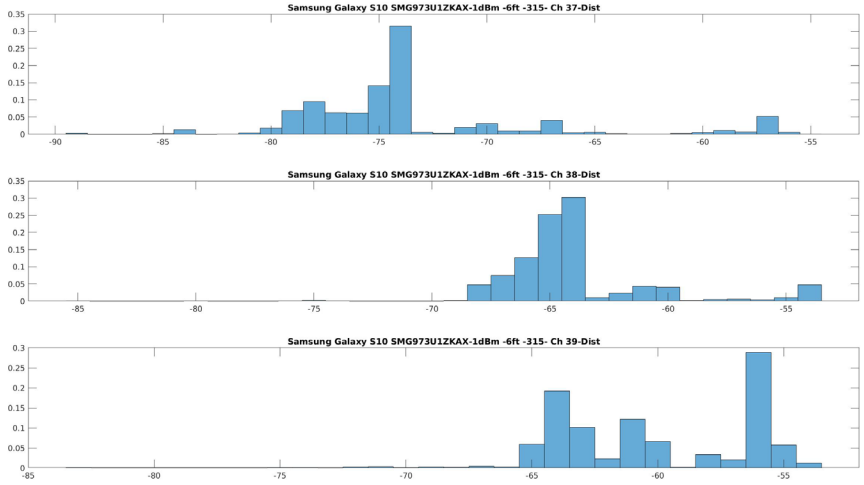

Samsung Galaxy S7-1dBm -12ft -V-Axis. 0 to 110. 110 to -240. -240 to 110- Ch 39
-60
-65
-70
-75
-80
-85
-90
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S7-1dBm -12ft -V-Axis. 0 to 110. 110 to -240. -240 to 110- Ch 38
-60
-65
-70
-75
-80
-85
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S7-1dBm -12ft -V-Axis. 0 to 110. 110 to -240. -240 to 110- Ch 37
-55
-60
-65
-70
-75
-80
-85
-90
0
200
400
600
800
1000
1200
1400
1600
1800
2000

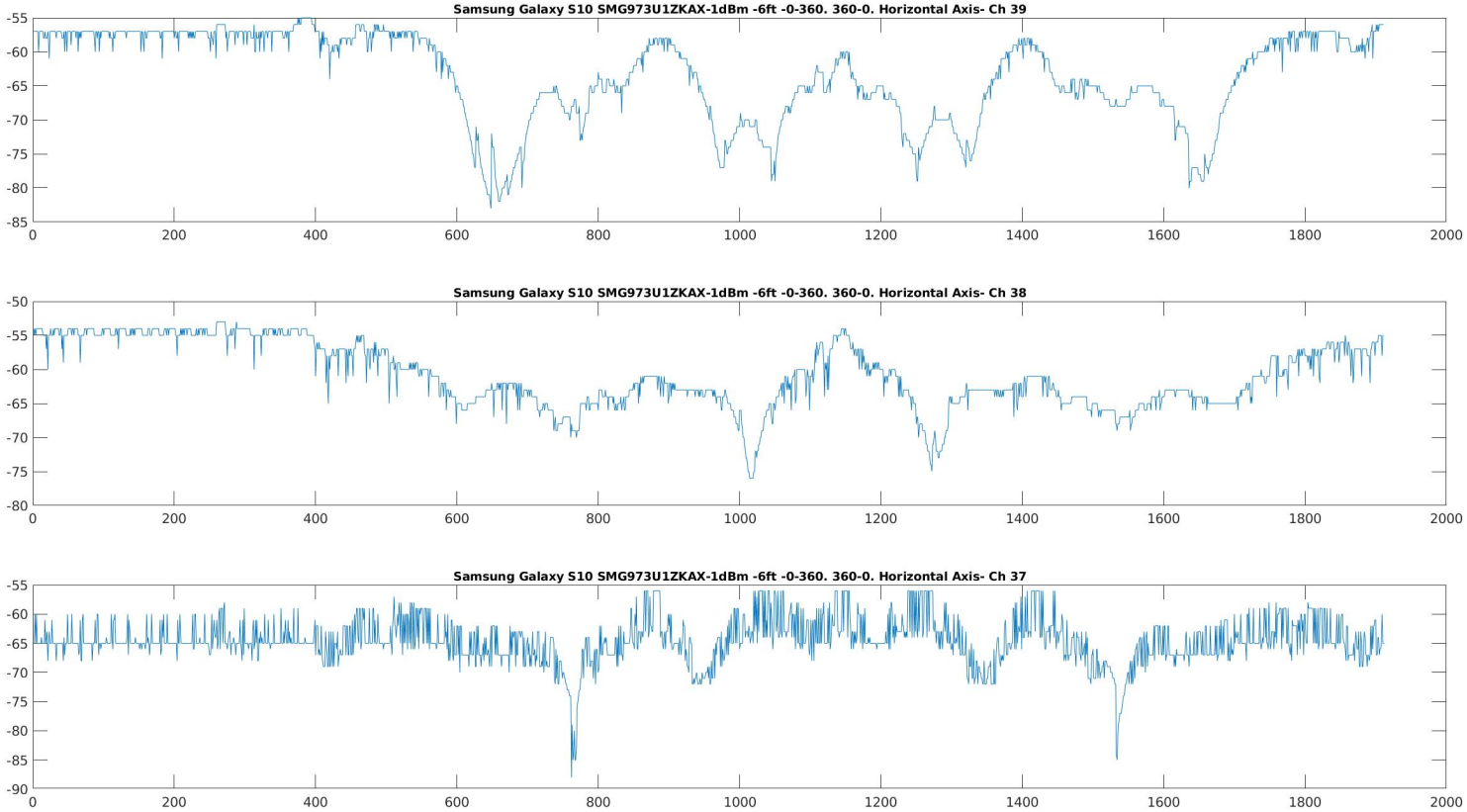
Dataset – Samsung Galaxy S10 (6ft)

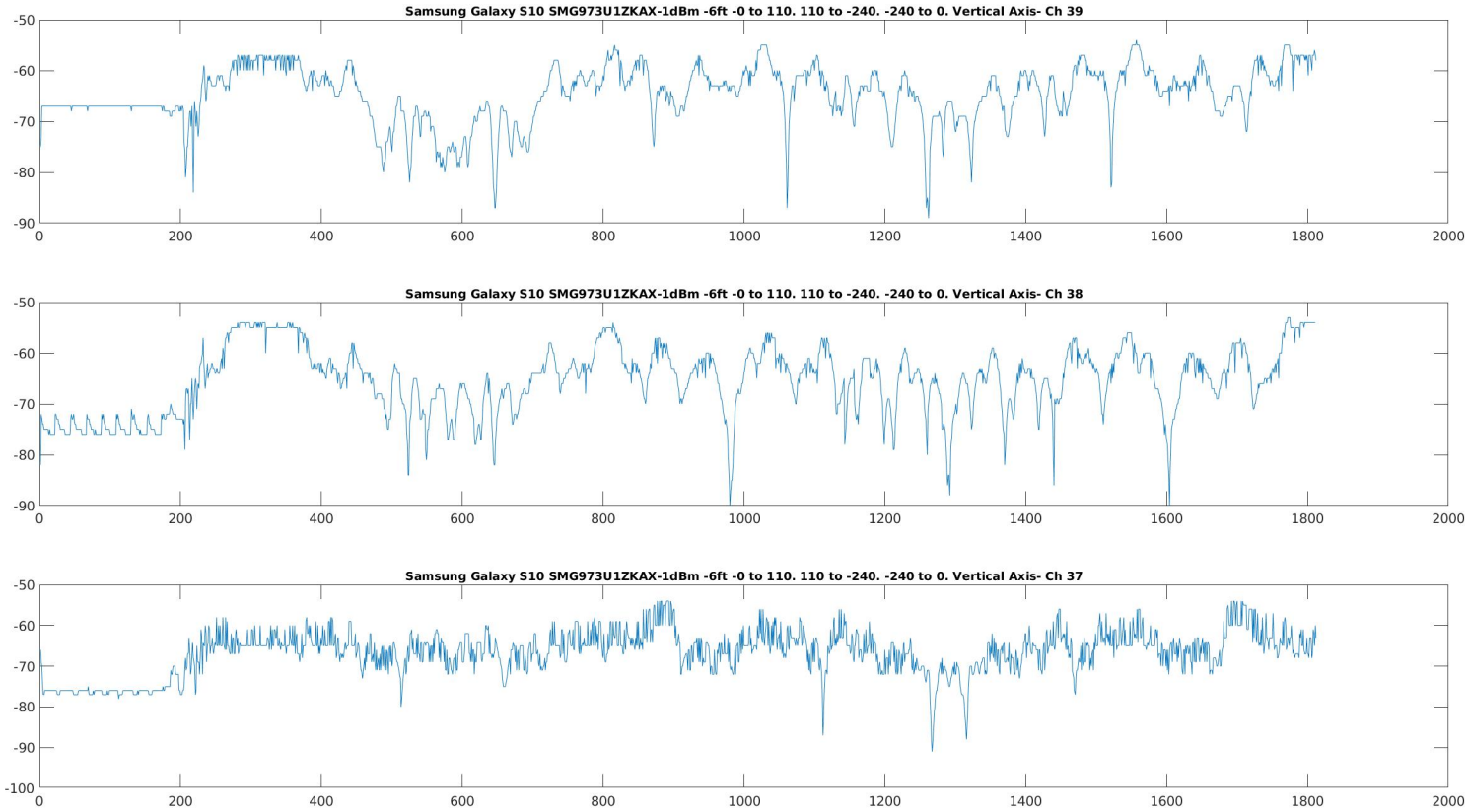
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -61.0 max = -53.0 mean = -56.194 median = -56.0 mode = -56.0 std = 0.633 range = 8.0	**Ch 38 Stats:** min = -62.0 max = -52.0 mean = -54.276 median = -54.0 mode = -54.0 std = 0.908 range = 10.0	**Ch 39 Stats:** min = -67.0 max = -55.0 mean = -62.376 median = -63.0 mode = -63.0 std = 2.249 range = 12.0
	**Ch 37 Stats:** min = -63.0 max = -55.0 mean = -58.385 median = -58.0 mode = -58.0 std = 1.007 range = 8.0	**Ch 38 Stats:** min = -65.0 max = -53.0 mean = -57.333 median = -57.0 mode = -57.0 std = 1.609 range = 12.0	**Ch 39 Stats:** min = -68.0 max = -56.0 mean = -62.421 median = -64.0 mode = -59.0 std = 2.945 range = 12.0

RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -63.0 max = -56.0 mean = -57.969 median = -57.0 mode = -57.0 std = 1.324 range = 7.0	**Ch 38 Stats:** min = -67.0 max = -57.0 mean = -59.534 median = -59.0 mode = -59.0 std = 1.303 range = 10.0	**Ch 39 Stats:** min = -69.0 max = -58.0 mean = -64.594 median = -65.0 mode = -65.0 std = 1.878 range = 11.0
	**Ch 37 Stats:** min = -78.0 max = -57.0 mean = -70.076 median = -70.0 mode = -71.0 std = 2.217 range = 21.0	**Ch 38 Stats:** min = -69.0 max = -59.0 mean = -62.990 median = -63.0 mode = -63.0 std = 1.249 range = 10.0	**Ch 39 Stats:** min = -70.0 max = -59.0 mean = -63.405 median = -64.0 mode = -65.0 std = 2.308 range = 11.0

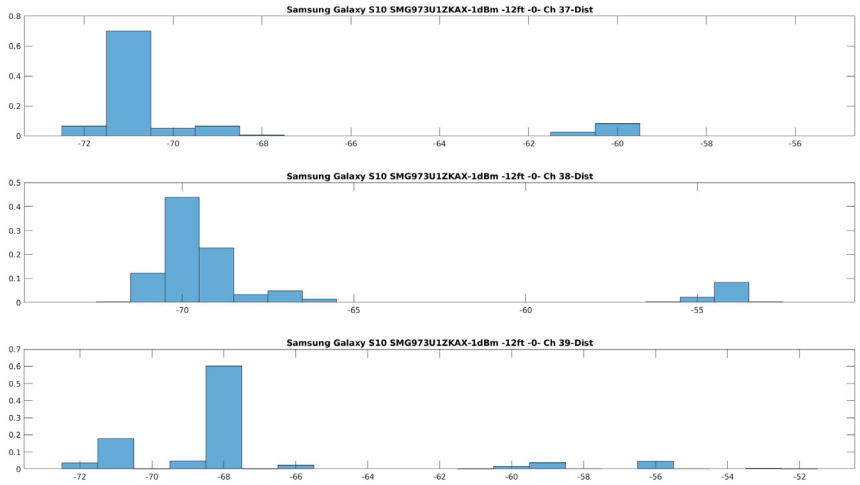
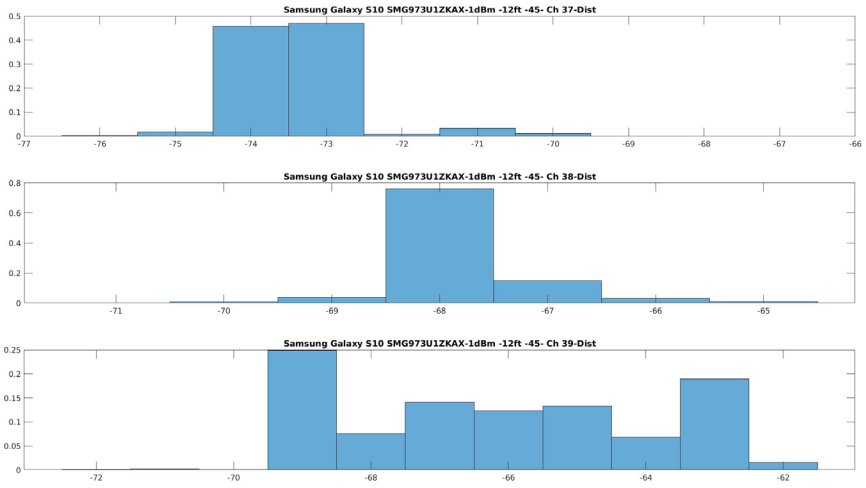
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	Ch 37 Stats: min = -74.0 max = -63.0 mean = -66.745 median = -67.0 mode = -67.0 std = 1.214 range = 11.0	Ch 38 Stats: min = -69.0 max = -62.0 mean = -66.545 median = -67.0 mode = -67.0 std = 1.216 range = 7.0	Ch 39 Stats: min = -72.0 max = -60.0 mean = -69.641 median = -69.0 mode = -69.0 std = 2.051 range = 12.0
	**Ch 37 Stats:** min = -69.0 max = -60.0 mean = -62.977 median = -63.0 mode = -63.0 std = 0.983 range = 9.0	**Ch 38 Stats:** min = -67.0 max = -58.0 mean = -61.094 median = -61.0 mode = -61.0 std = 1.358 range = 9.0	**Ch 39 Stats:** min = -74.0 max = -56.0 mean = -62.309 median = -63.0 mode = -63.0 std = 2.670 range = 18.0

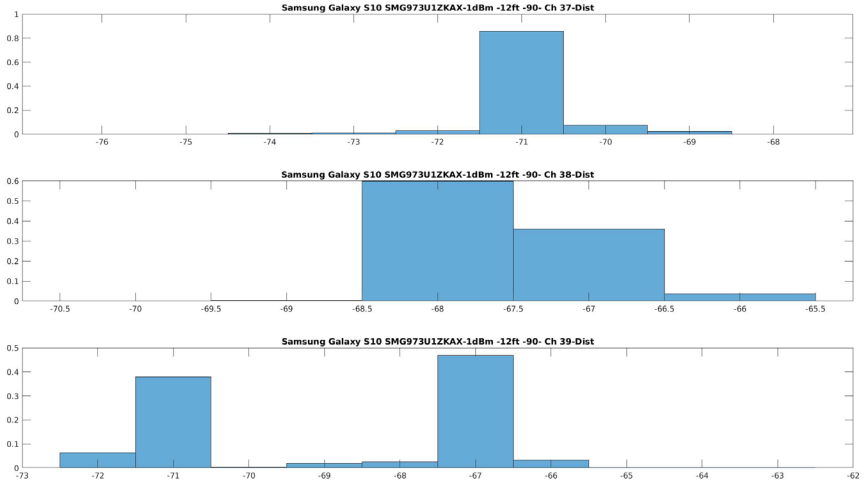
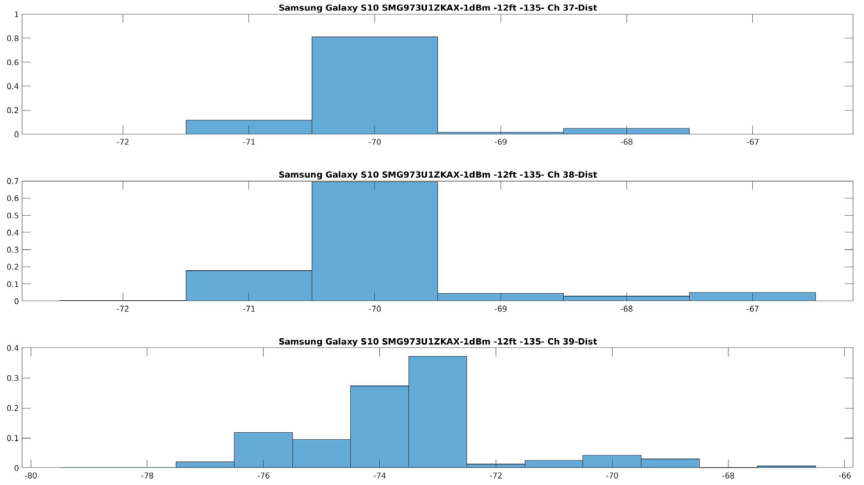
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -68.0 max = -57.0 mean = -65.140 median = -65.0 mode = -65.0 std = 0.769 range = 11.0	**Ch 38 Stats:** min = -68.0 max = -58.0 mean = -63.272 median = -63.0 mode = -63.0 std = 0.756 range = 10.0	**Ch 39 Stats:** min = -76.0 max = -56.0 mean = -71.482 median = -72.0 mode = -72.0 std = 2.124 range = 20.0
	**Ch 37 Stats:** min = -89.0 max = -55.0 mean = -73.452 median = -74.0 mode = -74.0 std = 5.818 range = 34.0	**Ch 38 Stats:** min = -85.0 max = -54.0 mean = -63.975 median = -65.0 mode = -64.0 std = 3.256 range = 31.0	**Ch 39 Stats:** min = -83.0 max = -54.0 mean = -60.097 median = -61.0 mode = -56.0 std = 3.845 range = 29.0

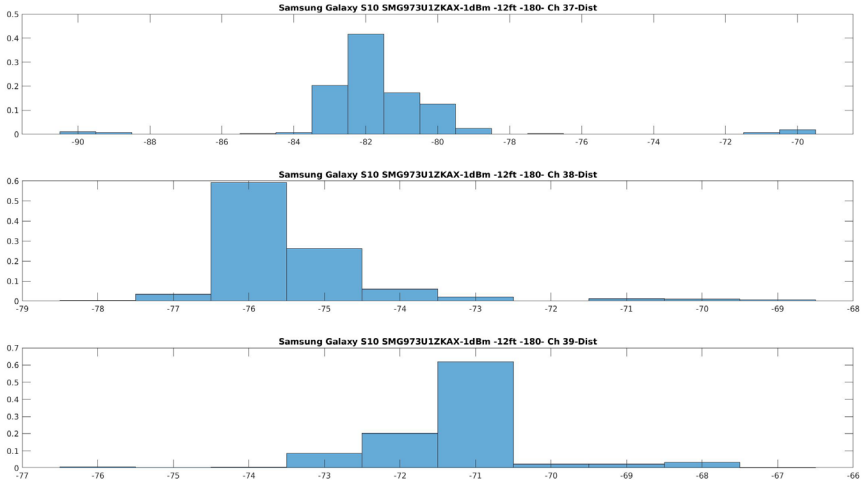
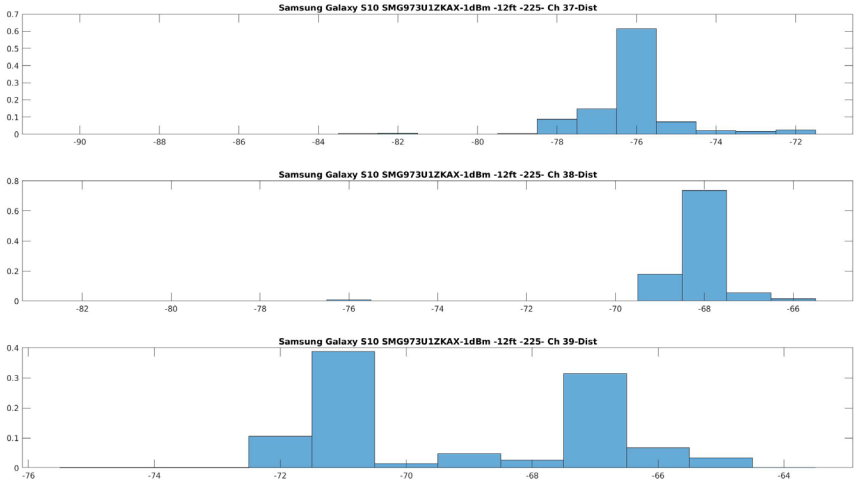

Samsung Galaxy S10 SMG973U1ZKAX-1dBm -6ft -0-360. 360-0. Horizontal Axis- Ch 39
-55
-60
-65
-70
-75
-80
-85
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S10 SMG973U1ZKAX-1dBm -6ft -0-360. 360-0. Horizontal Axis- Ch 38
-50
-55
-60
-65
-70
-75
-80
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S10 SMG973U1ZKAX-1dBm -6ft -0-360. 360-0. Horizontal Axis- Ch 37
-55
-60
-65
-70
-75
-80
-85
-90
0
200
400
600
800
1000
1200
1400
1600
1800
2000

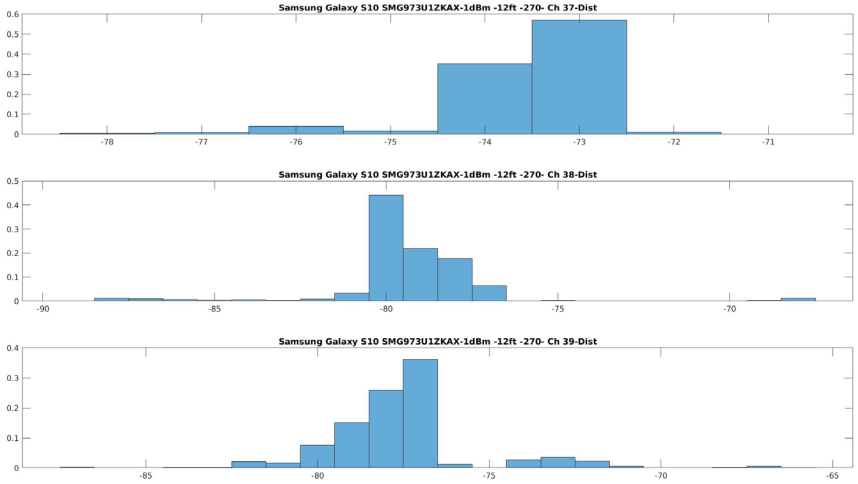
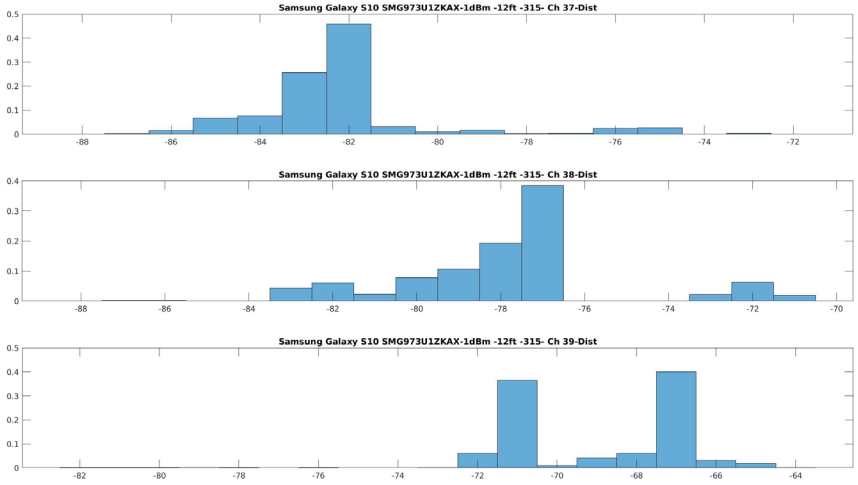

Samsung Galaxy S10 SMG973U1ZKAX-1dBm -6ft -0 to 110. 110 to -240. -240 to 0. Vertical Axis- Ch 39
-50
-60
-70
-80
-90
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S10 SMG973U1ZKAX-1dBm -6ft -0 to 110. 110 to -240. -240 to 0. Vertical Axis- Ch 38
-50
-60
-70
-80
-90
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S10 SMG973U1ZKAX-1dBm -6ft -0 to 110. 110 to -240. -240 to 0. Vertical Axis- Ch 37
-50
-60
-70
-80
-90
-100
0
200
400
600
800
1000
1200
1400
1600
1800
2000

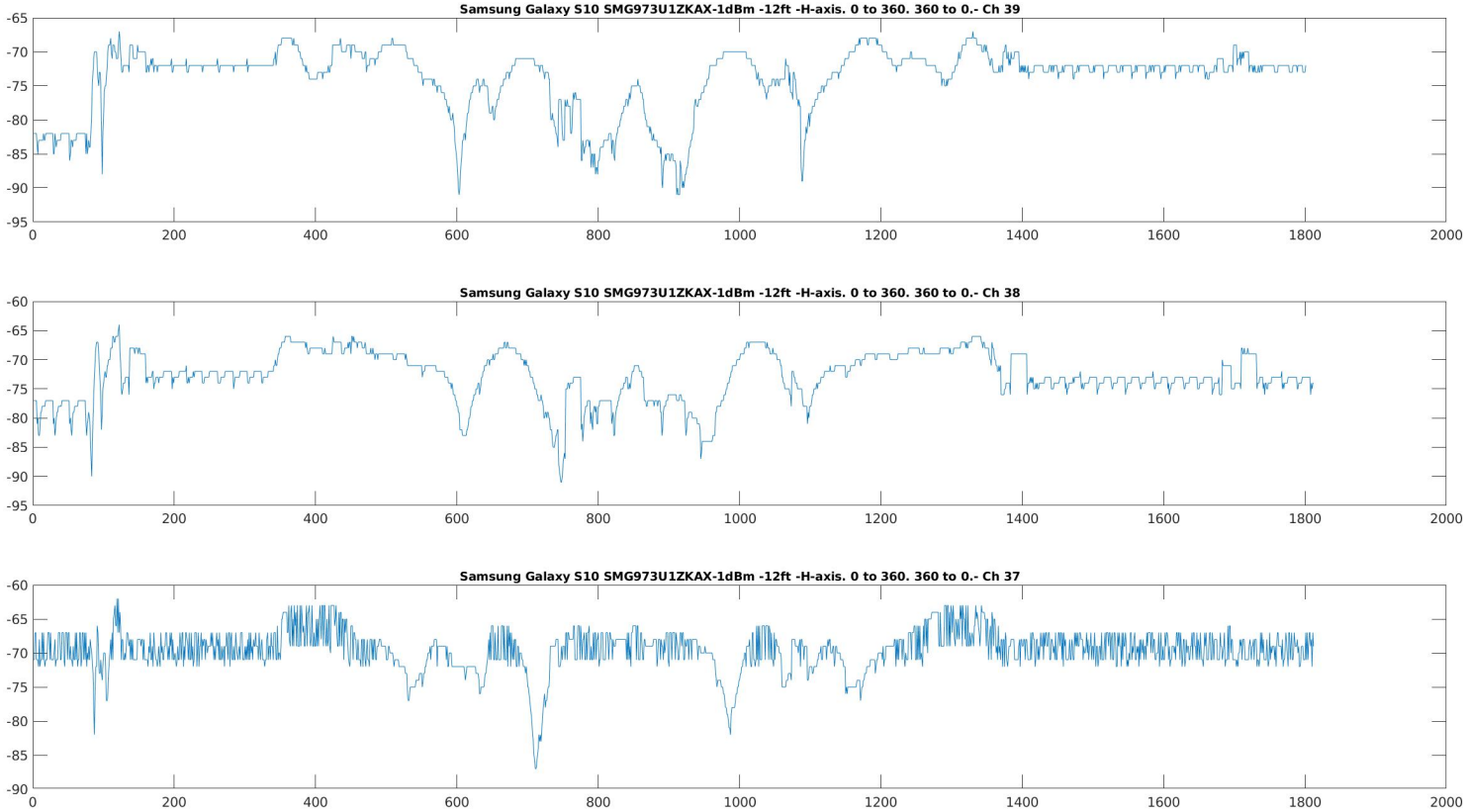
Dataset – Samsung Galaxy S10 (12ft)

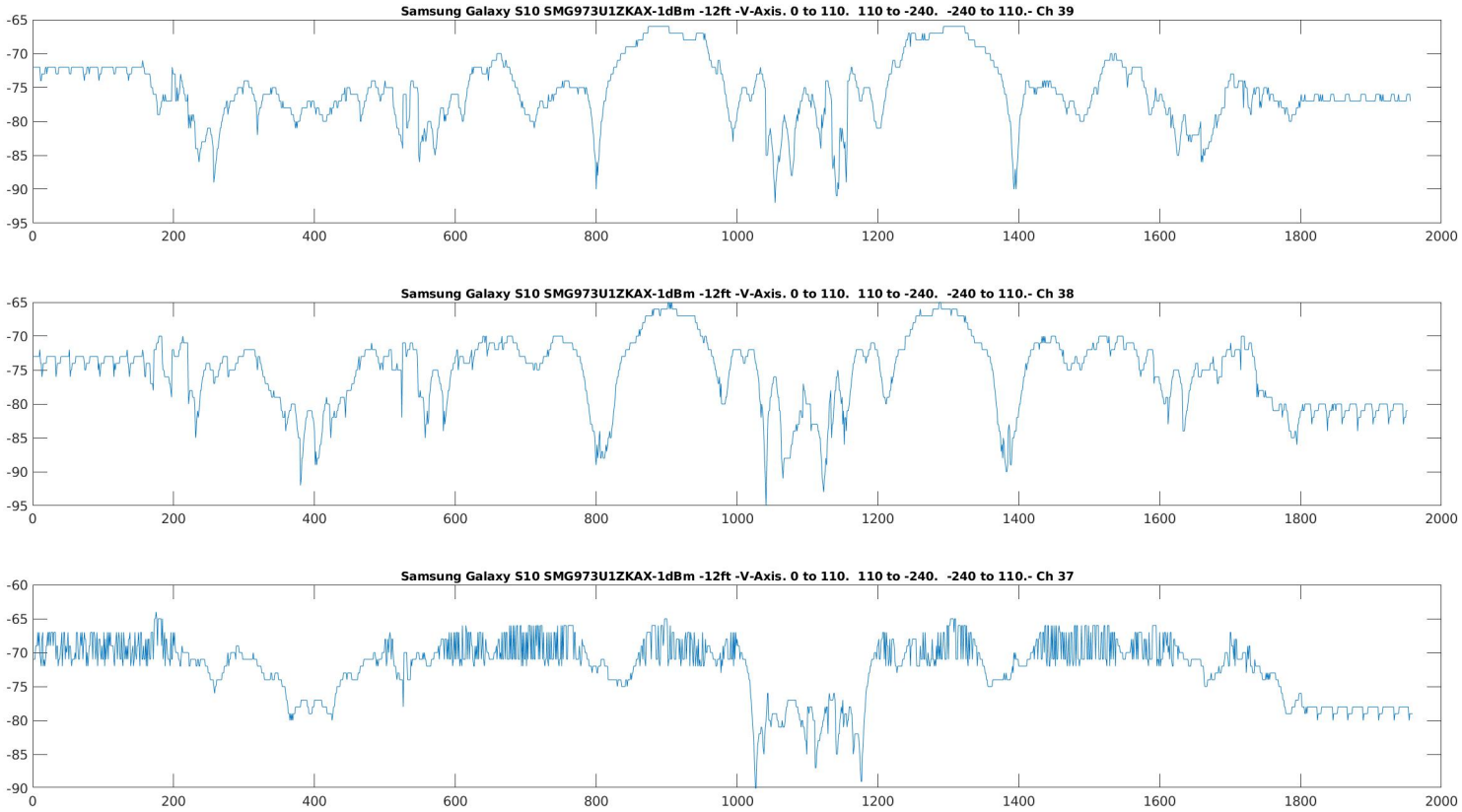
RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -72.0 max = -56.0 mean = -69.666 median = -71.0 mode = -71.0 std = 3.411 range = 16.0	**Ch 38 Stats:** min = -73.0 max = -52.0 mean = -67.877 median = -70.0 mode = -70.0 std = 4.936 range = 21.0	**Ch 39 Stats:** min = -72.0 max = -52.0 mean = -67.510 median = -68.0 mode = -68.0 std = 3.844 range = 20.0
	**Ch 37 Stats:** min = -76.0 max = -67.0 mean = -73.384 median = -73.0 mode = -73.0 std = 0.817 range = 9.0	**Ch 38 Stats:** min = -71.0 max = -65.0 mean = -67.818 median = -68.0 mode = -68.0 std = 0.652 range = 6.0	**Ch 39 Stats:** min = -72.0 max = -62.0 mean = -66.161 median = -66.0 mode = -69.0 std = 2.265 range = 10.0

RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -76.0 max = -68.0 mean = -70.950 median = -71.0 mode = -71.0 std = 0.551 range = 8.0	**Ch 38 Stats:** min = -70.0 max = -66.0 mean = -67.572 median = -68.0 mode = -68.0 std = 0.576 range = 4.0	**Ch 39 Stats:** min = -72.0 max = -63.0 mean = -68.858 median = -67.0 mode = -67.0 std = 2.106 range = 9.0
	**Ch 37 Stats:** min = -72.0 max = -67.0 mean = -69.998 median = -70.0 mode = -70.0 std = 0.591 range = 5.0	**Ch 38 Stats:** min = -72.0 max = -67.0 mean = -69.931 median = -70.0 mode = -70.0 std = 0.891 range = 5.0	**Ch 39 Stats:** min = -79.0 max = -67.0 mean = -73.567 median = -74.0 mode = -73.0 std = 1.750 range = 12.0

RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -90.0 max = -70.0 mean = -81.533 median = -82.0 mode = -82.0 std = 2.403 range = 20.0	**Ch 38 Stats:** min = -78.0 max = -69.0 mean = -75.432 median = -76.0 mode = -76.0 std = 1.176 range = 9.0	**Ch 39 Stats:** min = -76.0 max = -67.0 mean = -71.264 median = -71.0 mode = -71.0 std = 1.094 range = 9.0
	**Ch 37 Stats:** min = -90.0 max = -72.0 mean = -76.145 median = -76.0 mode = -76.0 std = 1.308 range = 18.0	**Ch 38 Stats:** min = -82.0 max = -66.0 mean = -68.186 median = -68.0 mode = -68.0 std = 1.028 range = 16.0	**Ch 39 Stats:** min = -75.0 max = -64.0 mean = -69.113 median = -70.0 mode = -71.0 std = 2.236 range = 11.0

RSSI Distribution	Channel 37 Stats	Channel 38 Stats	Channel 39 Stats
	**Ch 37 Stats:** min = -78.0 max = -71.0 mean = -73.541 median = -73.0 mode = -73.0 std = 0.845 range = 7.0	**Ch 38 Stats:** min = -89.0 max = -68.0 mean = -79.352 median = -80.0 mode = -80.0 std = 2.238 range = 21.0	**Ch 39 Stats:** min = -87.0 max = -66.0 mean = -77.513 median = -78.0 mode = -77.0 std = 2.218 range = 21.0
	**Ch 37 Stats:** min = -88.0 max = -72.0 mean = -82.174 median = -82.0 mode = -82.0 std = 2.119 range = 16.0	**Ch 38 Stats:** min = -88.0 max = -71.0 mean = -77.841 median = -78.0 mode = -77.0 std = 2.682 range = 17.0	**Ch 39 Stats:** min = -82.0 max = -64.0 mean = -68.944 median = -68.0 mode = -67.0 std = 2.251 range = 18.0


Samsung Galaxy S10 SMG973U1ZKAX-1dBm -12ft -H-axis. 0 to 360. 360 to 0.- Ch 39
-65
-70
-75
-80
-85
-90
-95
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S10 SMG973U1ZKAX-1dBm -12ft -H-axis. 0 to 360. 360 to 0.- Ch 38
-60
-65
-70
-75
-80
-85
-90
-95
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S10 SMG973U1ZKAX-1dBm -12ft -H-axis. 0 to 360. 360 to 0.- Ch 37
-60
-65
-70
-75
-80
-85
-90
0
200
400
600
800
1000
1200
1400
1600
1800
2000


Samsung Galaxy S10 SMG973U1ZKAX-1dBm -12ft -V-Axis. 0 to 110. 110 to -240. -240 to 110.- Ch 39
-65
-70
-75
-80
-85
-90
-95
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S10 SMG973U1ZKAX-1dBm -12ft -V-Axis. 0 to 110. 110 to -240. -240 to 110.- Ch 38
-65
-70
-75
-80
-85
-90
-95
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Samsung Galaxy S10 SMG973U1ZKAX-1dBm -12ft -V-Axis. 0 to 110. 110 to -240. -240 to 110.- Ch 37
-60
-65
-70
-75
-80
-85
-90
0
200
400
600
800
1000
1200
1400
1600
1800
2000

Weekly PACT Meetings/Collaborations

Weekly PACT meeting offered all participants an opportunity to share updates and collaborate with each other on numerous topics including data collection and algorithm development. The KRI testbed and datasets were presented to the entire group along with a descriptive whitepaper for use in algorithm development.

One problem with the PACT initiative is that the app developed by MIT LL for collecting RSSI data is not available through the App Store and only became available via Test Flight in late May. This presented many collaborators with the problem of standing up their own data collection capabilities. In order to provide standardized approaches, all software code and hardware diagrams for building the data collection testbed described in this report were shared with the team; this included a portable VM for deploying and running the RSSI data collection code quickly and efficiently. Additionally, a mobile rig was created and loaned to a small robotics company in NH with the goal of mounting it on a robot and collecting data from it under various scenarios. This has resulted with additional datasets being generated and shared with the entire community, including MIT, NIST, DARPA, Lawrence Livermore National Labs, Sandia National Labs, and many other universities and companies.

All data (KRI and other) collected for the PACT project is hosted on Github and advertised on the MIL LL website: https://mitll.github.io/PACT/datasets.html

All KRI data is posted and described on Github at: https://github.com/mitll/KRI-Anechoic-Chamber-Dataset.

Results/Next Steps

Analyzing the distributions of each phone/orientation combo has resulted in some interesting conclusions, listed below:

1) Orientation around both axes can have severe negative impact on RSSI, however nulls appear to be phone model dependent.
2) Unimpeded RSSI is typically distributed across a few dB range; note that in datasets collected the initial samples do not reflect the actual RSSI measurements and after further review it was determined that these are corrupted by the RSSI sensor going through some initialization steps.
3) RSSI distribution and levels are frequency dependent; this is likely due to antenna and hardware design factors of both the transmitter and receiver.
4) Mean RSSI values do not seem to follow the $\frac{1}{R^2}$ rule for signal attenuation over range.

Horizontal Axis Orientation: as the phone is rotated around the horizontal axis (see Figure 10) the RSSI measurements are severely degraded at certain points due to the antenna pattern and orientation. The iPhone has deep nulls when it is oriented near 90 and 270 degrees (i.e. laying on its back or face), however the Samsung phones have nulls in different locations indicating that understanding antenna radiation patterns will play a key role in estimating contact range from RSSI.

Vertical Axis Orientation: just as with the horizontal axis, as the phone is rotated around the vertical axis nulls can be observed for all phones tested but the iPhone appears to perform much better likely due to

a more consistent antenna pattern (the iPhone is also able to transmit BTLE signals at higher levels - +12dBm vs +1dBm). For all phones, the exact orientation of the phone can have severe negative impacts on RSSI, again indicating that understanding antenna radiation pattern will play a key role.

Orientation Conclusions: in order to build an effective contact tracer using RSSI, models of all available phones should be thoroughly tested in an anechoic chamber to characterize the RSSI behavior at different ranges and poses. This information can then be used to fine tune device specific parameters for the detector. Additionally, it will be critical to include phone orientation estimates from internal phones sensors in broadcast BTLE packets used for contact tracing. This will allow a receiving phone to make a better estimate of range by understanding the current state of another phone it is contact with.

BTLE Frequency Dependency: just as with orientation, the BTLE transmit frequency for advertising packets on channel 37, 38 and 39 contributes to overall variability of RSSI measurements. With a fixed orientation/pose of a transmitting device, a receiving device measures drastically different values on each channel indicating that there may be antenna or RF circuit factors that contribute to signal gain or attenuation at different levels across the frequency band. This means that the range detection algorithm must have knowledge of how RSSI is being sampled, which is a vendor specific implementation; for example, whether it is averaged over each channel and some preset time window, or whether it is sampled and reported for each channel independently.

$\frac{1}{R^2}$ **Rule for Signal Attenuation:** Additional analysis must be performed in order to understand exactly how the BTLE signal varies with range in an anechoic chamber environment, however a more advanced testbed is required to do this. For example, the BTLE receiver can be mounted on a sliding rail and adjusted in range during data collection.

Next Steps: The next steps for this effort are to continue data analysis and support of the collaborative PACT project through data and results sharing as well as to conduct additional data within the anechoic chamber for modeling actual range attenuation vs theoretical.