Noisy object detection using radio frequency waves

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Introduction

Radio frequency waves have been very intact and useful in modern times. Sonar and Radar technologies have been very effective in detecting objects. This paper is about a very simplified project that uses the same thought in technology, but with different aims. This project was inspired by the previous research at MIT which focused on detection of human beings using wi-fi waves. This research project aims at replacing radio waves with Wireless Local Area Network waves and documents an experiment and an improvement on what other researchers have been trying to achieve. The results in this project don't represent the final aim of the project because the project is not yet finished. The results shown in this paper represent a crucial step of being able to detect an object by the use of radio frequency signals.

Keywords: WLAN, SDR, RASBerryPI3(Pi), MATLAB, PYTHON, GPIO4, RF.

<u>Motives and Aim</u>

This research project aims at using radio waves to detect objects and using machine learning to build a neural network that would be able to recognize different objects and their specific positions— with accurate measurements of distances— in any space with respect to any other recognisable object in the room space. This project, further, pursues an interest in using Wi-Fi waves which are available almost everywhere to do the same work of detecting objects and identifying them.

Note: *The research documented in this report covers a few stages of the project. The full report of the project will be available at the completion of the project.*[1]

This project is necessary to understand better and improve the research which has been ongoing on at MIT[2] by Prof. Dina Katabi and Prof. Robert C. Miller which aims at the use of WLAN to track humans and objects. I am dedicating time to find a way to implement a section which can track objects and possibly human beings later by efficiently determining their positions and specifying their distances with respect to each other. This can be monitored and improved finally to map a whole set of places by only using radio waves. The personal end goal of this project is to get efficient results from a radio-locating experiment that mimics Batman's echolocation results in the '*The Dark Knight*'.

To refer to past experiments by the professors from MIT, I have learned a lot about the physics and maths behind this experiment. In addition to that, setting up my own experiment has allowed me to learn the computation and introduced me to advanced machine learning concepts. I expect my experimental setup to be able to show significant progress in being able to detect an object or not by using many materials which are specifically designed for it. Most of these materials are described in the sections below.

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[1] The research project was stalled because of the recent Covid-19 outbreak in March 2020. It will resume later.
[2] "WiTrack." http://witrack.csail.mit.edu/. Accessed 12 May. 2020.

Background

This project is not novel or revolutionary. As mentioned before, it builds from the shoulders of various researchers who have been contributing to the research of object detection using radio signals and achieved amazing results. A series of papers and books were carefully selected and consulted at each minor step in the project to understand better what was going on which was usually mathematics, computer science and physics mostly. The literature review of those papers are listed in the following:

1. 3D Tracking via Body Radio Reflections[3]

This paper is a groundbreaking review of the technical side of the famous WiTrack machine developed by MIT labs to detect objects. This was the first in their series of WiTrack(s) that they developed and built throughout the years which uses Radio frequency waves.

Primarily it talks about the ability of the Witrack to use Wi-Fi waves that are reflected by the person eliminating wearable devices as the only sole possibility of using any other machine to detect a person offering chances of future elimination of wearable devices. The device transmits a radio signal and uses its reflections to estimate the time it takes the signal to travel from the transmitting antenna to the reflecting object and back to each of the receiving antennas — time of flight. WiTrack then uses its knowledge of the position of the antennas to create a geometric reference model, which maps the round trip delays observed by the receive antennas to a 3D position of the reflecting body. This helped them a lot in being able to determine the distance between the transmitter and the receiver.

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2. Multi-Person Localization via RF Body Reflections[4]

This paper follows the first paper and focuses on the development and building of the WiTrack 2.0, the second in the WiTrack machines which uses wifi waves to detect objects. The second machine addresses some of the issues in the first one and comes with solutions. WiTrack 2.0 is the first machine which could detect a static person. It has further innovations of being able to realize that by detecting a static person through the series of movements that a human body makes when it is breathing and its hand movements. It is through these small patterns that the new machine is able to detect differences in times of flights. This can also be possible through the detection of multiple people.

They were able to come up with a new system called Successive Silhou1 ette Cancellation (SSC) an approach to address the near far problem, which is inspired by successive interference cancellation.

However, all these improvements are not fully accurate. They all have some margins of errors in terms of length and degrees of inclination.

3. A Survey on Behaviour Recognition Using WiFi, Channel State Information, https://arxiv.org/pdf/1708.07129.pdf[5]

This paper serves as an introduction to the CSI system— it describes how a signal propagates from the transmitter to the receiver and represents the combined effect of, for example, scattering, fading, and power decay with distance. The paper focuses on how to eliminate the use of wearable devices to monitor various

[3] "3D Tracking via Body Radio Reflections - WiTrack - MIT." http://witrack.csail.mit.edu/witrack-paper.pdf. Accessed 12 May. 2020.

[4] "Multi-Person Localization via RF Body Reflections - WiTrack." http://witrack.csail.mit.edu/witrack2-paper.pdf. Accessed 12 May. 2020.

[5] "Computer Science authors/titles Aug 2017 (489 ... - arXiv.org." https://it.arxiv.org/list/cs/1708?skip=489&show=2000. Accessed 12 May. 2020.

aspects about the human body detection and replace them with wifi detection. This paper was referenced by the MIT research team to research on the actual calculation of distances and time of flights of signals.

This paper also serves as a guide on one way of cleaning collected data by the receiver to be able to analyse it properly.

4. Making the Invisible Visible: Action Recognition Through Walls and Occlusions. https://arxiv.org/pdf/1909.09300v1.pdf

This paper also focuses on the ability to detect a human body by using radio frequency signals. However, this paper highlights the process of improving this detection by the use of machine learning.

It suggests a way of automating the process of action recognition from visual data. This means that they introduced a neural network model that can detect human actions through walls and occlusions by using reflected radio frequency signals.

Afterwards, the output of this model is a generation of 3D human skeletons as an intermediate representation. The model presented in this paper can learn from RF-based datasets and also vision based datasets.

The most interesting part that led me to choose this paper is that the model represented achieves comparable accuracy to vision-based action recognition systems in visible scenarios, yet continues to work accurately when people are not visible(using Radio frequency signals), hence addressing scenarios that are beyond the limit of today's vision-based action recognition.

5. Demo Abstract: FindIt - Real-time Through-Wall Human Motion Detection Using Narrow Band SDR

Contrary to other papers which did not spend a significant time explaining details on how to detect objects in motions, this paper establishes an exclusivity of this process.

It presents a system which uses SDR and Radio frequency signals to detect humans in motion through walls with high accuracy. This motion consists of motion orientation and relative moving direction.
The high accuracy presented in this paper in achieved by the use of Short Time Fourier Transform (STFT)[6] and statistical methods to receive signals.

Moreover, this paper presents classification methods and clustering that are used by its system called FindIt to provide real time detection results and identification of objects.

6. New indoor positioning system lets you do Batman-like echolocation on your phone

This essay was very important to learn from Batman's own echolocation powers. There is a mention of how usual GPS can't work indoors and that something needs to be creative enough to help people locate and position objects indoors.

From that, an indoors positioning system (IPS) is underway an active research at UC Berkeley to show how speakers and microphone can be used to map a room or building using echolocation, much like a bat. They call their system SoundLoc.

7. Software Defined Radio using MATLAB® & Simulink® and the RTL-SDR by Robert W. Stewart

In this project, this book was extremely crucial in learning important steps required to use Matlab

[6] "Short-Time Fourier Transform - an overview | ScienceDirect ...." https://www.sciencedirect.com/topics/engineering/short-time-fourier-transform. Accessed 14 May. 2020.

as a software handler of the whole processing of data.

This book has very specialized libraries which made the work easier and faster. The data collected in this project so far is time series data. This book gives information on how to search for methods to set the default interpolation method for time series object by using the MATLAB setter and getter method[7].
The book was also very crucial for understanding every groundwork possible to efficiently clean and analyse time series data to get it ready for the neural network.

8. MathWorks - Makers of MATLAB and Simulink - MATLAB & Simulink

This site was very essential in understanding Fresnel zones, Non-line-of-sight (NLOS) and near-line-of-sight (LOS) transmissions. It was very crucial in measuring the surface area of the experiment place and RSSI-based systems.

In this project, to reach its end goal, it would require to calculate the distance between objects detected and the receiver. Therefore, the time of flight measurement and VICON motion capture system were important things learnt on this site.
Furthermore, this site in learning about FMCW radio and exploring to see if I can use these data formats : timetables, time series objects, and labeledSignalSet.

Design/experiment

To implement this project, I was required to find a perfect medium with minimum radio waves as possible on campus. However, finding such a place in a campus crowded with wifi routers and phones, it is almost impossible. Therefore, the data collected was heavily noisy. The experimental setup consists of the following hardware: a Raspberry Pi3, Software Defined Radio type: RTL2832U RB20T2, Dipole Antenna, and computer to control the experiment digitally.

The Raspberry Pi3 is specifically needed to handle the antenna and the process of emitting radio waves through it. This was done by using special software processes which are described later in the paper.

The Software Defined Radio (RTL2832U RB20T2) is very important in the process of collection and receiving reflected radio waves for analysis using other different platforms as mentioned later in this paper.

The Dipole Antenna is very essential in the collection of reflected radio waves and directs them to the SDR. The positioning of the dipole antenna determined if radio waves were efficiently collected after the reflection process.

The experiment setup includes numerous steps carried out carefully to achieve reasonable results as follows:

- Connecting the Raspberry Pi3 to the PC or a power supply outlet and a screen to visualize it. The Pi is very important in acting as a second mini PC to handle the signal transmission. The Pi uses its GPIO4 port to emit radio signals at desired frequencies. To achieve this, a female jumber cable has to be attached to the GPIO4 port to act as a transmitting antenna.
- After starting the Pi, it is advisable to use its command prompt to access the radio signals control platform. This requires a special library and repository mentioned later in this paper.
    - Type in : **cd rpitx** to access the directory of the library that is going to be used.

[7] "Set default interpolation method for timeseries ... - MathWorks." https://in.mathworks.com/help/matlab/ref/timeseries.setinterpmethod.html. Accessed 14 May. 2020.

- Type in **./easytest.sh** to access a platform to control radio signals.
  - You can also command so many other things, just check the **rpitx repository** mentioned later in this paper.
  - Choose a suitable radio signal frequency and click ok to transmit it.
  - Click **enter** again to stop transmitting.
- Simultaneously while transmitting radio signals from the Pi, it is important to connect the SDR and the dipole antenna to the PC. For SDR installation on *Windows*, follow the following process:
  - Download and install **Zadig** which is a USB installer for SDR.
  - Open **Zadig**
  - Click **display all the devices**
  - Choose **RTL-SDR**
  - Download the right drivers for the SDR as recommended on the screen.
- Then form here it is recommended to check on if your SDR is receiving signals already in a perfect condition by doing the following:
  - Download **SDR Sharp** software
  - Open **SDR Sharp.**
  - Ensure the signal is well received in the SDR sharp
  - Observe the doppler effect on the frequency waterfall plot.

After a well setup and synchronization of a good system between the SDR and the Pi, the next work consists of having a system in which the collection of data, its cleaning and its analysis can be done before being fed into a neural network. This whole experience is based on a change in doppler effect[8] due to the detection of an object or not. To make this experiment smooth, we will use a water bottle to make a data set which has information on whether the bottle is reflecting the radio signal or not.

Therefore, I have used *Matlab* because it is a compelling software which has tools already built-in to help me use the SDR to collect data and analyse it properly.
It has been used as follows:

- Open Matlab on PC
- Ensure that the RTL-SDR is recognized by typing in this command: **hwinfo= sdrinfo**
  - If not, check Zadig again or check the book libraries directories again
- Ensure that it is in the right directory, type in this command: **SDR book/exploring_the_spectrum**
- From here, many other things can be done by exploring the SDR-Matlab book library.

Then the next step consists of using *Simulink* to perform further processes in Matlab. In this experiment, I am depending on a spectrum distribution graph which indicates very clearly the *doppler effect* once it is there. The spectrums in Matlab are going to be FFTs and Frequency waterfall plots. The simulink library will be used in the following way:

- Access the simulink library to get the RTL-SDR **add-on**
- Choose the save data rubrique
- Add it to the simulink chart properly
- Ensure a good design of a simulink before running the detection process.

After this, the process of collecting data can start. It is at this moment that the emission of radio signals is done from the Pi and positioning the water bottle so that the radio signals will be reflected or not by it. It follows this process:

[8] "Physics Tutorial: The Doppler Effect - The Physics Classroom." https://www.physicsclassroom.com/class/waves/Lesson-3/The-Doppler-Effect. Accessed 15 May. 2020.

- Run the *simulink* to receive signals from the Pi
- Time the process and ensure that all the samples run.
- Stop the process to analyse the collected data.

Then the next process consists of accessing the saved data file and using it in analysing and cleaning the data.

To Access the saved file

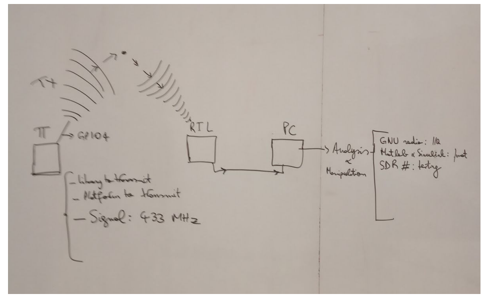
- Copy it somewhere else safe to avoid an overwrite during the next run time
- Rename it according to which experiment is being done

The data collected is in the form of time series. To clean this data for analysis does not come handy as an easy process. Therefore, we need to add a tool called ***Maintenance Toolbox* from matlab add-ons** to have access to sub-tools that can be used to clean the data and organize it.

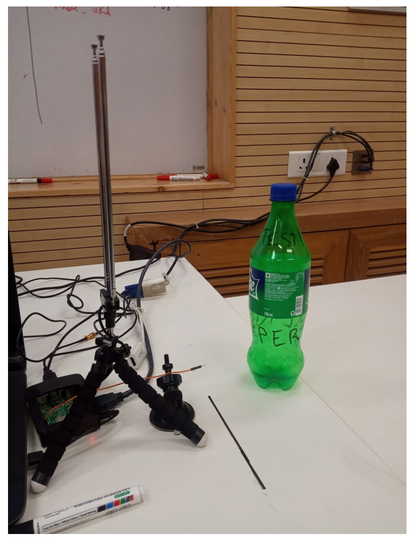
After this process, the next step is to build a machine learning neural network, preferably a CNN to learn the model and be able to respond if the radio signals detect a bottle or not.[9]

Then , the last step is to perfect the experiment by following the scientific methods' norms[10].

A few pictures of the experiment setup



A simple chart to explain the experiment



A dipole antenna, a Pi and SDR attached to the PC. The bottle is used to reflect the radio signals directed to it.

Implementation and softwares

The implementation of this project required a lot of knowledge about softwares and statistical handling to handle the data collected. The softwares used include: SDR Sharp, Matlab and its various add-ons, and a repository from Github called rpitx[11].

SDr-sharp is very essential in determining if the SDR connected to the PC works or not. Moreover, some people may end up using it also

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[9] This step was not reached in this experiment due to the Covid-19 outbreak in March 2020 which stalled the research project.

[10] "Science & the Scientific Method: A Definition | Live Science." 4 Aug. 2017, https://www.livescience.com/20896-science-scientific-method.html. Accessed 15 May. 2020.

[11] "F5OEO/rpitx: RF transmitter for Raspberry ...." https://github.com/F5OEO/rpitx. Accessed 15 May. 2020.

to collect the data. However, it was not favourable for me in this project because the collection of data and analysis can be done easier in matlab. To determine if the SDR works in SDR sharp, it is essential to observe the waterfall plots and check if there are changes if you put the bottle nearby the transmitting antenna (the jumber cable connected to the GPIO4 port of the Pi). Changes on the plots means that the dipole effect is confirmed and that the SDR is perfectly connected to the PC to perform its work in the project.

Matlab, as mentioned above, is very crucial in the collection of data, its cleaning and its analysis. However, matlab is not the sole and efficient method here. With matlab, it doesn't go easy with cleaning the time series data. It requires professional matlab usage and a very keen knowledge of its SDR and Data analysis simulink add-ons. I have not confirmed that my data was thoroughly cleaned and analysed through matlab. As the project goes on, there will be other efficient methods to handle the data work by using python libraries and other possible work.

The Rpitx repository on github is very simple to use and very essential in the process of handling signal frequencies. Instead of spending a lot of time discovering how to transmit signals, the repository code is already built to work on the Pi and to transmit radio signals from 5 KHz up to 1500 MHz. However, It has not been tested for compliance with regulations governing transmission of radio signals and this means that this must be used after checking with local radio transmission of radio signals guidelines and rule of your region or where your experiment is being conducted to comply with legality. Its installation and its usage manual can be easily found on its github README.md[12]

In this experiment, I have chosen to use 433 Mhz of radio frequency as a standard benchmark to start on. This is because it is a commonly used frequency band for all types of equipment that require little power and many inexpensive transmitters and receivers for switching devices and light dimmers[13].

Results

The results of this project are mainly what was achieved in experimental setup and data collection because the project was stalled due to Covid-19 outbreak. The project was not able to achieve its main goal of using a neural network to identify the detected objects and their positioning. However, in the next version of the project, this will be achieved.

The best result observed in this project is the ability to detect an object which is a bottle in our case. The emitted radio frequency signals were detected by the SDR and then the doppler's effect was observed by positioning the bottle in a perfect place to reflect the radio signals towards the dipole antenna.

As seen in the Appendix, figure 1 and figure 2 represent waterfall and FFT that show how the signal was being detected. One particular thing to mention here is that the experiment was done in a very noisy area (which possibly captured other objects at 433 Mhz). Therefore it requires a lot of attention to observe a change in a graph due to an obstruction of the signal by the control object — a bottle.

Figure 1 shows the experiment before the bottle was placed to reflect the radio signals. Figure 2 shows the dipole effect slightly at -0.55 and +0.55 on the FFT plot. This confirmed that the bottle was detected and the time at which the

[12] "F5OEO/rpitx: RF transmitter for Raspberry ...." https://github.com/F5OEO/rpitx. Accessed 15 May. 2020.

[13] "How 433MHz RF Tx-Rx Modules Work & Interface with Arduino." https://lastminuteengineers.com/433mhz-rf-wireless-arduino-tutorial/. Accessed 15 May. 2020.

bottle was recorded was revealed by the data saved from this experiment.

This means that the first milestone of the project — the ability to use radio signals to detect an object by reflecting them— was achieved. The plots showing the path carried out by all the materials and softwares to achieve this is shown in the chart in figure 3 in the appendix.

Conclusion

By observing the first milestone of this project achieved, there is no doubt that the project can go further to detect other objects, moving objects, objects through walls and be able to calculate the distances between them, determining their positions and naming them.
There is a substantial need to continue to stand on the shoulders of the people who have written papers documenting similar experiments or providing enough knowledge on how it can be done by reading more papers.

This research project shows that there are many things still needed to be done in the process of learning and achieving desired results. Therefore, the project still has open doors to be improved in the future.

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Appendix

Figure 1 : Results plots when there is no bottle detection

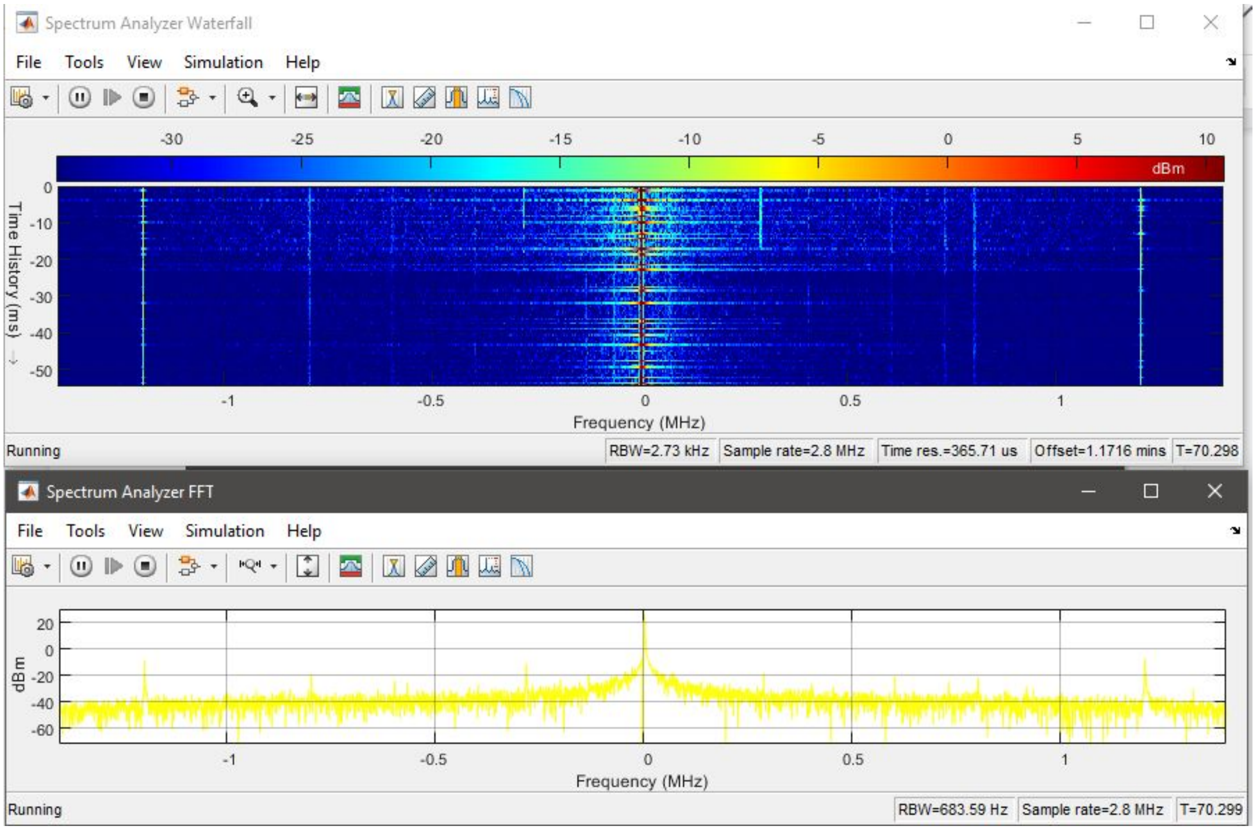


Figure 2 : Results plots when there is a bottle detection (*spikes observed at -0.55 and +0.55*)

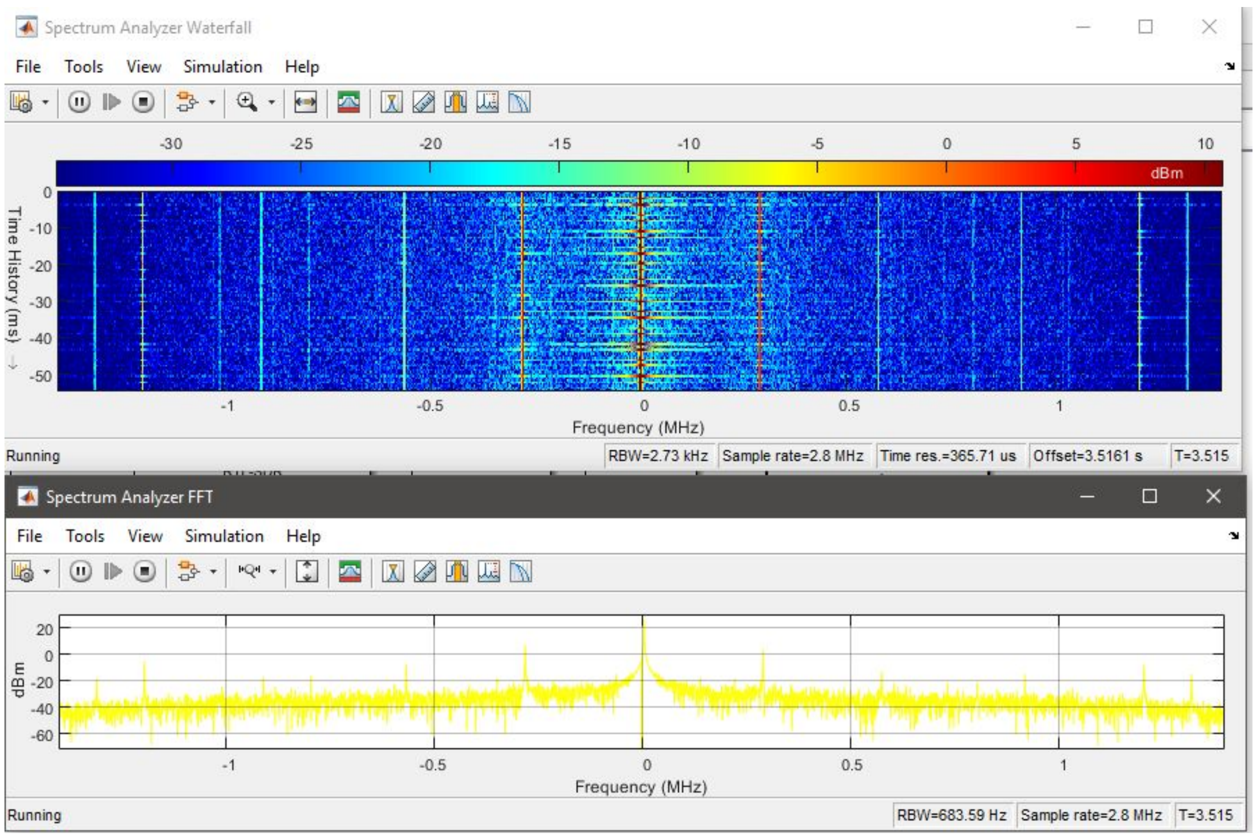
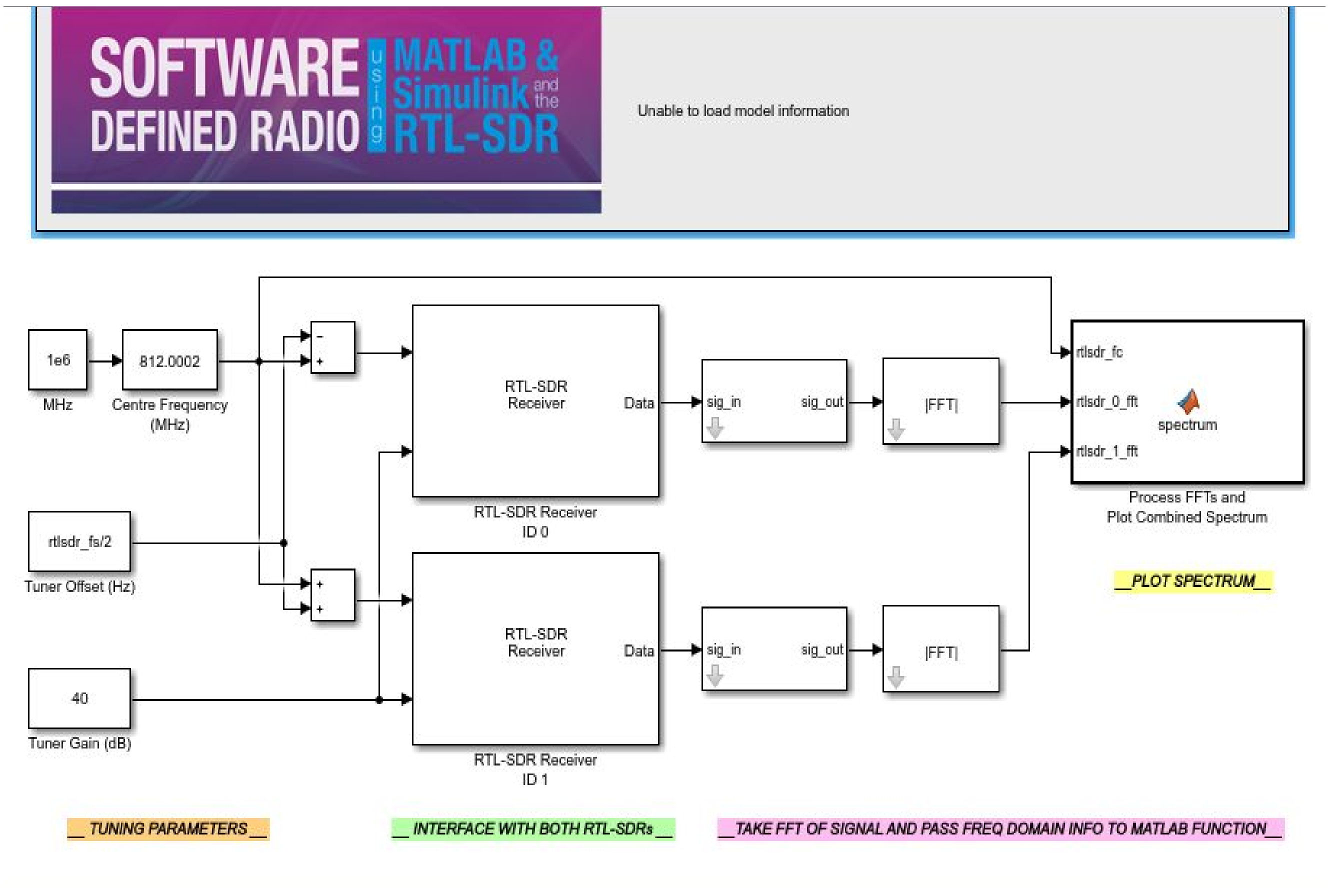


Figure 3: Simulink chart showing the experiment set up constructed



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