The Integration of Software Defined Radio and Matlab to Visualize and Analyze Communication Signals

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***Abstract*— This paper explores a laboratory experiment involving the integration of Software Defined Radio (SDR) and MATLAB for visualizing and analyzing communication signals, focusing on FM radio signal processing and urban coverage analysis using ray tracing. The RTL-SDR receiver was used to visualize FM signals in the 100.3 MHz band, employing a Simulink model for spectrum analysis and FM demodulation. The Simulink setup includes the RTL-SDR receiver, FIR decimation for signal downsampling, and an FM de-emphasis filter. The analysis is conducted using both a time scope and a spectrum analyzer to observe the modulated and demodulated FM signals. Additionally, a 3D simulation of the British Colonial Hotel, located in the Bahamas, was developed in MATLAB to analyze cellular base station coverage and communication links using urban link and coverage analysis with ray tracing. The experiment aims to evaluate and improve the accuracy of the simulation for use in radio planning and coverage analysis, enhancing the understanding of signal propagation, the effects of materials on signal strength, and the impact of environmental factors on cellular coverage**

Keywords—Software Defined Radio (SDR), MATLAB, Simulink, FM signal analysis, Ray tracing, cellular coverage, urban propagation model, RTL-SDR, Pluto SDR

I. INTRODUCTION

The integration of Software Defined Radio (SDR) and MATLAB is an efficient tool for analyzing and visualizing communication signals. This paper investigates the use of an RTL-SDR Blog V4 receiver, paired with MATLAB and Simulink, to study FM radio signals and urban cellular coverage. The system captures FM signals within the 100.3 MHz band, allowing for detailed spectrum analysis and FM demodulation. Additionally, MATLAB is used to model the British Colonial Hotel topology in the Bahamas, simulating cellular network coverage using ray tracing techniques.The integration of these technologies enhances our understanding of signal behavior in different environments, offering insights for radio planning and coverage optimization.

II. DISCUSSION

A. Experiment 1: Mono FM Radio Receiver with RTL-SDR and MATLAB

A RTL-SDR v4 was configured with MATLAB to perform the FM radio receiver experiment in Simulink. The Simulink block diagram consisted of the RTL-SDR Receiver, tuned to the FM signal frequency of 100.3 MHz with a tuner gain of 40 dB, to capture the FM signals from the 100.3 MHz band. The FIR Decimation block was then added to downsample the signal. Connected to the FIR Decimation block is the FM De-emphasis Filter, which corrects the FM de-emphasis applied during broadcast transmission. The Scope and Audio Output blocks were connected to visualize the frequency spectrum of the captured FM signal, observe the time-domain representation of both modulated and demodulated signals, and output the audio corresponding to the frequency.

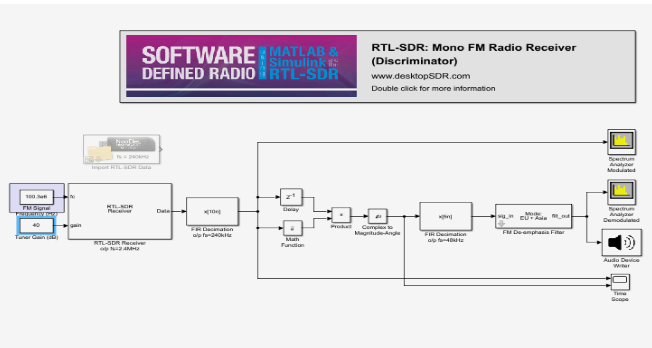


Figure 1: Simulink block diagram for FM radio receiver using RTL-SDR

Once the Simulink simulation is executed the time scope , spectrum analyzer modulated signals and the spectrum analyzer demodulated signal is displayed along with the audio output from the 100.3Mhz band from within my region from a local radio station called 100 jams.

The time scope shown consists of two waveforms . The top waveform represents the real and imaginary components of the signal output and the bottom waveform is the single channel output that represents the FM demodulated signal. On the x-axis is the time in milliseconds and the y-axis is the signal amplitude. With further analysis using the matlab measurement tools the cursor measurements and bilevel measurements were analyze and dissected. There were two cursor points within the waveform . Cursor one was positioned at 1.067ms with an amplitude value of -8.017e-02 while cursor two was positioned at 3.200ms, with an amplitude value of -2.026e-02. The time difference (ΔT) between the two cursors is 2.133ms and the amplitude difference (ΔY) between the cursors is 5.992e-02. The calculated frequency based on the time interval using 1/ΔT is 468.750 Hz. The slope between the two cursors points using ΔY/ΔT is 28.086 (units/ms). The bilevel measurements displays a high level of 2.187e-02 which is the average amplitude of the high state. The low level displays 2.695e-02 as the average amplitude of the low state. The peak to peak amplitude shown is 4.882e-02. The total number of edges which is the transition between high and low states is 86, the rise time which is the average time for the signal to transition from low to high is 3.511 µs and the fall time which is the average time for the signal to transition from high to low is 4.213 µs. The rising slew rate is 56.810 (units/µs) and the falling slew rate is 13.967 (units/µs).

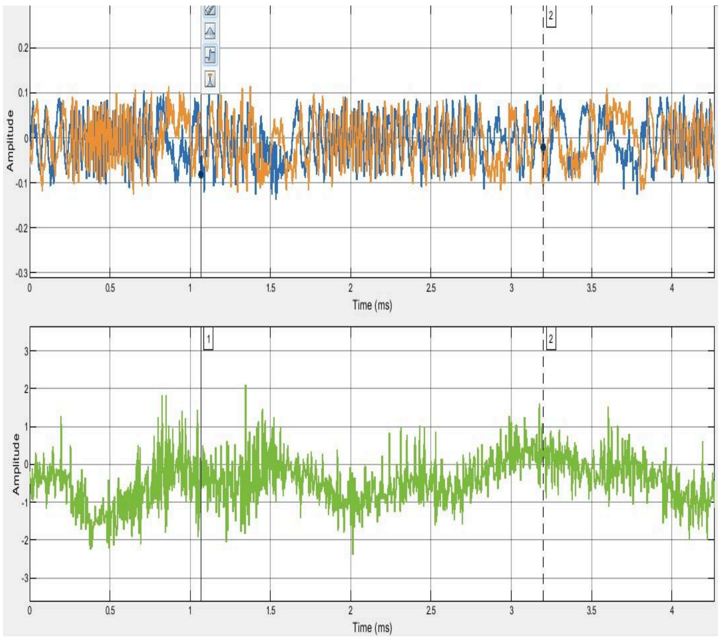
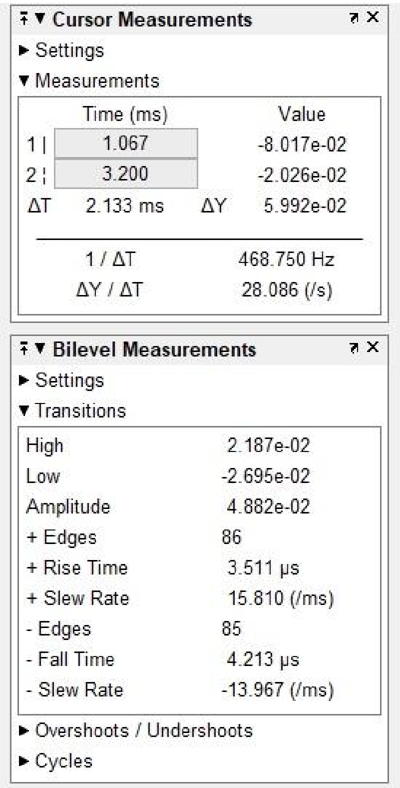


Figure 2 : Time scope to analyze signals `



Cursor Measurements

▶ Settings

▼ Measurements

	Time (ms)		Value
1	1.067		-8.017e-02
2	3.200		-2.026e-02
ΔT	2.133 ms	ΔY	5.992e-02
	1 / ΔT		468.750 Hz
	ΔY / ΔT		28.086 (/s)

Bilevel Measurements

▶ Settings

▼ Transitions

High	2.187e-02
Low	-2.695e-02
Amplitude	4.882e-02
+ Edges	86
+ Rise Time	3.511 µs
+ Slew Rate	15.810 (/ms)
- Edges	85
- Fall Time	4.213 µs
- Slew Rate	-13.967 (/ms)

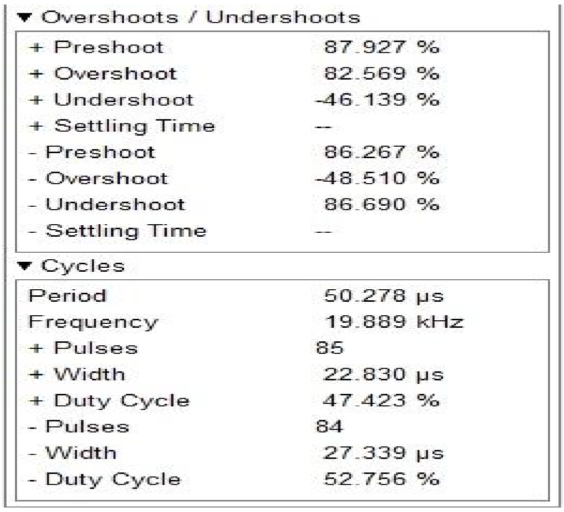
▶ Overshoots / Undershoots

▶ Cycles

Figure 3: Cursor and Bilevel Measurements for Signal Analysis

The overshoots/undershoots percentage were record with the +Preshoot being 87.927% this indicates how much the signal leads or overshoots the expected low to high transition. The -Preshoot is 86.267% which displays how much the signal undershoots or leads the expected high-to-low transition. The + overshoot is 82.569% which is the amount the signal exceeds its final value during a rising edge. The -overshoot is -48.510% which is the amount the signal exceeds its intended value during a falling edge. The +Undershoot is -46.139% which is the positive transition when the signal dips below its final value. The -undershoot is 86.690% which is a negative transition when the signal dips below its final value. Due to me experiencing a poor reception while performing the experiment the distortion have affected the overshoots and undershoots percentages in my analysis.

The periodic behavior of the signals were analyze . The time it took to complete one cycle of the waveform was 50.278 µs with the frequency being 19.889 kHz which is how many cycles occur per second. This frequency represents a part of the demodulated audio signal that represented a tone in the FM broadcast taken between the two cursors placed on the waveform. There are 85 rising transitions or positive pulses and 84 negative pulses or falling transitions . The signal remain high for 22.830µs in each cycle , and remain low for 27.339µs in each cycle represented as +width and -width respectively. The percentage of time the signal is high during a positive pulse in o0ne cycle, and low during a negative pulse in one cycle is 47.423% and 52.756% respectively.



▼ Overshoots / Undershoots

+ Preshoot	87.927 %
+ Overshoot	82.569 %
+ Undershoot	-46.139 %
+ Settling Time	--
- Preshoot	86.267 %
- Overshoot	-48.510 %
- Undershoot	86.690 %
- Settling Time	--

▼ Cycles

Period	50.278 µs
Frequency	19.889 kHz
+ Pulses	85
+ Width	22.830 µs
+ Duty Cycle	47.423 %
- Pulses	84
- Width	27.339 µs
- Duty Cycle	52.756 %

Figure 4 : Overshoots/Undershoots and cycles measurements for signal analysis

The measured frequency of 19.889 kHz and corresponding period of 50.278 µs represent a tone within the demodulated FM audio signal. The signal exhibited 85 positive pulses and 84 negative pulses, with a duty cycle of 47.423% (high) and 52.756% (low), indicating a nearly symmetrical waveform. Slight discrepancies in pulse counts and duty cycle may result from noise or distortion in the audio signal.

The modulated signal measured in the spectrum analyzer showed measurements of the distortion measurement. There are two fundamental frequencies shown with 0.703125kHz being the first fundamental frequency F1 and 49.2188KHz being the second fundamental frequency F2. The power level in dBm for F1 and F2 are -20.13 and -1.18 respectively. The power level is measured in decibels referenced to 1mW. The power level indicate the absolute power levels of the signals. Using the formula 2F2-2F1 the frequency is 97.9688kHz and the power is -29.78dBc. This is the power of the carrier signal in decibels. This value being a negative indicates that the distortion is weaker than the carrier.This is a good sign as it means that it is performing correctly.

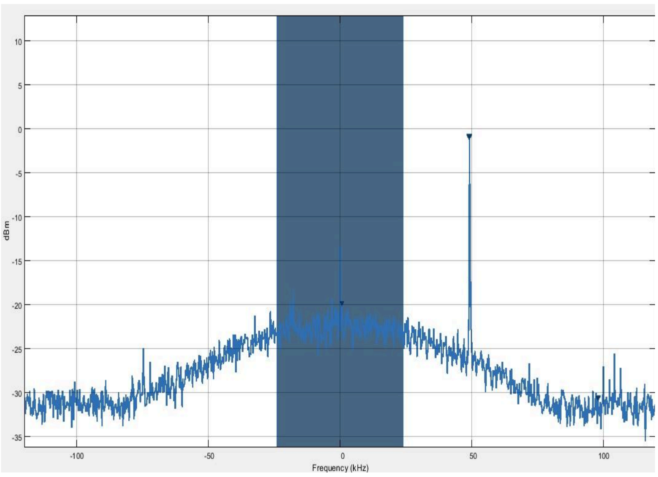


Figure 5 : Modulated signal measurement of spectrum analyzer

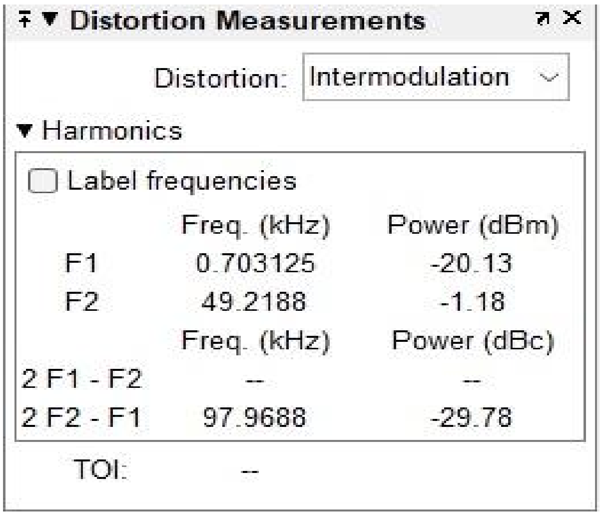


Figure 6 : Distortion measurement for modulated signal analysis

The channel measurements displayed the following with the occupied bandwidth being 99% of the total signal power .The total frequency range measured from the spectrum analyzer is 0hz to 48kHz. The centre frequency is set to 0 Hz which can indicate discrepancies within my experiment. The frequency error is 7.6169Hz which means that there is a slight deviation in the signal frequency from the expected value. The frequency is slight off from the center frequency by 7.6169 Hz. The channel power is -3.447 dBm which is a bit low but can still be measurable.

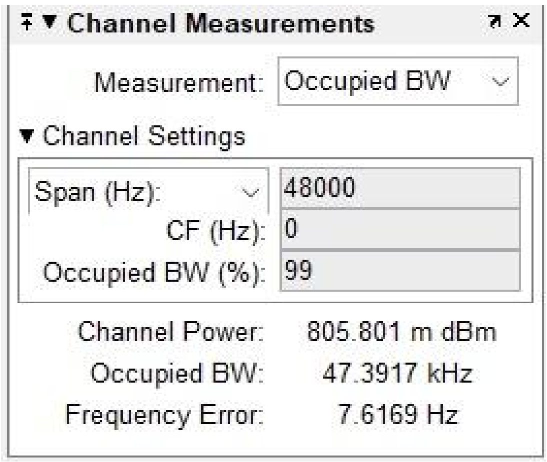


Figure 7 :Channel measurement for modulated signal analysis

For the analysis of the demodulated signal wave capture in the spectrum analyzer I focused only on the channel measurement which can be shown that a portion of the waveform represented in blue was analyzed . The occupied bandwidth being 99% of the total signal power .The total frequency range or span is measured from the spectrum analyzer from 0Hz to 9.6kHz. The centre frequency is set to 0 Hz which can indicate discrepancies within my experiment. The frequency error is -7.2760pHz which means that there is a very small deviation which can be negligible. The channel power is 22.947 dBm which is quite high which indicates a strong transmitted signal. When I captured the waveform it seemed that the frequency audio signal strength was good.

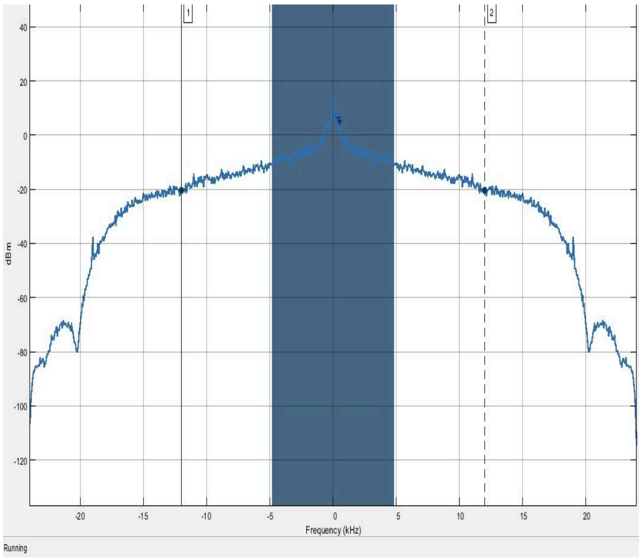


Figure 8 : Demodulated signal measurement of spectrum analyzer

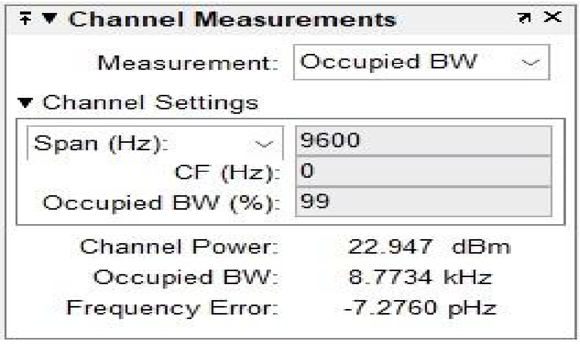


Figure 9 :Channel measurement for modulated signal analysis

B. Experiment 2 : Cellular Network Coverage Analysis Using Ray Tracing

This experiment focuses on analyzing cellular network coverage within the topology of the British Colonial Hotel in the Bahamas. MATLAB's ray tracing tools are used to simulate signal propagation, compute received power, and explore the effects of environmental factors such as materials and weather on cellular communication. A 3D model of theBritish Colonial Hotel and surrounding topology using openstreetmap map was generated using the matlab code

```
viewer = siteviewer(Buildings="/MATLAB Drive/Cell data lab/map.osm", Basemap="topographic");
```

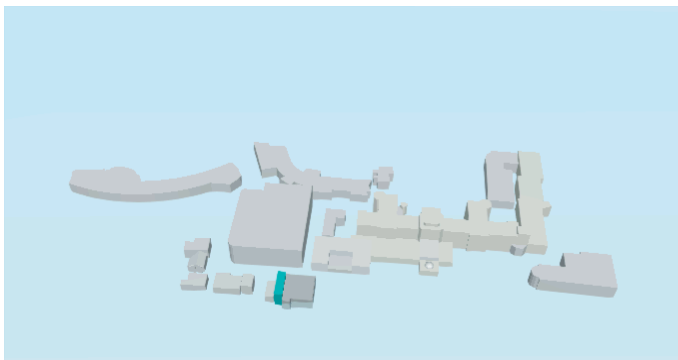


Figure 10 : 3D model of British Colonial Hotel and surrounding topology

This code initializes a site viewer environment in MATLAB and import the .osm file for the visual image of the topology in 3D. The Buildings parameter identifies the imported file and the Basemap identifier allows the map to be in a topographic view.

A cellular base station within the area was specified from results I found in cell mapper. The transmitter cell tower chosen is cell 21 with a system subtype of LTE 4G on the Aliv service provider network which is a local service provider here in the Bahamas. It has a uplink frequency of 1865Mhz and a downlink frequency of 1945Mhz.

Cell 21	
Cell Identifier	4884501
System Subtype	LTE
PCI	474 (158/0)
EARFCN	750
Maximum Signal (RSRP)	-53 dBm
Direction	N (0°)
Max / Avg DL Speed	7 Mbps / 7 Mbps
First Seen	06/01/2022
Last Seen	05/03/2022
Actions	• Go to Cell
Uplink Frequency	1865 MHz
Downlink Frequency	1945 MHz
...ency Band	PCS blocks A-F (B2 FDD)

Figure 10 : Cell mapper cell tower information

The longitude of -77.345815 and the latitude of 25.078253 are the transmitter location on the map . This information is inserted in the following matlab code

```
tx = txsite(Name="Small cell transmitter", ... Latitude=46.7563158, ... Longitude=23.5898615, ... AntennaHeight=10, ... TransmitterPower=5, ... TransmitterFrequency=28e9); show(tx);
```

In the matlab code the txsite function defines the transmitter identifiers such as the latitude, longitude, antenna height, power and frequency . The show command simulate the transmitter in site viewer.

Figure 11 : 3D model of chosen cell base station (transmitter)

The receiver site is then configured with the latitude being 46.756461, the longitude being 23.590221, the antenna height being 10m. The Method used in this matlab code is shooting and bouncing rays specified as SBR. The maximum number of reflections is zero with the buildingmaterial identified as concrete and the terrain material being identified as vegetation. The initial line of sight paths are computed which displays the interaction between the receiver and the transmitter displayed by function los(tx,rx). The matlab code that displays this is the following .

```
rx = rxsite(Name="Small cell receiver", ...
    Latitude=46.756461, ...
    Longitude=23.590221, ...
    AntennaHeight=10);

rtpm = propagationModel("raytracing", ...
    Method="sbr", ...
    MaxNumReflections=0, ...
    BuildingsMaterial="concrete", ...
    TerrainMaterial="vegetation");
```

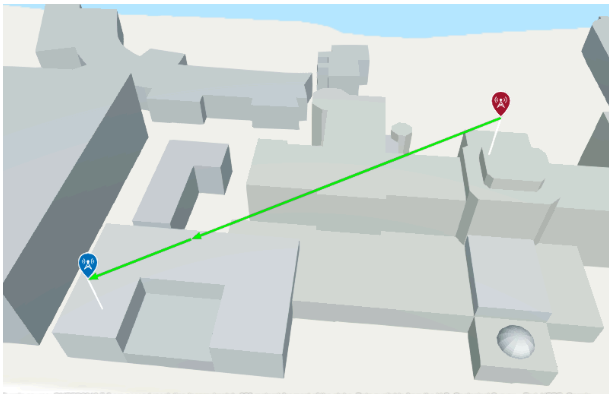


Figure 12 : Ray tracing propagation model using the shooting and bouncing rays (SBR) method

Based on the image you can see the ray tracing propagation model using the shooting and bouncing rays method that simulates the propagation of electromagnetic waves by tracing their paths as they travel the environment. The path loss is calculated based on free space loss, material reflections, diffraction and antenna polarization but in this case on the line of sight were observed by setting the maximum number of reflections to zero.

The propagation path using ray tracing was plotted which enable single reflection paths with the surrounding area. The matlab code is as followed

```
rtpm.MaxNumReflections = 1;

raytrace(tx,rx,rtpm);
```

The strength and effect of the material was then analyze . The signal strength is influenced by the material through which the electromagnetic waves propagates.Certain materials will introduce a higher attenuation due to their density and dielectric properties which can cause reduce received power. The received power measured in the simulation is -72.4 dBm. In the matlab code

In the previous matlab code ss = sigstrength(rx,tx,rtpm); this line computes the received signal strength (ss) in decibels (dBm) at the receiver site (rx) from the transmitter site (tx), using the defined ray tracing propagation model (rtpm). The following line disp("Received power: " + ss + " dBm") displays the calculated received power in dBm. This line of code rtpm.BuildingsMaterial = "brick"; updates the ray tracing propagation model to consider buildings material such as brick. The matlab code line rtpm.TerrainMaterial = "loam"; define the terrain material as loam which is a type of soil. The following line raytrace(tx,rx,rtpm) has the command that performs the ray tracing analysis it will calculate the signal propagation paths. The lines ss = sigstrength(rx,tx,rtpm); and disp("Received power using concrete materials: " + ss + " dBm") recalulates the received signal strength at the receiver and then displays the updated received power this portrays how the material changes the affect of the signal strength.

The weather loss is anlayze by implementing wether impairments into the propagation model to analyze their impact on signal strength. The command rtPlusWeather = rtpm + propagationModel("gas") + propagationModel("rain"); adds the effects of atmospheric gases and rain, which typically cause signal attenuation. The raytrace function then recalculates the propagation paths, including these weather effects. Finally, ss = sigstrength(rx,tx,rtPlusWeather); computes the new received power, which is displayed with the line disp("Received power including weather loss: " + ss + " dBm"). The inclusion of weather effects demonstrates an additional 1.5 dB of signal loss. Below is the matlab code

```
rtPlusWeather = ...
        rtpm + propagationModel("gas") + propagationModel("rain");

raytrace(tx,rx,rtPlusWeather)

ss = sigstrength(rx,tx,rtPlusWeather);

disp("Received power including weather loss: " + ss + " dBm")
```

The point to point analysis has been expanded to include two reflections and one edge diffraction . This is the signal path from the transmitter to a receiver . The two reflection points are two reflections of the signal path before reaching the receiver. The one edge diffraction occurs as the signal bends around the edge of an obstacle. The 3D image shows two reflection signal path from the cell tower transmitter at british colonial hotel being bounced from The Bahama Mama Factory and then back to the british colonial hotel. Below are the map topology of the area and the 3D visualization of the propagation path including two reflections and one edge diffraction.

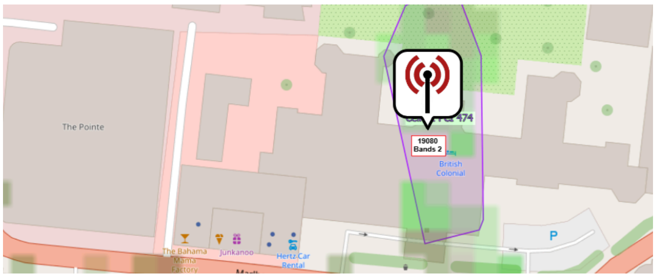


Figure 13 : Map topology of the british colonial hotel and surrounding area

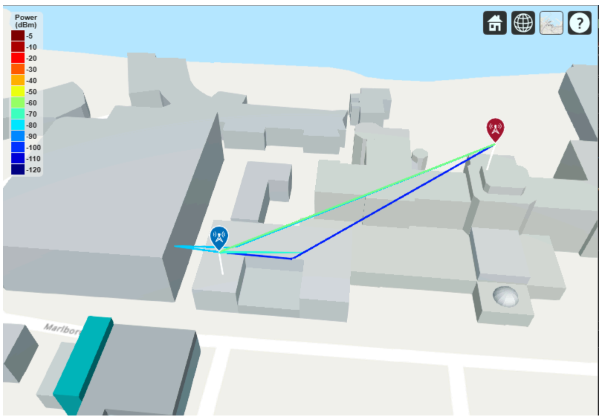


Figure 14 : 3D visualization of the propagation path including two reflections and one edge diffraction.

The plot for the matlab code to generate the 3D visualization of the path including two reflections and one edge diffraction included the maximum of reflection being equal to 2 this means that it is initalize to include paths up to two reflection. The max number of diffractions being equal to 1 which means it will have one diffraction path. The angular separation being low means that the angular separation between the rays is launched in the SBR method to be set ata a low value so the rays are closely spaced to capture the signal behavior. The function sigstrength(rx, tx, rtPlusWeather) calculates the received signal strength from the receiver and the transmitter. The line disp("Received power with two-reflection and one-diffraction paths: " + ss + " dBm") displays the calculated received strength in decibels. Below is the referenced matlab plot .

```
rtPlusWeather.PropagationModels(1).MaxNumReflections = 2;

rtPlusWeather.PropagationModels(1).MaxNumDiffractions = 1;

rtPlusWeather.PropagationModels(1).AngularSeparation = "low";


ss = sigstrength(rx,tx,rtPlusWeather);

disp("Received power with two-reflection and one-diffraction paths: " + ss + " dBm")

ss = sigstrength(rx, tx, rtPlusWeather);

disp("Received power with two-reflection and one-diffraction paths: " + ss + " dBm")
```

The coverage map with single reflection paths was generated for the area. The matlab code that generated the coverage map is as followed

```
rtPlusWeather.PropagationModels(1).MaxNumReflections = 1;

rtPlusWeather.PropagationModels(1).MaxNumDiffractions = 0;

clearMap(viewer)

show(tx)

coverage(tx,rtPlusWeather, ...

    SignalStrengths=-120:-5, ...

    MaxRange=250, ...

    Resolution=2, ...

    Transparency=0.6)
```

The first and second mathlab code function rtPlusWeather rperesents the propagation model object which will contain information about the environment and the behavior of the propagation. The function PropagationModels(1) indicates the first propagation model is being modified. The MaxNumReflections = 1 is the number of reflections and the MaxNumDiffractions = 0 indicates that there is no diffraction paths. The function coverage(tx, rtPlusWeather,..) is used to calculate and simulate the signal strength as it propagates outwards from the transmitter. The line SignalStrengths = -120:-5 initializes the range of the signal from -120dBm to -5dBm. With -5dBm being the stronger signal and -120dBm being the weaker signal. The line MaxRange = 250 is the maximum range in meters for the coverage. The lines Resolution = 2 and Transparency = 0.6 initializes the resolution of the map and the transparency level of the coverage map.

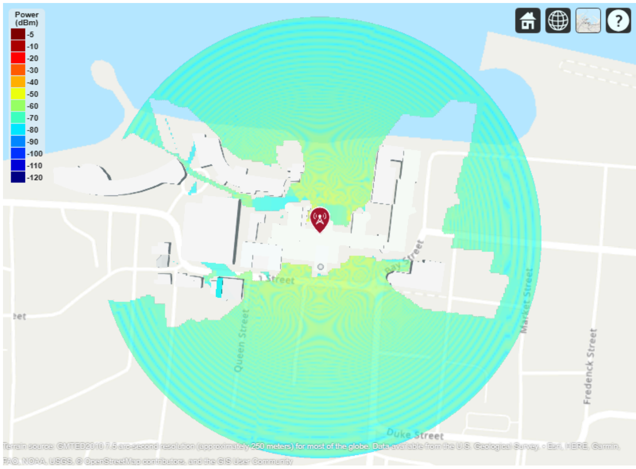


Figure 14 : 3D visualization of the coverage view map with single reflection paths

III. CONCLUSION

This study successfully integrated Software Defined Radio (SDR) with MATLAB to analyze FM radio signals and simulate urban cellular coverage. The FM radio experiment, using RTL-SDR and MATLAB Simulink, provided detailed insights into signal modulation, demodulation, and frequency analysis, which highlights the importance of signal measurements for communication systems. The cellular network coverage analysis utilizing MATLAB ray tracing tools demonstrated the impact of environmental factors like building materials on signal propagation and coverage in urban areas. Overall, the experiment specifies approaches for optimizing radio planning and improving coverage analysis for communication networks.

References

[1] R. W. Stewart, K. W. Barlee, and D. S. W. Atkinson, Software Defined Radio Using MATLAB & Simulink and the RTL-SDR. 2015.

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