MODELING AND EVALUATION OF RECEIVED SIGNAL STRENGTH USING RECONFIGURABLE ANTENNAS IN COMPLEX URBAN ENVIRONMENTS

An Undergraduate Research Scholars Thesis

by

SARAH B. RAINES

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ABSTRACT

Modeling and Evaluation of Received Signal Strength using Reconfigurable Antennas in Complex Urban Environments

Sarah B. Raines
Department of Electrical Engineering
Texas A&M University

Research Advisor: Dr. Gregory Huff
Department of Electrical Engineering
Texas A&M University

Today wireless communication has become paramount to everyday life. The strength of these signals can be diminished over long distances, which can increase in highly urban environments where more obstacles will hinder the signal's ability to propagate in a straight path [1]. The two types of antennas used today include fixed and reconfigurable antennas. Fixed antennas remain within a set boundary between one fixed location and another. With a reconfigurable antenna the receiving and transmitting antenna location may change dynamically, requiring the antenna be capable of adjusting itself to maximize performance [2].

This study will determine how living in an urban environment with complex obstacles will affect the signal path and strength of both fixed and reconfigurable antennas. To evaluate the effects of an urban environment the engineering quadrant and Academic Plaza of the Texas A&M campus will be simulated in a simplified CAD drawing using Wireless InSite (Remcom). The path of an autonomous vehicle through these areas will then be simulated to gather antenna strength 'measurements' for both fixed and reconfigurable antennas. The signal propagation can be mapped in the simulated campus and the measurements taken will be used to analyze how this path affects the signal strength with varying frequencies and paths.

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CHAPTER I

INTRODUCTION

Wireless signals undergo electromagnetic multipath propagation. This artifact of their propagation in complex scattering environments helps mobile platforms obtain and correlate the most desirable received signal strength (RSS). This often is accomplished by finding the path with minimal attenuation and delay. A signal with multiple paths may encounter many forms of constructive and destructive interference from the presence of obstacles in urban environments. This physical interaction with the local environment can diminish, or fade, the signal [3]. In cases of extreme destructive interference, signals may be cut off completely (referred to as an outage) or may be too severely diminished to be useful [4].

Multipath can best be explained using the following example shown in Figure 1. Given a transmitter on Building 1 and a receiver at Building 2, there are two paths that may be taken. Path 1 represents the line-of-sight path and Path 2 represents a path with reflection.

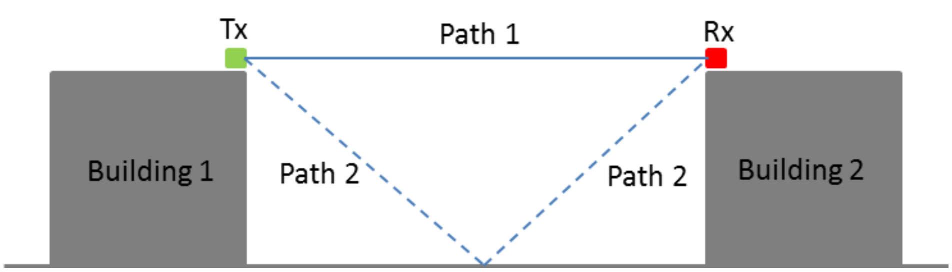

Figure 1: Multipath Example

The total received power can be modeled using Frii's Transmission equation [5], shown in Eq. (1), where the received power (RP) at a receiver can be obtained with the power from the transmitter (P_t), distance between transmitter and receiver (d), frequency of signal (f), speed of light (c), and the directivity of both transmitter (D_t) and receiver (D_R).

$$RP = P_t + D_t + D_R + 20\log_{10}(\frac{c}{4\pi df}) \quad (1)$$

Considering Equation 1, the equation of a wave with a spherical wavefront can be obtained as shown in Equation 2 [6], where the electric field of the wave (E) can be found with the initial electric field ($E_{0)}$, the wave number (β), and the length of the path (d).

$$E = \frac{E_0 e^{-j\beta d}}{4\pi d} \quad (2)$$

The addition of each path's wave equation yields the total received power. The total received power plotted against the distance traveled gives a visual representation of the RSS from the transmitter (Figure 2).

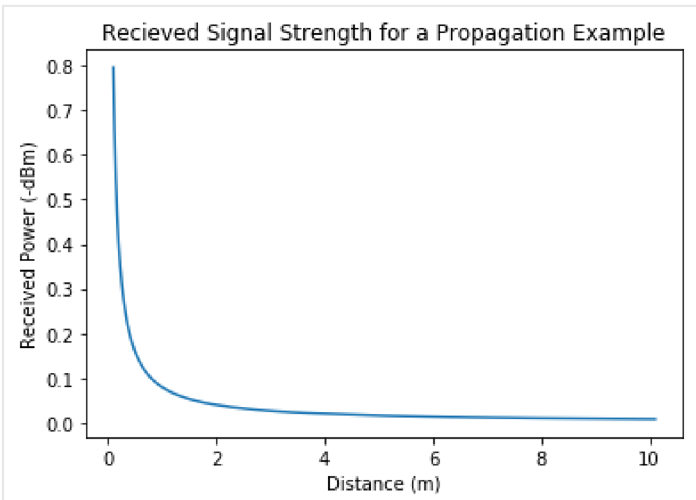

Figure 2: Received signal strength for the propagation example discussed

Analyzing the RSS of the above example demonstrates how the total RP of a signal decreases exponentially the further the signal travels. In addition, the above example only considers one path with reflections because there are no obstacles between the two antennas. Considering another example, as shown in Figure 3, it becomes apparent how the addition of obstacles may increase the number of paths taken and the number of reflections that begin to influence the total received power.

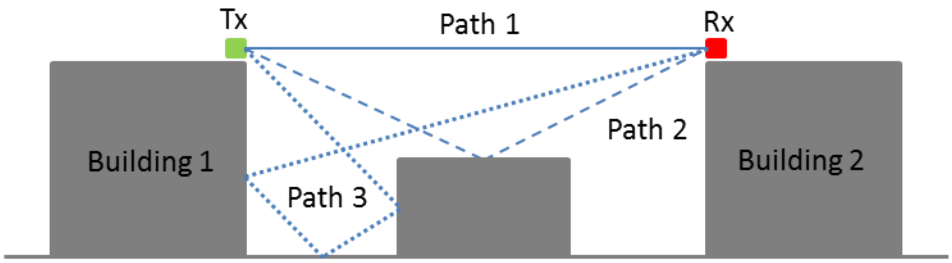

Figure 3: Multipath example with obstacle

The above example demonstrates the increased number of reflections that may occur due to the presence of obstacles. Remembering the relationship between total RP and distance traveled, it can be seen how Path 3 would be expected to have a much lower RP than Path 1 due to the number of reflections that Path 3 experiences. In another example shown in Figure 4, it can be seen how the total obstruction of the two antennas will produce no paths at all.

Figure 4: Propagation example with total obstruction

The above scenario is unlikely to happen because more objects will typically be present and provide a point of reflection for signals, thus creating a path. However, it does demonstrate the degree to which an obstacle may diminish RP despite multipath properties of a signal by eliminating paths in previous examples.

To avoid significant destructive interference and maximize signal RP, antennas can be placed in strategic locations. Several mathematical models can be used to justify an antenna location most suitable to maximize RP. Location fingerprinting is a technique that correlates distance dependent characteristics like RSS with known access points (transmitters) and a location (receivers). Other techniques, like angle of arrival (AOA), use time difference of arrival (TDOA) between two points in order to determine the angle of a propagating signal [7]. AOA may provide more mathematically accurate locations, however, the measurements accuracy decreases in small environments where multipath fading distorts the data. In addition, more sophisticated equipment is needed making the process longer and costlier. Therefore, it is better to consider RSS to determine signal propagation in high multipath environments [8]. As seen in the above multipath examples, superimposed signals may be received that will either increase or decrease the initial transmitted signal. This is referred to as constructive and destructive interference. With Equations 1 and 2, the distance from the transmitter to the receiver can be calculated from each received signal measured. Comparing the distance with the RP, a model based on RSS can be formed to determine the antenna location and type most conducive to signal propagation in multipath.

The two main antenna types for consideration are the fixed and reconfigurable antennas. Reconfigurable antennas can adjust frequency and pattern recognition to optimize the received signal strength. Fixed antennas, as the name suggests, are only configured in one way and, thus, can optimize only one particular signal. However, in multipath environments, where the signal may encounter interference, having only one optimized signal among a scattered array of signals may be inefficient [2]. In addition, antennas can produce varying amounts of directivity based on the type used. An omnidirectional antenna radiates a signal equally in all directions. A directional antenna concentrates the majority of the signal in one direction. Though this may seem limited, the use of reconfigurable antennas allows for the directivity of this antenna to change in order to optimize RSS.

This study focuses on the characterization and analysis of signal propagation in a complex physical environment where significant multipath exists. This includes advanced geometric optics modeling software to simulate wave propagation and the use of reconfigurable antennas to maximize RSS for a mobile platform (autonomous vehicle) navigating the area. Similar studies have been performed for radiolocation [3], but these lack the precise calculations that can be gained using a simulation with any range of frequencies to determine the exact received power and paths taken, including the number of reflections before reaching a receiving antenna. In addition, studies considering indoor multipath have developed many models for signal optimization. However, this study will focus on the effects of signal propagation in an outdoor environment where the multipath is far greater than in an indoor environment.

CHAPTER II

METHODS

Project Setup

In order to properly evaluate RSS in urban environments two city areas are used around the Texas A&M University campus, the engineering quad, which represents a significant level of obstacles and the Academic Plaza, which presents fewer obstacles (Figure 5). With each area simulations are run with and without terrain, with omnidirectional and directional antennas, and four varying frequencies.

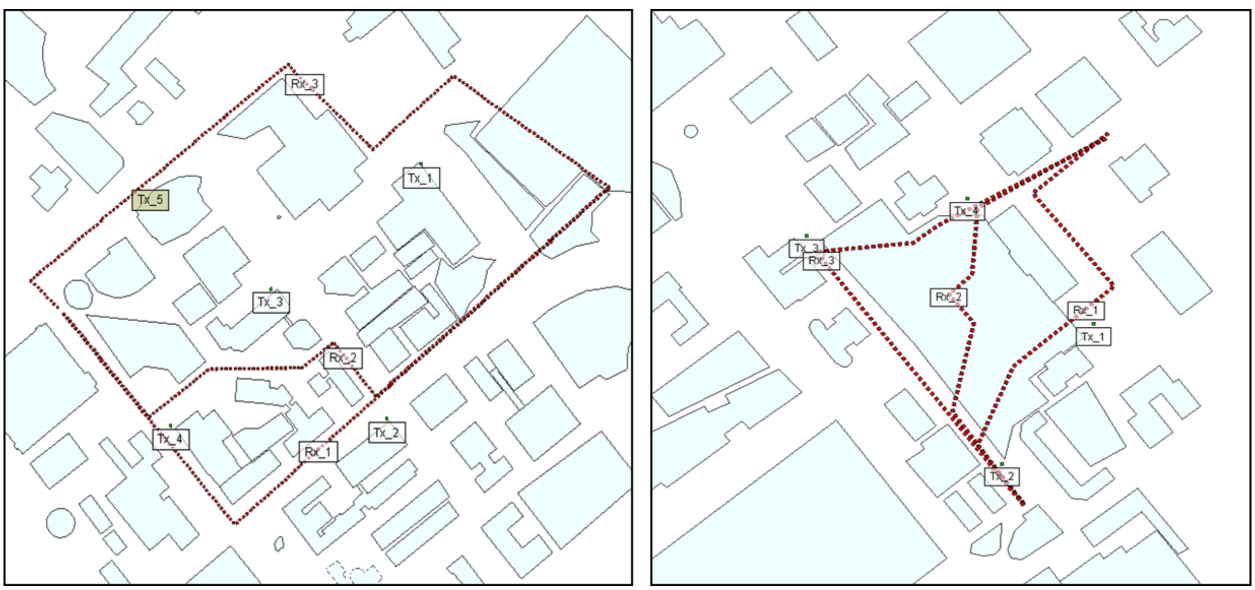

Figure 5: Engineering quad with receiver routes Rx 1-3 and transmitter points Tx 1-5 (left), and Academic Plaza with receiver routes Rx 1-3 and transmitter points Tx 1-4.

A project setup is what Wireless InSite uses to refer to all of the components used in a simulation, like imported city files, terrain files, receivers and transmitters, and various other features. In this experiment the two city files were used in four project setups. The first project included the city file for the engineering quad and the second included the corresponding terrain file to account for changes in elevation. Similarly, the third project included the city file for the Academic Plaza and the fourth included the accompanying terrain file.

City files are converted by Wireless InSite from AutoCAD DXF files and ESRI Shapefiles. Both file types can be found using an online database, Open Street Map (OSM), which includes infrastructure features around the globe. For the purposes of this experiment ESRI Shapefiles are obtained from OSM and imported as multi-polygon shapefiles. These files contain data that represents the area of buildings, fields, plazas, parking lots, and other structures such as water fountains and water towers. Once imported into the project using the UTM zone 14R, which corresponds to the College station area, the shapefile is automatically converted to a city file where the feature's height, material, and orientation can be modified. The heights of the buildings were estimated between 0 m and 50 m. Field and parking lots were set to 0.1 m, and water fountains were set to 0.5 m. All materials were set to concrete, and building orientation was not adjusted.

Terrain files, which represent the elevation of geographic areas, are imported as Digital Terrain Elevation Data (DTED) files. DTED files can be exported from a free online source, USGS Earth Explorer. The Bryan/College Station area can be obtained and imported into the project and overlaid with the city file (Figure 6). The latitude and longitude coordinates are aligned with the UTM zone of the city file imported previously.

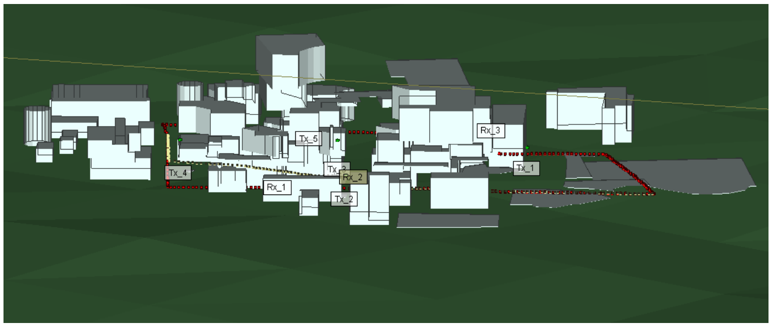

Figure 6: Engineering quad with imported DTED.

Antennas are placed throughout both city setups (Figure 5). For the engineering quad, receivers are set up as three individual routes that represent the paths an autonomous vehicle may take moving from the South West corner of Lot 51 to the North West corner of the Mitchell Physics Building. Next, five transmitters were placed around the city area on ground level. To gather data for omnidirectional antennas, transmitters were set as quarter wave monopoles, and for directional antennas, transmitters were set to horns. The placement of all transmitters and receivers was exactly the same for all simulations regarding the engineering quad. For the Academic Plaza simulations, receivers were setup into three separate routes moving from Rudder Statue to the Harrington Education Center (HECC), and four transmitters were placed at the four corners of the Plaza. Both quarter wave monopole and horn antennas were used and receivers and transmitters remained the same in all Academic Plaza related simulations.

Running Simulations and Collecting Data

In every project setup four different frequencies were used to determine how low versus high frequencies can impact RSS. The four frequencies used were 300 MHz, 900 MHz, 2.5 GHz, and 5.8 GHz, which roughly correspond to four of the most common industrial, scientific, and medical (ISM) radio bands [9]. A Study Area is a boundary that can be set around a desired area in which data will only be collected within the established boundary. This can help reduce simulation run time. Though various outputs can be requested before a simulation is run, this experiment focused on RP, measured in -dBm, at each receiver along the route from each transmitter in the area. The output data will be displayed in the Study Area folder of the Output tab in the software's Project Setup window. From there data can be exported and organized for comparison. RP at each receiver in a specified route is compared from each transmitter. The transmitter that supplies the greatest RP to the receiver is selected and the average of all RP along the route is used to compare different frequencies, antennas, and routes used. This method of selecting RP is intended to mimic the function of technology to automatically switch connections to always supply the user with the best RSS.

CHAPTER III

RESULTS

For each route tested, data from each transmitter was collected and compared to determine the transmitter which provided the maximum RP for that specific receiver in the route. The maximum RP for each receiver along the route was then averaged to identify the best combination of variables used at each route. An example of how the RP from each transmitter compares can be seen in Figure 7.

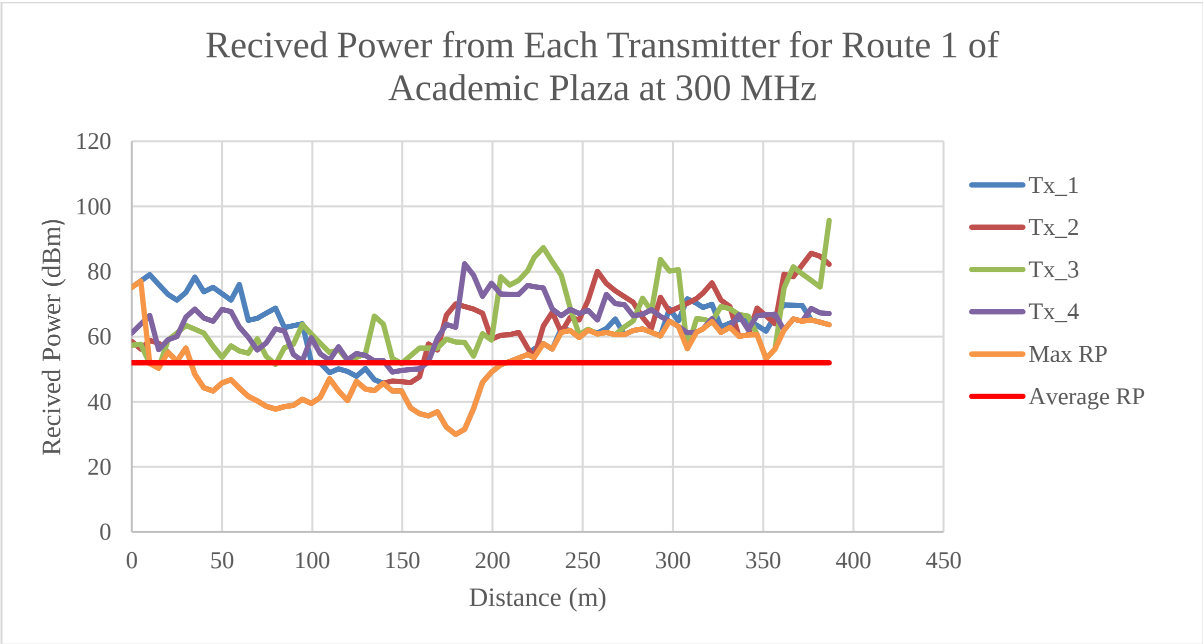

Figure 7: Example of RP from each transmitter for Route 1 in AP at 300 MHz and the Maximum and Average RP used to make comparisons.

Data was collected in -dBm. For the purposes of this analysis the absolute value of each data point was taken to present the data with positive trends. As a result it is important to consider that the increased values of RP in dBm, reflect decreased RP in -dBm for each route considered.

Influences of Terrain

Terrain in both EQ and AP produced averaged RP values, shown in Table 1, noticeably less than files without terrain (Table 2 & 3). However, the differences between files with and without terrain are proportional to one another.

Table 1: Average RP (dBm) for the EQ with terrain.

Frequency	Rx_1, Monopole	Rx_1, Horn	Rx_2, Monopole	Rx_2, Horn	Rx_3, Monopole	Rx_3, Horn
300 MHz	87.1507	107.9847	88.7669	70.4355	90.9899	81.8465
900 MHz	107.6064	102.1792	107.7998	79.0005	109.9476	78.0684
2.5 GHz	117.3225	114.4053	118.3073	89.4093	121.9494	89.1743
5.8 GHz	126.6156	131.3961	128.8888	104.4191	131.4934	102.9770

There are few large changes in elevation in the Texas A&M campus area, and thus, the results here are less affected by the terrain files than might be expected in areas with greater changes in elevation. In addition, terrain files produce lower RP due to the differences in dielectric constants between terrain files and non-terrain files. For every signal that reflects off of the ground in non-terrain files the dielectric constants experienced are assumed to be relative to free space. For terrain files, the material is considered wet earth. Dielectric properties of wet earth will cause far more attenuation compared to properties of free space explaining why a general dampening of RP occurs. Due to software difficulties data with terrain files was not collected for every frequency in AP. However, because the trends at each route are the same with terrain and without terrain, the RSS of each path will be analyzed using just the files without terrain.

Influence of Frequency

Considering Eq. (1), Frii's Transmission equation, you can see how larger frequencies would be expected to have lower RP. This is evident from the data in the EQ shown in Figure 8 and Table 2, where in every case RP is greatest at 300 MHz with a proportional decrease up to the highest frequency 5.8 GHz.

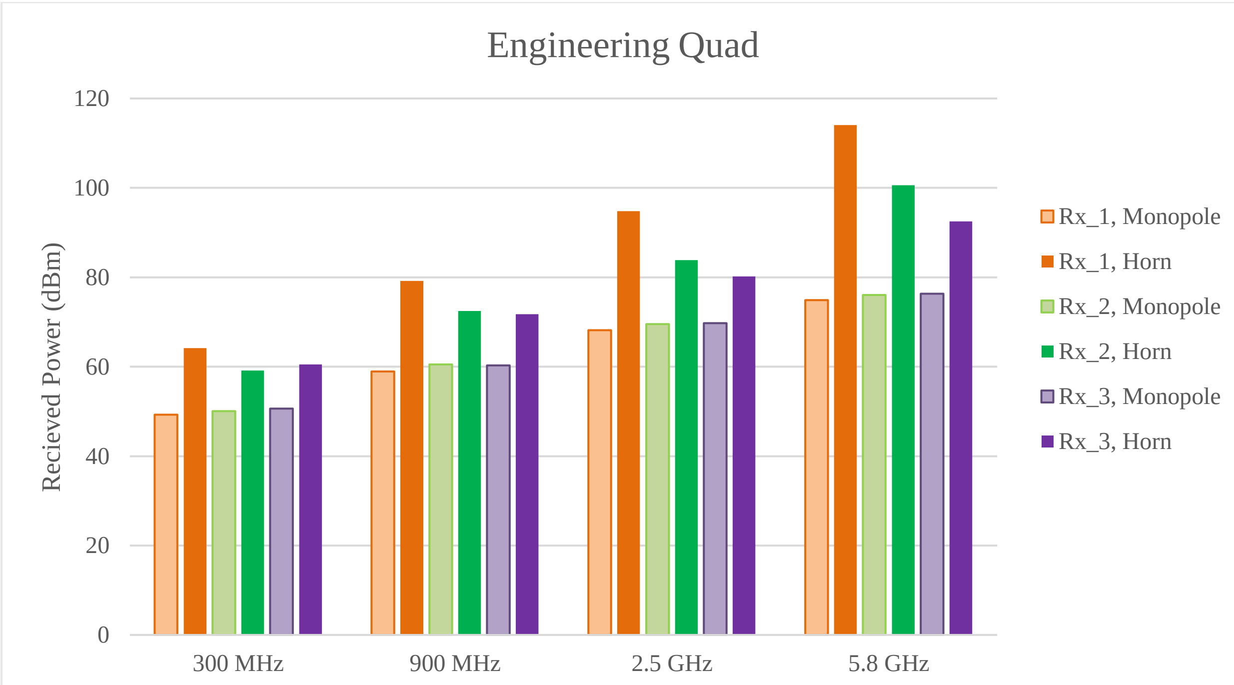

Figure 8: Average RP for Routes one, two, and three, at each frequency, and for each antenna type in the EQ.

Table 2: Average RP (dBm) for all three routes, antenna types, and frequency in the EQ.

Frequency	Rx_1, Monopole	Rx_1, Horn	Rx_2, Monopole	Rx_2, Horn	Rx_3, Monopole	Rx_3, Horn
300 MHz	49.2655	64.1902	50.0335	59.1742	50.6191	60.4990
900 MHz	58.8969	79.1885	60.4888	72.4402	60.3197	71.7438
2.5 GHz	68.1980	94.7961	69.5282	83.8338	69.7325	80.2253
5.8 GHz	74.8675	114.0598	76.0496	100.5627	76.3032	92.5217

Similar results are seen when considering AP as shown in Figure 9 and Table 3. As an area with considerably fewer obstacles the average RP of AP is higher for all combinations than the EQ. Just as in the EQ, lower frequency increases RP and higher frequency decreases RP. For wireless signaling, this analysis explains why devices like cell phones operate at very low frequencies around 2 MHz, rather than values in the GHz range. Lower frequency signals can travel longer distances without large amounts of attenuation dampening the signal.

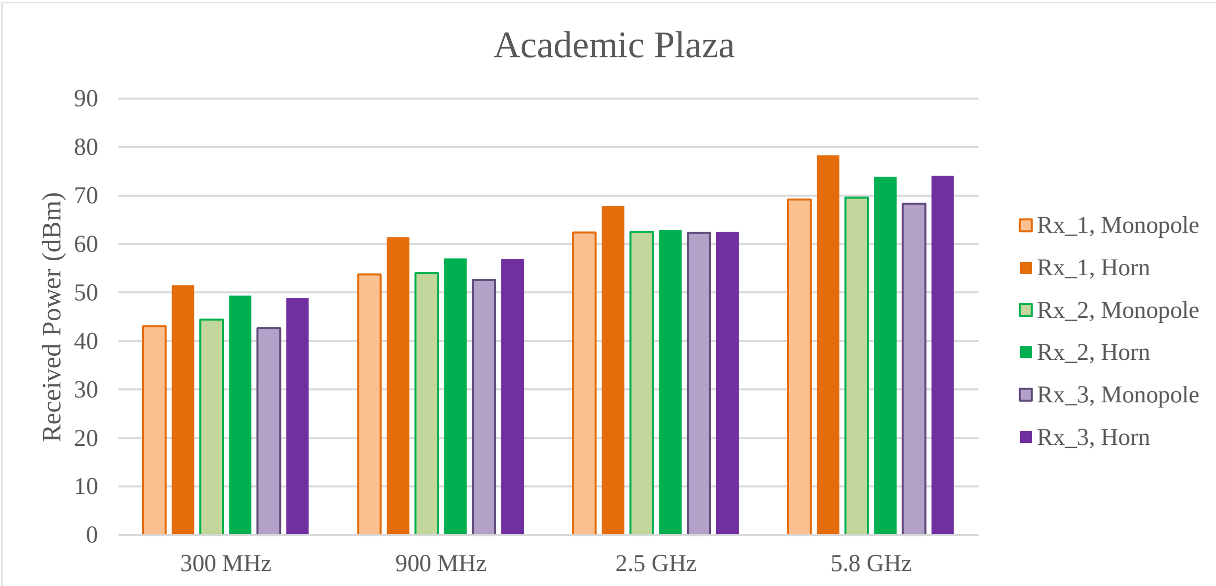

Figure 9: Average RP for routes one, two, and three, for each antenna and frequency in AP.

Table 3: Average RP (dBm) for all three routes, each type of antenna, and frequency in AP.

Frequency	Rx_1, Monopole	Rx_1, Horn	Rx_2, Monopole	Rx_2, Horn	Rx_3, Monopole	Rx_3, Horn
300 MHz	43.0535	51.4827	44.4116	49.3782	42.6366	48.8126
900 MHz	53.7015	61.3901	53.9846	57.0133	52.5913	56.9513
2.5 GHz	62.3876	67.8091	62.5017	62.8243	62.3239	62.4837
5.8 GHz	69.2066	78.3082	69.5483	73.8625	68.3081	74.0541

Influences of Antenna Type

When considering the quarter wave monopole and the horn antenna used in this study, the monopole antenna consistently provides a stronger averaged RP for each route (Figure 8 & 9). Between the EQ and AP, the differences between the two antenna types are noticeably larger in the EQ. This is likely because the direction for horn antennas was chosen arbitrarily to point directly into the center of each location under study. This means that in some cases a directional transmitting antenna may have been facing directly into a building limiting any direct paths that can be taken and decreasing RP. For an area with fewer obstacles like AP, the transmitters facing towards the center of the plaza do not meet immediate obstacles that prevent any direct paths. Thus, the variations between the omnidirectional and directional transmitter option becomes less pronounced.

Influences of Urban Infrastructure

As previously discussed the presence of obstacles hinders a signals ability to propagate in a direct path. This trend can be seen very clearly in analyzing the differences between Figure 8 and Figure 9. The differences between antenna types is less pronounced in AP than in EQ due to the directional transmitters inability to send signals with direct line-of-sight. In addition, the increased number of obstacles found in the EQ lead to more reflections and refractions that will cause more potential destructive interference. Therefore, overall the average RP in the EQ is lower than in AP where less multipath can be found.

CHAPTER IV

CONCLUSION

Areas with fewer obstacles, like academic plaza, have a stronger RP. Though staying away from large obstacles that may obstruct a signals path may not be feasible it does provide the greatest RSS. To optimize RSS in the EQ, it is best to follow Route 1. This path provided the most line-of-sight opportunities with the transmitters placed. In addition, Route 1 followed the outskirts of the EQ reducing the number of reflections needed, unlike Route 2. Though Route 3 also followed the outskirts of the EQ, the number of direct paths was more limited compared to Route 1. In AP, it is best to follow Route 3. Once again, this path provided the most line-of-sight opportunities for the transmitters. Route 1 loses significant RP because it moves behind a large building where no direct paths exist as in the example discussed in Figure 4. Route 2 has the lowest RSS most likely because the majority of the path moves through the center of the plaza distanced from the transmitters. To maximize RSS throughout campus it would be better to use omnidirectional antennas. The high number of obstacles associated with an urban environment significantly reduce the benefits of having a signal highly concentrated in one area.

This study provides insight for the optimal transmitting antenna type used. Future studies will focus on varying receiving antenna types. The same setups will be used as discussed here, however, transmitters will remain omnidirectional and receivers will vary between omnidirectional and directional. In addition, directional antennas will be tested facing north, south, east, and west. This analysis will help further understand the usefulness of reconfigurable antennas in urban environments. The RP will not be limited by an antenna only facing one direction, instead optimizing which direction the signal is received at each point along the path.

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