ANTENNA SELECTION FOR A PUBLIC SAFETY COGNITIVE RADIO

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Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirement for the degree of

Master of Science
in
Electrical Engineering

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May 2006

Key Words: Public Safety Cognitive Radio, Quadband Antenna

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ABSTRACT

Ever since the dawn of radio communication systems, the antenna has been the key component in the construction and performance of every wireless system. With the proliferation of new radio systems, a cognitive radio is a radio that has the capability to sense, learn, and autonomously adapt to its environment. The hardware components are essential to optimizing performance. Antenna hardware for cognitive radio applications presents distinctive problems, since in theoretical terms, a cognitive radio can operate anywhere in the spectrum.

The purpose of this thesis is to investigate a particular type of cognitive radio system and examine the potential affects the antenna will have on the system. The thesis will provide an overview of fundamental antenna properties, the performance characteristics of the particular antenna used in this research, and the system characteristics when the antenna is integrated. This thesis will also illustrate how the antenna and its properties affect the overall public safety cognitive radio performance. This information can be used to establish antenna selection criteria for optimum system performance.

ACKNOWLEDGEMENTS

"*Thanks be to God, who in Christ always leads us in triumph …*" (II Corinthians 2: 14)

First and foremost I would like to thank my advisor Dr. Charles Bostian for his guidance and support throughout this research. There are no words to express how much I appreciate everything he has done for me. He has always motivated me to strive to do my best. His advice and encouragement during my time here at Virginia Tech was very invaluable. He has certainly made a lasting impression on me and I will be forever grateful to have had the opportunity to work with him.

I would also like to thank Dr. Wayne Scales and Dr. Allen MacKenzie for their willingness to serve on my committee and for the helpful feedback they provided on my thesis. Appreciation is extended to Dr. Davis for his assistance with the antenna measurements that contributed to this work.

Special thanks are expressed to all of the team members of the Center for Wireless Telecommunications (CWT); without them, this work would not have been possible. Especially Bin, Tom, Daivd M., and David S., my sincere gratitude goes out to each of you, your enthusiasm for research is truly a motivation. Also thanks to Judy for helping me whenever I had questions and Rarick for reviewing my thesis document.

Finally, I would like to thank my family and friends for their continued support and encouragement during this effort and also life. I would especially like to thank my parents for giving me, much needed advice and immense strength and support every time I needed it; and for their constant reminders that if I just put everything in GOD's hands it will work out in the end.

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1 Introduction

In the 21st century where new facets of communication are being explored, advances in radio technology continue to revolutionize the face of wireless communications and technology. There is a continuous demand for data transmission at higher rates and over longer distances. The need for secure and robust communications is becoming more apparent. Wireless and mobile communication systems are at the forefront of current research activities. In addition, ever larger numbers of people are relying on wireless technology, either directly or indirectly. Since the first demonstration of wireless technology in a practical radio communication system by Guglielmo Marconi, the antenna has been a key building block in the construction of every communication system [1].

It is important that engineers designing wireless communications systems have some fundamental knowledge of antenna performance and radio wave propagation characteristics. This knowledge is essential to the proper selection of system antennas to ensure system coverage and performance. A properly selected antenna system has the capability of improving overall system performance and may lead to a reduction in system cost. Conversely, a poorly selected antenna system may degrade system performance.

The purpose of this thesis is to investigate the factors that influence antenna selection for a public safety cognitive radio and to report in detail on the properties of the commercial antenna that I selected. In the document, I will review the basic concepts of cognitive radio and explain the approach that my research group has taken to develop a working prototype. The frequency agility of the public safety cognitive radio requires an antenna capable of operating in at least four bands between 50 MHz and 1 GHz, and one with a form factor suitable for mounting on a hand held radio. After reviewing antenna characteristics in general, I will focus on the antenna's terminal impedance and resulting VSWR, the interaction of the antenna with the output network of the GNU radio transmitter, and the most important feature of the antenna's radiation pattern, the direction of maximum radiation. I will also report on some informal indoor measurements of radio link performance using this antenna. As far as I am aware, this is the first investigation of these topics for a cognitive radio.

1.1 Organization of Thesis

Following this introduction, Chapter 2 introduces the concept of Cognitive Radio and describes the VT Cognitive Radio Platform. Chapter 3 gives a description of performance criteria for antennas. Chapter 4 aims to illustrate a real world example by showing how an antenna affects the cognitive radio platform. Chapter 5 indicates what possible antenna solutions are available for CR. The section also aims to discuss the tradeoffs needed for antenna performance of a cognitive radio and also certain issues that may arise for selecting a CR antenna. The final chapter presents some conclusions and recommendations for future work.

1.2 References

[1] O. Dunlap, *Marconi: The Man and His Wireless*. New York: Arno Press, 1971.

2 Cognitive Radio (CR)

The objective of this chapter is to discuss the concept of cognitive radio and describe the CR SDR platform being developed by the Center for Wireless Telecommunications (CWT) at Virginia Tech.

2.1 CR Concept

The term Cognitive Radio was first coined by Joseph Mitola as "the point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to: (a) detect user communications needs as a function of use context, and (b) to provide radio resources and wireless services most appropriate to those needs" [5]. However the concept of CR is not limited strictly to wireless devices such as PDA's. There has been a lot of ambiguity over how to actually define the concept of CR. This is apparent by the number of proposed definitions give by various organizations and prominent individuals [1]. The working definition of CR. constructed by the SDR Forum Cognitive Radio Working Group, allows for future evolution of CR as well as strictly defining the concept:

> "***A Cognitive Radio is a software-defined radio that possesses the attributes of being RF and spatially aware with the ability to autonomously adjust to its environment accordingly (frequency, power, & modulation)." [2]***

Cognitive radios have the capability to sense their environment and learn how to adapt to various situations. This allows a CR to handle unanticipated signals, channels, and events that may arise. Thus a CR is able to automatically select the best waveform for a radio transmission and is even able to delay or bring forward certain transmissions depending on the currently or future available resources. The learning and reasoning capabilities needed for CRs to fulfill this goal which would more than likely be implemented in software as a high layer functionality have been investigated [4][5]. In more piratical terms the idea of cognitive radio can be thought of in the analogy "knobs (observable parameters) and meters (writable parameters)" [9]. See Figure 2-1.

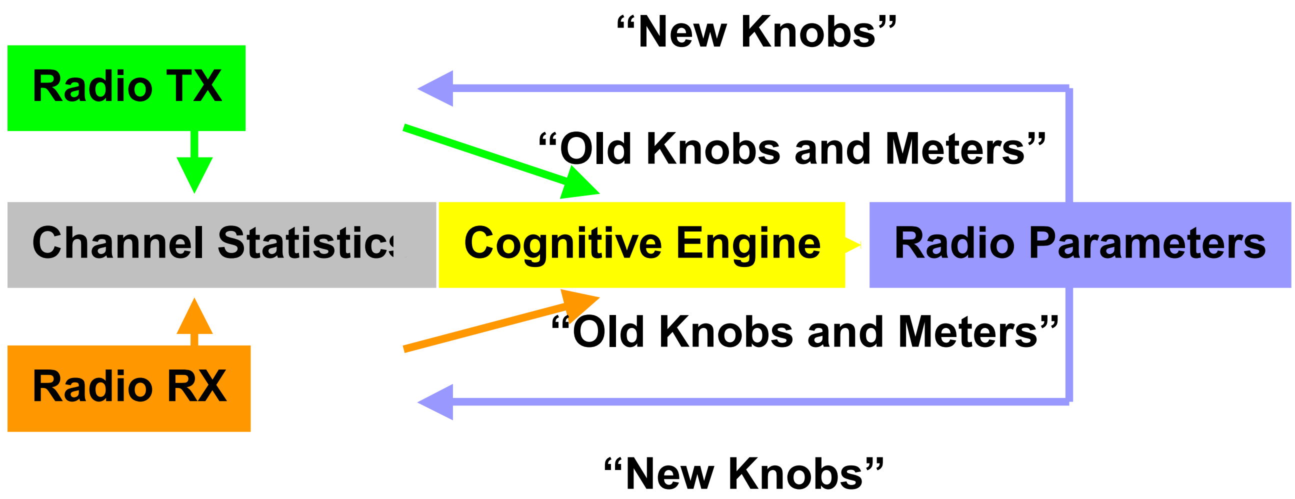

Figure 2-1 "Knobs and Meters" Methodology [11]

Meters are all possible outputs or information that can be available from the radio. Knobs are all possible actions that the radio can take, in other words how the radio adjusts what is being read. The most important use for the "meters" of the cognitive radio is sensing the RF environment, determining what signals are present and their properties. This can be termed signal detection and signal classification. Signal detection is the process of collecting a signal, in the presence of noise, so that an action can be performed. Signal classification is the process of identifying the signal and determining its technical characteristics.

2.1.1 Cognition Cycle

CR can better be explored by introducing the cognition cycle, which explains what a cognitive radio is. Since being introduced by Mitola [5], the operation of cognitive radios has been frequently illustrated by the cognition cycle illustrated in Figure 2-2. The cognition cycle is a state machine that resides in the cognitive radio and defines how the radio learns about and reacts to its operating environment.

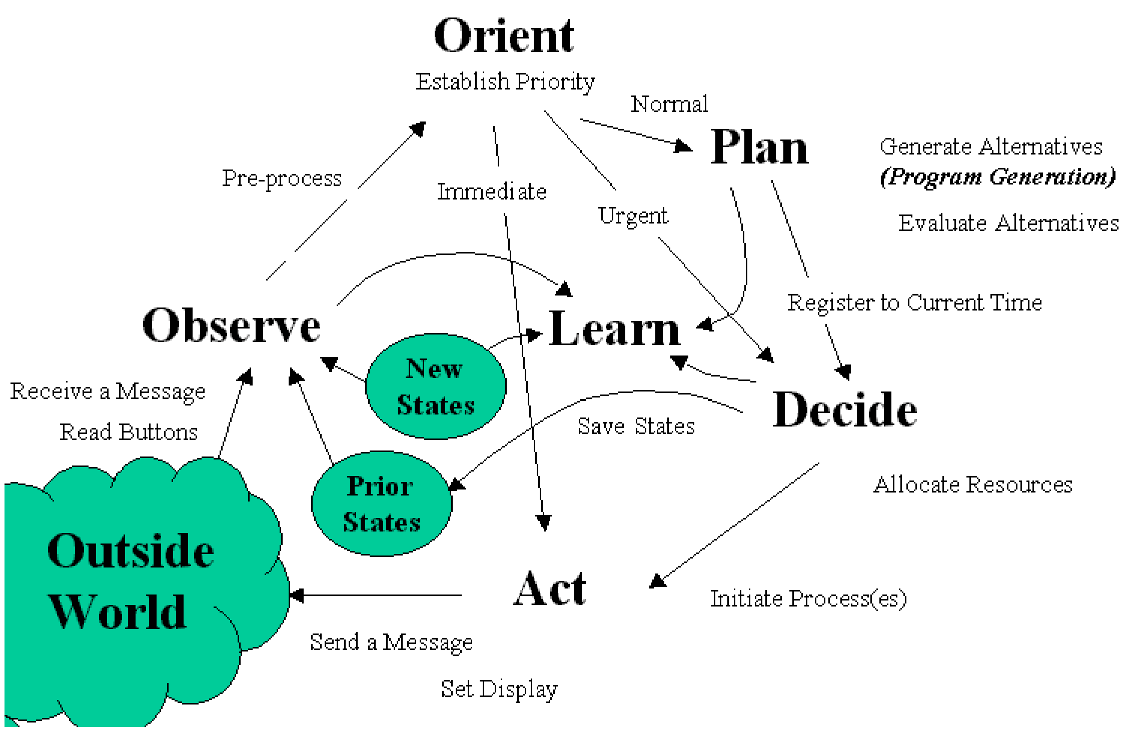

Figure 2-2 Cognition Cycle [1]

The first step of the cognition cycle is to observe the outside world. The radio receives information about the operating environment. This information is then analyzed to determine the meaning of what is being observed. The cognition cycle determines the importance of certain information. Based on this information, the radio generates and evaluates alternatives that can be employed. After assessing the various alternatives it decides which method will presumably improve the system. The radio then implements the chosen alternative by adjusting its resources and performing the appropriate signaling. These changes are then reflected in a message presented by the cognitive radio. Throughout the process, the radio is using these observations and decisions to improve its operation. The radio is learning about the outside world and is evaluating the user's needs. This will help to improve the performance of the system, because now the CR can enhance the system by creating new modeling states by generating new alternatives.

2.2 CR Criteria & Capabilities

Three major features define a cognitive radio. A CR must be able to sense, adapt, and learn from its environment. These are the characteristics that make CR unique from other spectrum sharing and wireless communication techniques.

2.2.1 Sense

The radio has awareness of what kind of environment it is currently or potentially operating in. A CR must be able to sense wireless channels and user networks across the multiple signal dimensions of time, frequency and physical space [7]. This information is key to opportunistically providing wireless links that best meet the user requirements and needs.

2.2.2 Adapt

Adaptability is a key concept when you refer to mobile networks and limited resources for transmitting signals. Cognitive radios are aware of their environment and intelligently adapt their performance to the user's needs [8]. The radio knows how to adjust to the spectral environment and dynamically change modulation and frequency to use unoccupied spectrum that avoids congestion and jamming. The knowledge of the operational environment is referred to as situation awareness and includes information about the physical environment, RF channel, radio resources, and user requirements.

2.2.3 Learn

The concept of a radio that can learn is a fundamental change in the perception of typical radio systems. The ability of a CR to learn from its previous experience is what sets this particular technology apart from any existing system. The learning processes of a CR allow the system to know about certain environmental parameters so that it can adjust itself accordingly when the same situation occurs.

2.3 Cognitive Radio Advantages & Disadvantages

2.3.1 Advantages

There are several advantages of a technology as ubiquitous as CR, but there are three essential aspects of why CR is so important. The main three advantages of CR are:

- Improved link performance
- Improved spectrum utilization
- Potential cost reduction

The idea of improved link reliability arises in the situation where you lose a signal or connection in rural areas or vicinities where coverage is minimal. CR could essentially play a major role in the improvement of link performance by being able to adapt to bad channels or connections. The technology also has the capability of improving on a good channel by increasing the data rate. The CR looks at its available alternatives and learns the best course of action for the situation. Another aspect that CR will help improve, is indirectly related to link reliability regarding the issue of interoperability. Interoperability refers to the ability of different types of wireless devices and applications to work together effectively, without prior communication, in order to exchange information in a useful and meaningful manner. As an example, suppose a national emergency occurs and public safety personnel from different parts of the U.S. respond to the disaster, all jurisdictions will be able to communicate seamlessly without interference. CR will become a must-have technology for situations as these with its, frequency agility and/or flexibility, the ability to enhance interoperability between different radio standards, and the capability to sense the presence of interferers [12]. With spectrum sharing capabilities, cognitive radios can prove their effectiveness by utilizing some of the existing spectrum that is not widely used while help in maintaining call priority and response time. The spectrum is already allocated for the U.S.; the major problem is not spectrum scarcity but access and utilization of it.

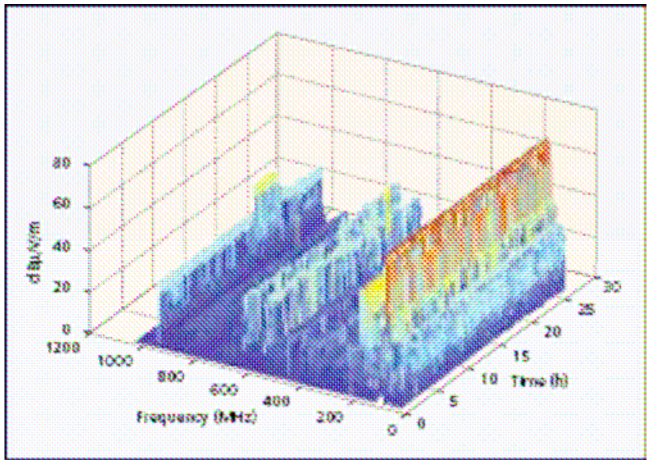

Figure 2-3 Spectral Utilization during One Day (50 MHz–1 GHz) [6]

It is apparent from Figure 2-3 that there are several frequency bands that are not occupied throughout the day. One can see constant use in the frequency bands below 300 MHz, which is allocated to analog audio and video broadcast. However, wide ranges in between show almost no activity. Considering the shortage of bandwidth in public frequency bands like the industrial, scientific, and medical (ISM) bands at 2.4 GHz and 5.1 GHz, this circumstance is a waste of resources in a modern society, depending more and more on the availability of mobile communications can hardly afford [6]. CR can aid in improving this problem by filling in unused spectrum and shift away from over occupied spectrum. A concept that can be utilized by CR to enhance spectrum utilization is to, have radios (or networks) identify spectrum opportunities at run-time and transparently (to legacy systems) fill in the gaps (time, frequency, space) [1].

It is hoped that the concept of CR will lead to the deployment of cheaper radio modules. For CR the goal is to incorporate, inexpensive RF components and cheaper processing [1]. The emergence of CR will change the face of current commercial wireless products, such as, cellular phones, PDA's, high speed internet, commercial radios, video conferencing, GPS, etc. The major areas where CR will be most beneficial are: military applications, government and regulatory areas, and public safety. Cognitive radio technology is an important innovation for the future of communications and likely to be a part of the new wireless standards, becoming almost a necessity for situations with large traffic and interoperability concerns [12].

2.3.2 Disadvantages

With any emerging technology there are drawbacks that can potentially affect the development of the system. Key problems that arise for CR include:

- Encompasses the same drawbacks as software defined radio
- Loss of control
- Regulatory concerns
- Significant research remains to be done to realize commercially practical cognitive radios [11]

With any software define radio based technology there are always complexity drawbacks. Since the core of CR resided with software defined radio, CR inherits most of the same problems associated with software defined radio. Some of the drawbacks associated with software defined radio are:

- Security
- Software reliability
- Keeping up with higher data rates [1]

The process of CRs sense, learn, and adapt cycle changes the outside world for other cognitive radios with each cycle. This can potentially result in loss of control if a group of radios interact with each other causing chaotic networks [1]. As far as regulatory concerns apply to CR the current FCC regulations are not specified or designed for CR use. The fear is that regulations will retard the development of cognitive radio or actually reduce available spectrum [1]. The concept of CR is still evolving and there are many research areas that need to be addressed for the systems. This includes: information collection and modeling; decision processes; learning processes; hardware support [11].

2.4 CWT Cognitive Engine

The radio architecture and functionality of the CWT cognitive engine can be expressed as an intelligent agent that controls a software defined radio's set of "Meters" and "Knobs" [9]. The CWT cognitive model is based on biologically motivated techniques, such as the use of genetic algorithms (GA). GA's in simple layman's terms are basically chaotic searches that build upon certain hypothesis in order to reach an optimal solution that will improve the performance of CR. The basic model for the CWT cognitive radio can be shown through the cognition loop in Figure 2-4:

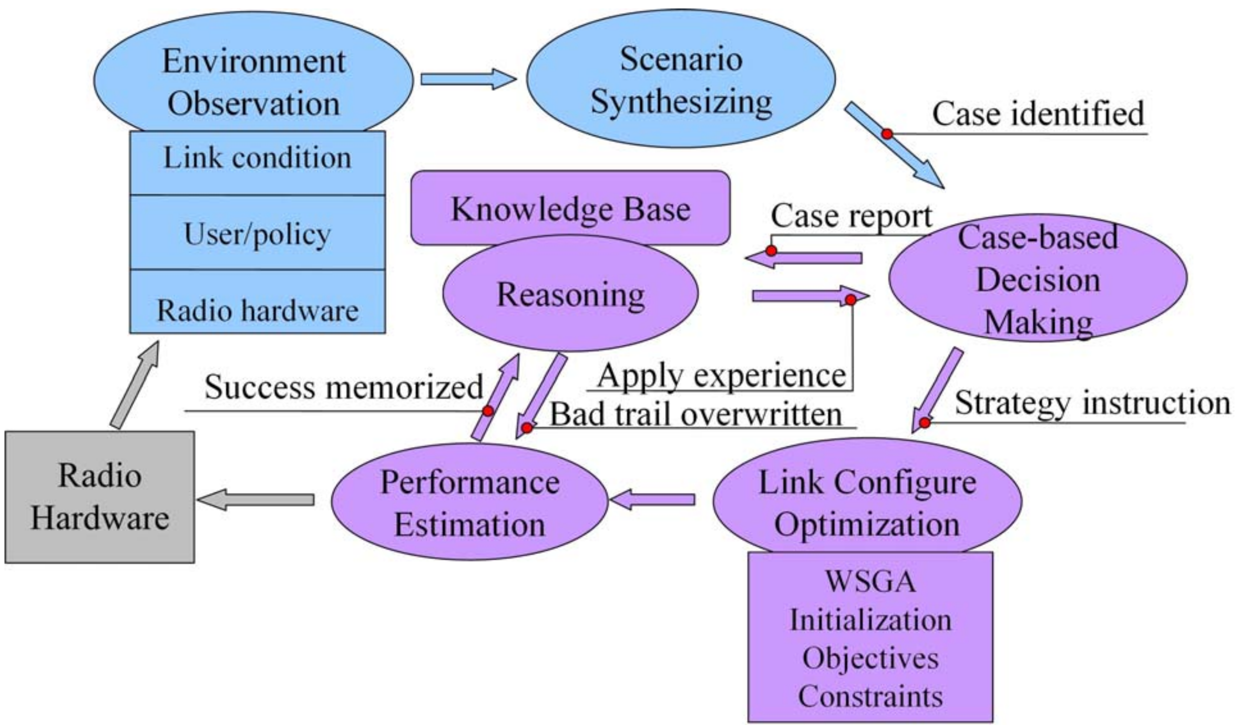

Figure 2-4 CWT Cognition Loop [9]

After the radio receives the surrounding environment and acknowledges the users needs, the use of case-based decision theory is used to determine the best course of action. The GA is then used to update and select the best parameters to optimize performance. Performance estimation is then used to monitor the feedback from the radio to understand the overall system performance. The CWT Cognitive engine is free standing software that has the potential to work with any cognitive radio. The use of a universally available GNU radio, which is a low-cost radio developed specifically for building and deploying software defined radios, will serve as the SDR platform. We are testing it with the GNU radio platform because it is open source, inexpensive, and currently available. Since the GNU radio system serves as the SDR platform, which the CWT's cognitive engine controls, this will be the basis of my real world example on how antennas affect the performance of a public safety CR. There will be a practical assessment of the performance advantages or disadvantages of antenna hardware on CR.

2.5 References

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[2] SDR Forum Cognitive Radio Working Group, "Cognitive Radio Definitions and Nomenclature", January 2006

[3] J. Mitola, "Cognitive Radio for Flexible Mobile Multimedia Communications", IEEE Mobile Multimedia Conference, pp 3-10, 1999.

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[9] T. Rondeau, B. Le, D. Maldonado, "Introduction to the Cognitive Engine", NIJ Project Meeting, September 2005

[10] V. Tuzlukov, *Signal Detection Theory.* New York: Birkhauser Publishing, 2001.

[11] C. Bostian, J. Reed, "Understanding the Issues in Software Defined Cognitive Radio", tutorial presented at IEEE DySPAN, Baltimore, MD, November 2005.

[12] D. Maldonado; Bin Le; A. Hugine; T.W. Rondeau; C.W. Bostian,, “Cognitive radio applications to dynamic spectrum allocation: a discussion and an illustrative example”, IEEE DySPAN**,** Page(s):597 – 600, November 2005

3 Typical Communication Antennas

Cognitive radios need antennas that cover a wide frequency range. Antennas serve as transducers between electromagnetic wave travelling in free space and guided electromagnetic signal in circuits [1]. As such, they play a critical role in the performance of CR systems. If you ignore the antenna, then the radio may not attain maximum effective range. An effective antenna solution increases the range and corresponding coverage of a CR.

3.1 Performance Criteria for Antennas

There are many characteristics of antennas that determine whether the antenna is efficient or not. Some of the most important characteristics of antennas are: gain, size, radiation pattern, bandwidth, and voltage standing wave ratio (VSWR).

3.1.1 Radiation Patterns

The radiation pattern of an antenna is a plot of the relative power versus angle. The radiation pattern defines the radiating characteristics of the antenna. The most basic radiation pattern is isotropic, which means the antenna transmits radio waves in all directions equally. An isotropic radiation pattern resembles the shape of a beach ball, with an antenna at its center. An isotropic antenna is an ideal antenna that radiates power with unit gain uniformly in all directions and is often used as a reference for antenna gains in wireless systems [3]. There is no actual physical isotropic antenna.

The more common antenna types for wireless communications have omni-directional and directional radiation patterns. Omni-directional antennas propagate RF signals in all directions equally on a horizontal plane are directional in the vertical plane [2]. Typical omni-directional antennas have gains ranging up to 6 dBi. The gain of an omni-directional antenna can be increased by narrowing the beamwidth in the vertical or elevation plane [4].

Higher gain antennas will have a narrower beam width, which limits coverage on the sides of the antennas. High gain antennas work best for covering large, narrow areas, or supporting point-to-point links. Directional antennas are used in some base station applications where coverage over a sector by separate antennas is desired.

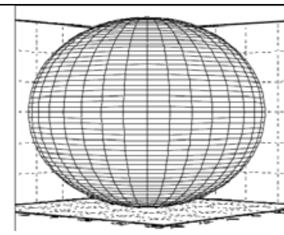
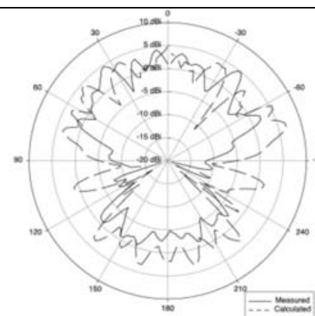
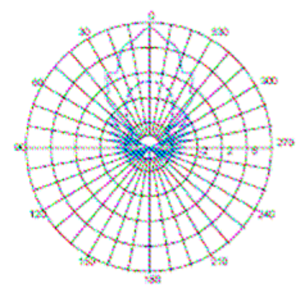
Type	Radiation Pattern
Isotropic	
Omni-Directional	
Directional	

Table 3-1 Some Typical Radiation Patterns

3.1.2 Gain

The key characteristic of comparing antennas performance is the gain of an antenna which is the ratio of its radiation intensity to that of an isotropic antenna radiation the same total power [1]. Most antenna manufacturers specify gain in dBi, which is the gain relative to an isotropic antenna [5].

3.1.3 VSWR

Voltage Standing Wave Ratio (VSWR) is defined as the ratio of the maximum/minimum values of standing wave pattern along a transmission line to which a load is connected. VSWR is a measure of how well the antenna's impedance matches the transmission line that will be used to feed the antenna. The higher the VSWR value, the greater is the mismatch. The minimum VSWR, i.e., which corresponds to a perfect impedance match, is unity [4]. A VSWR of 2:1 or less is considered good.

3.1.4 Bandwidth

The bandwidth of an antenna is a measure of its ability to operate over a wide frequency range. An antenna's bandwidth might be said to be the frequency spread between those frequencies for which the antenna VSWR is 2:1, in other words the impedance bandwidth. The bandwidth of an antenna can also be given in terms of percent bandwidth [2]. Percent bandwidth is found by the equation:

$$\begin{aligned} BW &= 100 * \frac{F_H - F_L}{F_c} \text{ where :} \\ F_H &= \text{highest frequency in band} \\ F_L &= \text{lowest frequency in band} \\ F_c &= \text{center frequency of band} \end{aligned} \quad \textbf{(3-1)}$$

An example of using percent bandwidth would be for an antenna that operates in the range of 500MHz – 525MHz. It would cover at least $100 * \frac{525 - 500}{512.5} = 4.9\%$ bandwidth. The bandwidth of an antenna is especially important for CR, due to the fact that it operate on a wide variety of frequencies in the RF spectrum.

3.2 Types of Antennas

In this section we discuss some of the antennas commonly used for wireless handsets and which, therefore, are candidates for use with a cognitive radio.

3.2.1 Monopole

A monopole is a wire connected to a ground plane and excited at its base [1]. A monopole antenna is a resonant antenna that can be thought of as being one arm of a dipole antenna, with the other arm being the image under the ground plane. Monopoles are preferred over diploes because of the simplicity of the monopole feed system when compared to those of a dipoles system. Monopoles tend to have a broad main beam and small sidelobes. The impedance of a monopole antenna can vary from about 7-10Ω to over 600 Ω depending on the frequency. The principal advantage of a monopole antenna is its simple construction. However, the device's performance characteristics are greatly affected by the size and shape of the ground plane.

3.2.2 Diamond & Rounded Diamond

A diamond antenna is an inverted bowtie with triangular upper and lower halves whose height and base are both a quarter-wavelength at the center frequency of interest. The diamond and rounded diamond antennas have been shown to have wide-band properties suitable for ultra wide-band (UWB) applications [6]. Like all antennas, the radiation field of the diamond antenna is completely determined by its current distribution. The diamond dipole antenna configuration follows from theory that thickening a dipole increases its impedance bandwidth. A rounded diamond gives a broader frequency response than the diamond antenna. The rounded diamond has virtually the same dimensions as the diamond, except that the bottom edge of the upper half and the top edge of the lower half are rounded. Intuitively, it appears that by designing the curvature of the rounded diamond, one could broaden the antenna response in the higher frequency range [6]. Figure 3-1, compares the S_{11} parameters of a diamond and rounded diamond antennas. S_{11} parameters are the reflection coefficients measured at the input of the antenna. Both antennas render basically the same result, except in the range between 5 - 6 GHz.

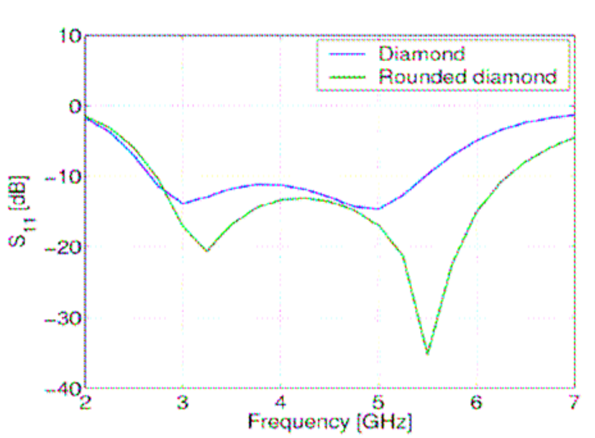


Figure 3-1 Impedance of Diamond & Rounded Diamond [6]

3.2.3 Biconical

A bicone is a dipole which has become an aperture antenna in one plane. Biconical dipole antennas can provide uniform omni-directional gain in the horizontal plane and slowly varying gain with elevation across a wide frequency range. The phase varies also but the phase center is constant in position. Wide-angle biconical antennas are frequently used as broadband antennas. The broadband impedance characteristics occur when the angle of the cones, θ_o lies between 30 degrees to 60 degrees. The exact value of θ_o is not of critical importance, since it is chosen so that the characteristic impedance of the biconcial dipole matches closely to the impedance of the line which feeds the antenna. In general, the antenna exhibits lower characteristic impedance and wider bandwidth as the flare angle is increased. This is shown in the angle θ_o vs. impedance (K) plot shown in Figure 3-2.

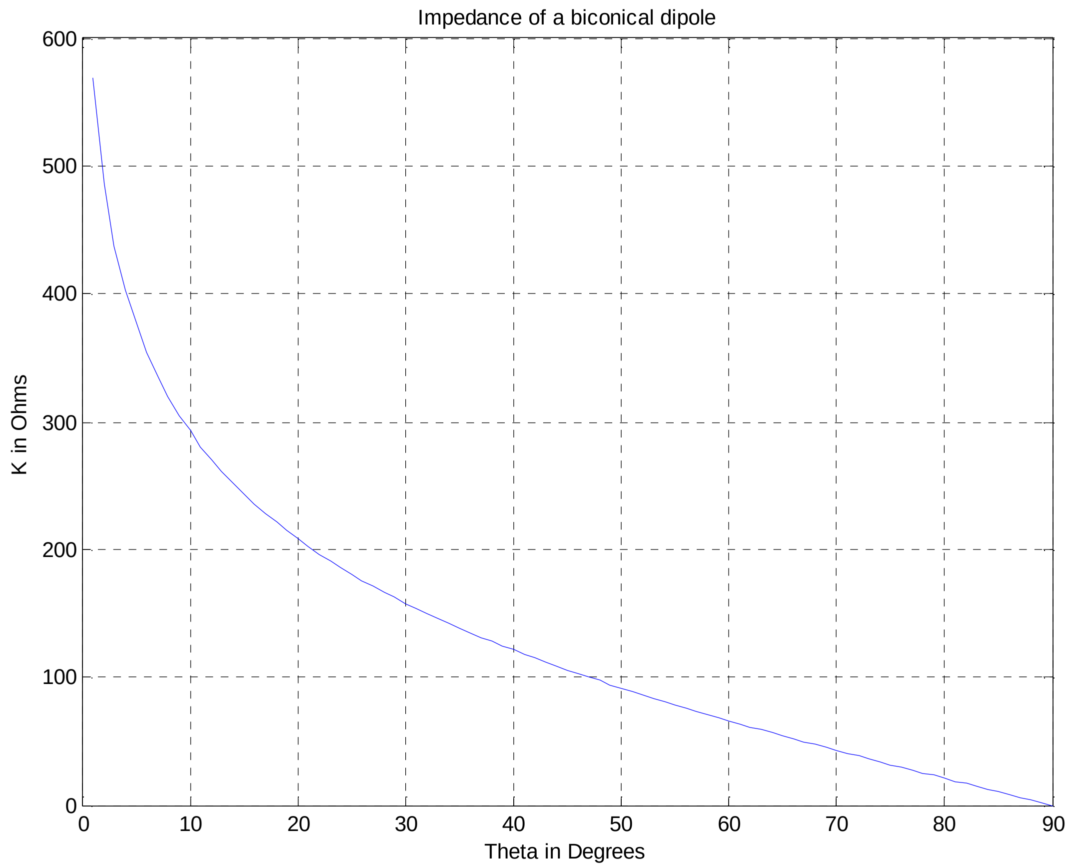


Figure 3-2 Impedance of a Biconical Dipole

3.2.4 Summary

The above mentioned antennas are just a few types that are commonly used for wireless applications. Table 3-2 summarizes their characteristics.

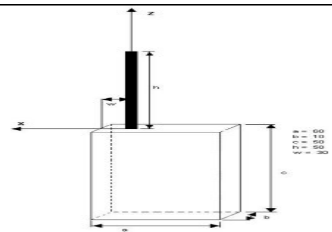
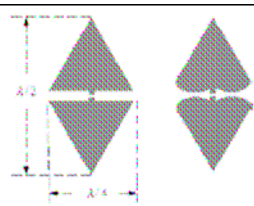
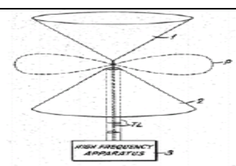
Antenna Type	Picture	Directivity	VSWR	Frequency	Gain
Monopole		Omni-directional	< 2.4:1	400-1000 MHz	Gain varies from 0.42 dB to 4.2 dB.
Dipole		Omni-directional	<2.5:1	HF (2-30)Mhz V/UHF (30-500Mhz)	Gain of about 2 to 3 dB
Diamond & Rounded Diamond		Near Omni-directional	Less than 1.5:1	4.5- 7.4 GHz	3 dB
Biconical		quasi-perfect omni-directional	3.4:1	30 MHz-300 MHz [2.75-16] GHz	2 dB

Table 3-2 Commonly Used Antennas

3.3 References

[1] L. Godara, *Handbook of Antennas in Wireless Communications*. Boca Ranton, FL: CRC Press, 2002.

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4 Public Safety Bands

For this particular research we are focusing on designing a CR that operates and functions in the public safety bands of the RF spectrum.

4.1 Specific Public Safety Operating Bands

Public safety service personnel are individuals who perform emergency first response missions to protect and preserve life, property, and natural resources and to serve the public welfare through local, state, or federal governments as prescribed by law [6]. The organizations that are usually included in the public safety domain are; law enforcement, fire personnel, and EMS:

First Responders	
Community Element	**Functions**
Emergency Medical Services	Public protection, public health, emergency medication/ medical services
Fire Services (fire marshal, volunteer and professional fire protection districts, etc.)	Public protection, protection of property, identification of hazardous situations
Law Enforcement (identification services, laboratory, operations, juvenile department, etc.)	Public protection, law enforcement, identification, investigation/evidence gathering, arrest, filing of charges

Table 4-1 Public Safety Personnel [1]

In order to proficiently respond to emergencies, personnel such as law enforcement, EMS, and the fire department must be able to communicate with each other. Unfortunately each of these divisions often operates on a different part of the spectrum using radios with different technical standards and they can not easily communicate with each other. According to a report by the National Task Force on Interoperability, the public safety community has identified limited and fragmented planning and coordination and limited and fragmented radio spectrum as some of the key issues that hamper public safety wireless communications today [6]. This interoperability issue is a something the can be alleviated with CR technology.

In order to transmit and receive on different frequencies, emergency response personnel use certain types of operation for their conventional radio systems. The typical operation is a simplex or repeated duplex system. In a simplex system all users transmit and receive on one frequency and must take turns using the channel. This system is usually used for on the scene calls. The repeated duplex systems utilize a repeater, which is usually located at a high elevation to listen to the input channel at one frequency and then retransmit what it receives on the output channel in real time. Public safety radio frequencies are distributed across four isolated frequency bands from lowband VHF (25-50 MHz) to 800 MHz (806-869 MHz) [1]. The range of frequencies from 698-806 MHz was recently allocated for state and local public safety services. This so-called 700 MHz band is currently occupied by TV broadcasters and is not expected to be cleared before December 31, 2006 at the earliest [4]. The expectation is that all analog TV transmitters will transition to digital format and migrate below channel 52 (below 698 MHz), provided at least 85 percent of households in their respective areas have sets with digital TV capability [4]. Table 4-2 lists the various spectral bands and, in a few cases, the amount of spectrum assigned to local, state, and federal public safety users.

Spectrum (MHz)	PS (state, local)	PS (federal)	Use
25–50	6.3	3.8	Military, fed agencies, state highway patrol, and other nontrunked
138–149.9		4	Includes mobile stellite services (MSS)
150.05–150.8			
150–162			Maritime and private mobile radio (PMR)
162.0125–173.2	3.6		Includes telemetry, National Oceanic and Atmospheric Administration (NOAA) weather, and wireless microphone
173.2–173.4		8.25	
173.4–174			
220–221/221–222	0.1	0.69	10 channels for public safety with 5 more for EMS
406.1–420		8.3	Includes space sciences
421–430	?		Available in three urban areas (47cfr90.273)
450–470	3.7		Air-to-ground, PMR, family radio service (FRS)
470–512	10		UHF TV, PMR
698–716/728–746			UHF TV — reassigned for mobile
716–728			UHF TV — reassigned for mobile
746–764/776–794			UHF TV — reassigned for mobile
764–776/794–806	24		Public Safety
806–821/851–866	7.5		Public safety, specialized mobile radio services (SMRS), PMR; it includes 4 MHz following the reorganization of the band
821–824/866–869	6		Public safety — National Public Safety Planning Advisory Committee (NPSPAC)
824–849/869–894			850 commercial
932–941	0.125		Public safety — FCC Docket No.97-81
1710–1755/2110–2155			DoD, multipoint distribution service (MDS), deep space reassigned for advanced wireless services (AWS)
1850–1915/1930–1995			1900 commercial including 2 × 5 MHz assigned to Nextel as part of the 800 MHz consensus
1915–1920/1995–2000			Unlicensed PCS-broadcast auxiliary services — suggested for AWS 2020-2025 Broadcast auxiliary services — suggested for AWS
2155–2180			MDS 2A (2155–60), fixed µwave (2160–65), MSS (2165–80) suggested for AWS
2305–2320/2345–2360			Wireless communications services (WCS)
2495–2690			Rechannelized multichannel multipoint distribution service (MMDS) in blocks of
4940–4990	50		Public safety (federal could be given use)

Table 4-2 Spectrum Utilization [4]

4.1.1 Law Enforcement

There are multiple operational frequency ranges for law enforcement personnel. . The nationwide police emergency frequency is 155.475 MHz [3]. Table 6-1 lists some of the common frequencies.

Police Frequencies (MHz)
42.02 - 42.98
44.62 - 46.02
154.65 - 156.21
159.09-159.21
453.0125 - 453.9625
460.0125 - 460.5625
810.00 - 816.00
855.00 - 861.00
866 – 869

Table 4-3 Sample of Common Police Frequencies [3]

In many jurisdictions the frequencies actually used are unpublished.

4.1.2 Emergency Medical Services (EMS)

Emergency medical service frequency bands are used for ambulance dispatch, ambulance to hospital, and ambulance to ambulance. Medivac frequencies are used to relay vital patient information between the paramedic and hospitals [3].

Paramedic Frequencies (MHz; || = paired with)
462.950 || 462.9625
462.975 || 462.9875
463.00 || 463.0125

463.025 || 463.0375
463.050 || 463.0625
463.075 || 463.0875
463.100 || 463.1125
463.125 || 463.1375
463.150 || 463.1625
463.175 || 463.1875
Other frequencies are 155.16,155.28,155.34

Table 4-4 Sample of Common Medical Frequencies [3]

4.1.3 Fire Services

The frequency ranges for fire departments can vary depending on whether it is a dispatch call or on the scene communication. An important factor to remember is that fire dispatched frequencies are always separate from the frequencies that are used on the actual fire scene [3]. On the scene radios are usually handheld radio and therefore operate on a different frequency than regular radios. Below is a list of commonly used frequency ranges for fire services:

Fire Department Frequencies (MHz)
33-34 (Land Mobile Radio)
153.770-154.070
154.130-154.445
460.5125-460.6375
461-462.5375
821-824

Table 4-5 Partial Listing of Fire Department Frequencies [2 & 3]

4.1.4 Summary of Public Safety Bands

As illustrated from the tables above, there is a plethora of frequency bands that can be used for different divisions of public safety. For each branch under the public safety spectrum there is a certain range that is commonly used. Public safety services operate in 10 separate bands, which has added capacity, but which has also caused the fragmentation that characterizes the public safety spectrum today [6].

Public Safety Frequency Bands	
Public Safety Branches	Frequency Range (MHz)
EMS	462.7375 – 470
	150.05-155.6
Fire Service	154.01-154.445
	461-462.5375
Law Enforcement	148-149.9
	152.855-159.21
	453.0125-460.5625
National Public Safety Planning (Fire & Police Radio)	821-824 (Mobile to Base) 866-869 (Base to Mobile)

Table 4-6 Public Safety Bands [2]

4.2 Virginia Tech Public Safety Bands

So far the public safety frequency bands that were discussed have been very broad and covered a vast range. Each public safety jurisdiction has a set licences frequency that they are allotted to communicate with. To give a more specific example of how the frequencies in the public safety ranges are allocated, we will examine the radio licenses that are held by Virginia Tech. Below is a table that illustrates the frequencies that can be used for the Virginia Tech police department and rescue squad:

Virginia Tech Frequency Licenses	
Division	Frequency (MHz)
VTPD	39.54
	155.35-155.535

	460.85-460.8875
	462.7625-462.9125
	464.9625-465.8875
	467.9125
	469.9625
VT Rescue Squad	150.79
	155.205-155.34
	159.195

Table 4-7 Virginia Tech Frequency Bands [5]

4.3 References

[1] The SAFECOM Program - Department of Homeland Security, "Statement of Requirement for Public Safety Wireless Communications & Interoperability", March 2004, Washington D.C.

[2] B. Kobb, "Spectrum Guide- Radio Frequency Allocation in the United States, 30 MHz -300 GHz" , New Signals Press, Falls Church, VA, 1996

[3] B. Kay, "Tuning in to RF Scanning – From Police to Satellite", TAB Books, New York, 1994

[4] T. Doumi, "Spectrum Considerations for Public Safety in the United Sates", IEEE Communications Magazine, January 2006

[5] Virginia Tech- Network Infrastructure & Service, "Radio Frequency License held by Virginia Tech", April 2004

[6] National Task Force on Interoperability, "*Why Can't We Talk?* Working Together to Bridge the Communications Gap to Save Lives", February 2003, Washington D.C.

5 Characteristics of the SRH999 Quadband Antenna

After surveying the available products, our research group selected the SRH999 Quadband Antenna for use with our cognitive radio. There is little information available about the performance characteristics of HT antennas; therefore we have to carry out detailed measurements on the SRH999 antenna to understand how it will perform in our cognitive radio application.

5.1 Diamond Antenna SRH999 Quadband Antenna

For this particular project, we need an antenna that has good performance in the common public safety bands. The antenna that was purchased is an SRH999 Quadband HT Antenna, from Diamond Antenna. It is advertised for use in these bands.

High quality, high gain HT antenna. Flexible whip with SMA.
Increase the performance on your handheld or wideband scanner
with a Diamond® SRH Series antenna.

Specifications:

Bands:	6m/2m/70cm/23cm
Watts:	10
Height:	19.5"
Connector:	SMA

Remarks: Ideal for IC-T81A.

Figure 5-1 SRH999 Quadband HT Antenna [2]

The SRH999 is a monopole whip antenna with an SMA connecter that offers about 3dB gain. The 50 ohm antenna is rated to handle a power of 10 watts. The antenna is advertised to operate in four different bands which correspond to approximately the following frequency ranges:

6m	**50-54MHz**
2m	**148-150 MHz**
70cm	**430-450 MHz**
23cm	**1.2GHz**

Table 5-1 Operating Bands of the SRH999 Antenna

According to the data sheets, the SRH999 operates as a 1/4 wave on 6 and 2 meters, a 1/2 wave on 430 MHz and a 5/8 wave on 1.2 GHz. The antenna is optimized to receive and transmit at the following bands: 150, 300, 450 and 900 MHz bands.

5.2 Antenna Measurement Setup

I took a wide variety of measurements in order to gather a good assessment of how the antenna performed. The measurements involved measuring the S_{11} values of the antenna using a network analyzer. S11 is the complex reflection coefficient at the antenna input port. The measurement setup involved using two types of network analyzers and also measurement with and without the presence of a ground plane. A ground plane is an electrically conductive surface that serves as the near-field reflection point for an antenna, or as a reference ground in a circuit [1]. A ground plane is utilized to limit the downward radiation of the antenna and to shield the antenna radiation pattern from the distorting effects of nearby objects. The following sections will illustrate the measurement procedures utilized for this particular analysis.

5.2.1 Measurement 1: 50-500 MHz No Ground Plane

The first measurement was taken using an 8751A HP Network Analyzer. This particular network analyzer only has a sweep range from 5Hz-500 MHz; therefore this was the range over which the measurement could be taken. The sweep incorporates a total of 801 points spanning between the start and end frequencies.

Figure 5-2 1st Measurement: 50-500 MHZ; No Ground Plane

5.2.2 Measurement 2: 50 -1200 MHz No Ground Plane

This particular measurement incorporated a different type of network analyzer. The test equipment that was used is an 8720C Network Analyzer, which spans from 50 MHz - 20 GHz and includes 801 points. The upper bound of the span exceeds the value needed for this particular project; therefore we stopped at 1200 MHz.

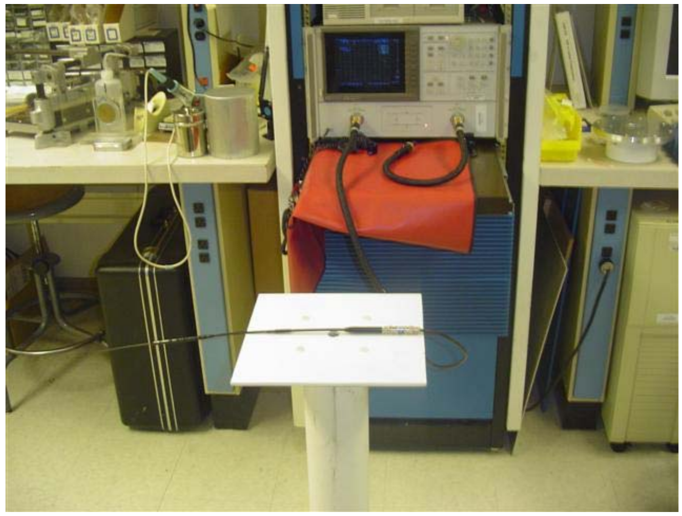

Figure 5-3 2nd Measurement Setup for 50-1200 MHZ with No Ground Plane

5.2.3 Measurement 3: 50-2000MHz Circular Ground Plane

The next measurement is the first that utilizes a ground plane. This particular measurement utilizes that same network analyzer that was used in the second measurement, using the same span a number of points. The first ground plane measured was a flat circular plate with a diameter of 1.2446m. This dimension is over twice the length of the antenna to ensure an effective ground plane.

Figure 5-4 3rd Measurement: 50-1200 MHZ; Circular Ground Plane

5.2.4 Measurement 4: 50-2000 MHz Metal Box Ground Plane

The next type of ground plane was a metal rectangular box, which is a model for a handheld radio used by public safety personnel. This type of measurement will give us a more accurate account of how the antenna will perform once it is integrated with the public safety CR. Again the same network analyzer and frequency span is used in this measurement. The metal box has a capacity of 0.17272m x 0.0254 m x 0.09652m.

Figure 5-5 4th t Measurement: 50-1200 MHZ; Metal Box Ground Plane

5.3 Antenna Performance Characteristics

5.3.1 Antenna Impedance Characteristics

The first performance metric that we will investigate is the input impedance characteristics of the SRH999 quadband antenna. For single port devices (We are only measuring one antenna.) the network analyzer needs only to measure the S_{11} characteristics. Below is a sample representation of the data collected by the network analyzer:

```
"8751A REV5.01"
"CHANNEL: 1"
"MEASURE TYPE: S11"
"FORMAT TYPE: LIN MAG"
"NUMBER of POINTS: 801"
"SWEEP TIME:  321 ms"
"SWEEP TYPE: LIN FREQ"
"SOURCE POWER:  15 dBm"
"IF BANDWIDTH:  4 kHz"

"Frequency"      "Data Real"      "Data Imag"
5.00000000000E+07    7.513148E-01   -3.751057E-01
5.05625000000E+07    7.429105E-01   -3.862982E-01
5.11250000000E+07    7.258245E-01   -3.978730E-01
5.16875000000E+07    6.983957E-01   -4.052251E-01
5.22500000000E+07    6.628757E-01   -4.059341E-01
5.28125000000E+07    6.215913E-01   -3.967443E-01
5.33750000000E+07    5.750272E-01   -3.718169E-01
5.39375000000E+07    5.321384E-01   -3.224407E-01
5.45000000000E+07    5.173906E-01   -2.442817E-01
5.50625000000E+07    5.446764E-01   -1.631547E-01
```

Figure 5-6 Sample Representation of Network Analyzer Data

The sweep between the frequency ranges collects 801 points between the start and end frequency values. We use the following equation to calculate impedance values.

$$S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0}$$
$$where,$$
$$Z_L = antenna\ impedance \qquad (5\text{-}1)$$
$$Z_0 = 50 ohms$$

Solving S_{11} for Z_L:

$$Z_L = Z_0 * \frac{1 + S_{11}}{1 - S_{11}} \qquad (5\text{-}2)$$

This is the equation that will be used to find the impedance of the SRH999 antenna.

We will now analyze the real and imaginary components of the antenna impedance as recorded in each of the four types of measurements that were taken. Each display will examine the overall impedance over the entire frequency span and then focus on the actual frequency ranges for which the antenna is advertised an in which our cognitive radio will operate. In each of the figures, the real and imaginary components of the input impedance are shown for the entire frequency sweep. The graphs also focus on an approximate range of which the antenna is advertised to be designed.

Measurement 1: Real & Imaginary Components of Input Impedance:

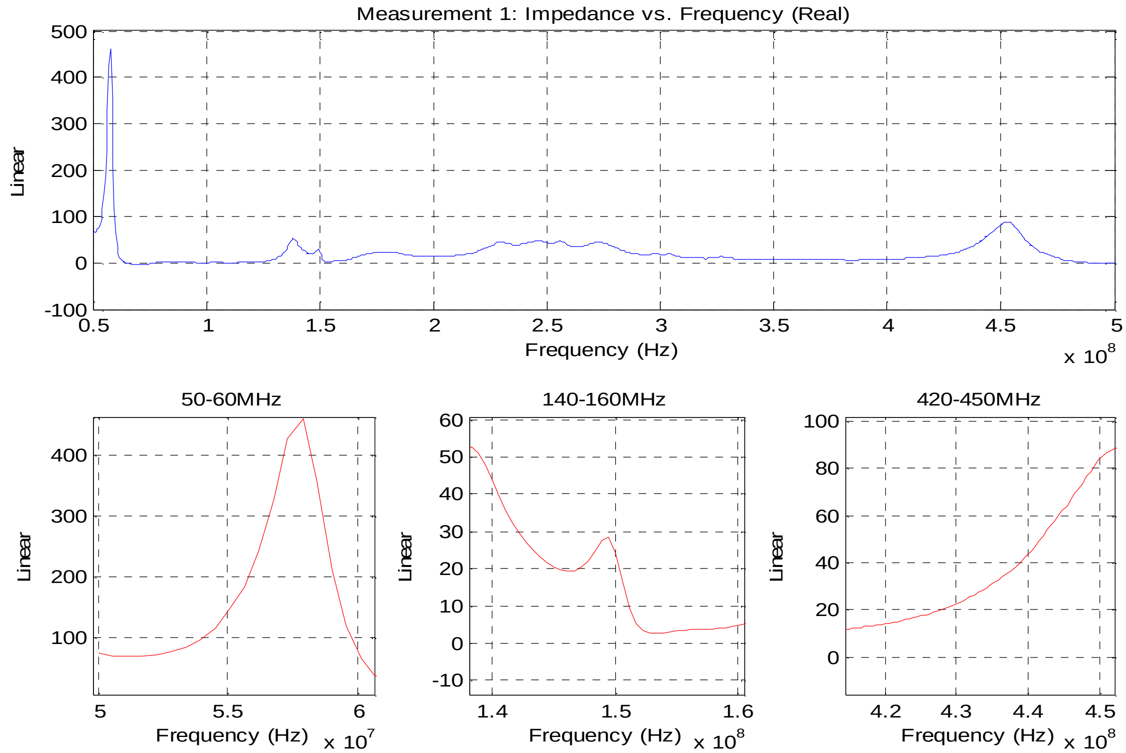

Figure 5-7 Real Impedance 1st Measurement: 50-500 MHZ; No Ground Plane

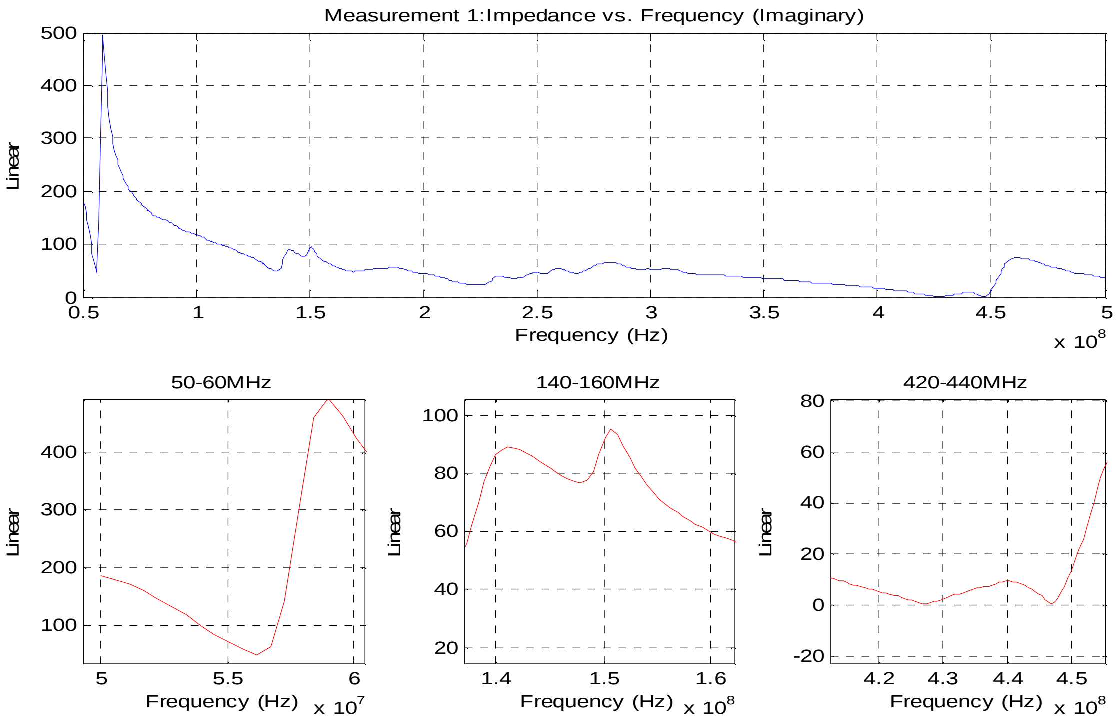

Figure 5-8 Imaginary Impedance 1st Measurement: 50-500 MHZ; No Ground Plane

Measurement 2: Real & Imaginary Components of Input Impedance

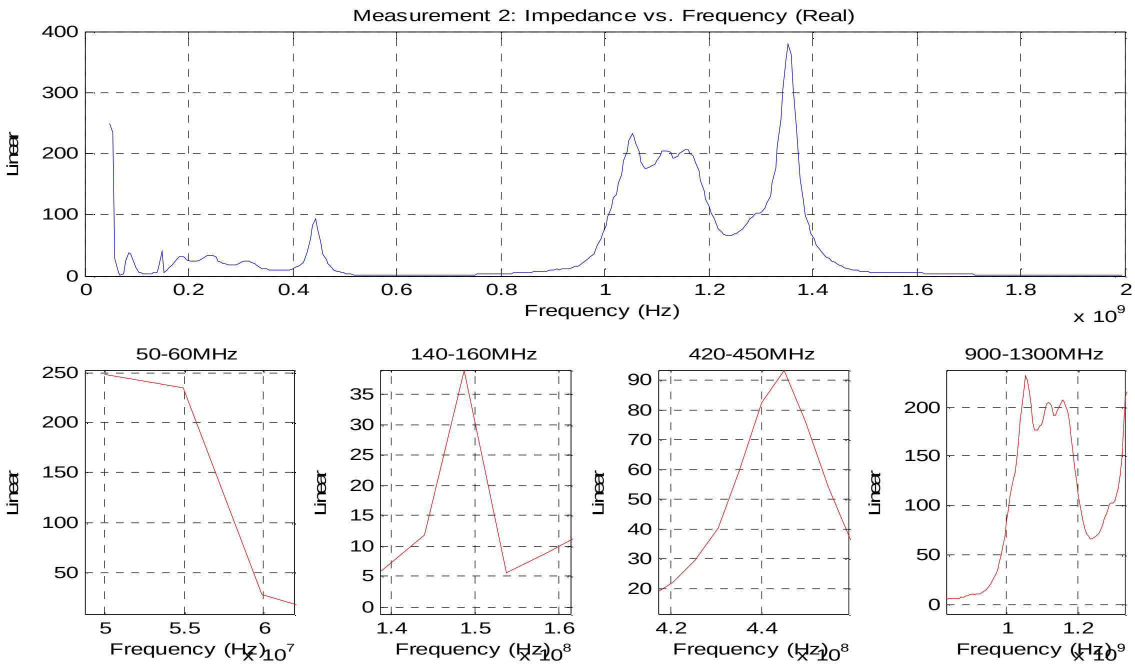

Figure 5-9 Real Impedance 2nd Measurement: 50-1200 MHZ; No Ground Plane

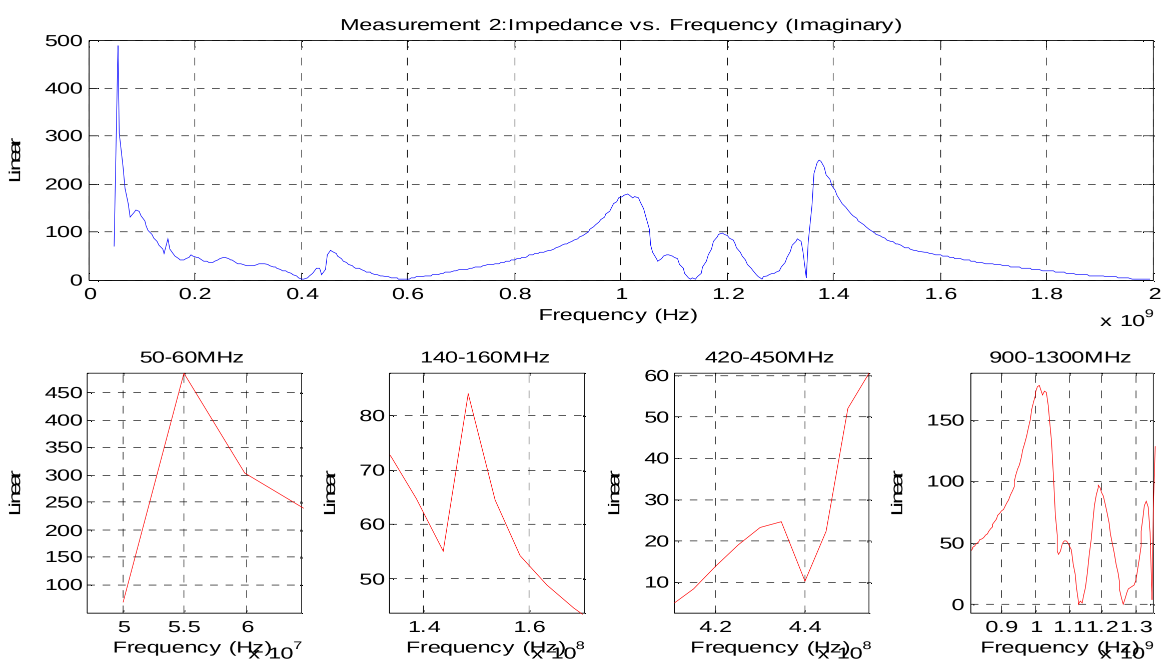

Figure 5-10 Imaginary Impedance 2nd Measurement: 50-1200 MHZ; No Ground Plane

Measurement 3: Real & Imaginary Components of Input Impedance:

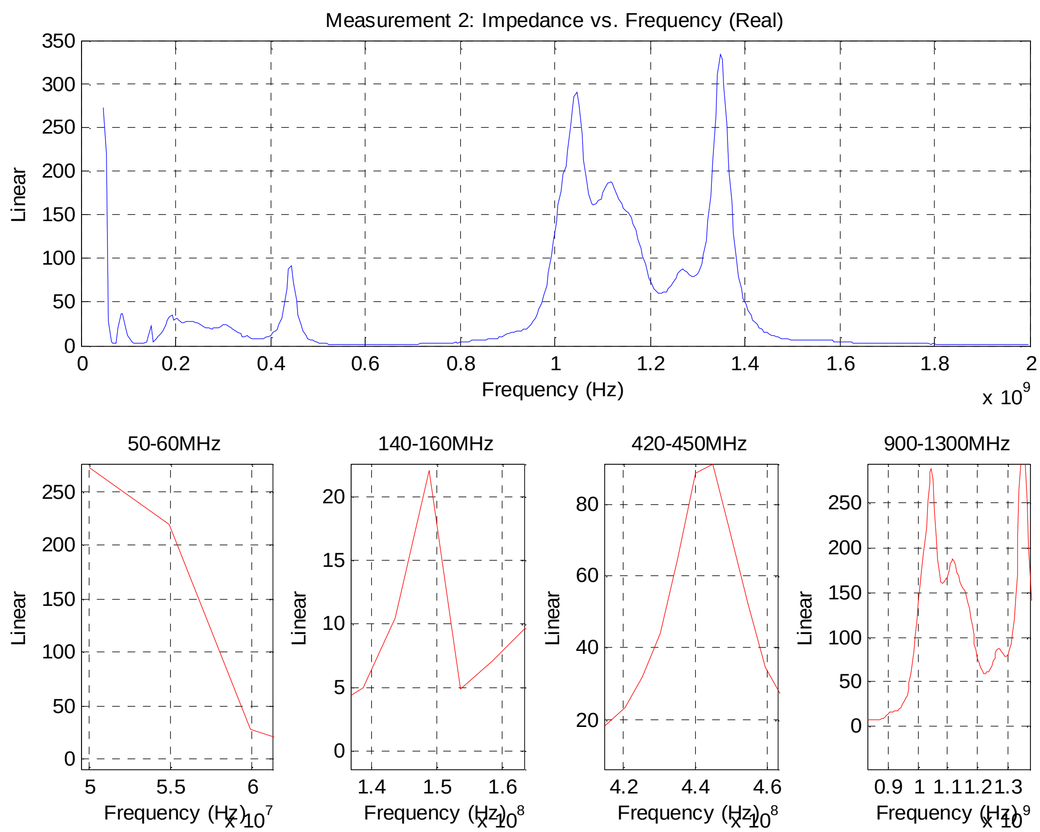

Figure 5-11 Real Impedance 3rd Measurement: 50-1200 MHZ; Circular Ground Plane

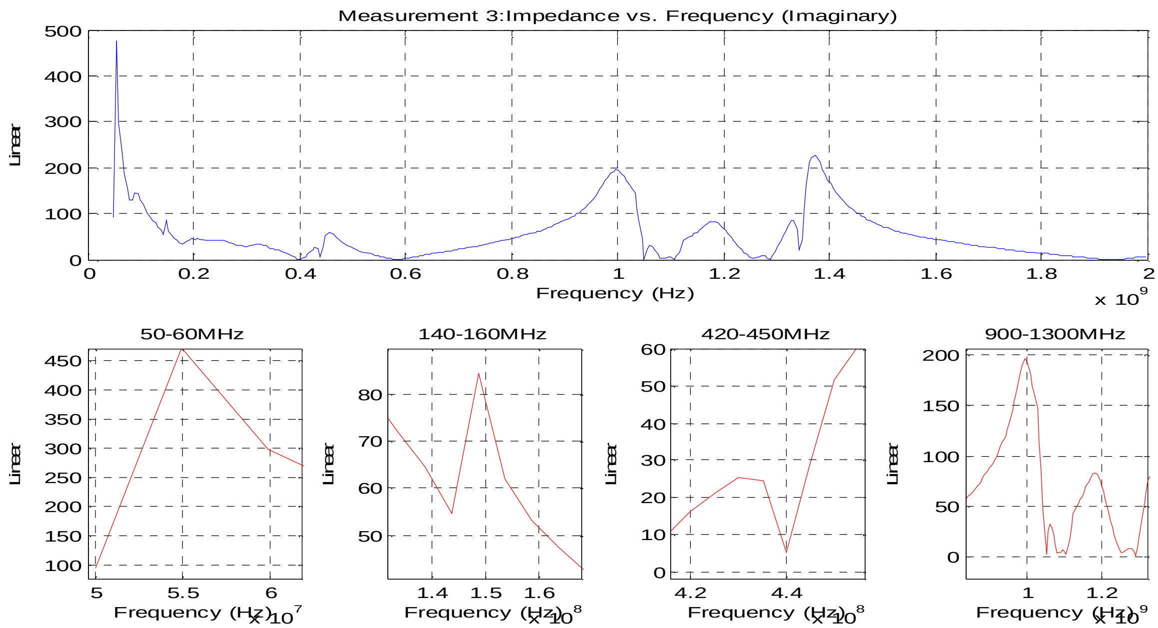

Figure 5-12 Imaginary Impedance 3rd Measurement: 50-1200 MHZ; Circular Ground Plane

Measurement 4: Real & Imaginary Components of Input Impedance:

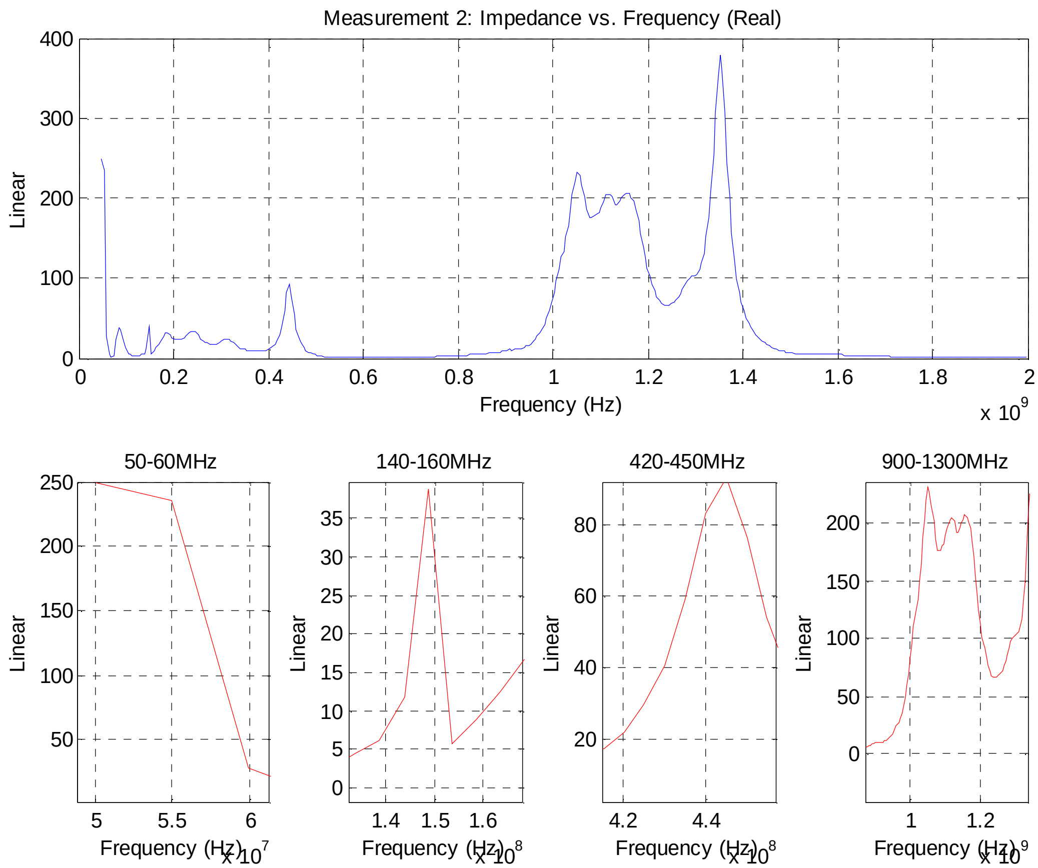

Figure 5-13 Real Impedance 4th Measurement: 50-1200 MHZ; Metal Box Ground Plane

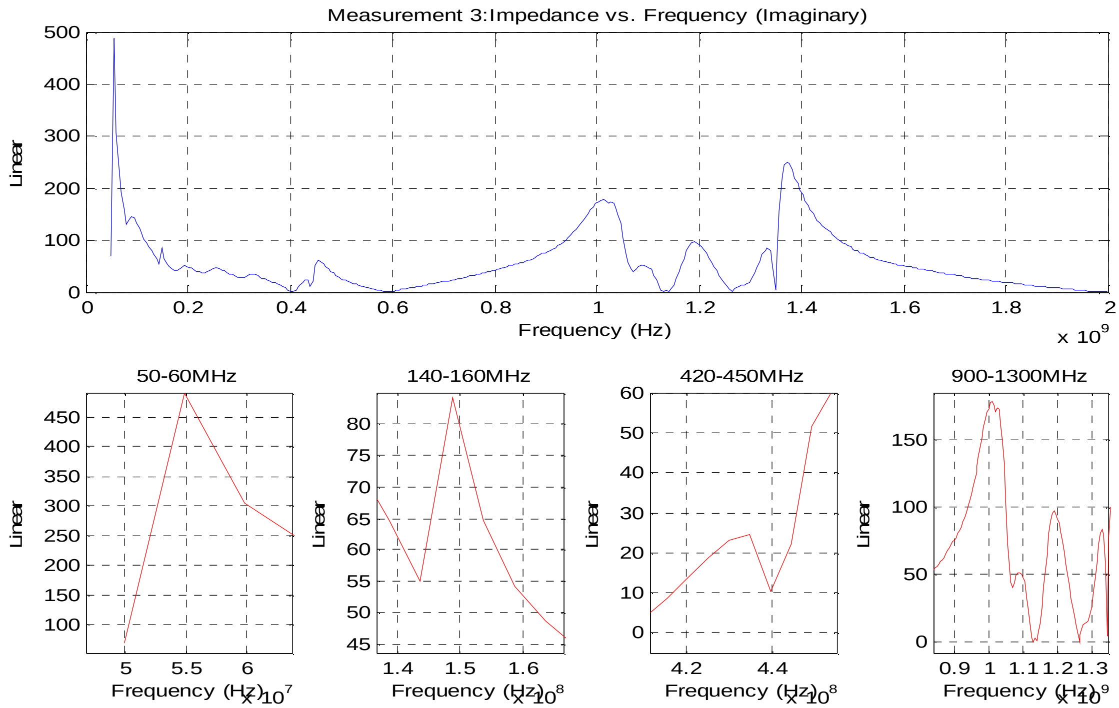

Figure 5-14 Imaginary Impedance 4th Measurement: 50-1200 MHZ; Metal Box Ground Plane

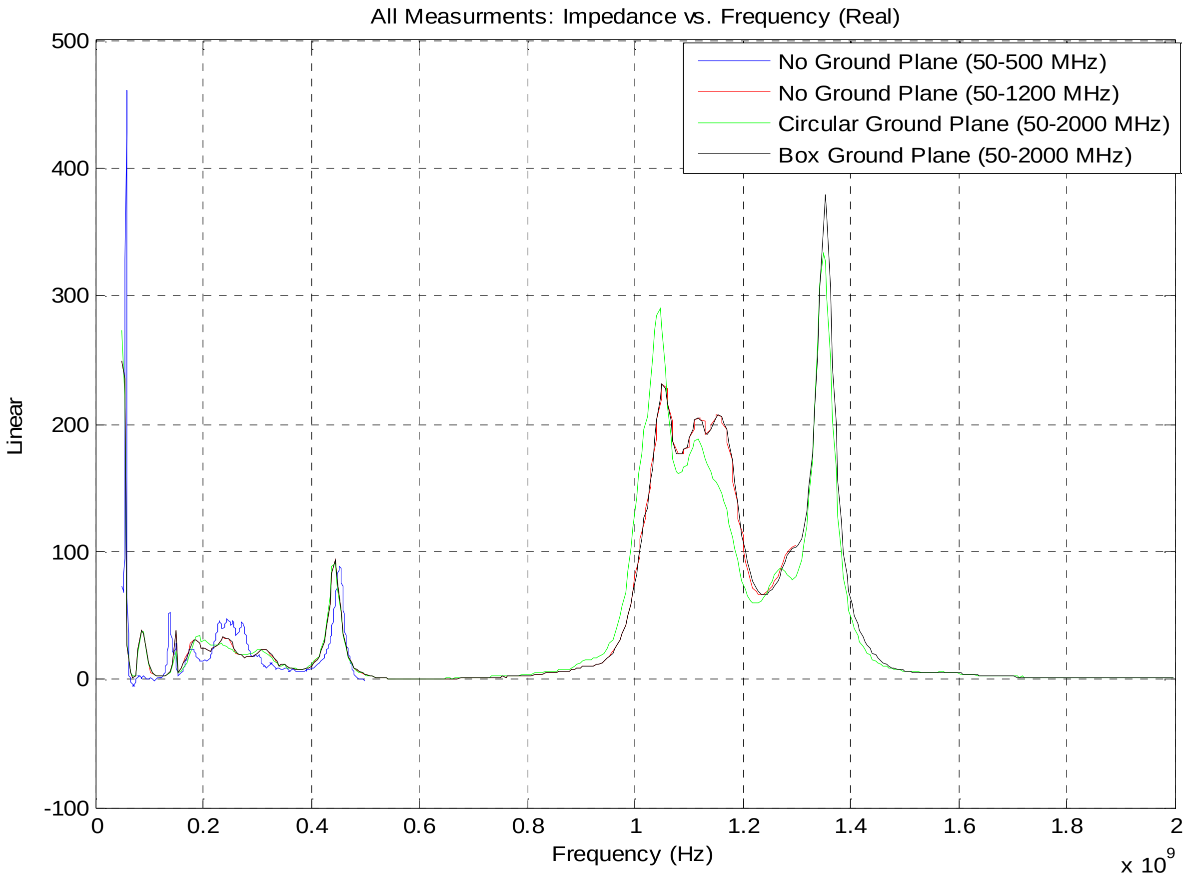

Figure 5-15 Real Impedance: All Measurements

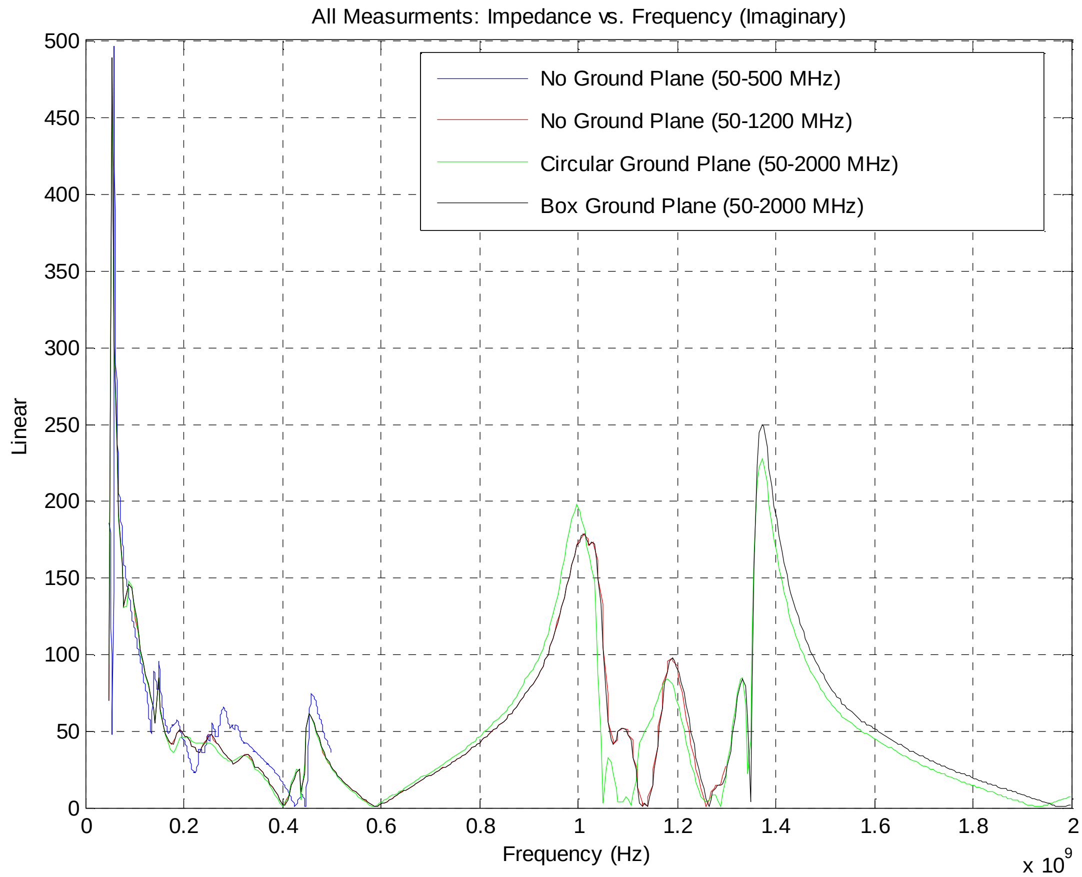

Figure 5-16 Imaginary Impedance All Measurements

5.3.2 Antenna Impedance Magnitude Characteristics

The magnitude components of the impedance are given by the following equation:

$$|Z| = \left|\sqrt{real(Z)^2 + imag(Z)^2}\right|$$
$$where,$$
$$Z = total\, impedance \qquad \textbf{(5-3)}$$

Measurement 1: Impedance Magnitude

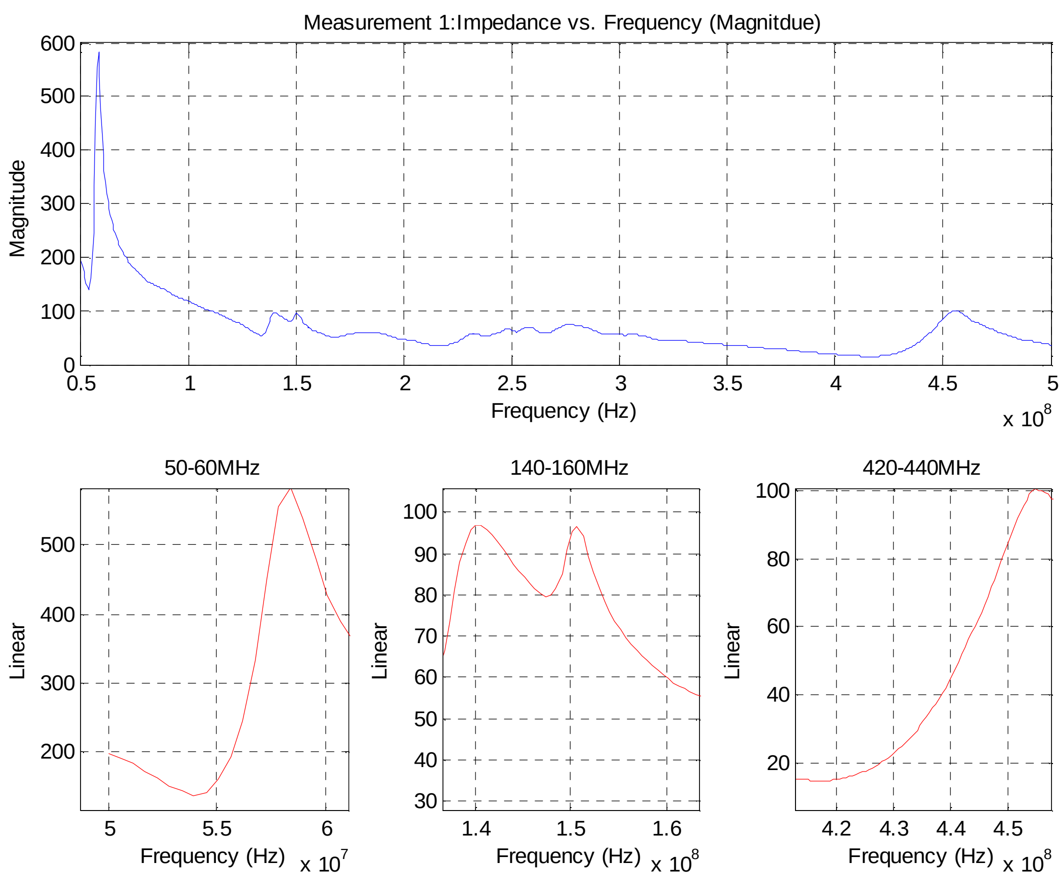

Figure 5-17 Magnitude Impedance 1st Measurement: 50-500 MHZ; No Ground Plane

Measurement 2: Impedance Magnitude

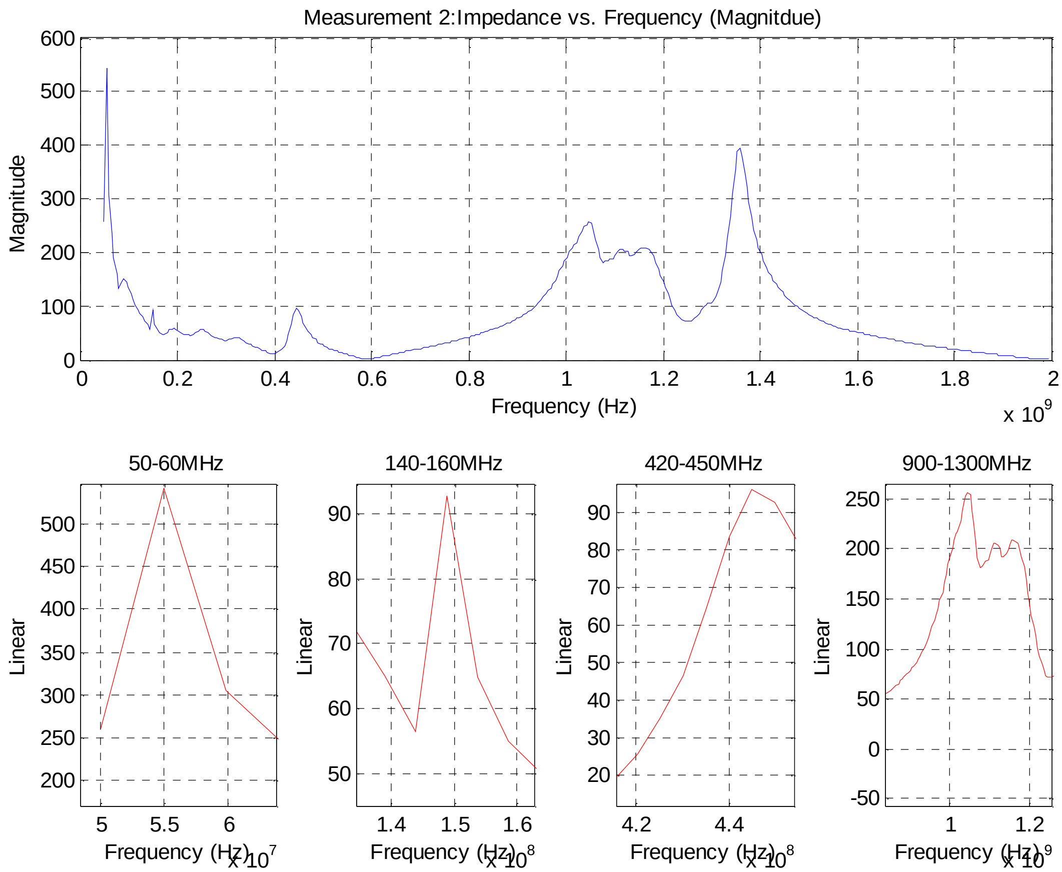

Figure 5-18 Magnitude Impedance 2nd Measurement: 50-1200 MHZ; No Ground Plane

Measurement 3: Impedance Magnitude

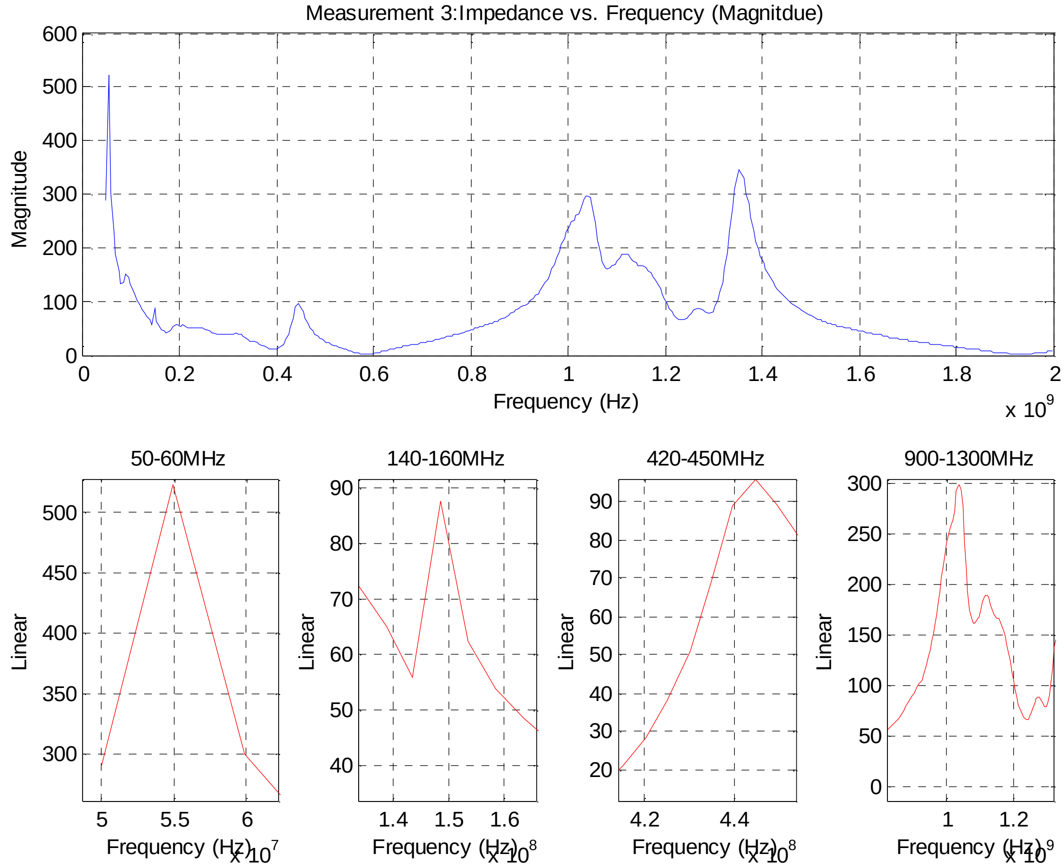

Figure 5-19 Magnitude Impedance 3rd Measurement: 50-1200 MHZ; Circular Ground Plane

Measurement 4: Impedance Magnitude

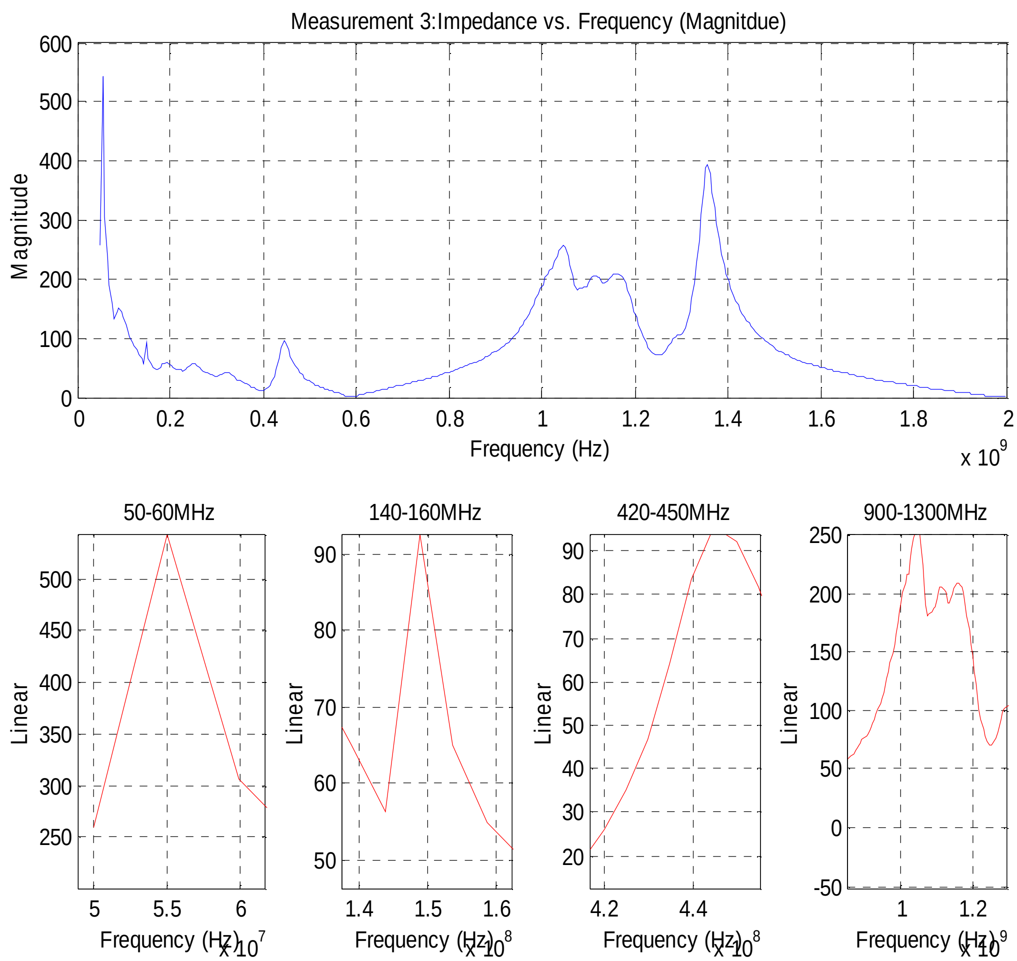

Figure 5-20 Magnitude Impedance 4th Measurement: 50-1200 MHZ; Metal Box Ground Plane

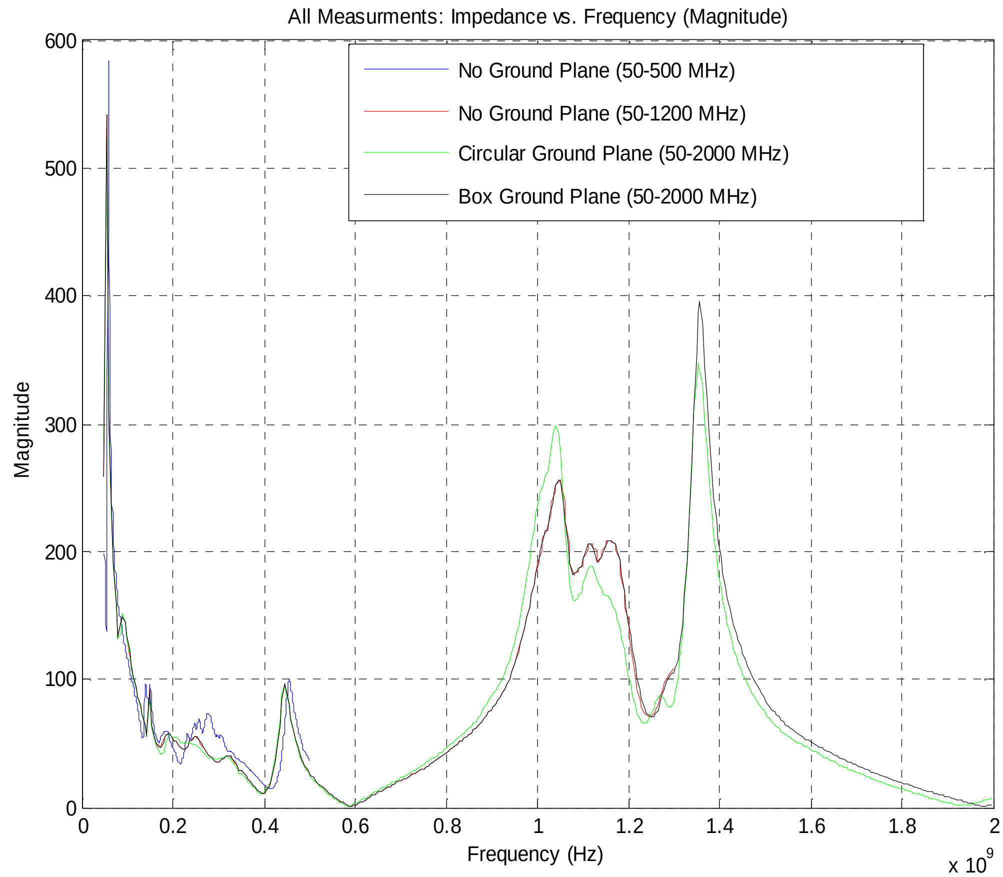

Figure 5-21 Impedance Magnitude All Measurements

From the impedance plots, it can be shown that overall the antenna demonstrates good impedance performance in the designated antenna ranges of the antenna. There is a good agreement between all four antenna measurements that were taken. At the upper and lower band ranges there is a dramatic peak in the impedance values. From the graphs at the 50MHz range and 1.2 GHz range the impedance is extremely high, which indicates a severe mismatch. The antenna displays relatively good impedance performance in the designated operating bands. For most antennas optimal performance is achieved when the impedance values are around 50ohms, but in general the real part of the impedance should be approximately between 35-75 ohms. The SRH999 impedance plot demonstrates that in the desired ranges the impedance is around these particular values, from the real impedance figure. This is also a good indication that the antenna will have satisfactory performance in most of our desired public safety bands.

5.3.3 Antenna VSWR Characteristics

The next category that we will consider is the VSWR characteristics of the antenna. The same measurements were utilized from the network analyzer, except that the equation is modified to find the VSWR values for the antenna:

$$VSWR = \frac{1 + |S_{11}|}{1 - |S_{11}|} \qquad \textbf{(5-4)}$$

For reasonably good performance the VSWR should be 2 or less.

Measurement 1: VSWR

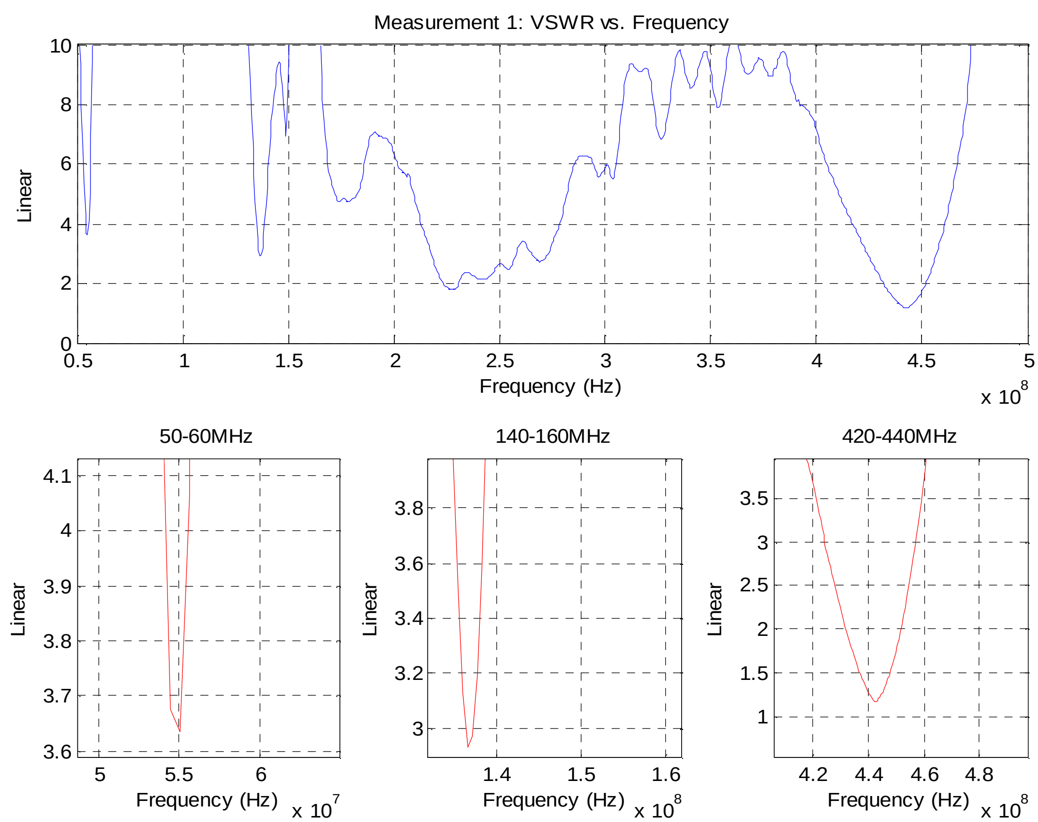

Figure 5-22 VSWR 1st Measurement: 50-500 MHZ; No Ground Plane

Measurement 2: VSWR

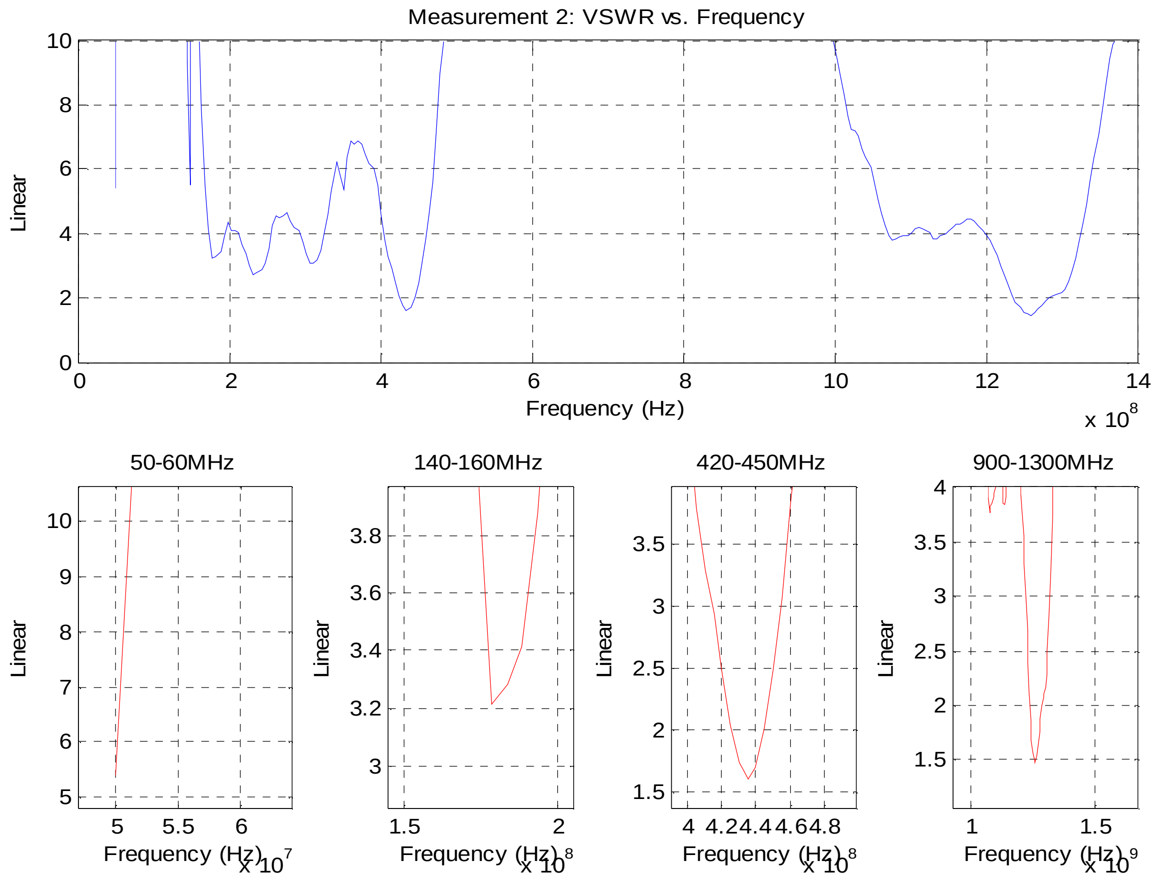

Figure 5-23 VSWR 2nd Measurement: 50-1200 MHZ; No Ground Plane

Measurement 3: VSWR

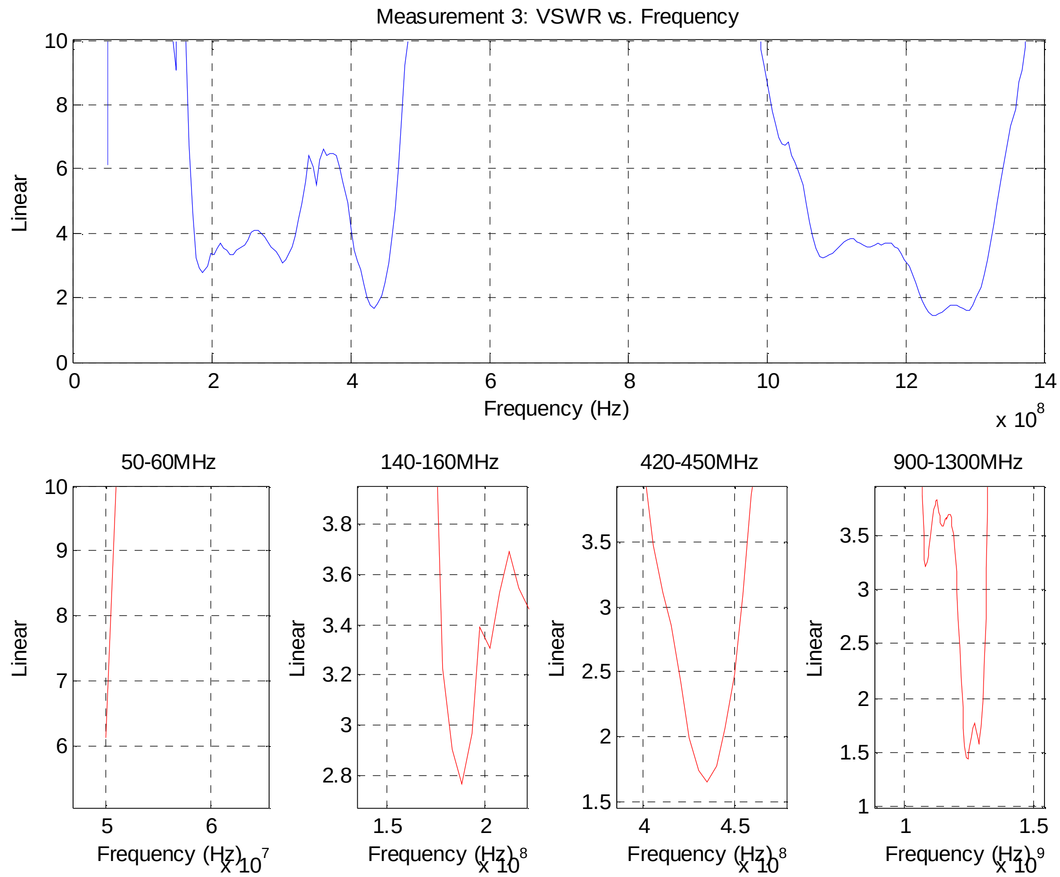

Figure 5-24 VSWR 3rd Measurement: 50-1200 MHZ; Circular Ground Plane

Measurement 4: VSWR

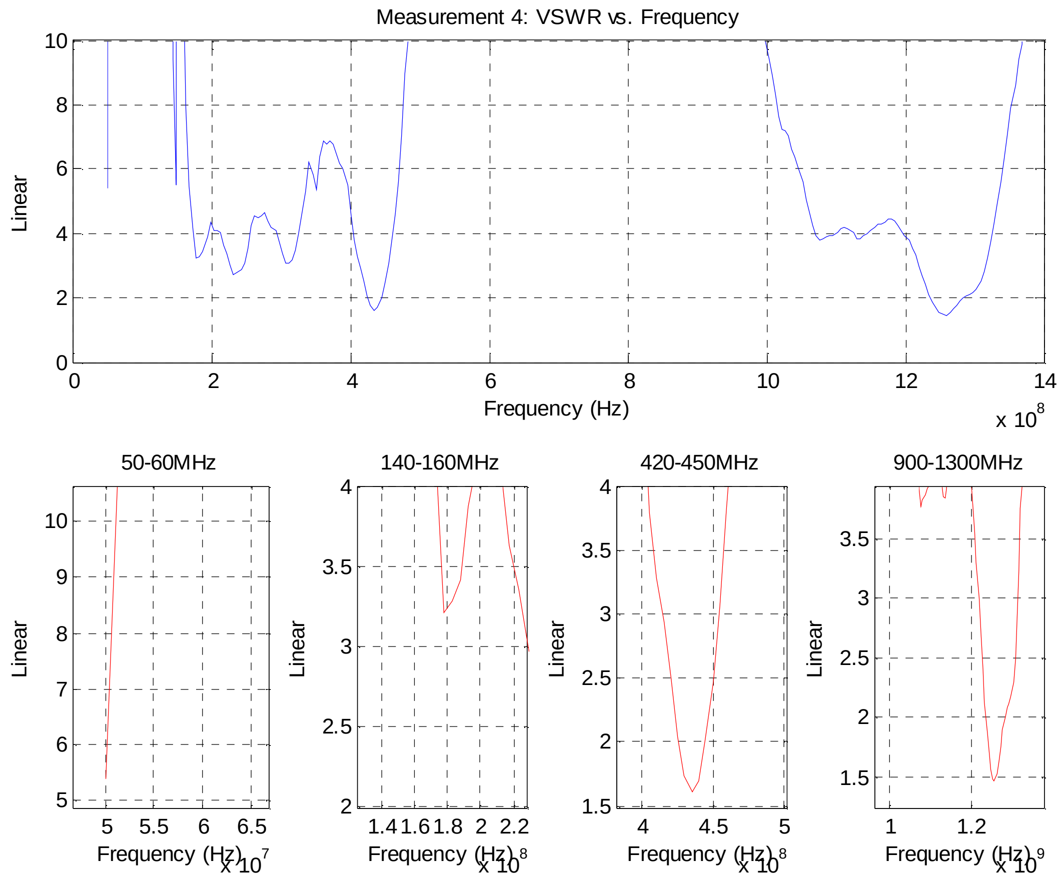

Figure 5-25 VSWR 4th Measurement: 50-1200 MHZ; Metal Box Ground Plane

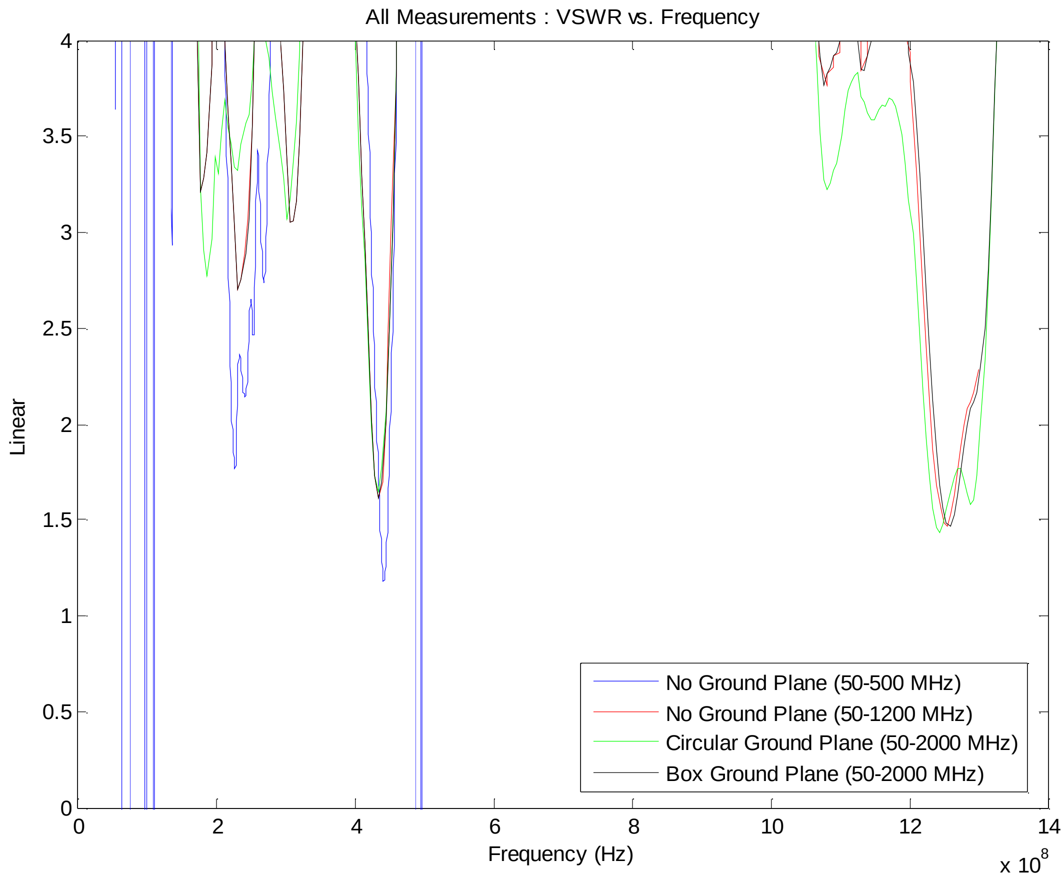

Figure 5-26 VSWR All Measurements

The VSWR graphs indicate that the antenna has relatively high values for the VSWR. This indicates that the antenna has only tolerable impedance matching. In the most of the bands of interest the VSWR falls in the range between the values of 0.5 to 4. The average value of VSWR for the antenna falls around the range of 2.0 to 3.5. The VSWR characteristics seem to be similar for each measurement.

5.3.4 Antenna Power Characteristics

A simple test was conducted in order to see how well the SRH999 antennas perform in transmit and receive scenarios and to observe the losses associated with the antennas. The first antenna was attached to a MG3700A signal generator, which sent out an FM signal. The FM waveform that was created in MATLAB had an SNR of 100dB, a sampling rate of 20 kHz, and a deviation of 2000 Hz. The power level of the signal generator was set to 0dBm for this particular test. For the receive side, the second antenna was attached to a MS2781A spectrum analyzer to observe the signal that was being transmitted. The antennas were approximately 2m apart during the test. We note that this is in the near field, and that Multipath effects may also be severe. The frequencies were selected for operation in the desired bands where the antennas should have optimal performance. Below are the results from varying the frequencies:

Received Power	
Frequency (MHz)	Power (dBm)
50	-37
150	-70
300	-38
430	-45
900	-75
1200	-63

Table 5-2 Measured Received Power between Tx/Rx

At the 50 MHz range the best received power was shown to be around -37dBm. Overall the results show in general that as frequency increases the power received decreases. As expected the receive power values are relatively low due to the fact that since the antennas are oriented close together you can not account for multipath affects between the transmit and receive antennas. For these particular measurements we will have to take in account the dependence of path loss on frequency, which is given by: $20\log_{10}(f)$, where f equals frequency. The received power measurements indicate that the SRH999 antenna operates reasonably well in a rich multipath environment where the public safety cognitive radio could potentially be used.

5.4 References

[1] Wikipedia, "Ground plane" , *http://en.wikipedia.org/wiki/Ground_plane*, 2001.

[2] Diamond Antennas, "SRH999 Quadband HT Antenna", http://www.rfparts.com/diamond/srh999.html.

6 Effects of the Antenna Characteristics on Public Safety CR

In this chapter we will investigate the interaction between the antenna and the radio. This interaction is crucial to system performance. The essential factors that we will examine include: the antennas performance characteristics; effects of the antenna impedance on the transmitter output circuit; the relative radiated power; and the angle of maximum radiation. These factors should establish a reasonably clear picture representation of the affects of the antenna hardware on the public safety CR system.

6.1 System Components

6.1.1 GNU Radio

The cognitive engine will control the GNU radio software defined radio platform. A GNU radio is a set of software signal processing building blocks that allow users to create their own software defined radio [3]. Below is a typical software defined radio block diagram:

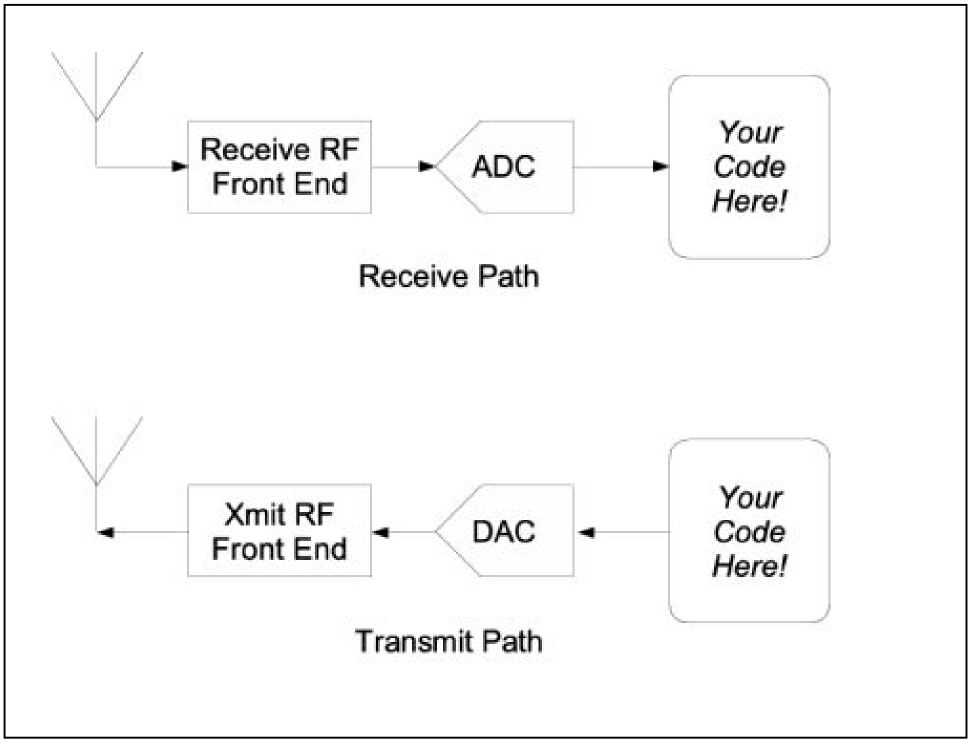

Figure 6-1 Typical SR Block Diagram [3]

Figure 6-1 indicates that in the section label "Your Code Here!" is where the GNU radio code is implemented in the software radio setup. The analog parts of the transmitter and receiver, the ADCs and DACs, and the software that runs the GNU code are included in the Universal Software Radio Peripheral (USRP). The USRP enables individuals to rapidly design and implement powerful, flexible software defined radio systems, which makes up the hardware solution for the SDR. The USRP can simultaneously transmit and receive two separate complex (or four real) RF signals in real time [2].

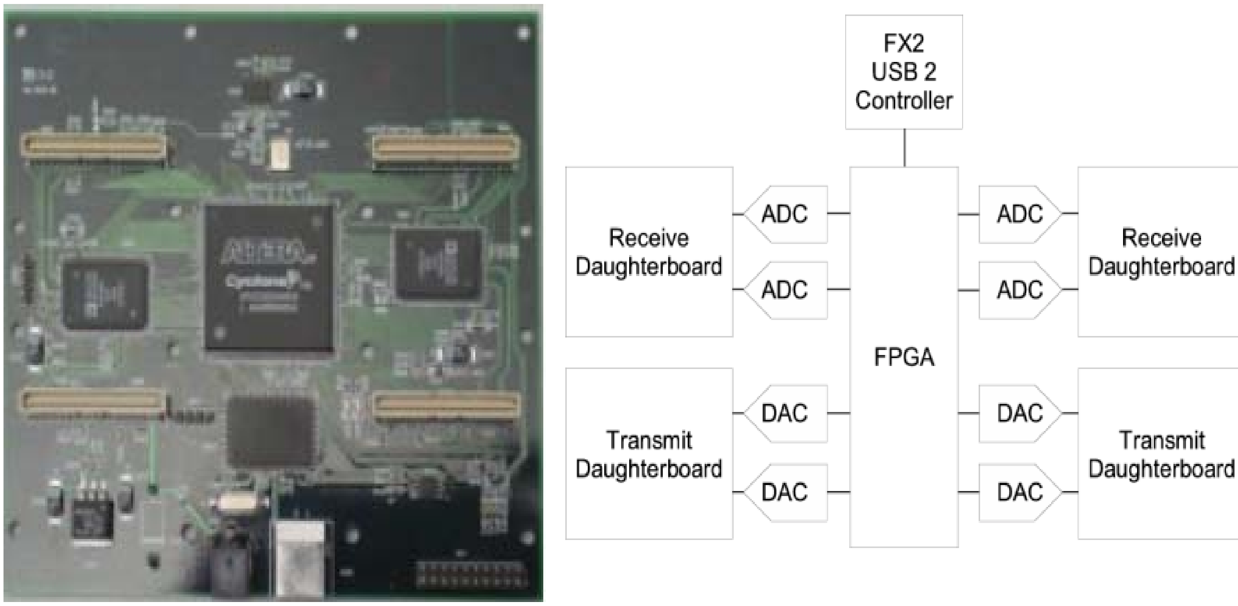

Figure 6-2 USRP Circuit Board and Block Diagram [2]

6.2 Experiment Architecture

In order to estimate the effects that the antenna will have on the cognitive radio system it is essential to observe various characteristics in order to understand the behavioural influence of the antenna hardware. The objective is to analyze the antenna characteristics and subsequently utilize the data to process how it will affect the potential public safety cognitive radio which is being developed through the use of a GNU radio and USRP. Below is a schematic of the transmitter output circuitry on the Basic Tx Daughterboard of the USRP:

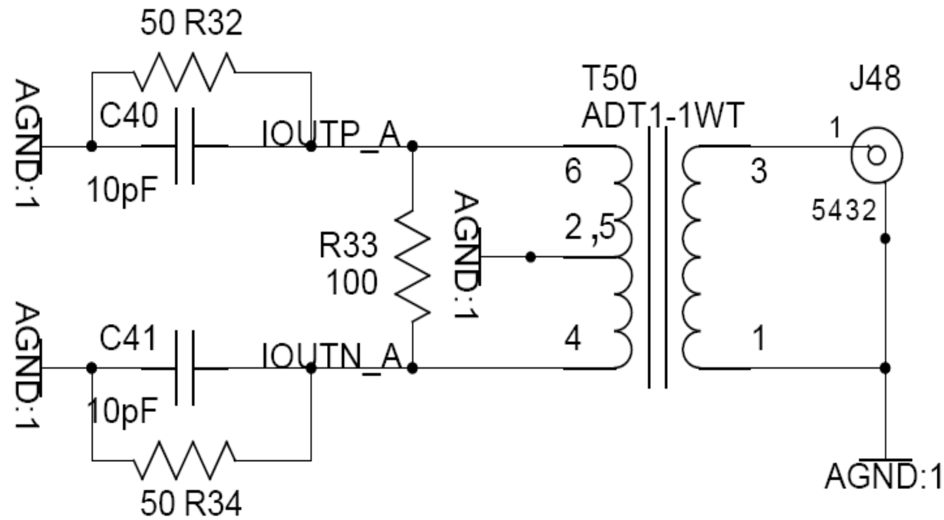

Figure 6-3 Portion of USRP Transmitter Output Circuitry [2]

On the transmit side J48 represents the location of the SMA connector for the antenna. The two RC parallel circuits are connected to the output terminals of the Programmable Gain Amplifier (PGA) chips, which is represented by IOUTP_A and IOUTN_A. Within the RC parallel circuit, the resistor is utilized to convert current to voltage and the capacitor serves as a filter.

6.2.1 USRP Output Impedance

In this section we look at the interaction between the GNU radio output network and the antenna impedance. To do this we first must determine the thevenin impedance looking into the antenna connector, J48 in Figure 6-4.

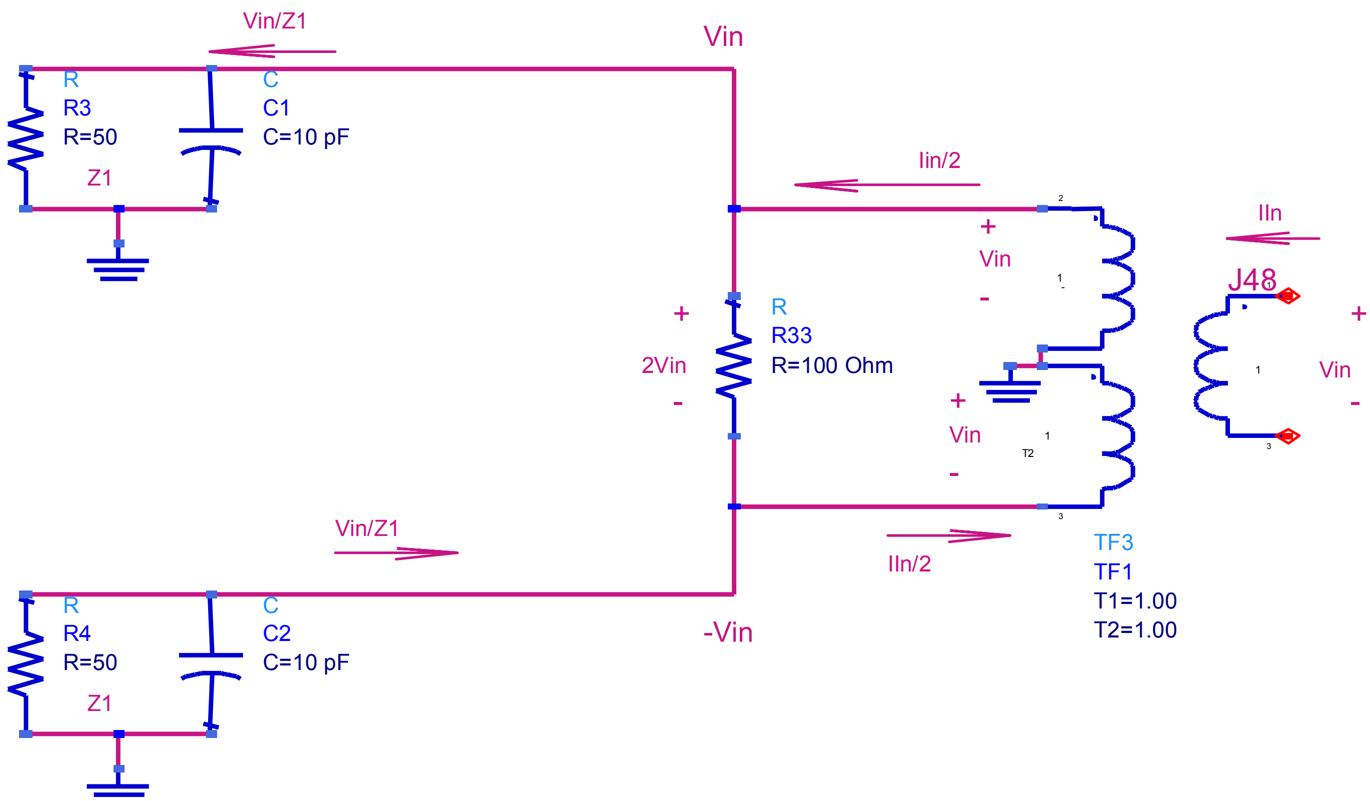

Figure 6-4 Schematic of Impedance seen by GNU Radio

By performing a KCL from the node V_{IN} it can be concluded that:

$$\frac{I_{IN}}{2} = \frac{V_{IN}}{Z_1} + \frac{2V_{IN}}{R33}$$

$$I_{IN} = V_{IN}\left[\frac{2}{Z_1} + \frac{4}{R33}\right]$$

$$Z_{IN} = \frac{V_{IN}}{I_{IN}} = \frac{1}{\frac{2}{Z_1} + \frac{4}{R33}} \qquad \textbf{(6-1)}$$

Substituting in numerical values, we can now display the source impedance of the GNU radio transmitter versus frequency.

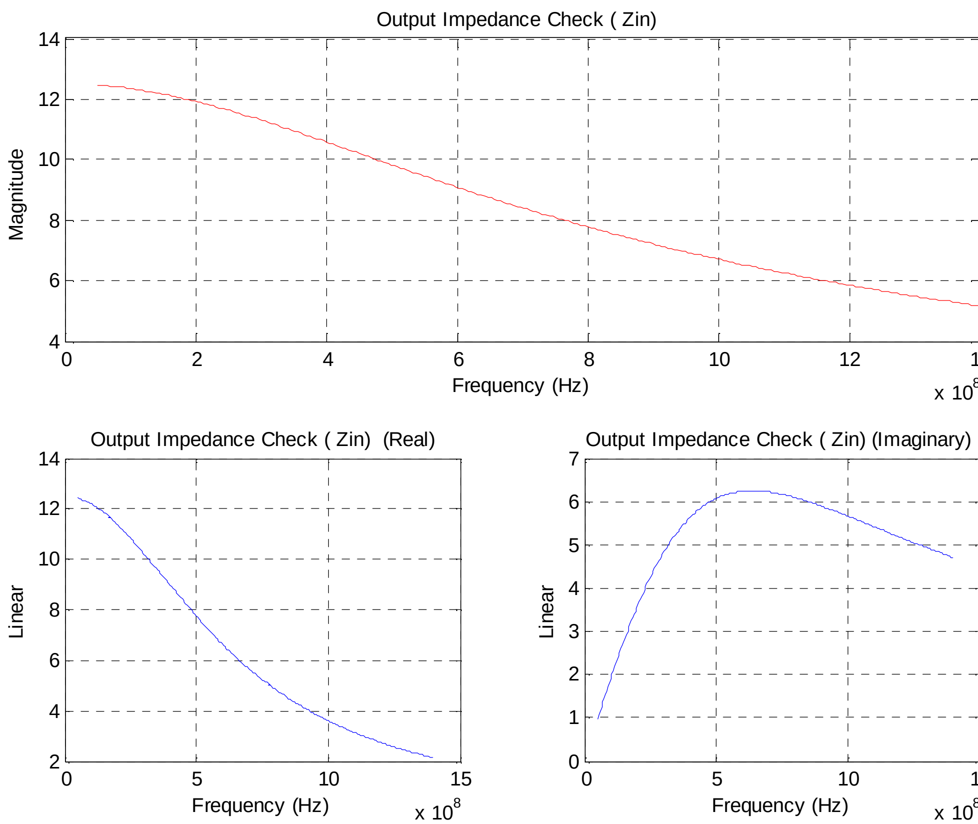

Figure 6-5 Real, Imaginary, Magnitude vs. Frequency of Impedance Presented by GNU Radio

These graphs indicate that the GNU radio output impedance is fairly low and varies slowly with frequency. We would therefore expect the GNU radio to behave reasonably like a voltage source and be relatively insensitive to variations in antenna impedance.

6.2.2 Relative Radiated Power

The interaction between the antenna impedance Za and the GNU radio source impedance Zin determines the relative power radiated by the antenna. Figure 6-7 is a schematic used to determine the radiated power for the cognitive radio system. Obviously, maximum power would be radiated if Za = Zin*.

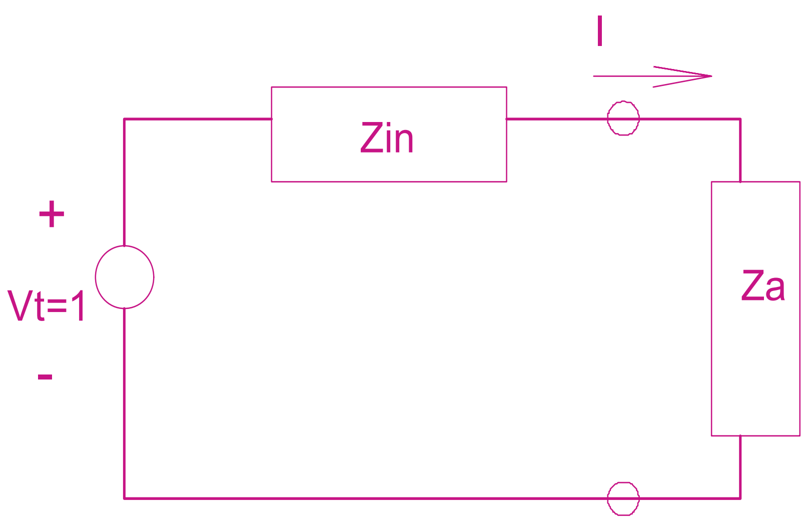

Figure 6-6 Schematic for Determining Radiated Power

From Figure 6-7 Zin represents the GNU radio impedance and Za represent the antenna impedance. To compute the radiated power we use the following equations:

$$I = \frac{V_T}{Z_{in} + Z_A}$$
$$P_{RAD} = |I|^2 * \mathrm{Re}\left[Z_A\right]$$
$$R_{RAD} = 10 \log\left[\frac{P_{RAD}}{P_{MAX}}\right] \qquad \textbf{(6-2)}$$

R_{RAD} represents the relative radiated power in dB. P_{MAX} is determined by selecting the highest value from the output of P_{RAD}. Note that it is a somewhat artificial concept in that its numerical value may exceed the maximum output power of the GNU radio USRP. It simply serves as a basis for comparing the output power values that the antenna and GNU radio transmitter would radiate at different frequencies. The relative radiated power was computed for each of the four types of measurements to see if there would be a consistency in the values of the measurements.

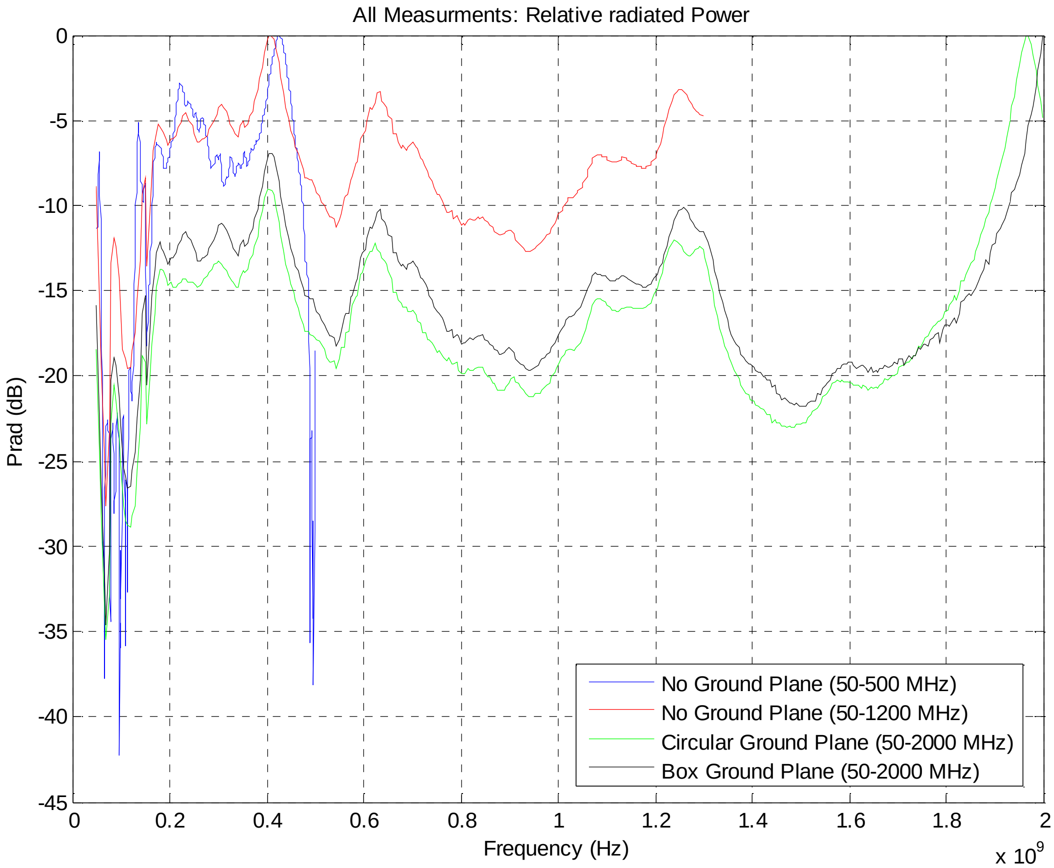

Figure 6-7 Radiated Power All Measurements

The conclusion after comparing the measured radiated power for the different measurement setups, respectively, is that there is not a high correlation in the results. The estimation of the radiated power appears to be steady except for the places where the antenna experiences severe impedance mismatch which cause degradation in the performance. The use of a ground plane show more effective radiated power at higher frequencies. The relative radiated power results here have a better outcome compared to the received power measurements that were shown in Table 5-2. Ideally the measurements should have some correlation between each other, but due to adverse multipath affects that occurred when conducting the received power test, the system performance is degraded.

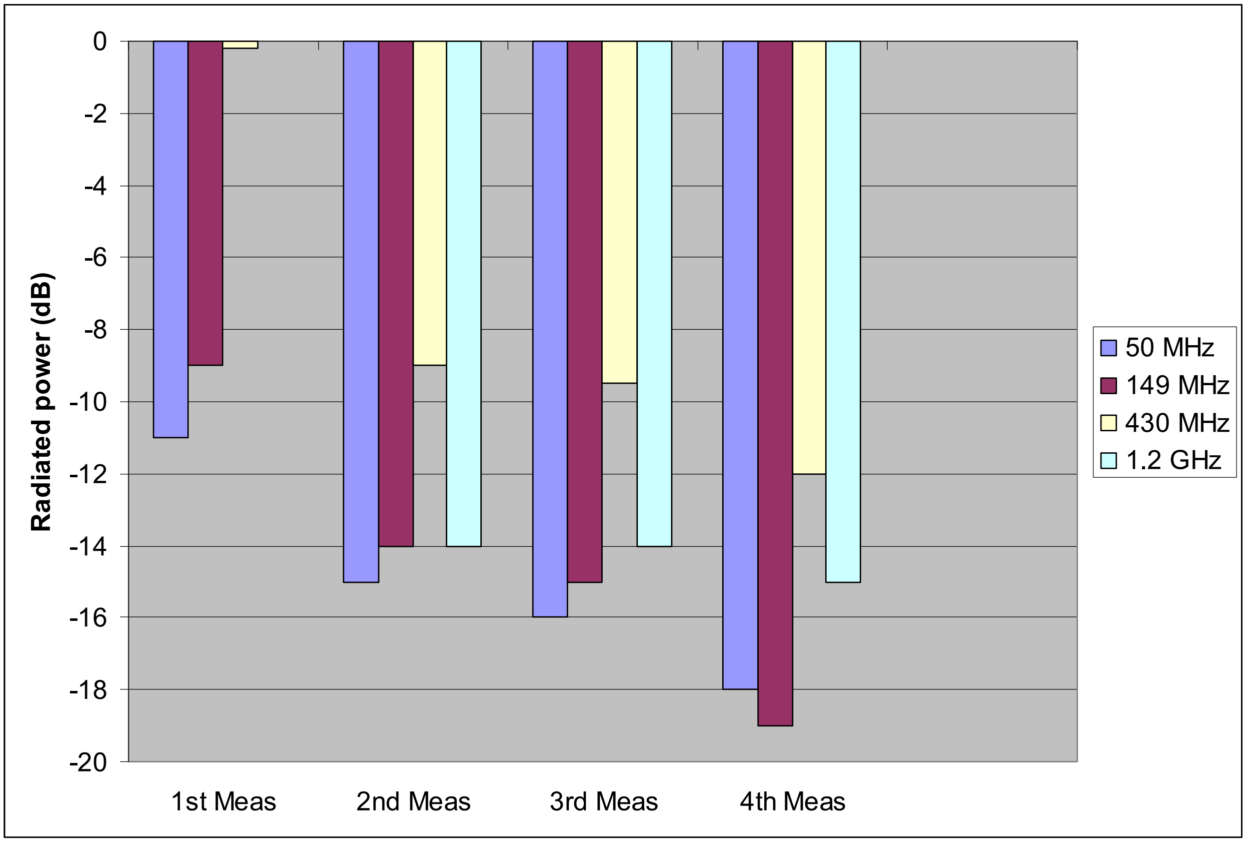

Figure 6-8 Radiated Power for Test Measurements

Measurement Type	Maximum Radiated Power (dBm)
1st Measurement: 50-500 MHZ; No Ground Plane	13.76
2nd Measurement: 50-1200 MHZ; No Ground Plane	20.04
3rd Measurement: 50-1200 MHZ;	23.21

Circular Ground Plane	
4th Measurement: 50-1200 MHZ; Metal Box Ground Plane	21.14

Table 6-1 Maximum Radiated Power

From Figure 6-8, we can see that the radiated power stays within a 10 dB range in all the bands of interest under a variety of different measurement conditions. Table 6-1 shows the outcome from the maximum radiated power that was calculated for each measurement setup. The resulting values could have rendered better results, but are still in a range to help achieve optimal performance. The maximum radiates power values that may also be beyond the capability of the GNU radio transmitter.

6.2.3 Angle of Maximum Radiation

Angle of maximum radiation is an important aspect for antenna characteristics in determining the maximum radiation direction for a particular antenna. The value of the maximum angle can change for a variety of reasons. Usually in most scenarios the radiation angle is always higher than the elevation angle as long as there are ground effects [4]. For typical linear antenna the angle of maximum radiation can be found by observing the far-field pattern of the antenna. For each far-field pattern the space pattern is a figure of revolution of pattern shown around the axis of the antenna [1]. The far-field at a full wavelength has more of a directional pattern than typical antennas. In order to obtain the value for the angle of maximum radiation for our antenna we will utilize a set of standard equations to estimate the angular dependence of the far-field [1]:

$$\lambda = \frac{c}{f}$$

$$\beta = \frac{2\pi}{\lambda}$$

$$E = \left[\frac{\cos((\beta L \cos\theta)/2) - \cos(\beta L/2)}{\sin\theta} \right]$$

$$\textit{where},$$

$$f = 50\,MHz \ \ to \ \ 1.2\,GHz$$

$$L = 0.9906\,m$$

$$\theta = 0^o \ \ to \ \ 90^o$$

(6-3)

For the equations the frequency is varied from 50MHz to 1.2GHz, the maximum value of E is found, and the corresponding value of θ is θ_{max}. Ideally the radiation angle would be toward the horizontal when the antenna is held vertical as it would be on a handset. Therefore we take 90 minus θ_{max} to obtain the angle of maximum radiation, which is the angle above the horizontal.

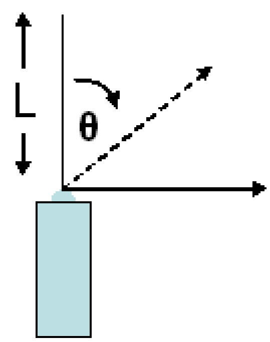

Figure 6-9 Defining Theta

Figure 6-10 shows the angle of maximum radiation for the frequency range:

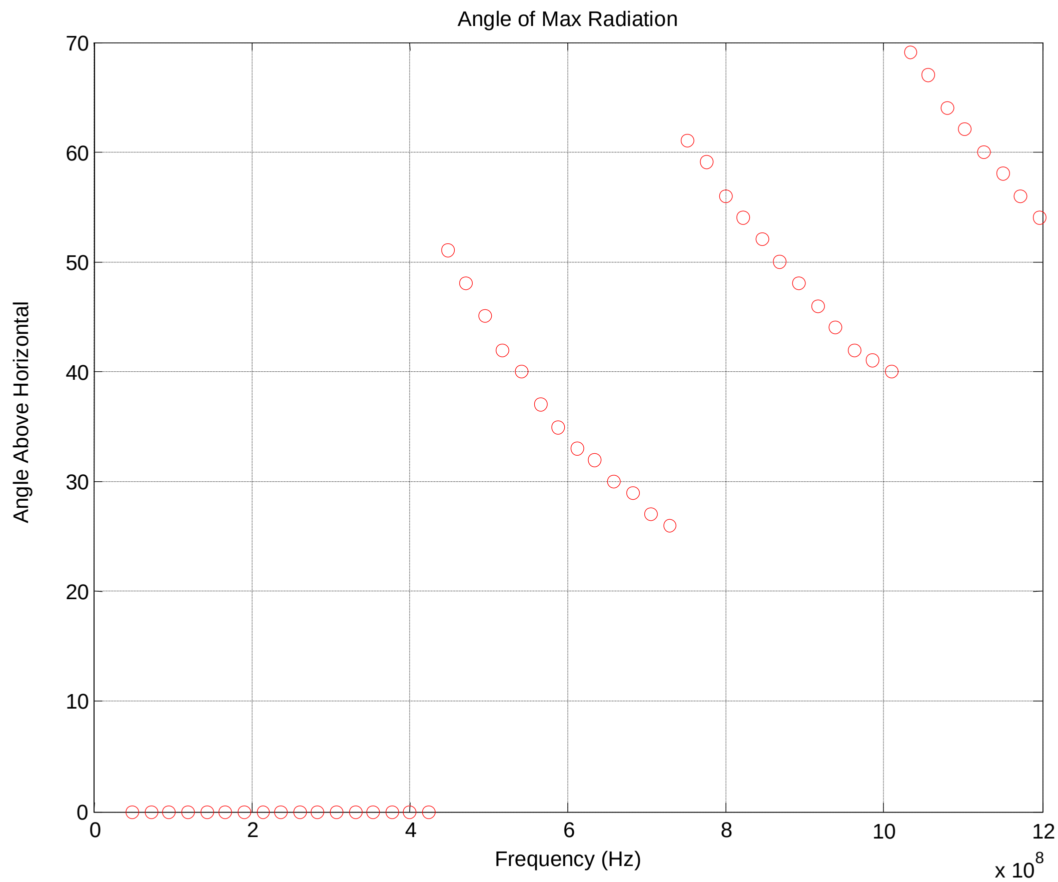

Figure 6-10 Angle of Maximum Radiation

Figure 6-11 shows the angle of maximum radiation direction as a function of frequency. The angle of maximum radiation direction remains at 0° from 50 MHz to about 430 MHz. After this point the max angle shifts upward. As the frequency goes up and the antenna gets longer in terms of wavelength and the direction of maximum radiation moves upward toward the end of the antenna. This phenomenon is typical for short antenna radiation that is perpendicular to the antenna's axis. An infinitely long antenna would radiate in the direction of its axis.

6.3 Evaluation of Antenna Affects

6.3.1 Implementing Antenna Hardware with GNU Radio

A test scenario was implemented to test whether incorporating the antenna hardware with the USRP and GNU radio would affect the performance of the system. The test involves attaching the SRH999 to the USRP daughterboard.

Figure 6-11 Antenna Hardware with USRP

Once the hardware is in place an FM audio signal at approximately 100 MHz is then transmitted from the GNU radio. Using a conventional radio we were able to obtain reception on the radio and hear the audio being sent. We also performed the test without the antenna and could not find the signal. Clearly the antenna works.

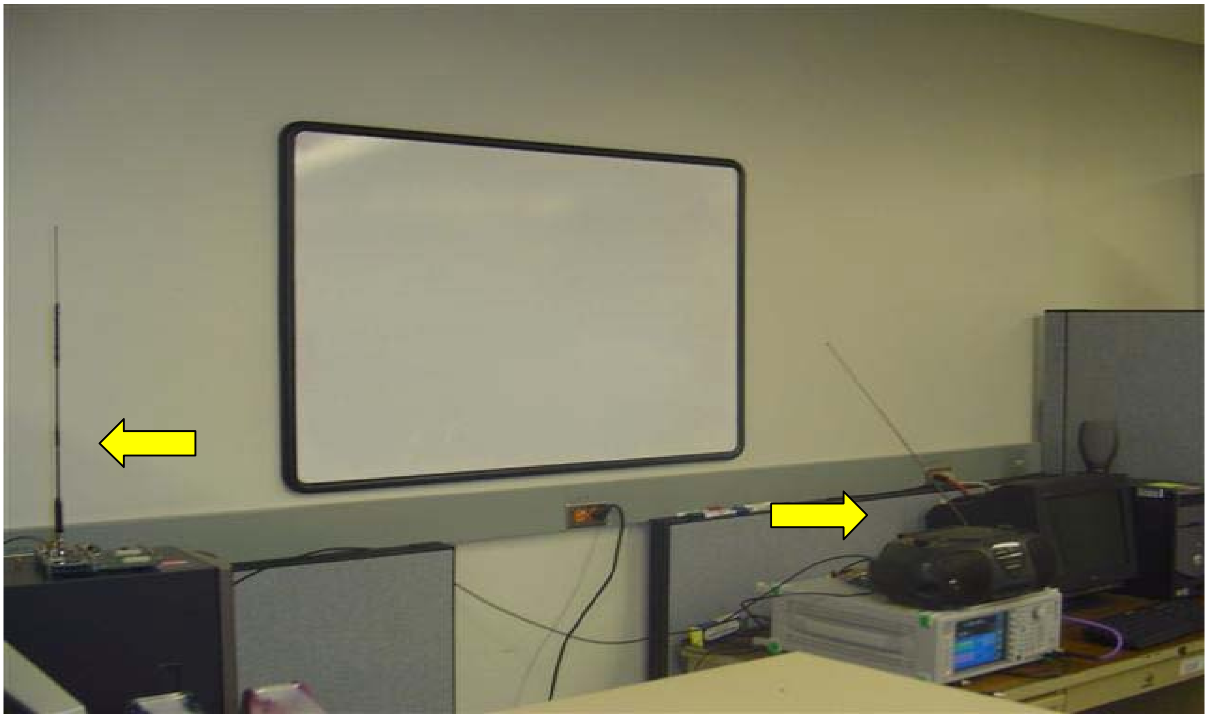

Figure 6-12 Antenna Hardware Test Setup

Above is the test scenario which shows the USRP with the antenna hardware and the radio that was used to receive the transmitted audio. The components are approximately 2 meters away from each other. Another test was performed in order to see the maximum distance the signal could be transmitted. The maximum distance that the radio was still able to clearly receive the signal was around 10 meters. This limitation is a consequence of the low power of the USRP transmitter and the difficult indoor propagation environment.

6.4 References

[1] J. Kraus, *Antennas*. New York: McGraw-Hill Book Company, 1950.

[2] Ettus Research, "Universal Software defined radio Peripheral (USRP) ",

http://www.ettus.com/custom.html

[3] GNU Radio - The GNU Software defined radio, "Exploring GNU Radio", *http://www.gnu.org/software/gnuradio/doc/exploring-gnuradio.html*, November 29, 2004.

[4] J. Cunningham, *The Complete Broadcast Antenna Handbook- Design, Installation, Operation & Maintenance*. Blue Ridge Summit, PA.: TAB Books, 1977.

[5] J.D. Jraus, "Antennas," in *McGraw-Hill Electrical & Electronic Engineering Series*, New York: McGraw-Hill Book Company, Inc., 1950

7 CONCLUSIONS

In this thesis I have investigated the factors that influence antenna selection for a public safety cognitive radio and reported on the properties of the SRH999 antenna that was selected. While the impedance of the SRH999 varies significantly with frequency, it is relatively insensitive to the presence or absence of a ground plane or to the construction of the ground plane that is used. The antenna presents a reasonable match to a 50 ohm line, with an average VSWR of about 2.3 in the public safety frequency bands. Variations with frequency of the antenna impedance and the transmitter source impedance will cause transmitted power to fluctuate over a range of about ±10 dB from nominal, but this will be relatively insignificant in comparison with multipath effects and variations in path loss under operational conditions.

This antenna is a good choice for a public safety cognitive radio because it performs well in the public safety bands of interest. When incorporated with the GNU radio transmitter it does not degrade performance and is very lightweight and somewhat flexible, which will not add any undue weight to the top of the mobile radio. Its undesirable features are that the antenna does not perform well outside of the public safety bands and performance of the antenna is slightly degraded at short ranges (i.e. 2m).

For future recommendations or work, tests should be conducted using a number of different commonly used public safety antennas. Another recommendation would be to test the antennas in scenarios where they will be utilized to get a better understanding of how the system will perform.

VITA

Akilah L. Hugine was born on September 17, 1982 in Orangeburg, SC. She received her Bachelor of Science Degree in Electrical Engineering from North Carolina A&T State University in May 2004. In the Fall of 2004 she enrolled in the Bradley Department of Electrical and Computer Engineering at Virginia Polytechnic Institute and State University to pursue a Master's degree. She joined Dr. Charles Bostian and his Center for Wireless Telecommunications research group and has since been involved in research related to cognitive radio. She is currently in the process of completing the requirements for the M.S. Degree in Electrical Engineering at the Virginia Polytechnic Institute and State University.