MAXIMIZING THE UTILITY OF RADIO SPECTRUM: BROADBAND SPECTRUM MEASUREMENTS AND OCCUPANCY MODEL FOR USE BY COGNITIVE RADIO

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MAXIMIZING THE UTILITY OF RADIO SPECTRUM: BROADBAND SPECTRUM MEASUREMENTS AND OCCUPANCY MODEL FOR USE BY COGNITIVE RADIO

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You're not as stupid as you look, or sound or our best testing indicates.

- Montgomery Burns, from “The Simpsons”

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AMPS	Advance Mobile Phone System
AMSR-E	Advanced Microwave Scanner Radiometer for Earth Observing System
ARSR	Air Route Surveillance Radar
BW	Bandwidth
CDMA	Code Division Multiple Access
CMIS	Conical Scanning Microwave Imager/Sounder
CW	Continuous Wave
dB	Decibel
dBc	Decibel with respect to the carrier
dBd	Decibel with respect to an dipole antenna (0 dBd = 2.15 dBi)
dBi	Decibel with respect to an isotropic radiator
dBm	Decibel with respect to 1 mW
dBW	Decibel with respect to 1 W
DSP	Digital Signal Processing
FAA	Federal Aviation Administration
FAR	Frequency-Agile Radios
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
GA	Georgia
GEO	Geostationary Earth Orbit
GPIB	General Purpose Interface Bus

GPS	Global Positioning System
GSM	Global System for Mobile Communications
HEO	Highly Elliptical Orbit
IEEE	Institute of Electrical and Electronic Engineers
IF	Intermediate Frequency
IM	Intermodulation
ISM	Industrial, Scientific, and Medical
ITU	International Telecommunications Union
JIT	Just-In-Time
LNA	Low-Noise Amplifier
MAC	Media Access Control layer
MEMS	Microelectromechanical System
MIMO	Multiple Input Multiple Output
MSIL	Microsoft Intermediate Language
NASA	National Aeronautics and Space Administration
NC	North Carolina
NF	Noise Figure
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NTIA	National Telecommunications and Information Administration
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PARI	Pisgah Astronomical Research Institute
PHY	Physical Layer

QoS Quality of Service

RAM Random Access Memory

RF Radio Frequency

RFI Radio Frequency Interference

RSES Radio Spectrum Evaluation System

SDR Software-Defined Radio

SNR Signal-to-Noise Ratio

SPFD Spectral Power Flux Density

RBW Resolution Bandwidth

UPCS Unlicensed Personal Communications Service

UNII Unlicensed National Information Infrastructure

US United States

UWB Ultra-Wideband

VISA Virtual Instrument Software Architecture

VLBI Very Long Baseline Interferomertry

VSWR Voltage Standing Wave Ratio

WISP Wireless Internet Service Provider

SUMMARY

Radio spectrum is a vital national asset; proper management of this finite resource is essential to the operation and development of telecommunications, radio-navigation, radio astronomy, and passive remote sensing services.

To maximize the utility of the radio spectrum, knowledge of its current usage is beneficial. As a result, several spectrum studies have been conducted in urban Atlanta, suburban Atlanta, and rural North Carolina. These studies improve upon past spectrum studies by resolving spectrum usage by nearly all its possible parameters: frequency, time, polarization, azimuth, and location type. The continuous frequency range from 400MHz to 7.2 GHz was measured with a custom-designed system. More than 8 billion spectrum measurements were taken over several months of observation.

A multi-parameter spectrum usage detection method was developed and analyzed with data from the spectrum studies. This method was designed to exploit all the characteristics of spectral information that was available from the spectrum studies.

Analysis of the spectrum studies showed significant levels of underuse. The level of spectrum usage in time and azimuthal space was determined to be only 6.5 % for the urban Atlanta, 5.3 % for suburban Atlanta, and 0.8 % for the rural North Carolina spectrum studies. Most of the frequencies measured never experienced usage. Interference was detected in several protected radio astronomy and sensitive radio navigation bands.

A cognitive radio network architecture to share spectrum with fixed microwave systems was developed. The architecture uses a broker-based sharing method to control spectrum access and investigate interference issues.

CHAPTER 1

INTRODUCTION

1.1 The Demand for Radio Spectrum

The use of the radio spectrum has increased since it was first used to transmit information over 100 years ago.[1] Demand for radio spectra has risen as the number and type of users has increased; radio broadcasting, TV transmission, fixed and mobile wireless communication, satellite connections, radio navigation systems, and numerous scientific services, all compete for access to the airwaves. An example of the increasing demand for radio spectra is the cellular telephone system; this service was first allocated 42 MHz of bandwidth in 1981. Since then, an additional 340 MHz of spectrum has been allocated for mobile and third-generation communication devices.[2,3]

1.2 Radio Spectrum Licensing

Within the United States the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) who regulate non-federal and federal government spectrum usage respectively have generally allocated blocks of frequencies for specific uses and then licensed users within those allocated blocks.[4] Radio spectra are regulated over the continuous frequency range from 9 kHz to 300 GHz. The entire regulated radio spectrum has been fully allocated, limiting access to the radio spectrum by new spectrum users.[5]

A spectrum license is a grant of exclusive access to a channel of defined bandwidth for a defined geographic area. Owners also have obligations placed on them by the FCC, both technical and policy-based. Commercial spectrum users historically have not paid for licensed access to the spectrum. If there was only one applicant for a specific license, then they were awarded the license. When there were several applicants for a specific license, the FCC would hold competitive hearings, and eventually the party deemed most suitable to "operate in the public interest" received the license. This often-protracted process became known as a "Beauty Contest." In 1982 the FCC was authorized by Congress with legislation to use a lottery system to assign licenses.[6] The lottery award system lasted for over a decade until it was replaced by an auction-based award process by the Omnibus Budget Reconciliation Act of 1993. The auction method has persisted and has spread from telecommunications spectrum to even media broadcast (TV and radio) and satellite licensees.[7] The use of auctions has transferred the vesting of licensees from the FCC to the marketplace.

In general, the assigning of spectrum in distinct frequencies bands allows for standardized media and telecommunications uses. This allows for TV, radio, terrestrial microwave, terrestrial cellular, satellite communications, radio navigation, and wireless networks to have fixed frequency ranges, regardless of locality. Hence the cost to develop wireless equipment can be absorbed by a larger market base; additionally completive forces are more powerful, reducing the cost of equipment. System interoperability at the radio frequency (RF) level is another advantage of banding.

The current practice of managing radio spectrum with static allocations and licenses has resulted in inefficient utilization of this limited resource. This management scheme was designed to minimize the possibility of interference between different licensed users. For example, when a broadcast radio station is awarded a license, it is assured that in its listening area there will not be any other station transmitting on its channel, or even on adjacent channels.[8] Static licensing is appropriate for broadcast spectrum users who continually occupy their channel, including radio, TV, geostationary satellites, and some radio navigation services. Applying the static spectrum licensing paradigm to mobile and dynamic spectrum users has resulted in underuse of the spectrum that they are allocated. This group of spectrum users often transmits intermittently, from different locations, at varying power levels, with variable bandwidth, and can mitigate interference. As stated earlier, all the radio spectrum in the U.S. has been allocated, but not all of it has been licensed. Additionally, a license does not represent actual usage (the channel may be underused or not used at all). The FCC and NTIA attempt to accommodate new spectrum users by reallocating the spectrum assignment of existing users who the regulators have concluded are underusing their allocation, or by making, a policy decision in which the new user is found to be more important to the public interest than the current licensees. This reallocation process can consume several years, especially if the incumbent spectrum users are resistant to relinquishing their spectrum, and is often fruitless in attaining spectrum for new users.[9,10]

1.3 Radio Noise

Radio noise is another aspect of the spectral environment. Every radio receiver produces thermal noise internally from its electronics. This thermal noise referred to the input of the receiver, has a Gaussian random voltage distribution and mean power:

$$P_N = kTB \tag{1.1}$$

where k is Boltzmann's constant, T is the equivalent noise temperature of the receiver, and B is the noise bandwidth.[11] The noise floor P_N in a receiver limits its ability to detect signals below that level. Other external noise sources can affect a receiver. Known as environmental noise it originates from several sources. The cosmic background is one broadband environmental noise source with an equivalent noise temperature of only 2.7 K.[12] A significant noise source at low frequencies is galactic noise: this noise source is inversely proportional with frequency. Above 1 GHz, galactic noise has an equivalent noise temperature of less than 50 K and is typically much lower, often in the single digits, depending on the position of the galactic center in the sky.[13] Thermal radiation by objects in the environment, known as blackbody or more correctly "grey body" radiation produces thermal noise approaching the physical temperature of such objects.[14] Excluding minor contributions from additional extraterrestrial noise sources, all other sources of environmental noise are from anthropogenic emitters. Man-made noise sources include emissions from electric motors, microwave ovens, spark plugs, AC power systems, and undesired signals from communication systems (intermodulation, oscillator leakage, etc.). Pulsed noise sources are known to emanate from vehicle spark plugs and radar's out-of-band emissions.[15,16] Desired transmitted signals from communication systems are not noise, even if their power level is below the minimum required for their intended operation and though they may cause interference.

Several measurements of the environmental noise floor have been made, nearly all below 300 MHz.[17,18] There have been very few studies of environmental noise above 1 GHz; results from these measurements show very low levels of noise except for emissions from microwave ovens centered at 2.450 GHz.[19,20,21]

Radio noise, unless used for passive remote sensing or radio astronomy, reduces the utility of the spectral environment.

1.4 Spectrum Usage by the Passive Services

Significant portions of the radio spectrum are allocated for passive services, including remote sensing, both terrestrial and space based, and radio astronomy. These users only observe noise sources and do not transmit. They are allocated several bands of spectrum, domestically by the FCC and NTIA, and internationally be the International Telecommunications Union (ITU). Since these users are passive, they often operate (receive) on bands allocated for active services; the increased usage of these bands has reduced their access to the spectrum.[22,23] The sensitivity of passive services makes them vulnerable to interference. Anthropogenic signals emitted both into and adjacent to passive bands can produce harmful interference, even if they are at very low power levels.

1.5 Determine Level of Spectrum Usage

To determine the current level of spectrum usage several spectrum studies were performed. While some coarse information can be attained from spectrum licenses, essential details, including the location of transmitters, transmitter output power, and antenna type, are often unknown. Additionally, licenses do not specify how often the spectrum is being occupied if at all. Furthermore, the local environment affects the propagation of radio waves; while this effect can be simulated, the results offer only moderate precision. Hence, to categorize spectrum usage, measured data is vastly preferable to theoretical analysis.

The spectrum studies were performed in different geographic locations: urban, and rural. These studies, improve upon past spectrum studies by resolving spectrum usage by nearly all its possible parameters: frequency, time, polarization, azimuth, and location type. The continuous frequency range from 400MHz to 7.2 GHz was measured with a custom-designed system. More than 8 billion spectrum measurements were taken over several months of observation.

A multi-parameter spectrum usage detection method was developed and analyzed with data from the spectrum studies. This method was designed to exploit all the characteristics of spectral information that was available from the spectrum studies to detect usage with grater accuracy.

1.6 Spectrum Sharing

A cognitive radio network architecture has been developed to share spectrum with incumbent spectrum licensees. The architecture uses a broker-based sharing method to control spectrum access and investigate interference issues. Analysis of the spectrum studies has identified spectrum in the 5.925 – 7.125 GHz band used by the fixed microwave service for potential sharing by a cognitive radio network with available spectrum totaling up to 1200 MHz.

CHAPTER 2

RADIO SPECTRUM SHARING

2.1 Spectrum Sharing Technologies

To increase the access of the radio spectrum to new users, several sharing technologies and regulatory models have been developed. This chapter introduces several current and proposed sharing technologies.

Regulatory management of the radio spectrum is experiencing increased attention. The FCC formed the Spectrum Policy Task Force in June 2002 to administer its spectrum management activities; this group has initiated several concepts and rulemakings.[24] Under the directive of an executive memorandum signed by President George W. Bush, the NTIA has also started a comprehensive review of spectrum management.[25,26]

2.1.1 Unlicensed Band Sharing

Some portions of the spectrum are declared unlicensed. The unlicensed spectrum is used as a shared commons. Compared to the licensed spectrum, the unlicensed spectrum generally offers lower quality of service (QoS) and higher user obligations.[27,28] The user is not guaranteed exclusive use, and confining limits are placed on transmission power, transmission method, and usage etiquette.[29] Relatively little spectrum is unlicensed, but the amount in this category has significantly increased. Until recently, the only unlicensed spectrum used for advanced telecommunications was the 2.4 GHz Industrial, Scientific, and Medical band (ISM), but now there is the Unlicensed National Information Infrastructure (UNII), which is a 555 MHz noncontiguous band between 5.15 GHz and 5.825 GHz, and the Unlicensed Personal Communications Service (UPCS) centered at 1920 MHz, which offers 20 MHz of bandwidth, spectrum access for Ultra-Wideband (UWB) systems, and access to several extensive millimeter wave bands.[28] These new unlicensed bands have different QoS and user obligations.

Radios operating in unlicensed bands under FCC Part 15 Rules have grown in popularity. Local area networking devices based on the Institute of Electrical and Electronic Engineers (IEEE) 802.11a, b, and g standards have proliferated; these devices operate over relatively narrow portions of the spectrum. Users in the unlicensed bands have minimal spectrum rights and must accept interference from other users and other services.[28] For the 2.4 GHz unlicensed band, other in-band emitters include leakage from microwave ovens and amateur radio operators transmitting at up 1.5 KW.[30,31,32] Low data rates and poor QoS result from these impediments. The popularity of unlicensed devices results from their simplified access to the spectrum (no license required).

2.1.2 Ultra-Wideband

Ultra-Wideband (UWB) is a controversial "sharing" technology that has recently attained FCC acceptance. Several uses of UWB have been developed, including communications, radar, and imaging systems.[33] UWB communication devices transmit over the spectrum from 3.1 GHz to 10.6 GHz, with a minimum bandwidth of 500 MHz and a power spectral density of -41.3 dBm/MHz.[28] With a wide possible bandwidth and low signal-to-noise ratio (SNR), UWB communication devices rely on Shannon's information channel capacity theorem to operate at high data rates:

$$C = B\log_2(1+SNR) \tag{2.1}$$

where C is the information capacity of the channel in bits per second, and B is the bandwidth of the channel.[34,35] UWB communication systems have been proposed that can operate at a distance of 10 m with data rates above 100 Mb/s.[36] The spectrum used by UWB devices is occupied by numerous other allocated and licensed services. UWB operates as an "underlay" service, transmitting without regard to the other spectrum users, presenting the possibility of interference.[37]

2.1.3 Cognitive Radio

The term cognitive radio has been used to signify a radio that has an ability to adjust its operation to its spectral environment.[38,39,40,41,42] This is in comparison to broadcast radio and several two-way radio systems whose operation is irrespective of their time-varying surroundings. Today, several million consumer radios have some ability to optimize their operation in the spectral environment, with cell phones being the most prolific example. The first-generation cell phone system Advance Mobile Phone System (AMPS), had the ability to control the transmit power of its user's nodes as the propagation loss varied.[43] This gave preference to network optimization over the performance of each individual user. Additionally, the user benefited from longer battery life. Subsequent cell phone standards have placed greater emphasis on network optimization and have resulted in finer control of the user's nodes. Modern cell phones use precise power control to minimize the radio spectrum (measured in power and bandwidth) used for a voice call.

The cell phone system is an excellent example of a technology that optimizes the use of a frequency band, with every new standard adding more efficient modulation and information coding. Other band-optimizing technologies include multiple input multiple output (MIMO) and orthogonal frequency division multiplexing (OFDM).[44] In contrast to these band-optimizing systems, frequency-agile radios (FAR) are designed to maximize the utilization of a much larger portion of the spectrum, not just a designated band.

Software-defined radio (SDR) is a term that has been used interchangeably with cognitive radio, but its meaning has a nuance toward the intermediate frequency (IF) section of radios.[45] For this thesis SDR is treated as a subset of cognitive radio to be used in describing radios whose dynamic functionality is contained in software, not software-controlled analog components. A universal cell phone base station that can use several different waveforms all in the same frequency bands is an example of an SDR, since the waveforms are shaped in software. Unfortunately recent FCC rulemaking has merged the meanings of the terms SDR and cognitive radio.[46]

2.1.4 Frequency-Agile Radios

Frequency-agile radios are a subset of cognitive radios; they have the ability to opportunistically occupy the spectrum across a broad frequency range.[47] They have a secondary right to access the spectrum compared to other users (incumbent or primary). The frequencies in which a FAR operates are temporary and change as their spectral environment changes. Ideally, these frequencies are unoccupied when chosen, and their use is discontinued when a primary spectral user begins to operate in them. Figure 2.1 displays measurements of spectrum usage in the 2.4 GHz ISM band over a period of 150 minutes; a FAR could operate in the “white spaces” (unused spectrum) of this band (areas displayed as black and dark blue in the plot). FAR devices could provide access to large swaths of spectrum that are presently underused.

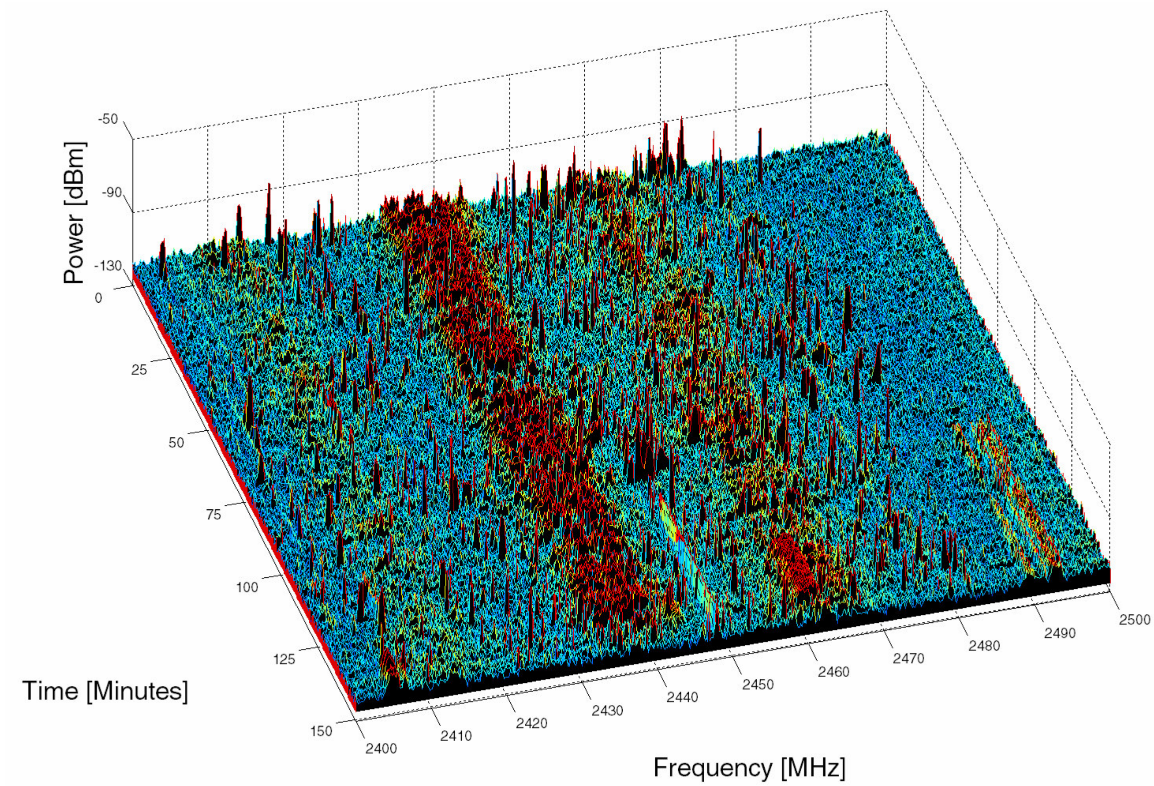

Figure 2.1: Spectrum utilization over time for the 2.4 GHz ISM band.

Frequency-agile radios are a bridge technology between statically licensed and unlicensed technologies, offering greater spectrum access (bandwidth) with improved QoS. Recently, the FCC has encouraged the development of FAR to increase spectrum utilization through a rulemaking process.[48]

There are several challenges to developing FAR networks. Frequency-agile radios need to identify, in real time, potential unoccupied spectrum for sharing. Determining the spectrum that is unoccupied is a nontrivial task. Ideally, a FAR would be sensitive enough to detect all spectral users, but this is technically difficult and cost prohibitive. Protocols can be developed to assist a FAR search for the unoccupied spectrum. For example, a FAR could attempt to search the spectrum for sharing that is only used by devices that have a poorer sensitivity than the FAR. Additionally methods can be developed to detect weak-signals spectrum users with advanced signal analysis.

In the ideal FAR system, radios would be able to operate on a scattering of frequencies over several decades of spectrum. Producing such a broadband radio with reasonable cost, power consumption, and size is technically challenging. The RF components in a broadband FAR, including the low-noise amplifier (LNA) and power amplifier (PA), would need to be broadband and have low distortion because of non-linearites.

2.1.5 Intermodulation

The production of intermodulation (IM) products results from nonlinearities in amplifiers, causing the production of additional signals in amplifiers from the mixing of input signals.[11,49]

Typically, radios operate over relatively narrow spans of the spectrum, allowing them to use filters to reduce the power of signals that are received and transmitted out-of-band, significantly reducing the power of IM products. A broadband FAR with nonlinear components and without narrow-band filters could produce IM products in the receiver, which could obscure actual spectrum usage. In transmit mode a FAR may emit IM products, causing spectrum pollution and potential interference to other users. Figure 2.2 displays two measurements of radio spectrum usage from a broadband receiver (500 MHz to 8 GHz); the blue line shows the spectral image when no RF filter is present and the red line is the spectral image when an octave-band filter has been placed in front of the LNA. This filter is centered at 2400 MHz, with a bandwidth of 1600 MHz.

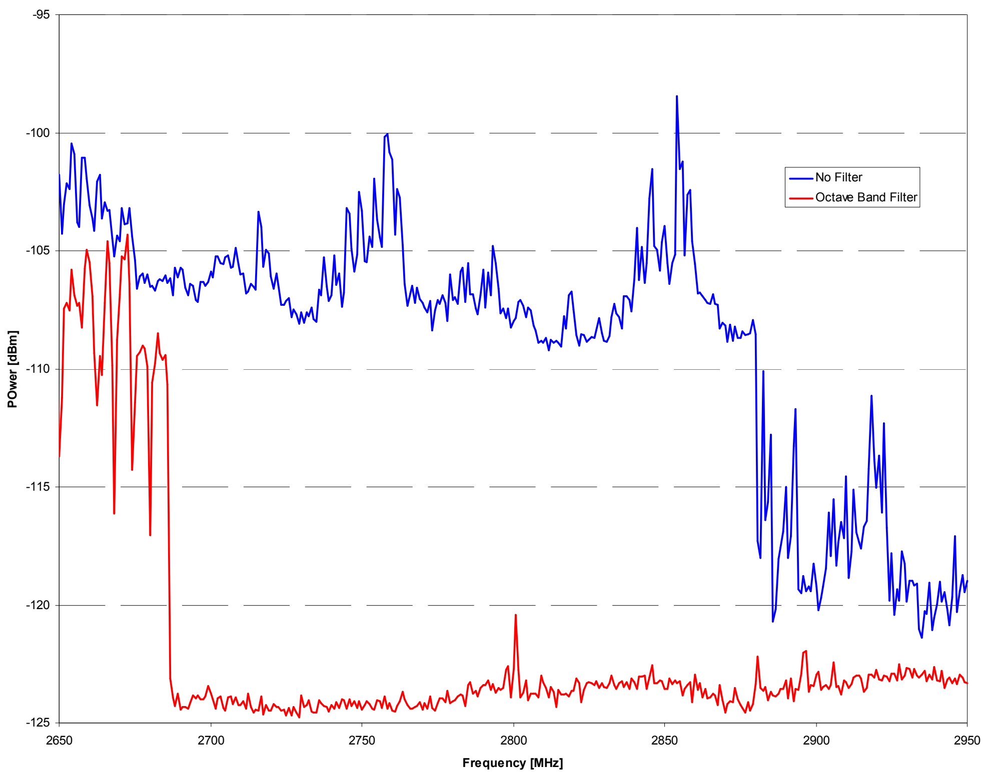

Figure 2.2: Production of intermodulation products.

It can clearly be seen from the plot that IM products produce the appearance of spectrum usage, reducing the perceived amount of spectrum available for sharing.

Tunable or switched filter banks could be used in a FAR to reduce the power of IM products. Several microelectromechanical systems (MEMS)-based tunable filters and switches that can be used in filter banks have been developed.[50,51,52,53] Several techniques for PA linearization have been demonstrated to reduce the filtering requirement needed to suppress IM product emission.[54,55,56,57]

CHAPTER 3

RADIO SPECTRUM MEASUREMENT SYSTEM

3.1 Measuring Radio Spectrum Usage

To maximize the utility of the radio spectrum, knowledge of its current usage is beneficial. While some coarse information can be attained from spectrum licenses, essential details, including the location of transmitters, transmitter output power, and antenna type, are often unknown. Additionally, licenses do not specify how often the spectrum is being occupied if at all. Furthermore, the local environment affects the propagation of radio waves; while this effect can be simulated, the results offer only moderate precision. Hence, to categorize spectrum usage, measured data is vastly preferable to theoretical analysis.

Several spectrum studies were performed to provide multidimensional usage information. These studies, improve upon past spectrum studies by resolving spectrum usage by nearly all its possible parameters (e.g., time, polarization, etc).[58,59] Very few other wide-bandwidth spectrum studies have been performed. The last published broadband spectrum study was conducted by the NTIA in 1995, nearly a decade ago. [58,59] There has never been a comprehensive *high-sensitivity* spectrum study conducted in the United States; this has led to mismanagement of the spectrum, a crucial national resource.

3.2 Spectrum Study

In the studies, spectrum usage was measured as a function of frequency, time, polarization, azimuth, and location type. The contiguous frequency range from 400MHz to 7.2 GHz was measured. This covers emitters from UHF TV, several land-mobile communication systems, radars (both air search and weather), satellites (uplink and downlink channels), fixed microwave services, and several passive bands.

To measure spectrum usage in the time dimension, two schemes were employed. One measured the short-term usage of the spectrum, which provided a metric of spectrum usage over a span of a few minutes. This metric can aid in the identification of periodic spectrum users. For most of the spectrum studies, a collection of 50 measures in quick secession (about 1 second apart) at the same frequency was used to analyze short-term usage.

The other method employed was designed to measure usage of the spectrum over the course of the day; determining if temporal variations exist and to what extent. Six time periods, each four hours long, were defined for this task: 12 AM to 4 AM, 4 AM to 8 AM, 8 AM to 12PM, 12 PM to 4 PM, 4 PM to 8 PM, and 8 PM to 12 AM.

All spectra were measured in both linear polarizations (vertical and horizontal). If both linear polarizations have equal magnitude, slant or circular polarization can be inferred from these measurements. Finally, the azimuthal distribution of spectrum usage was measured across the horizon. This facilitates discriminating between multiple emitters operating on the same frequency in the spatial-dimension.

To provide a statistically valid model of the spectral environment, a large number of data samples were taken. For each frequency, resolved with a filter of 10 kHz bandwidth, 3,600 measurements were taken, thus 360,000 measurements of spectrum usage were taken for every 1 MHz of spectrum. More than 8 billion spectrum measurements have been taken over several months of observation.

The spectrum studies also determine the effects of the demographic location type. Three types of locations were measured: urban, suburban, and rural. One spectrum study was performed for each of these location types, one in urban Atlanta, one in suburban Atlanta, and one in rural North Carolina.

3.3 Spectrum Measurement System

The spectrum studies conducted required the design and construction of a spectrum measurement system composed of several hardware and software subsystems. A block diagram of the hardware that composed the spectrum measurement system is shown in Figure 3.1. Shown in this figure is the antenna sub-system (including an azimuthal positioning system), an RF-subsystem, a spectrum analyzer, and finally a data acquisition and control system.

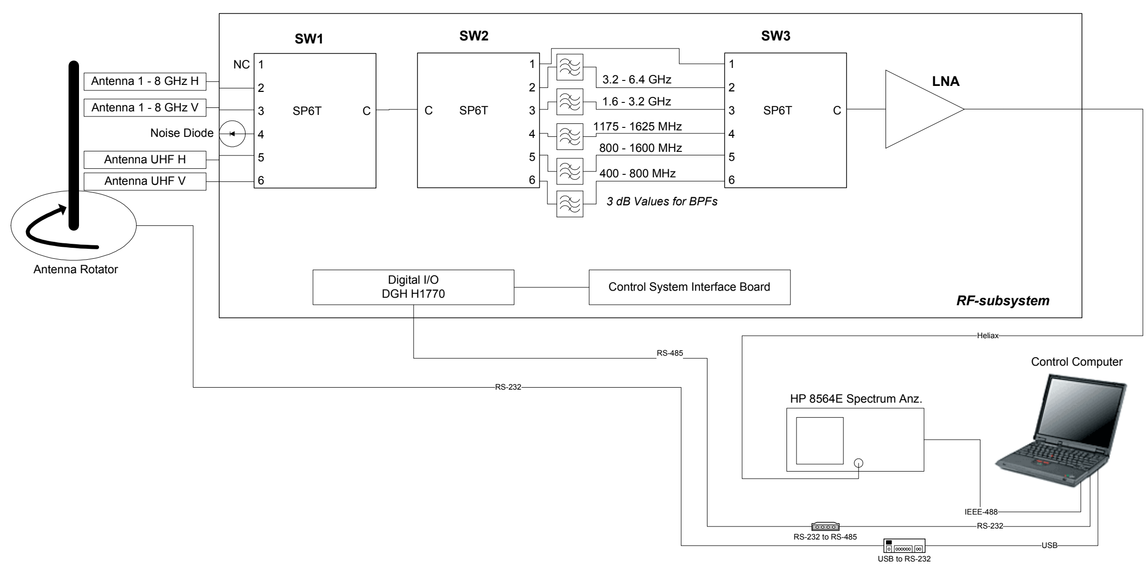

Figure 3.1: Radio spectrum measurement system.

3.3.1 Antenna System

Directive antennas were chosen to increase the system's sensitivity and to resolve spectrum usage as a function of azimuth. Four log-periodic antennas were selected to cover the frequency range from 400 MHz to 7.2 GHz with both linear polarizations (horizontal and vertical). The antenna system is shown in Figure 3.2. The two larger antennas shown in this figure are used in the frequency range from 400 MHz to 1.2 GHZ. These log-periodic dipole antennas are manufactured by Creative Design (CLP-5130-2) and have a measured gain of 8 dBi to 9 dBi depending on frequency, front-to-back ratio of >15 dB, and cross-polarization isolation of >15 dB and a 3 dB beamwidth of 65°. Gain and beamwidth measurements were performed with a far-field antenna test range at Georgia Institute of Technology at 915 MHz. The front-to-back ratio and cross-polarization measurements could not be performed at the test range because of the presence of near-by reflectors. These values were deduced from results of the spectrum study at the Pisgah Astronomical Research Institute where no near-by reflectors were present.

The measured performance for this antenna differed from the manufacture's specifications, which quoted a gain of 11 dBi to 13 dBi.[60] To verify the measurements of this antenna it was simulated in SuperNEC, a Method of Moments software tool.[61] Simulations with this tool yielded gain performance in accordance with the measured performance tests. This large discrepancy between measured and specified gain performance of this antenna was most likely caused by the manufacture converting from dBd to dBi units twice, hence adding 2.15 dB to its gain.

The two smaller antennas mounted at the top of the mast shown in Figure 3.2 are the feeds from a Singer Empire (LPA-112) parabolic reflector antenna. This antenna is now manufactured by Electro-Metrics with model number: EM-6970. These pyramidal log-periodic of antennas are used to perform measurements from 1.2 GHz to 7.2 GHz. These antennas have a measured gain of 8 dBi to 9 dBi depending on frequency, front-to-back ratio of >15 dB, and cross-polarization isolation of >10 dB. Gain measurements for this antenna were performed at the Georgia Institute of Technology at 2.45 GHz and 5.85 GHz. The front-to-back ratio and cross-polarization measurements were deduced from results of the spectrum study at the Pisgah Astronomical Research Institute at several frequencies. The voltage standing wave ratio (VSWR) measured for these antennas was typically 2.3 : 1, and no higher than 2.9 : 1.

The near-constant gain versus frequency of the log-periodic antennas also provides close to constant beamwidth.[62,63] These antennas are mounted on a rotating mast; azimuthal position is remotely controlled by the data acquisition and control system. Six directions are used to azimuthally resolve the spectrum and offer omni-directional sensitivity: 0º, 60º, 120º, 180º, 240º, 300º, all relative to north being 0º.

Depending on the spectrum measurement site, different cables are used to connect the antennas with the RF-subsystem. For the urban and suburban Atlanta studies 7.6 m of

Belden RG-8 9913 is used to connect the Singer Empire antennas and 5.5 m of RG-214 is used for the Creative Design antennas. The rural site offered the opportunity to mount the antennas on a tower, hence longer cabling was required. The Belden RG-8 9913 and RG-214 from the other studies were concatenated to connect the Creative Design antennas. For the higher frequency Singer Empire antennas, 20 m of Andrew FSJ4-50B Superflexible HELIAX was employed. Each cable was tested and a model was developed based on the standard cable attenuation equation:

$$L = a\sqrt{F} + bF \tag{3.1}$$

where L is the loss in the cable (dB), F is frequency in MHz, and a and b are cable-specific constants. This model is used in the post-processing software to determine the cable losses and thus the correct noise figure for the complete system. Table 3.1 details the values of the constants a and b for the different cables.

Table 3.1: Values of constants for cable attenuation equation.

Cable	**Length [m]**	**a**	**b**
RG-8 9913	7.6	0.032500	0.0002000
RG-214	5.5	0.028571	0.0005360
FSJ4-50B	30	0.056050	0.0003176

Figure 3.2: Antenna Sub-system.

3.3.2 RF-Subsystem

Antenna selection, filtering, amplification and calibration are performed by the RF-subsystem shown in Figure 3.3. This system has 5 type-N inputs for the 4 antennas described in the previous section and one input for future growth. These antenna inputs and a noise diode are all connected to an electromechanical switch; this allows for antenna selection and calibration of the complete system relative to the input of this switch.

This noise diode emits noise with a Gaussian random voltage distribution 26 dB above the thermal noise seen with a 50 Ω room-temperature load.[64,65] Comparing the power measured with the spectrum analyzer with some IF-filter bandwidth (the final component in the receiver chain) and the predicted value that would be experienced with a lossless system, the gain of the systems relative to the input of the RF-subsystem can be attained.[66] When the noise diode is turned off it appears as a 50 Ω load. These two states of the noise diode allow for a Y-factor measurement that is used to determine the noise figure of the spectrum measurement system.[67]

A matrix of filters with an octave or less of bandwidth is used to reduce the creation of IM products in the subsequent stages of the system. The filters used are shown in Table 3.2. After filtering, signals pass through a LNA with a high (+27 dBm) third-order intercept point. The LNA is needed to lower the total system's noise temperature, since the spectrum analyzer used has a very high noise figure (27 to 29 dB, depending on frequency).[68] The noise figure of the RF-subsystem and spectrum analyzer combination is shown in Table 3.3; this table also shows the site-specific noise figures that include antenna cabling. The filter and LNA combination has an instantaneous spurious-free dynamic range that is better than that for the spectrum analyzer alone, which has a third order intercept point of 8.5 to 15 dBm depending on frequency. For many of the spectrum measurements, the spectrum analyzer limits the system's intermodulation performance and thus sensitivity, since the power of the intermodulation products is above the thermal noise floor. Below 1.2 GHz the LNA is not used because IM products generated reduce the sensitivity more than the benefit received with lower system noise. To reduce intermodulation for the urban study in the frequency region from 1.6 to 2.4 GHz, 10 dB of attenuation is added in the spectrum analyzer. This reduces 3rd order IM products since they increase in power at twice the level (in dB) of the input signal, hence 10 dB of attenuation reduces 3rd order IM products by 20 dB.

Electromechanical switches were chosen for this system because of their high isolation (>100 dB) and low insertion loss (<0.5 dB).[69] The main limitations to using electromechanical switches are their slow switching time (15 ms), and switching lifetime of 5 million cycles. The switches chosen for the RF-subsystem have optoelectronic position indicators that are used by the control system to determine if a switch is set to its intended selection and to monitor the health of the switch over time.

As with all of the subsystems, the RF-subsystem is remotely controlled by the data acquisition and control system. To perform this task the RF-subsystem has two boards: a serial to digital I/O board and a signal distribution and relay board. The serial to digital I/O board has a RS-485 link back to the PC based controller allowing the controller to be up to 1200 m away. The signal distribution and relay board is the interface between the serial-to-digital I/O board and the noise diode and microwave switches. The reed relays on this board control the larger voltages and currents that exceed that which the TTL outputs of the digital IO board could handle. Figure 3.4 shows the connections for the control of the RF-subsystem.

The RF-subsystem uses two linear power supplies to provide the 5V, 15V and 24V DC sources required for its components. Linear power supplies are used because of the low level of radio frequency interference (RFI) they produce. One major disadvantage of linear power supplies is their low efficiency and hence high thermal radiance. A high power 120 V fan is used to provide required the case cooling.

Proper shielding of the RF-subsystem's components is crucial to prevent disruption from external RFI. The enclosure for the RF-subsystem is a 4U rack-mount aluminum case to provide shielding. Additionally all perforations in the case larger that 1 cm were covered with aluminum shielding tape.

To reduce the amount of shock experienced by the spectrum analyzer if a lighting strike occurred, a HyperGain HGLN-06 gas discharge lighting protector was affixed to the output of the RF-subsystem. This lighting protector added only 0.5 dB to 1 dB of loss to the systems after the LNA.

The RF-subsystem was connected with the spectrum analyzer in two ways depending on the measurement site. For the midtown Atlanta site 38 m of Andrew HELIAX LDF4-50A cable was used for the connection. The attenuation of this cable reduced the output of the LNA, whose gain was required to overcome the high noise figure of the spectrum analyzer, thus the thermal noise of the measurement system was increased. For the suburban Atlanta and rural North Carolina measurement sites the RF-subsystem was connected to the spectrum analyzer with 1 m Pasternak PE-142LL cable, which offered a fraction of the loss of the 38 m HELIAX cable. This arrangement improved the system's thermal noise compared to the midtown Atlanta setup.

The RF-subsystem connection cable was accounted for in the calibration of the systems, since the noise diode preceded the cable components. The loss from the lightning protector was accounted for with the data analysis software.

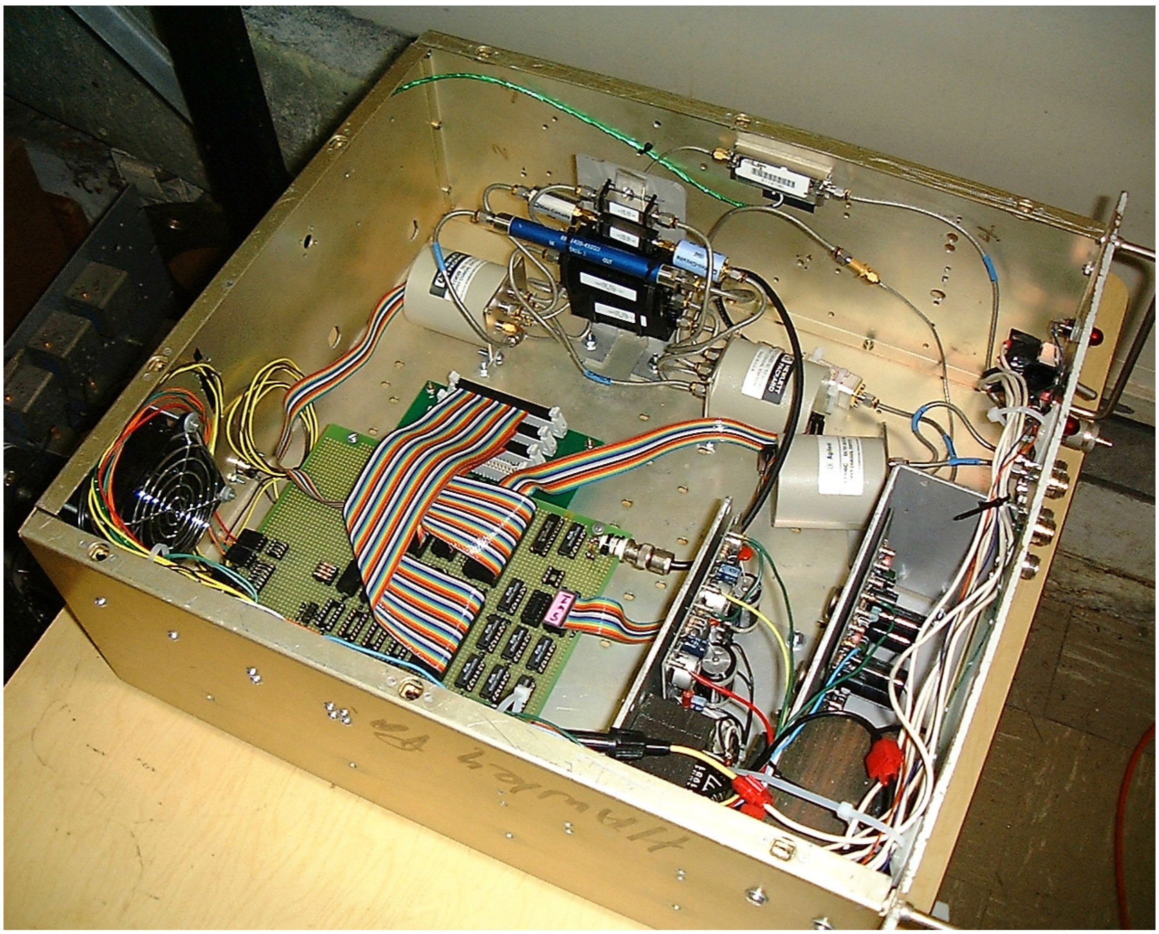

Figure 3.3: RF-subsystem.

Table 3.2: Filters used in the RF-subsystem.

Description is Software	Manufacture	Part Number	Center Freq	Loss at CF	Design 3 dB BW	Used Start Freq	Used Stop Freq
			[MHz]	[dB]	[MHz]	[MHz]	[MHz]
NONE	No Filter	NA	NA	NA	NA	NA	NA
CF600	Lark	XMC6000-400-7AA	600	0.57	400	400	800
CF1200	Lark	XMC1200-800-7AA	1200	1.15	800	800	1200
CF1400	Reactel	BB2-1400-450LL	1400	0.43	450	1200	1600
CF2400	Lark	X3B2400-1600-7AA	2400	0.5	1600	1600	3200
CF4800	Lark	X3B4800-3200-7AA	4800	0.5	3200	3200	6400
HPF3000	Mini-Circuits	VHP-26	5285	0.9	5430	6400	7200

Note: CF1200 includes three filters in series: Lark XMC1200-800-7AA, Mini-Circuits SHP-800 and SHP-900.

Table 3.3: Nose figure of the RF-subsystem and spectrum analyzer combination.

		Spectrum Analyzer & RF-Subsystem Only	Urban Atlanta Site	Suburban Atlanta Site	Rural NC Site
Frequency Range	LNA Present?	Noise Figure	Noise Figure	Noise Figure	Noise Figure
[GHz]		[dB]	[dB]	[dB]	[dB]
0.4 - 0.8	No	31.94	32.96	32.96	33.87
0.8 - 1.2	No	32.6	34.04	34.04	35.26
1.2 - 1.6	Yes	6.29	7.99	7.80	8.83
1.6 - 2.4	Yes	5.77	12.43*	7.69	8.91
2.4 - 3.2	Yes	5.52	8.24	7.72	9.37
3.2 - 4.0	Yes	5.02	8.46	7.65	9.52
4.0 - 5.0	Yes	4.75	9.23	7.81	9.94
5.0 - 6.0	Yes	4.84	10.57	8.36	10.47
6.0 - 6.4	Yes	5.08	12.32	8.82	11.46
6.4 - 7.2	Yes	6.87	16.27	NA	13.64

* 10 dB attenuation added in the spectrum analyzer

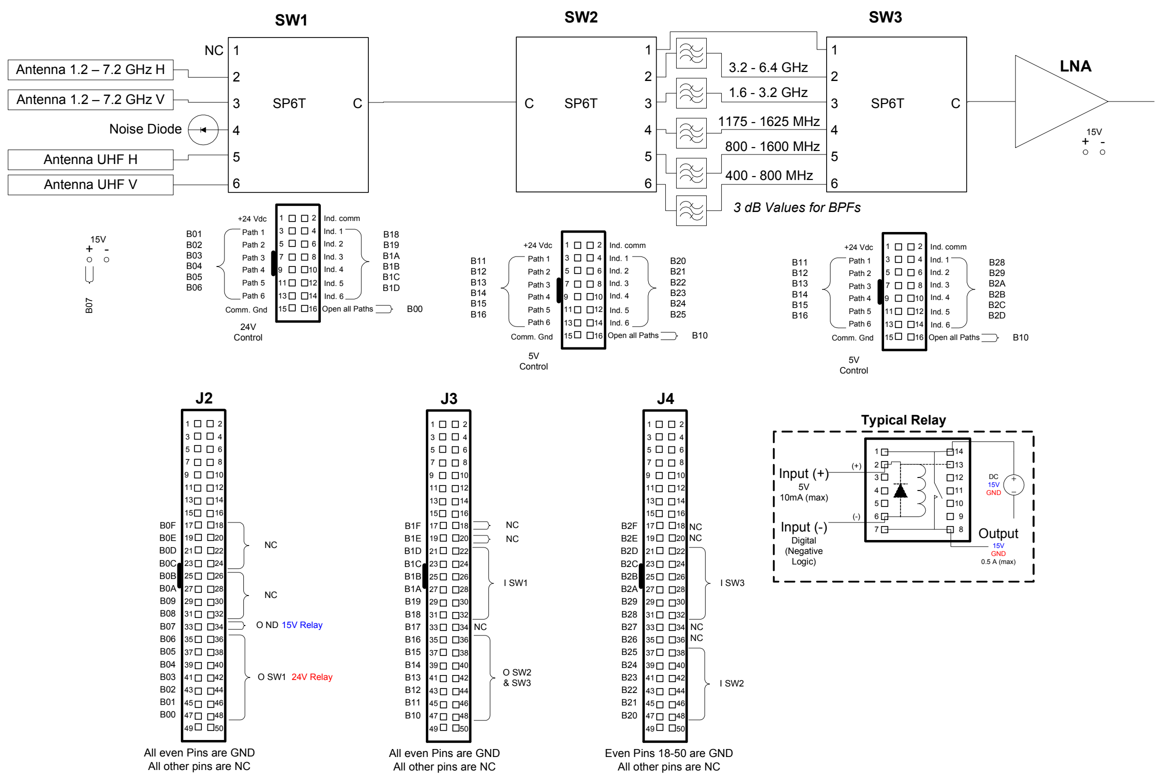

Figure 3.4: RF-subsystem control connection diagram.

3.3.3 Spectrum Analyzer

An advanced Agilent 8564e spectrum analyzer was used in this system to provide spectral power measurement, over the complete frequency range. The different modes of the spectrum analyzer can significantly alter the results of a measurement; proper settings selection is crucial to producing valid and substantive measurements. The setting for resolution bandwidth, detector type, span, swept time, video bandwidth, reference level, attenuation level, and data collection method were chosen with the intent of maximizing the probability of detection.

A narrow 10 kHz resolution bandwidth was employed to maximize the detection of narrowband signals and to resolve the spectral content of wider bandwidth signals. One disadvantage of using a narrow bandwidth filter is the reduced ability to observe pulsed signals. The measured power of pulses with duration of less than 0.2 ms is attenuated by the use of a 10 kHz filter. Some measurements were undertaken with 100 kHz resolution bandwidth to improve the ability to observe pulsed signals. It was determined that this wider bandwidth filter reduced sensitivity and spectral content information significantly with only on incremental benefit in the detection of pulsed signals; hence 10 kHz was employed for nearly all of the spectrum measurements.

A positive peak type detector was used; this detector records the highest power level sensed in one resolution bandwidth over one sweep of the spectrum analyzer. This detection method was selected for it ability to detect pulsed or intermittent signals, although their presence can be overstated with this method.

The span is the bandwidth that the spectrum analyzer covers in one sweep. While it would have been possible for the spectrum analyzer's span to be set to cover the full bandwidth of measured frequencies, this would have produced coarse and inaccurate results. Spectrum analyzers have a defined number of discrete frequency bins to store the results of a scan; for the Agilent 8564e there are only 601 bins.[70] Hence if 1000 MHz of spectrum is covered in one sweep, the spectrum analyzer will only be able to resolve measurements to a precision of 1.66 MHz. Additionally, if the resolution bandwidth is less than the span divided by 601, then the spectrum analyzer must choose one of several measurements, to represent the power reported in the entire frequency bin. The Agilent 8564e spectrum analyzer is designed to report the largest power measurement of a resolution bandwidth within the frequency bin if it is in positive peek mode; this feature was found to not work reliably. To provide the maximize amount of valid data for data analyses after collection, it was desired to transfer the measurements of every resolution bandwidth to the control and data collection system. This was done by setting the span to 601 times the resolution bandwidth, hence 6.01 MHz. Since 601 is a prime number and not efficient to use as a basis of the data storage system, the first 600 points of the scan are saved, and the spectrum analyzer is stepped in 6 MHz increments.

The amount of time it takes the spectrum analyzer to sweep through a span is known as the sweep time. The spectrum analyzer can automatically select the minimum sweep time, which is limited by the rise time of resolution bandwidth filter being used. Shorter sweep times result in an understatement of received power. Larger sweep times increase the amount of time the resolution bandwidth filter rests at a given frequency. The observe time OT in seconds, can be calculated by with:

$$(OT) = \frac{(RBW)}{(Span)(ST)} = \frac{(RBW)(ST)}{(Span)} \tag{3.2}$$

where RBW is the resolution bandwidth in Hz, Span is the span in Hz, and ST is the sweep time in seconds.[71] Since the minimum observation is approximately 1/RBW, the minimum value for sweep times with a 10 kHz resolution bandwidth and a span of 6.01 MHz is 150 ms, which was used for all the measurements.

The video bandwidth is a function that dates to analog spectrum analyzers, but is now nearly obsolete. It can be used to average successive measures performed in one resolution bandwidth. With a modern digital spectrum analyzer this averaging can be performed in software in a better-controlled fashion. To eliminate this analog form of averaging the video bandwidth was set to equal the resolution bandwidth.

The reference level is the maximum power of a signal that enters the spectrum analyzer, signals higher than the reference level cannot be measured accurately. The lower limit of the reference level is also influenced by the limited vertical storage format used by the 8564e spectrum analyzer, only 600 levels are available. Of these levels only the highest 540 are valid. Hence to produce valid power measurements of signals, the reference level needs to be set so that all signals are always lower than the reference level and higher than the reference level minus 90 dB (assuming 10 dB per division).

3.4 Measurement Sites

There were several attributes used in the selection of the measurement sites. First each site had to offer as unobstructed a view as possible of the surrounding area, to increase the detection of signals and to accurately measure the azimuthal distribution of spectrum usage. This qualifier narrowed the selection of possible sites to an antenna tower or the roof of a building, given the local topographic environments. The availability of utilities including power and internet access to support the measurement system was a primary selection criterion.

The presence of transmitters close to the proposed measurement sites also was a factor in site selection. These spectral emitters in near proximity to the spectrum measurement system could excite the creation of IM products in the RF-subsystem or spectrum analyzer and thus distort the measurement of spectrum usage.

The locations of the three measurement sites are shown plotted on a map in Figure 3.5. Two of the measurement sites are in the Atlanta, Georgia metropolitan area, with the third rural site in North Carolina. Figure 3.6 shows the location of the urban and suburban measurement sites with the map cropped to only the Atlanta Georgia metropolitan area. The locations in terms of latitude, longitude and elevation are shown in Table 3.4. The locations of urban and suburban Atlanta sites were determined with a handheld Global Positioning System (GPS) receiver; the location of the rural North

Carolina site listed is that of a surveyor's mark that was 200 m NNW of the antenna tower.

Table 3.4: Location of measurement sites.

Site	Latitude	Longitude	Elevation [m]	Height of Tower [m]
Urban Atlanta	33º 46.564'	84º 23.831'	306	4
Suburban Atlanta	33º 42.605'	84º 14.076'	320	4
Rural North Carolina	35º 12.115'	82º 52.555'	925	11

The urban measurement site is situated in midtown Atlanta, Georgia on the campus of the Georgia Institute of Technology. This site is show in Figure 3.7 and offers a complete 360° line-of-site view to the surrounding area. The midtown location of this site is the center of the spectral environment in Atlanta, surrounded by several airports, downtown skyscrapers, Buckhead to the north with dense housing and commercial buildings, and several nearby towers with broadcast TV, microwave, and cellular antennas. The Hartsfield - Jackson Atlanta International airport, the busiest in the nation is situated 16 km south from the urban measurement site.[72] Located 19 km northwest of the site is Dobbins Air Reserve Base, an active military airbase. This site is on the roof of the Van Leer building. The antenna tower shown in Figure 3.8 and Figure 3.9 was used at this and the suburban Atlanta sites.

The suburban spectrum study was performed in Clarkston, GA on the campus of Georgia Perimeter College. This site shown in Figure 3.10, is between Atlanta's city center and Stone Mountain, offers an ideal suburban location. The roof of the library was chosen since if offer the highest platform for the measurement system on the campus. The only deficiency at this location is an obstruction caused by a penthouse on the roof of the library, shown in Figure 3.11. The penthouse obscures a 30º field of view in the NW direction.

For the rural measurements, a radio astronomy facility located in North Carolina was chosen. This site, known as Pisgah Astronomical Research Institute (PARI), is located in the Pisgah National Forest. At this facility, local population density is less than 17 persons per km^2, and it is over 50 km from any city with a population greater than 50,000.[73] Figure 3.12 shows an overhead image of this facility. The measurement system was situated on the top of a hill at the site on an 11 m tower. The antennas of the measurement system cleared both the ridge line and tree line, as shown in Figure 3.13. The spectrum measurement system was controlled remotely at this site because of the availability of internet access. Both data taking and post processing to ensure valid results was performed from Atlanta.

Safety was a paramount concern with all the spectrum study locations. The antenna tower, RF-subsystem, and antenna rotator controller were all well grounded. The antenna towers at the sites were anchored to withstand winds of at least 80 km/h.

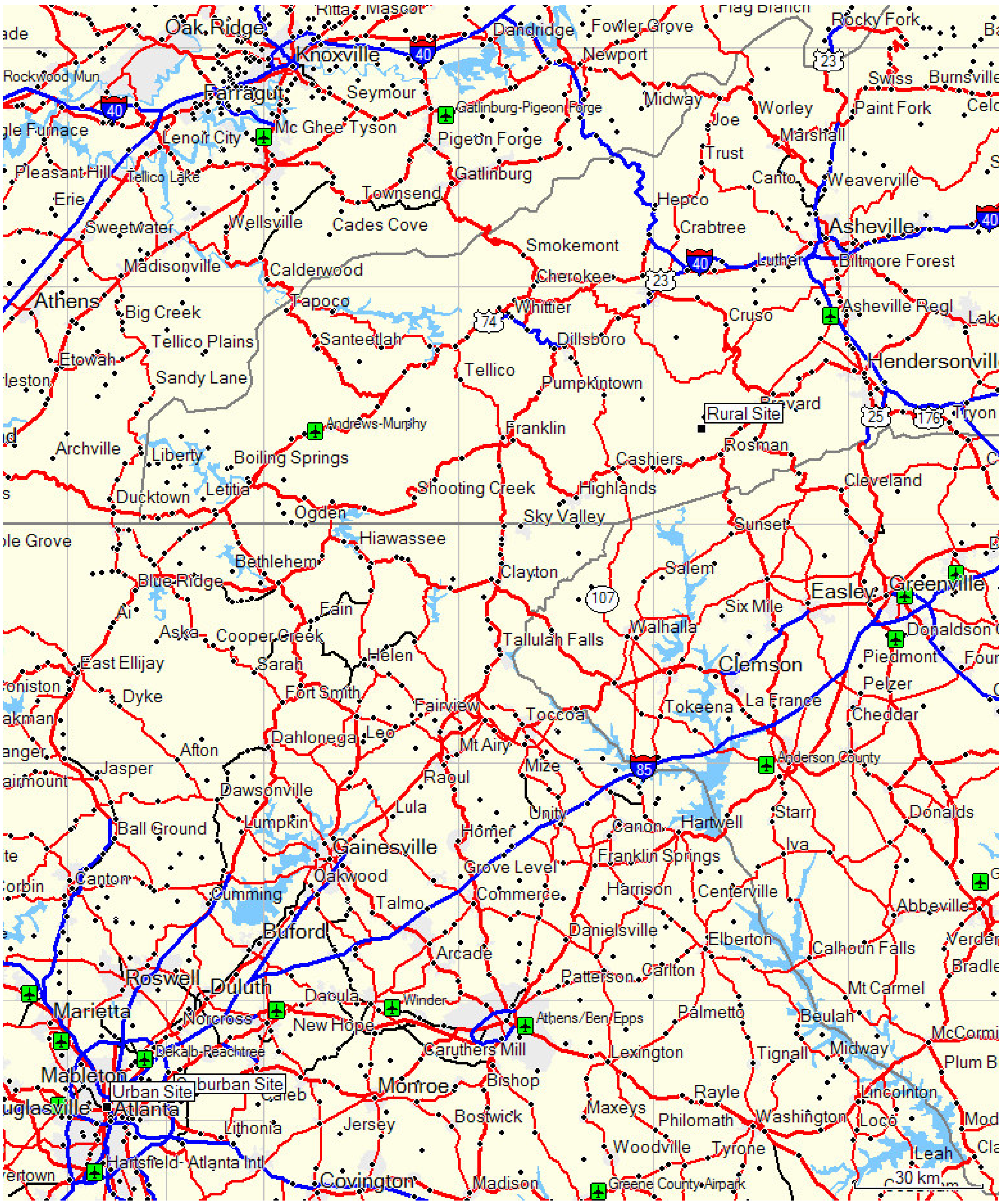

Figure 3.5: Map covering spectrum measurement sites.[74]

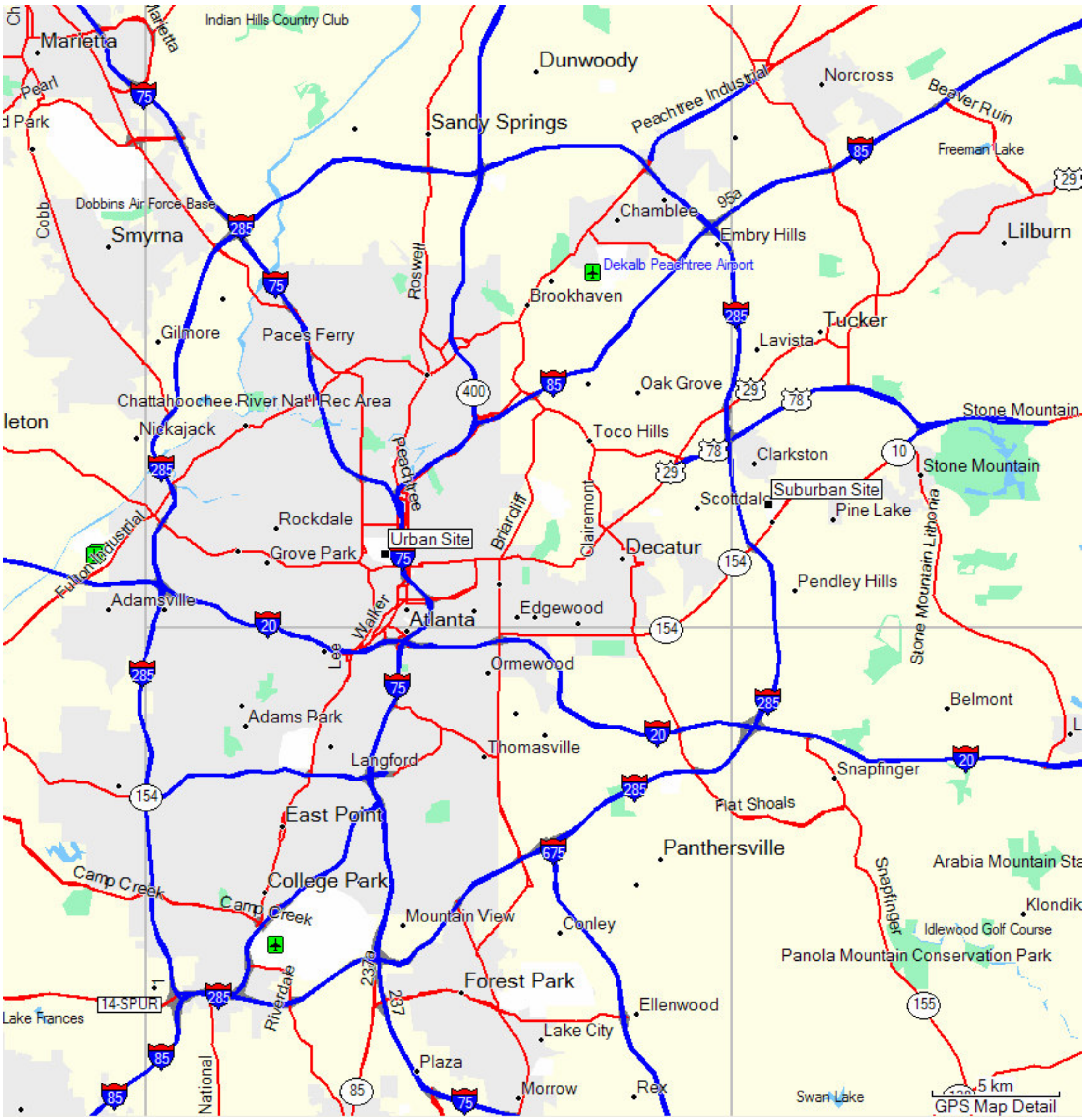

Figure 3.6: Map of Atlanta Georgia metropolitan area.[74]

Figure 3.7: Urban spectrum measurement Site in Atlanta Georgia.

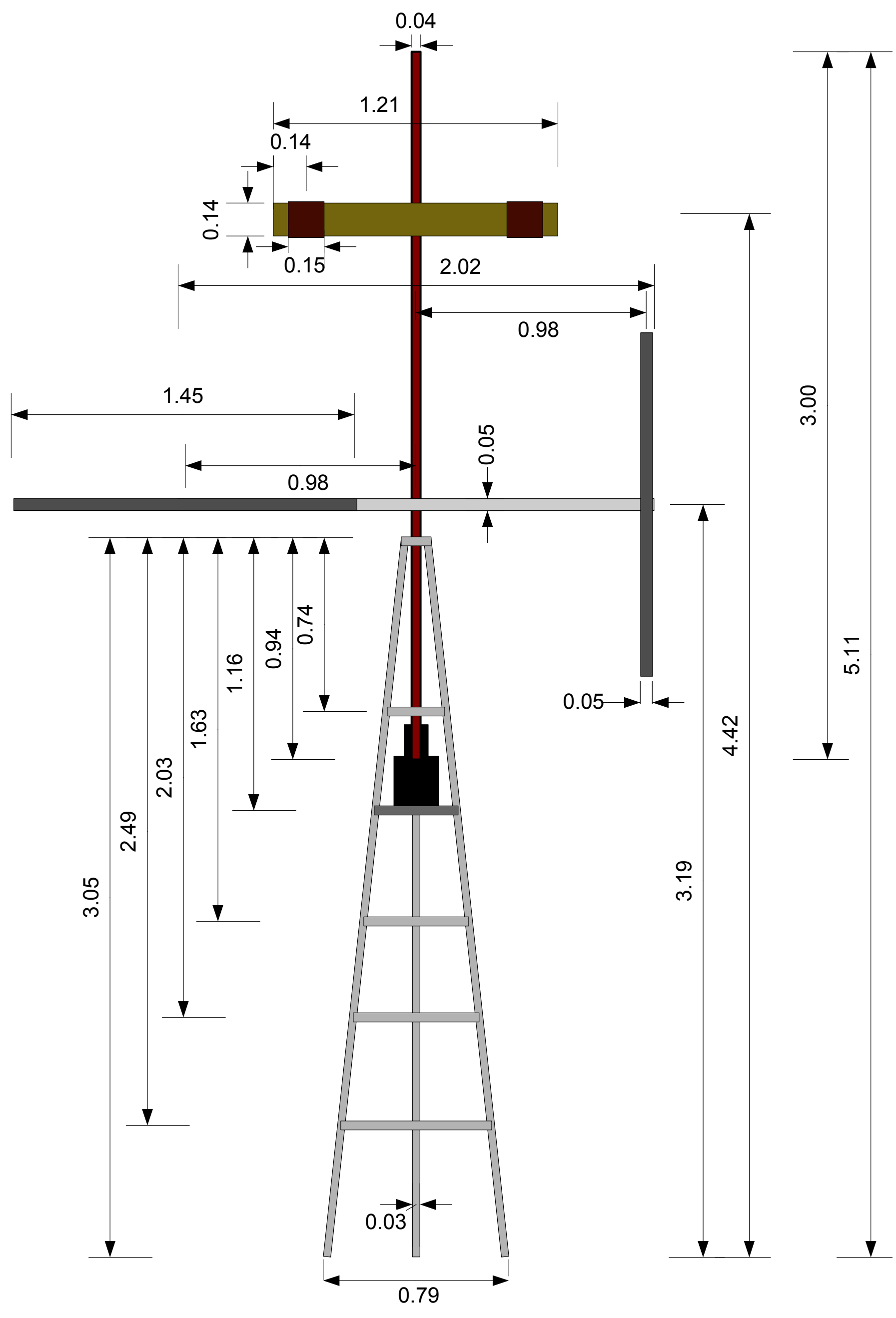

Figure 3.8: Antenna tower for urban and rural Atlanta measurement sites. All units are in meters.

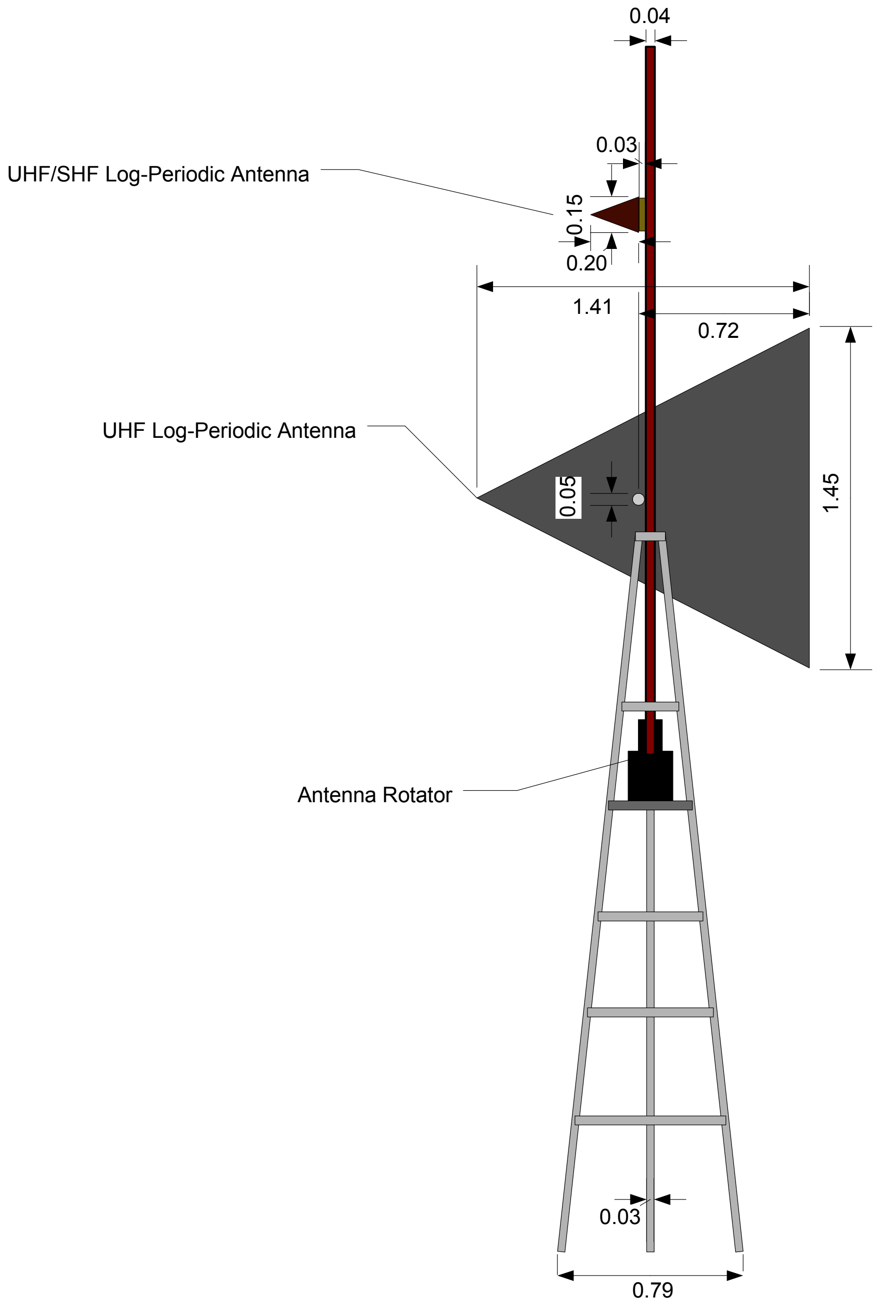

Figure 3.9: Antenna tower for urban and rural Atlanta measurement sites, side view. All units are in meters.

Figure 3.10: Suburban measurement site in Clarkston Georgia.

Figure 3.11: Penthouse at the suburban measurement site.

Figure 3.12: Rural spectrum measurement site.

Figure 3.13: Antenna installation at the rural measurement site.

3.5 Data acquisition and control system

An automated system was developed to control the position of the antennas, choose the desired antenna and filter, perform calibration, and communicate with the spectrum analyzer. Another design requirement was very high reliability, which is needed for unattended multi-week data acquisitions. The system developed to meet these requirements incorporates fault detection and correction at all levels. Only a hardware failure can produce a fatal error (e.g. LNA burnout); every other fault mode is accommodated by the system. The complete spectrum measurement system has achieved better than 99.99999 % operational reliability. For servicing, the system is able to identify the exact component that needed replacing (e.g. microwave switch #2). Additionally, the software keeps statistics on the health of each subsystem (to the component level for the RF-subsystem), recording the time and number of corrected fault events. This allows for the prediction and preventive replacement of components before they fail completely.

The software for data collection is based on Microsoft Visual Studio .NET 2003 with Framework 1.1 running on a PC with Microsoft Windows XP Professional. Commercial data acquisition products including Agilent's HP-VEE and National Instrument's LabView were used in early versions of the radio spectrum measurement system. Both these products offered simpler software design but at the cost of flexibility, power, and speed. The advantages of coding the software in Microsoft Visual Studio .NET 2003 are multiple: extensive object support, vast software pool with Microsoft and 3rd party classes, managed environment with built-in memory allocation and garbage collection, mature driver support, low-level flexibility with C++, 64-bit upgrade path, error control, and speed, A 100 fold increase in data acquisition speed was achieved when the control software was moved to Microsoft Visual Studio .NET 2003; this made the acquisition of billions of spectrum measurements possible. All the software is written in classes to ease software coding, testing, and maintenance; improve readability; and facilitating code reuse.

The data acquisition software known as radio spectrum evaluation system (RSES) is mature, now in version 7, with no known bugs, and with fully commented code. The software is composed of 5 primary classes: Form1, RFControl, HGRotator, RSESFile, and Spectrum; with all these classes but Spectrum written in Visual Basic, with Spectrum written in C++. It should be noted that in Microsoft Visual Studio .NET 2003, there are marginal differences between Visual Basic and C++ when the code is written with managed extensions enabled.[75] Both languages offer full object and system operation support. Primitive type checking and array index checking is employed by the complier for both languages at compile time and runtime. The speed of code execution is near identical, since the complier transforms the source code into Microsoft Intermediate Language (MSIL), a processor independent code, which is then converted to assembly language by a just-in-time (JIT) compiler.[76] This software code abstraction eliminates most of the historical low-level abilities and vulnerabilities of C++.

The Form1 class is the main object: forming the user interface, initializing the other classes, and initiating high-level events. The RFControl class is the interface to the RF-subsystem. The HGRotator class is the interface to the antenna rotator controller. The RSESFile class is the basis of the object-oriented database that is used to store all the data acquisitions. The Spectrum class interfaces to the spectrum analyzer; this class is a wrapper for C code written by Agilent, with several speed and compatibility improvements.

One method used to increase the reliability of the RSES software was to disable and reinitialize the drives for the General Purpose Interface Bus (GPIB) card and serial ports. This reduced the possibly of a stack and buffer, underflow or overflow condition, which would produce a fatal error.

The collection of spectrum measurements in multiple dimensions (e.g., time, polarization, etc) required a scheduling algorithm that was designed to minimize the time needed and equipment wear to perform the spectrum studies. The scheduling algorithm also adapts the data collection process to produce data measurements with higher statistical significance. Figure 3.14 shows the basic operation of this algorithm. There are two givens for this algorithm: the predefined bandwidth that it is given to cover, typically less than 1 GHz, and the time of day which relates to one of six predefined time periods each four hours long. The antennas are first directed to North (0º); then the algorithm starts at the beginning of this predefined bandwidth and takes 50 sweeps, each 6 MHz wide (or 600 times the RBW if 10 kHz is not being used) with the spectrum analyzer, in one antenna polarization. Next, the opposite antenna polarization is selected and 50 sweeps are taken with the spectrum analyzer. Assuming the time period has not changed, the algorithm steps through the rest of the predefined bandwidth until it has been completed. If the complete predefined bandwidth has been completed and the time period has not changed, the algorithm then moves the antennas to their next azimuthal position, and starts the process again. If the time period changes, the algorithm starts the above process in that time period, initially at the beginning of the predefined bandwidth. This process continues until there are 50 measurements of each 6 MHz wide sweep over the predefined bandwidth for every antenna polarization, antenna azimuth, and time period. The above described process relates to version 2 of the scheduling algorithm, which was used for all of the suburban and rural spectrum studies and some of the urban spectrum studies. For most of the urban spectrum studies an earlier (version 1), scheduling algorithm was employed. This algorithm differed by changing antenna polarization after every sweep, instead of after 50 sweeps. While this earlier algorithm produced better polarization information on signals, it reduced the life span of the micromechanical microwave switches to an unacceptable level.

This software also produces calibration data for use by the post-processing software. The calibration data is stored in a format similar to the spectrum measurement data. To perform a calibration the RSES software sets up the RF-Subsystem and spectrum analyzer into the same configuration that they are in for data acquisition. Then it selects the noise diode instead of an antenna and takes 10 sweeps each 6 MHz wide (or 600 times the RBW if 10 kHz is not being used) with the noise diode turned on, and 10 with it turned off for the complete predefined bandwidth.

The data acquisition and control software outputs several files: a data file that contains the results of the measurements, and a log file that details the data collection process and lists any errors. For measurements of spectrum usage the data file has an .RFDat suffix, for the calibration information an .RFCal suffix is used. Both data acquisition and calibration modes produce a log file that is in text format (*.txt), readable by Notepad or a similar text editor.

The data acquisition and control software integrates two operating modes: interactive and automated processing. Figure 3.15 displays the graphical user interface for this software. For interactive operation the user inputs valid parameters and simply presses the "Start Data Collection" or "Get Calibration Data" icon. All the user defined parameters are checked with predefined valid values; if an invalid parameter is entered, a popup window will appear displaying the valid possible options. The automated mode used for multi-week unattended data acquisitions, performs several separate data collections and calibrations in series. The tasks to be completed in this mode are prelisted in a subroutine.

The batch processing method subdivides the 400 MHz to 7.2 GHz frequency range into smaller bands to speed data acquisition and post-processing.

Table 3.5 lists the bands used for this process. They were chosen so that the complete bandwidth will fit into one RF filter (listed in Table 3.2). For the bands from 400 MHz to 800 MHZ and from 800 MHz to 1.2 GHz the LNA was circumvented to minimize the creation of IM products, because of the very high power of the signals in these bands. For the band from 6.4 GHz to 7.2 GHz a filter was added manually in front of the LNA and the "through" connection was used in the filter switch matrix. The RSES software was modified to accomplish this task, this modified version known as RSES HPF allows values for frequency up to 8.0 GHz to be entered (in the standard version values above 6.4 GHz would result in a pop up box warning) and uses the through connection in the filter switch matrix at all times.

Table 3.5: Predefined bands used for spectrum measurements.

Frequency Range		**Bandwidth**
Start	**Stop**	
[MHz]	**[MHz]**	**[MHz]**
400	800	400
800	1200	400
1200	1600	400
1600	2400	800
2400	3200	800
3200	4000	800
4000	5000	1000
5000	6000	1000
6000	6400	400
6400	7200	800

To provide a direct interface to the RF-subsystem with no other functions, a simple user interface was developed. Shown in Figure 3.16, this software controls the RF-subsystem in an interactive fashion, and provides immediate confirmation of option selection, and displays any errors encountered. This interface was used to perform a quick analysis at each spectrum measurement site, to determine the correct parameter for the subsequent extensive spectrum study.

Remote control of the RSES software is possible through the use of Microsoft Window's Remote Desktop feature. This control method was employed at the rural spectrum measurement site via the internet, for both data acquisition and analysis. Any future spectrum study should employ this powerful and productive feature.

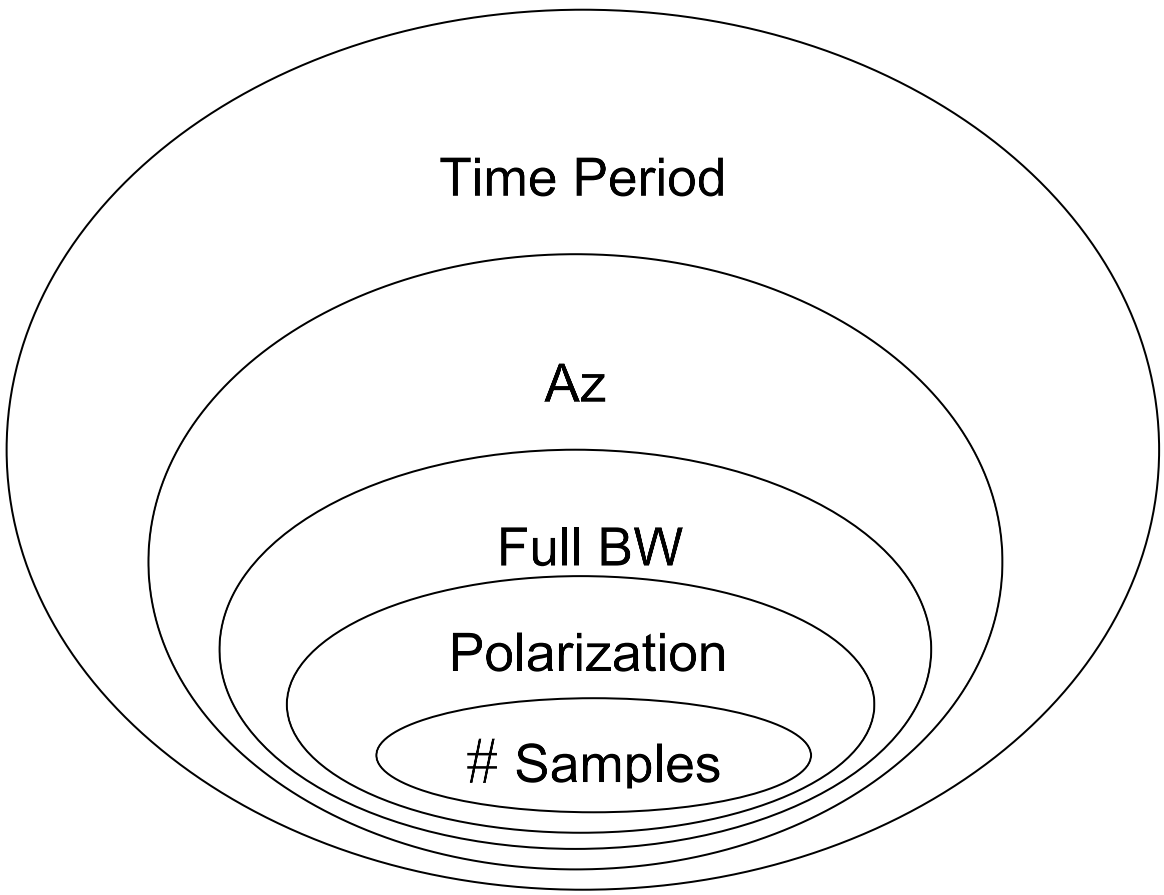

Figure 3.14: Data scheduling algorithm, basic operation.

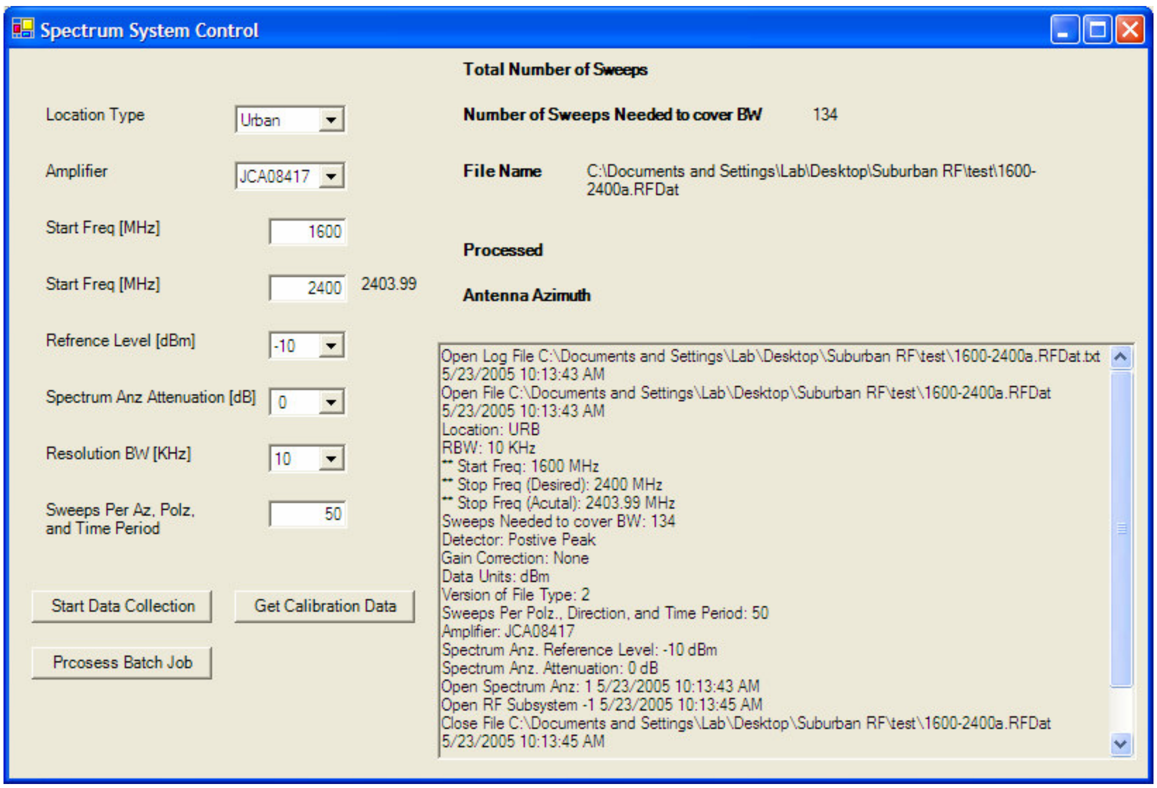

Figure 3.15: Automated spectrum measurement system software interface.

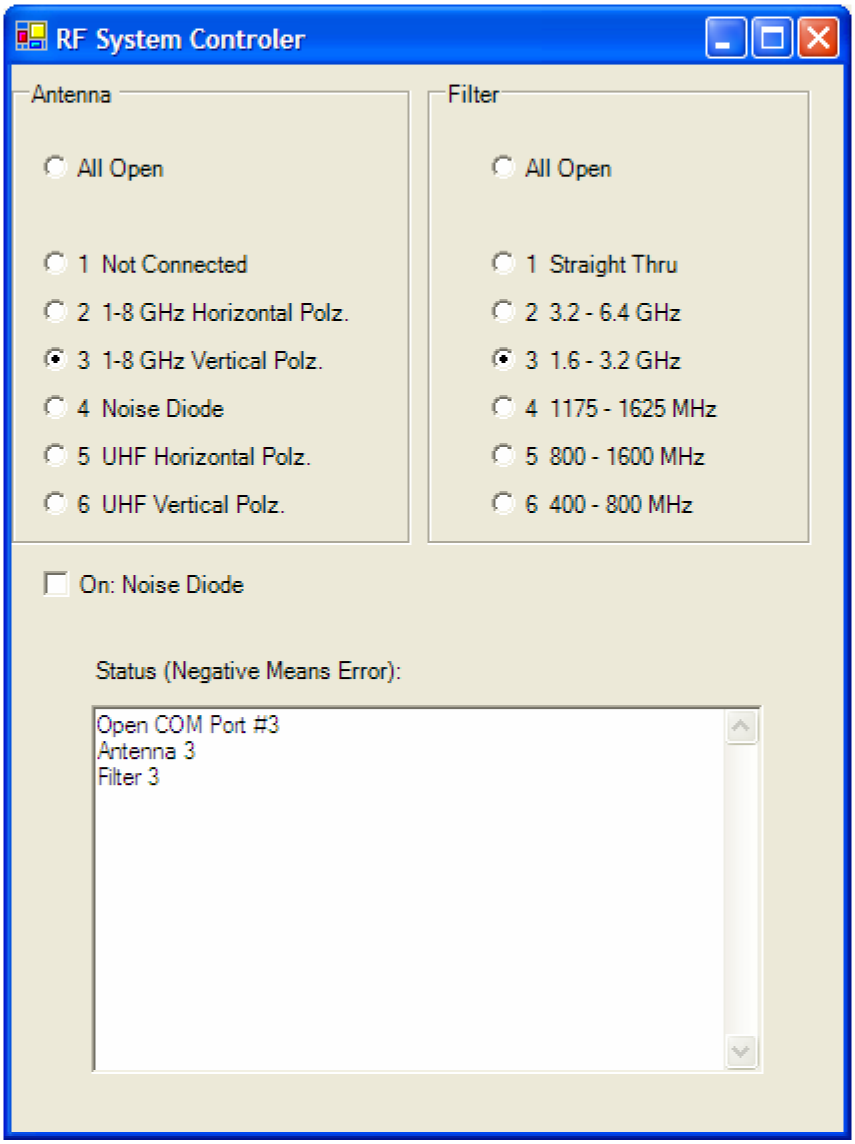

Figure 3.16: RF-subsystem software interface.

3.5.1 Database Structure

All data is saved in a database as a collection of objects, with each object containing one sweep from the spectrum analyzer and 21 other essential parameters. The content of the class RSESFile that is the basis for the database object is shown Appendix A. This format retains all the data produced by the spectrum analyzer in its raw form, thus allowing for later post-processing. This proprietary object-oriented database was required to meet stringent feature and performance objectives, including speed and minimal memory footprints for both long-term (hard drive) and short-term (random access memory, RAM) memory. The improvement in speed and increased flexibility of this database has facilitated data collection and post-processing analysis on 32-bit PC computers.

3.6 Analysis Software

The raw collected data is calibrated and analyzed by a software tool known as ProcData. Similar to RSES this software is written in Microsoft Visual Studio .NET Framework 1.1, in Visual Basic code exclusively. This software takes in the RFDat and RFCal (if the LNA is used) files and created several EXCEL files that contain information on the spectrum study measurement parameters and plots of the results. The graphical user interface for this software is shown in Figure 3.17.

To process data the calibration file (RFCal) is first opened; data is calibrated by averaging the power measured with the noise diode switched on for every 6 MHz of spectrum (or 600 times the RBW if 10 kHz is not being used) with the 6,000 measurements taken. This is then compared to the power output from the noise diode:

$$P\ [\text{dBm}] = -174\ [\text{dBm/Hz}] + 10*\log10(B\ [\text{Hz}]) + ENR\ [\text{dB}] \qquad (3.3)$$

where P is the power in dbm of the noise diode, -174 dBm is the power spectral density at 290 K, B is the bandwidth of the filter in Hz, and ENR is the excess noise ratio of the noise diode.[77] A correction factor of 1.128 is applied to the 3 dB bandwidth of the resolution bandwidth filter to attain is equivalent noise power bandwidth.[66,70] When the spectrum analyzer is in positive peak mode, a correction factor of 4 dB is added to the power figure. Thus all the calibrated data is relative to a continuous wave (CW) signal.

The noise figure (NF) of the system is calculated using:

$$NF\ [\text{dB}] = ENR - 10*\log_{10}(Y-1) \qquad (3.4)$$

where Y is the ratio of the power measured with the noise diode on and off. This is calculated for every 6 MHz of spectrum with 12,000 measurements, 6,000 measurements averaged for the noise diode on, and 6,000 measurements averaged with the noise diode off.

When no LNA is being used for data acquisition the noise figure and losses of the system are estimated with a model based on measures of each individual component in the system.

The ProcData software produces several EXCEL files, with each covering 100 MHz of bandwidth. Each file includes plots resolving spectrum usage in frequency versus time, polarization, azimuth, and average received power. All the plots are rendered with a reduced frequency resolution of 100 kHz. Each plot is 1,001 points wide to ease viewing on a PC monitor and printing. The plots are one point wider then necessary to overlap with the pervious EXCEL file. The EXCEL file stores all the information regarding how the measurements plotted in it were performed. Table 3.6 shows an excerpt of the information included in the file.

The plots produced by ProcData can show: power in dBm normalized to isotropic gain antenna, or spectral power flux density (SPFD) in units of dBW/m^2/Hz.

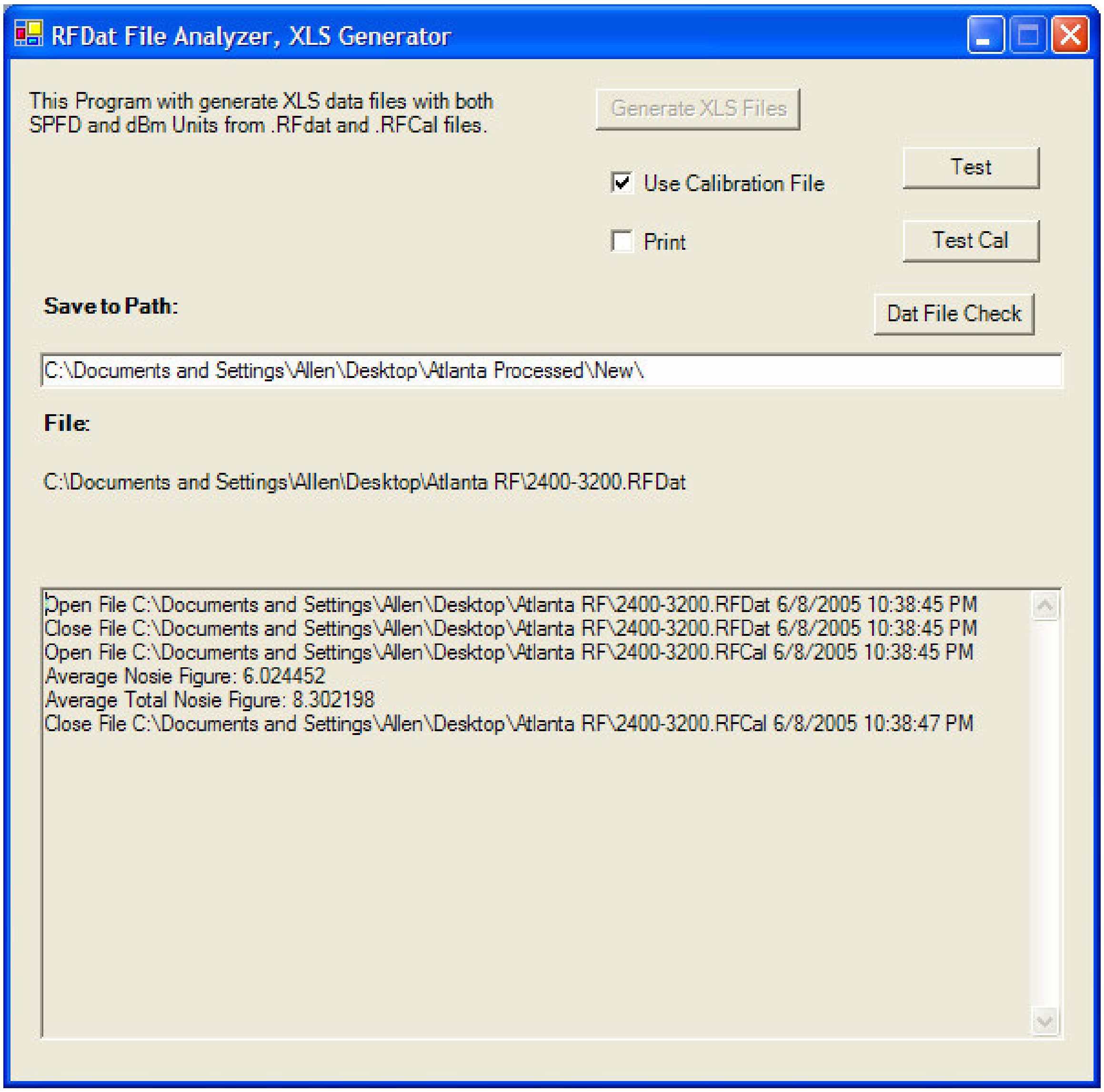

Figure 3.17: User interface for the data analysis software

Table 3.6: Information sheet from EXCEL file, from the rural North Carolina spectrum study.

Location	Urban Atlanta	
Start Date	3/7/2004 9:41 PM	
Stop Date	3/12/2004 6:00 PM	
Start Frequency	2000	MHz
Stop Frequency	2100	MHz
Source Data	1600-2400nm.RFDat	
Source Calibration	1600-2400nm.RFCal	
Number of Data Points	36,036,000	
Points Over Reference Level	0	
Sweeps per Frequency	50	In one Polz. one Az. one Time Pd
Total Points per Frequency	3,600	
Data Points for Plot Point	36,000	
Plot Freq. Resolution	100	kHz
Measurement Version	2	Polz. Switch after each Sweep
Antenna	Singer Empire LPA-112	
Gain	8.5	dBi
Average NF of RF-Subsystem	10.57	dB
Average NF of System	12.43	dB
Average Thermal Noise Floor, with 250K Antenna	-129.6	dBm
Filter	Bandpass: 1600 to 3200	MHz
LNA	JCA08-417	
Spectrum Analyzer	HP8564E	
Resolution Bandwidth	10	kHz
Sweep Time	150	ms
Detector Type	Positive Peak	
Reference Level	-10	dBm
Attenuation	10	dB

Time Region		
Day	8AM to 4PM	
Night	8PM to 12AM, 12AM to 4AM	
Morning & Evening	4AM to 8AM, 4PM to 8PM	

CHAPTER 4

DETECTION OF SPECTRAL EMITTERS

4.1 Spectral Emitter Detection

Accurate detection of active spectral emitters is essential to determine the level of spectrum activity which is useful in development of cognitive radios. Analyzing the spectrum studies to determine where spectrum is being used and to what level provides information on the current level of spectrum usage and shows possible opportunities for spectrum reuse or sharing. Detection of spectrum usage is critical in a cognitive radio that uses a listen-before-talk protocol to find available spectrum in real-time.

Several methods exist to determine the presence of active emitters. The main goal of these methods is to discriminate between the internal thermal noise of the receiver and spectral emitters in the environment.

4.1.1 Signal Types

Several different systems occupy the spectral environment: communications, broadcast, and radio navigation. Most signals are of terrestrial origin, but they are also emitted by aircraft and spacecraft. These signals can be transmitted with varying duty-cycles from continuous to very infrequent, using periodic or random on and off durations. The signals occupy different bandwidths of spectrum, from less than a kHz for beacons to several GHz for some spread spectrum signals (UWB). The emitters may be fixed or moving relative to the receiving system.

A significant amount of *a priori* knowledge may exist for some signals including frequency plan, modulation type, bandwidth, antenna type, transmit power, pulse rate, and higher-level information (bit prefix). This information can aid in the detection and identification of signals.

4.1.2 Threshold Detection

In a threshold detection system, the threshold, which is some value above the average noise power level, represents the minimum required SNR for detection. Any measurement that is above the threshold level is determined to be a signal. Setting a low threshold will increase the probability of detecting signals, but it will also increase the likelihood of mistaking noise for a signal. Conversely, a high threshold will miss more signals but produce fewer false detections of noise as signals.

The theoretical basis for threshold detection using an envelope detector has been thoroughly investigated.[78,79,80,81] The false detection of a signal, known as a false alarm, has probability:

$$P_{FA} = e^{\left(\frac{-V_t^2}{2\psi_o}\right)} \tag{4.1}$$

where V_t is the threshold voltage, and ψ_o is the rms noise power. The noise is assumed to have a Gaussian voltage distribution. The probability of detecting a sinusoidal signal with amplitude A in the presence of noise is:

$$P_D = \int_{V_t}^{\infty} \frac{R}{\psi_o} e^{\left(-\frac{R^2+A^2}{2\psi_o}\right)} \mathrm{I}_o\left(\frac{RA}{\psi_o}\right) dR \tag{4.2}$$

where R is the voltage envelope of the input signal.[82] These two equations can be related to required SNR for different probabilities of false alarm and detection.[83] A SNR of 8.07 dB is required for a P_{FA} of 10^{-3} and P_D of 0.5, using Albersheim's approximation.[84,85] Table 4.1 summarizes several results for different P_{FA} and P_D combinations.

Table 4.1: Required SNR for a sinusoidal signal to achieve P_D and P_{FD} using Albersheim's approximation.

Prob. of Detection	**Prob. of False Alarm**	**Required S/N [dB]**
0.2	1.00E-03	4.77
0.3	1.00E-03	6.36
0.4	1.00E-03	7.33
0.5	1.00E-03	8.07
0.6	1.00E-03	8.70
0.7	1.00E-03	9.29
0.8	1.00E-03	9.92
0.9	1.00E-03	10.72
0.95	1.00E-03	11.35
0.2	1.00E-04	6.91
0.3	1.00E-04	8.05
0.4	1.00E-04	8.80
0.5	1.00E-04	9.40
0.6	1.00E-04	9.92
0.7	1.00E-04	10.42
0.8	1.00E-04	10.97
0.9	1.00E-04	11.67
0.95	1.00E-04	12.24

Figure 4.1 shows the effect of using different threshold levels to determine usage in the spectrum region from 2300 MHz to 2350 MHz from our urban Atlanta spectrum study. The signals seen in this band are from continuously-broadcasting satellite radio systems: Sirius and XM Radio. Sirius has licensed spectrum from 2320 MHz to 2332.5 MHz. This system uses three satellites in highly elliptical orbits (HEO) and several terrestrial repeaters to provide coverage. XM Radio is licensed spectrum to operate Sirius from 2332.5 MHz to 2345 MHz. XM Radio's system differs by using two satellites in a geostationary earth orbit (GEO), known as Rock (at 85° W) and Roll (at 115 ° W). XM also uses terrestrial repeaters to fill in gaps in their coverage caused by shadowing of the satellite's signal. The terrestrial repeaters occupy spectrum that is centered at the satellite radio system's allocation, while the satellites occupy spectrum at the edges of the allocation. From 2300 MHz to 2320 MHz this band appears to have no activity, with a low usage level, which relates to false alarms. For the portions used by the satellite different levels of usage are shown depending on the level of the threshold.

Several detection methods have been developed with improved performance beyond threshold detection. These methods were developed with some knowledge of the signals they are detecting to optimize their performance.

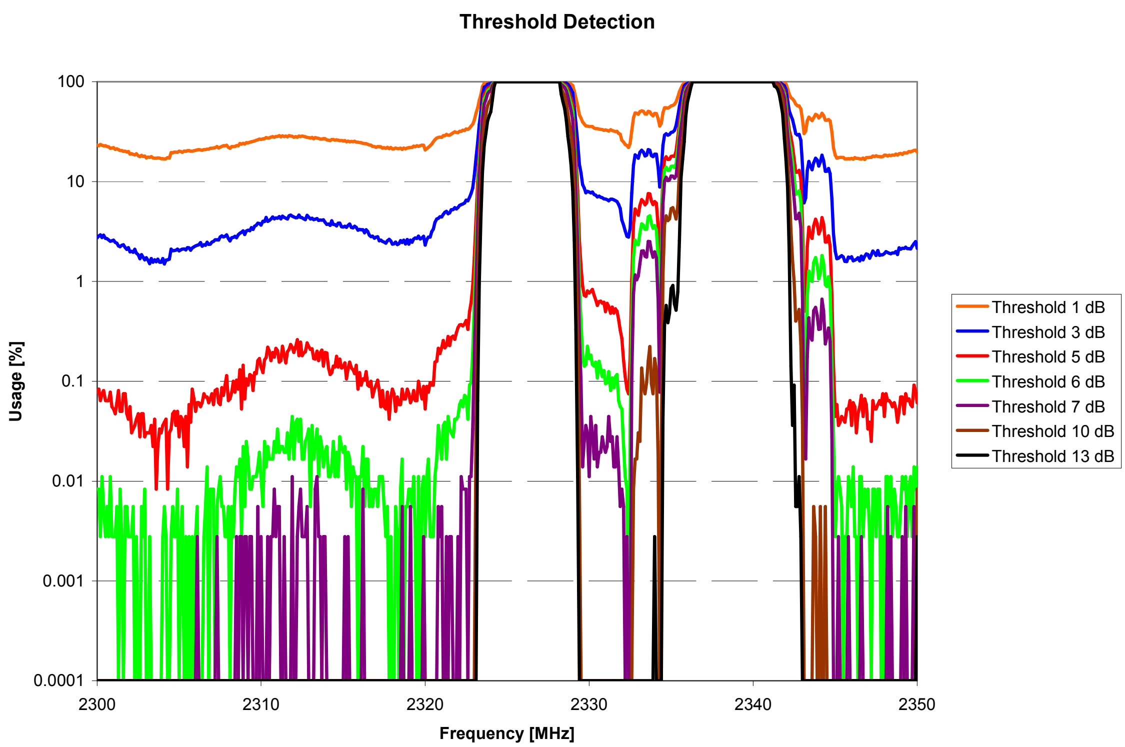

Figure 4.1: Usage detected with varying thresholds, applied to the urban Atlanta spectrum study data from 2300 MHz to 2350 MHz.

4.1.3 Radiometric Detection Techniques

Averaging the power of several successive measurements at the same frequency can be used to improve probability of detection and to reduce false alarm rates. One method referred to as radiometric detection, has been developed by the radio astronomy and the remote sensing communities to separate signals from the thermal noise of a receiver. For a receiver using an envelope detector and exhibiting no gain variations, the minimal detectable change in a system's noise floor in units of Kelvins is:

$$\Delta T_{IDEAL} = \frac{T_{SYS}}{\sqrt{B\tau}} \tag{4.3}$$

where T_{SYS} is the system's thermal noise (Kelvin), B is the bandwidth (Hz) being examined, and τ is the observation time (seconds).[12,14] This can be related to power in units of watts with:

$$P = k\Delta T_{IDEAL}B \tag{4.4}$$

where k is Boltzmann's constant (1.38×10^{-23} W/K/Hz). For coherent signals, use of complex signal information improves the performance of this method by up to 3 dB compared to signals that have been envelope detected.

The performance of his method is limited by the gain stability of the receiving system, and the accuracy and frequency of calibration. Because radiometric detection averages the power of a signal over time, it is ability to detect pulsed or low-duty cycle signals is limited.

4.1.4 Radar Detection Methods

Many radar systems use a pulse integration detection scheme to improve their discovery of targets. This method averages the power received over several discrete intervals where a pulse echo is expected before making a decision on the presence of a target. [80,81,82] This method is similar to radiometric detection with the difference that it only observes when signals are expected. The *a priori* knowledge requirement limits the application of pulse integration for surreptitious receivers.

4.1.5 Cyclostationary Feature Detection

Digitally modulated signals that exhibit statistics with periodic mean and autocorrelation are known as cyclostationary.[86] Cyclostationary signals can be detected in the presence of Gaussian noise by examining the results of an autocorrelation function for periodic patterns. [87,88,89] This detection method offers the ability to discover the presence of signals even when they are received with very-low or negative SNR.[90]

As with other detection methods a longer integration time correlates with a lower required SNR to detect the presence of signals. Software simulations have demonstrated the detection of cyclostationary signals with less than -10 dB SNR with an integration time of several milliseconds.[90] The length of this integration time is necessarily limited for intermittent signals, increasing the minimum SNR necessary to detect cyclostationary intermittent signals.

Implementing cyclostationary feature detection is costly in that significant amounts of digital signal processing (DSP) or specially designed hardware to perform the autocorrelation function and associated filtering are required.

4.2 Multi-Parameter Detection

A detection method can be developed to utilize several different indicators of usage to determine the presence of spectral emitters. The objective of multi-parameter detection is to achieve better performance then any of the individual detection methods alone.

Several different usage detection methods were developed and analyzed with data from the spectrum studies. These methods were designed to exploit all the characteristics of spectral information that was available from the spectrum studies. This section will introduce each method separately. In the implemented multi-parameter detection technique these methods are used in combination to offer the best performance.

4.2.1 Threshold Detection of Signals with Varying Bandwidth

If a signal is transmitted with constant power, its spectral power density will decrease as its bandwidth is increased. This attribute of transmitted signals can be used to increase their probability of detection and reduce false alarm rates when threshold detection is used. A threshold can be set to vary from a high level for narrow band signals, to a lower level for wideband signals. The high threshold level for narrow band signals reduces false alarm rate. For wider-band signals the power in several frequency bins can be averaged before the lower threshold level is applied, reducing false alarms because the magnitude of the Gaussian noise variance is reduced.

Communication signals that have been FM or digitally modulated have bandwidths from tens of kHz to a several MHz: the AMPS cellular phone system has a channel bandwidth of 30 kHz, the digital Global System for Mobile Communications (GSM) system has a channel bandwidth of 200 kHz, and the IEEE 802.11b wireless networking system emits signals with up to 22 MHz of bandwidth.[91,92,93]

The signals emitted by Radar systems vary from less than a MHz to several GHz for tube based radars with high phase noise; advanced frequency hopping radars can occupy several hundred MHz of spectrum. [94,95]

Figure 4.2 and Figure 4.3 show the level of usage detected when one 10 kHz frequency bin is threshold detected, and when the power in 10 adjacent 10 kHz frequency bins is averaged before threshold detection, respectively. The periodic changes of usage detected shown in these figures can be attributed to small gain variations of the broadband log-periodic antennas. When a 5 dB threshold is used both plots show similar usage levels, which relate to probability of detection, because the signals in this plot are at least 100 kHz wide.

The single 10 kHz bin detection method needs to use a threshold of at least 10 dB to have the same false alarm rate as the 100 kHz frequency bin averaging method with a 5 dB threshold. The higher threshold requirement for the single 10 kHz bin detection method relates to a reduced probability of detection

A simple detection method can be constructed by applying a bandwidth dependent threshold TH, with components from equation 3.3:

$$TH(B)\ [dB] < P(B)\ [dbm] + 174\ [dbm] - 10*LOG_{10}(B\ [Hz]) - NF\ [dB] \qquad (4.5)$$

where B is the bandwidth under investigation, P is the power averaged over the bandwidth, and NF is the noise figure of the receiving system. When the terms to the right of the equation exceed the threshold TH, then a signal is determined to be present. The values for TH and the number and width of channels to be investigated can be determined with *a priori* knowledge of the signals to be detected, or by empirical analysis.

The bandwidths to be analyzed can be adjacent to one another or a sliding window method could be used as shown in Figure 4.4. In the adjacent method, sequential bandwidths are analyzed with threshold detection, with the center of each bandwidth analyzed, one bandwidth away from each other. With a sliding window method the bandwidth chosen is swept through the frequency data, and threshold detection is continuously applied. This increased the probability of detection when the frequency usage plan is unknown or varying.

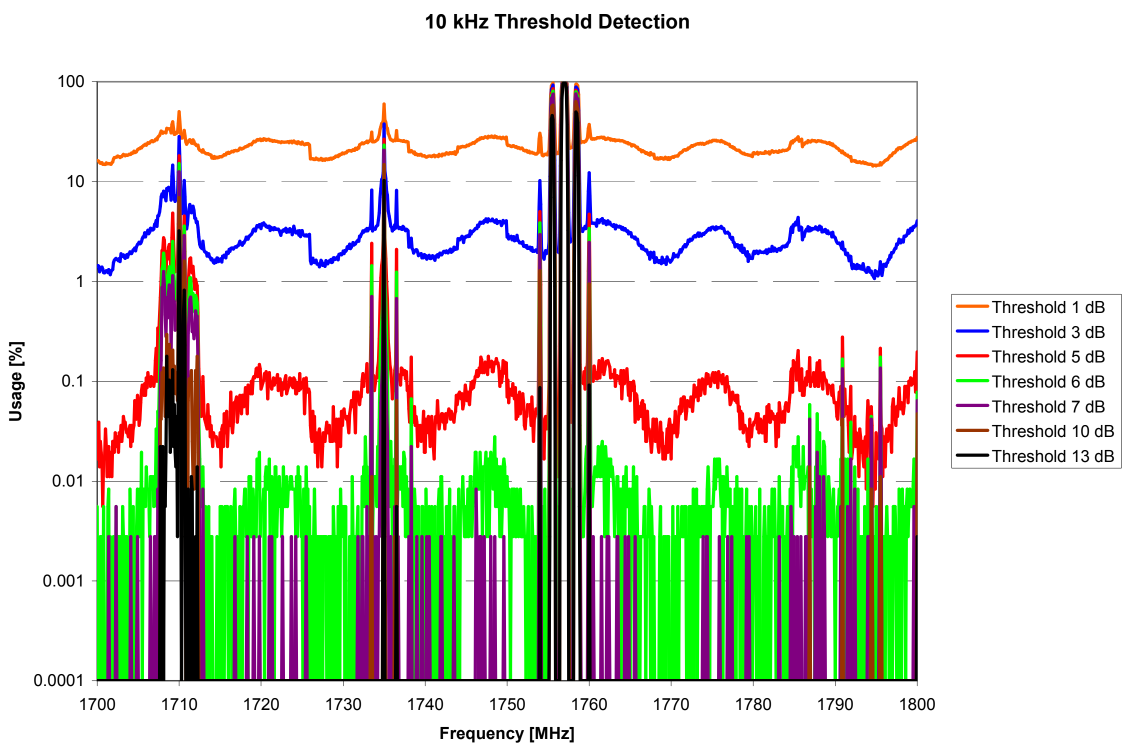

Figure 4.2: Usage detected with 10 kHz frequency bins and varying threshold, applied to the urban Atlanta spectrum study data from 1700 MHz to 1800 MHz.

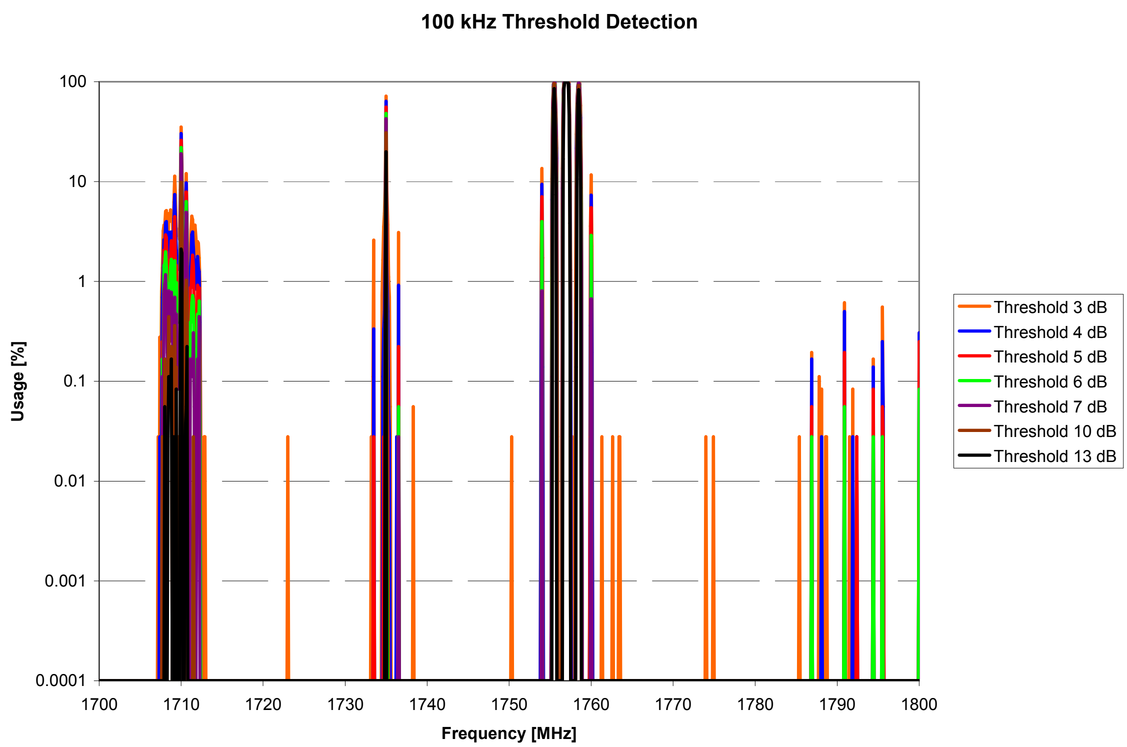

Figure 4.3: Usage detected with 100 kHz frequency bins and varying threshold, applied to the urban Atlanta spectrum study data from 1700 MHz to 1800 MHz.

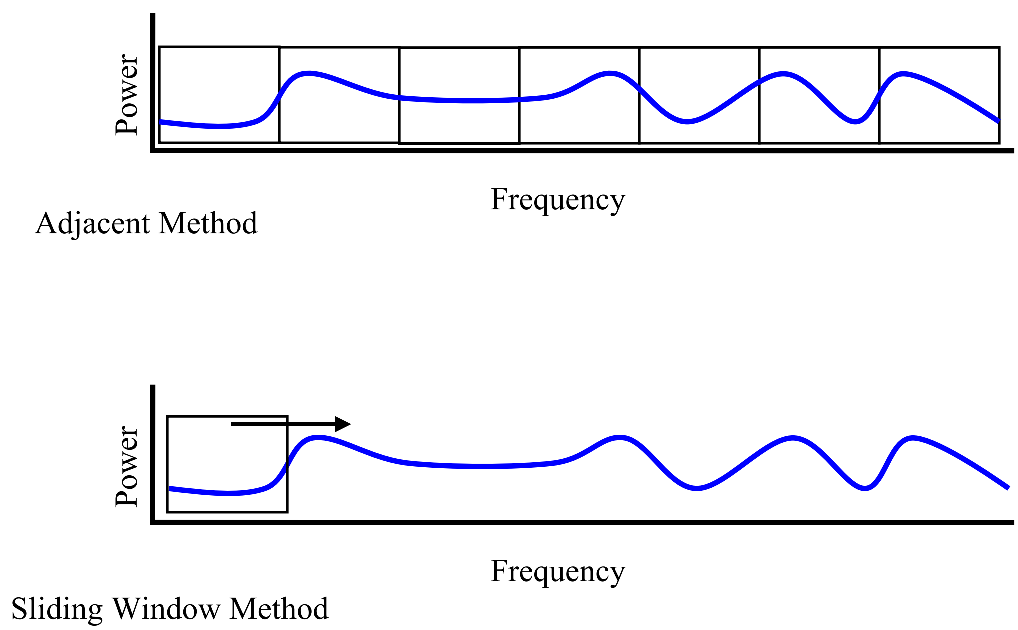

Figure 4.4: Comparison of adjacent and sliding window methods.

4.2.2 Detection of Persistent Signals

The persistence of signals at the same frequency can be used to increase their probability of detection. Figure 4.5 shows the usage level that was detected will varying levels of threshold for the frequency range from 600 MHz to 700 MHz, which is part of the broadcast UHF TV band. Nearly all of the signals in this band are detected at the 100 % usage level, since they are continually broadcast and received at a high SNR. Intermittent communication signals, while not continually broadcasting, use spectrum for a defined amount of time; the bursts of information they transmit often last a few milliseconds. The probability of detection for both broadcast and intermittent signals can be increased by analyzing several data samples to determine the presence of signal emitters. A simple averaging function can accomplish this:

$$TH(\tau)\ [dB] < P(\tau)\ [dbm] + 174\ [dbm] - 10*LOG_{10}(B\ [Hz]) - NF\ [dB] \qquad (4.6)$$

where τ is the duration of time analyzed, TH is the threshold relative to the analysis time, P is the average power of the signals over the time τ, and the bandwidth B can be constant or varying using the method described in the pervious section. When the terms to the right of the equation exceed the threshold TH, then a signal is determined to be present. The values for TH and τ can be determined though *a priori* knowledge of the signals to be detected, or by empirical analysis. If signals with different transmission characteristics are expected, then several values of τ could be used in parallel.

Since *a priori* knowledge of a signal's timing is usually unavailable, a sliding window method that continuously analyses the incoming data is preferred.

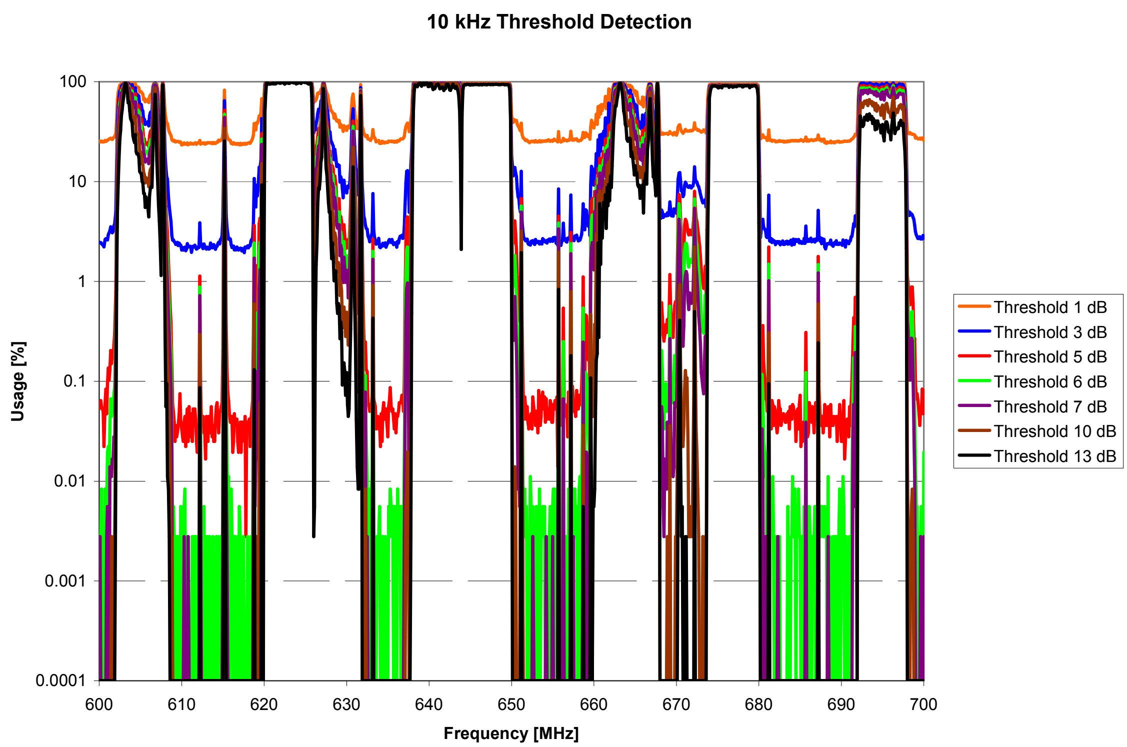

Figure 4.5: Usage detected with 10 kHz frequency bins and varying thresholds, applied to the urban Atlanta spectrum study data from 600 MHz to 700 MHz.

4.2.3 Multipath Detection

The propagation environment affects signals after they are transmitted. Multipath components of a signal result from the signal reflecting off terrain, man-made structures, and other objects. These multipath components are a time shifted version of the original signal. A detection method could be developed by examining received spectral information for multipath components; this could be implemented with an autocorrelation function. The integration time required for detection would depend on the maximum delay of the multipath components. This method would be able to detect signals with little dependence on their transmitted structure (modulation, cyclostationary attributes) by using the propagation environment to add characteristics to signals.

The urban Atlanta spectrum study found significant levels of multipath for the signals present in the environment. Figure 4.6 shows several digitally modulated signals that have experienced multipath propagation. The frequency dependent nature of multipath produces coherent and non-coherent combining of the multipath components at different frequencies. The signals in this figure which were originally transmitted at equal power exhibit this characteristic.

In addition to detection, multipath can also be used to detect the location of some emitters. Figure 4.7 shows the different spectral information received, for 6 different azimuthal pointing directions of the receiving antenna. The direction of the emitter is most likely the direction in which the lowest amount of multipath is experienced; this corresponds to the signal received with the flattest power spectral density.

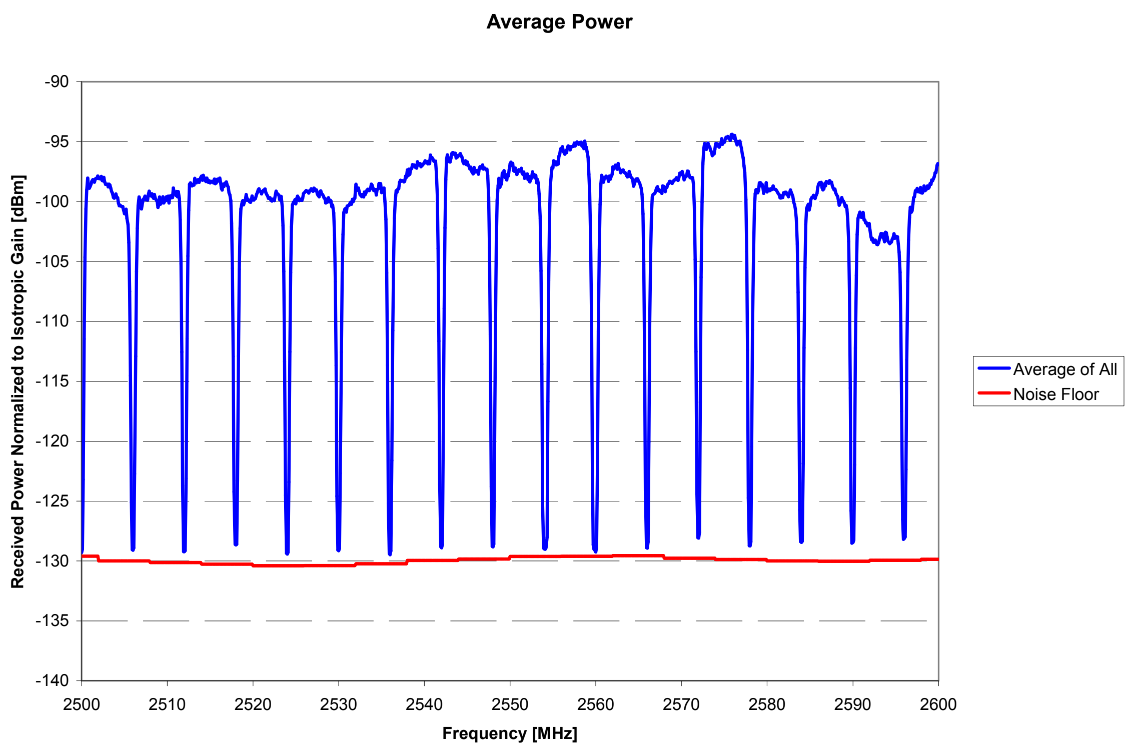

Figure 4.6: Average power measured, from the urban Atlanta spectrum study data from 2500 MHz to 2600 MHz.

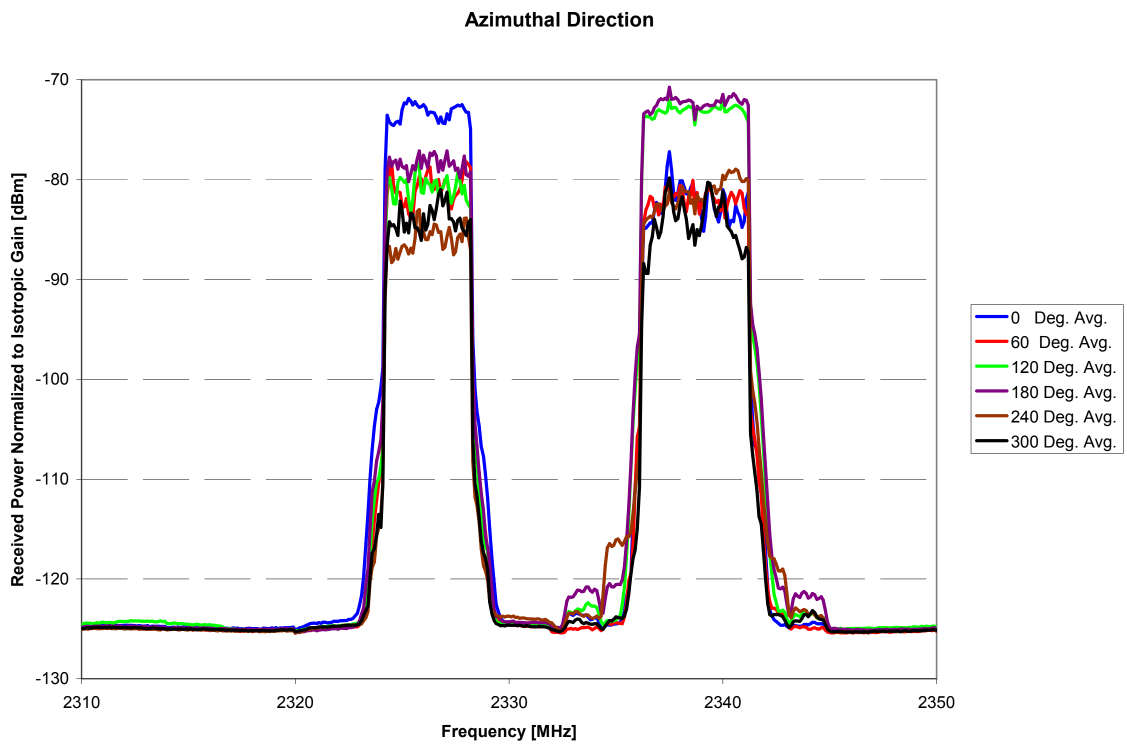

Figure 4.7: Average power measured for different azimuthal pointing directions of the antennas, from the urban Atlanta spectrum study data from 2310 MHz to 2350 MHz.

4.2.4 Polarization Detection

Detection of signals can be enhanced by examining polarization information.[22] Signals are often emitted by the transmitters' antenna with a fixed linear polarization. Figure 4.8 shows the horizontal and vertical constituents for received signals in the UHF TV band. Most of the signals shown in the figure have a 10 dB difference between their different linear polarizations; a few of the signals show low amounts of differential linear polarization (about 3 dB), most likely because they are circularly polarized. The propagation environment can polarize signals through reflections off terrain and other objects, hence slant-linear and circularly polarized signals can gain some level of horizontal or vertical polarization.

Detecting polarized signals can be accomplished with:

$$TH_{PLOZ}\ [\text{dB}] < |\ P_H\ [\text{dBm}] - P_V\ [\text{dBm}]\ | \tag{4.7}$$

where THPLOZ is the polarization difference threshold, PH is power received in the horizontal polarization, and PV is the power received in the vertical polarization. When the terms to the right of the equation exceed the threshold TH_{PLOZ}, then a signal is determined to be present. If circularly polarized receiving antennas are used, then the terms P_H and P_V would be replaced with the terms for right and left hand circular polarization.

An advantage to polarization detection is that at frequencies above about 300 MHz only signals can be polarized; whereas the thermal noise received is independent of the polarization of the receiving antenna.

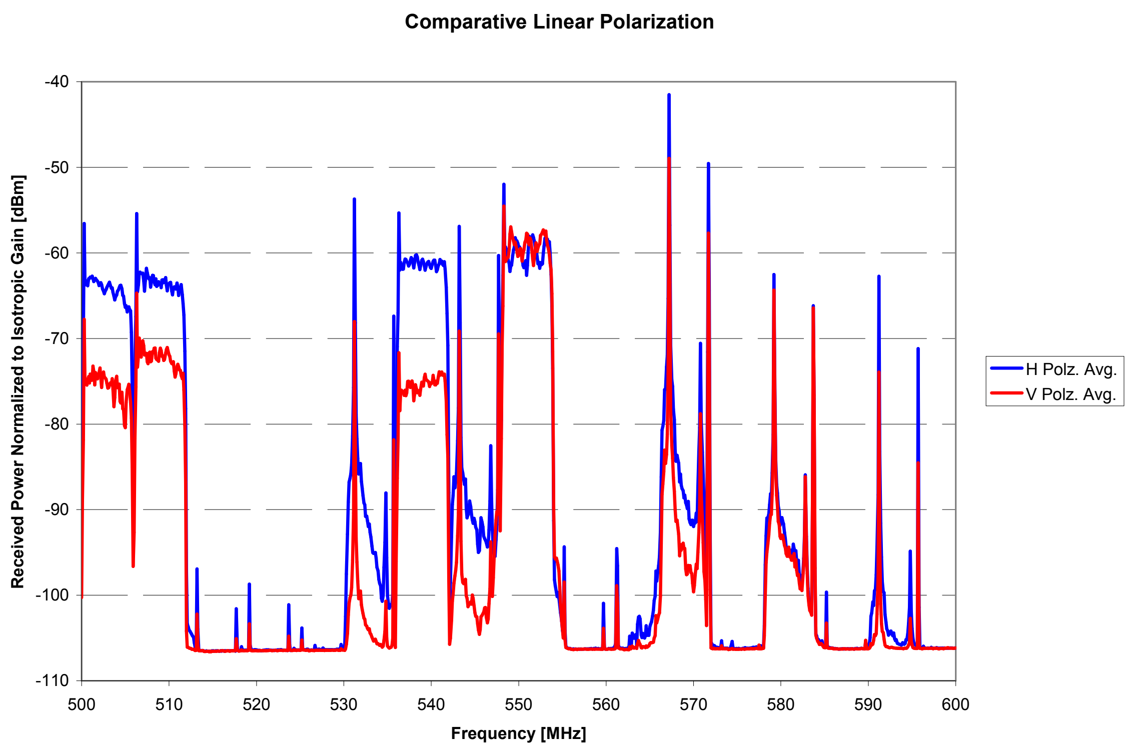

Figure 4.8: Average power measured in horizontal and vertical polarizations, from the urban Atlanta spectrum study data from 500 MHz to 600 MHz.

4.2.5 Spatial Detection

Knowledge of the location of a transmitter can aid in the detection of its signals. The location of an emitter can be known with *a priori* information or determined with azimuthal scanning of the environment or other location finding methods.[96] Figure 4.9 shows the power received from different emitters at different azimuthal pointing directions for the receiving antenna. The location of the emitter can be assumed to be in the direction with highest received power. A detection method can exploit spatial detection by incorporating a term for direction:

$$TH(Az)\ [dB] < P(Az)\ [dbm] + 174\ [dbm] - 10*LOG_{10}(B\ [Hz]) - NF\ [dB]. \quad (4.8)$$

where Az is the pointing azimuthal angle (degrees), and TH(Az) is azimuthal specific threshold. The threshold would be set lower for directions where emitters are known to be present. Knowledge of the frequencies used by an emitter at a particularly direction could also be used to increase detection performance:

$$TH(Az, F)\ [dB] < P(Az, F)\ [dbm] + 174\ [dbm] - 10*LOG_{10}(B\ [Hz]) - NF\ [dB] \quad (4.9)$$

where F is the frequency (Hz), and TH(Az, F) is lower in the direction and frequency of known emitters.

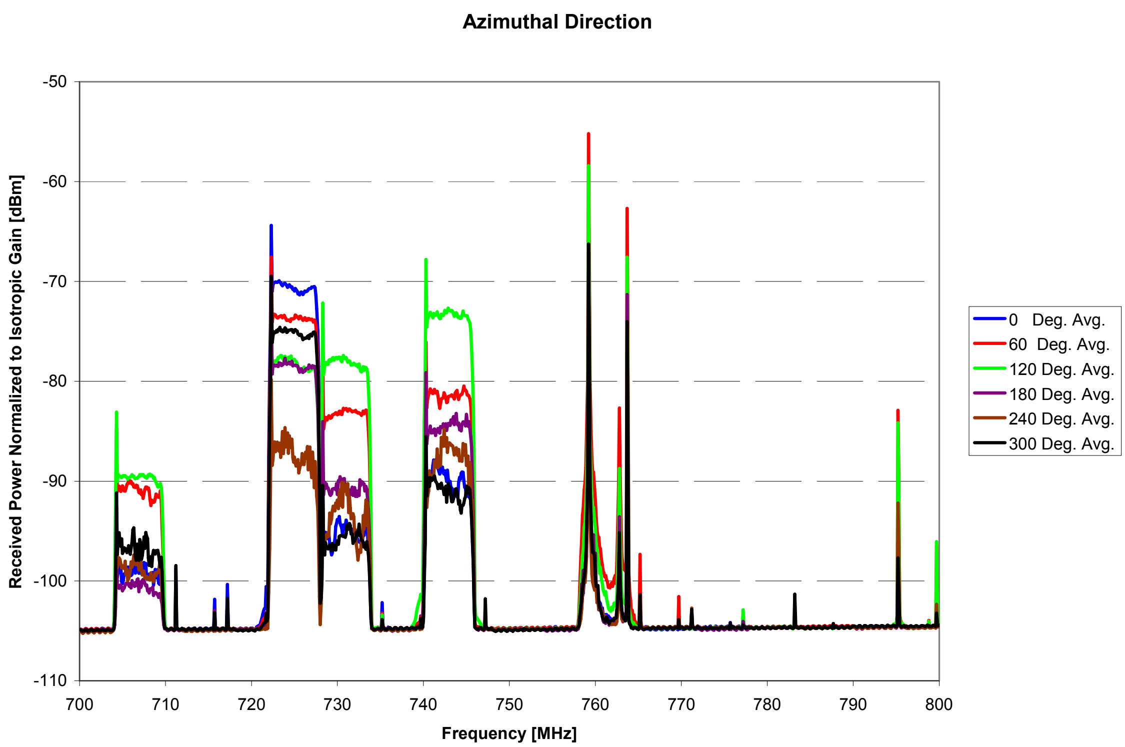

Figure 4.9: Average power measured for different azimuthal pointing directions of the antennas, from the rural North Carolina spectrum study data from 700 MHz to 800 MHz.

4.2.6 Frequency Plan Discovery

Signals are often transmitted with a defined frequency plan. This plan is typically static, not changing for several decades or at a minimum several days. Knowledge of the frequency plan can greatly assist in the detection of signals. The frequency plan can be discovered by data mining the results of usage detected, using the detection methods described in sections 4.2.1, 4.2.2, 4.2.3, and 4.2.4. Then the frequencies that have the highest usage would be assigned a lower threshold. To exploit the frequency plan information the detection method adds a term for frequency:

$$TH(F)\ [dB] < P(F)\ [dbm] + 174\ [dbm] - 10*LOG_{10}(B\ [Hz]) - NF\ [dB]. \qquad (4.10)$$

A priori knowledge of the frequency plan could also be used to assist in detection and prediction of usage. Communication systems often pair uplink and downlink bands, with this knowledge a detection method could assume both of these bands are being used when usage is detected on either uplink or downlink. This feature is very useful when the received power for the uplink band is much weaker than the power received for the downlink band, as is the case for satellite and cellular phones systems.

4.2.7 Temporal Detection Assistance

Emitters often confine their transmission to particular times of the day. Figure 4.10 shows the temporal nature of spectral emitters. The time period in which an emitter is more likely to be transmitting can be determined by data mining past spectrum measurements, or with *a priori* knowledge of the emitter's temporal characteristics. Integrating this temporal knowledge into the detection method yields:

$$TH(TP)\ [dB] < P(TP)\ [dbm] +174\ [dbm] - 10*LOG_{10}(B\ [Hz]) - NF\ [dB] \quad (4.11)$$

where TP is the time periods when transmission is expected. The threshold will be reduced for time periods where emitters have in the past have been detected. Terms for transmitter location and frequency, discussed in previous sections can be integrated into this detection method, to maximize probability of detection:

$$TH(TP, Az, F)\ [dB] < P(TP, Az, F)\ [dbm] +174\ [dbm] - 10*LOG_{10}(B\ [Hz]) - NF\ [dB].$$

(4.12)

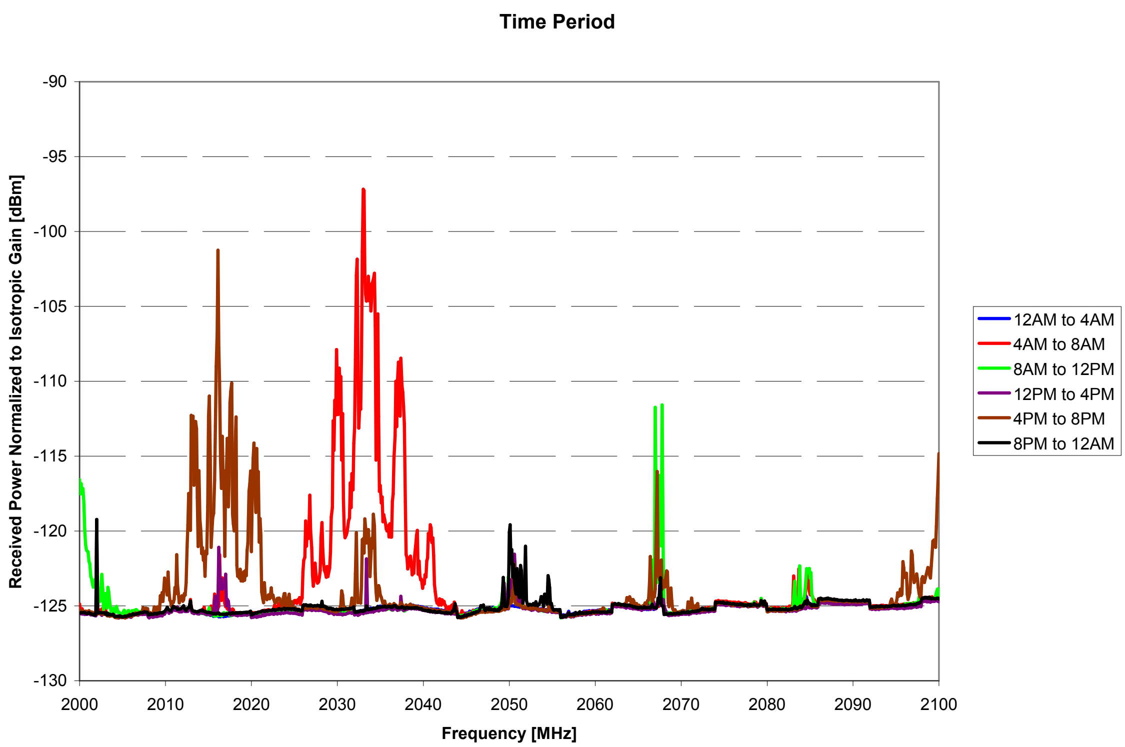

Figure 4.10: Average power measured over different time periods, from the urban Atlanta spectrum study data from 2000 MHz to 2100 MHz.

4.3 Implemented Detection Method for Spectrum Study Analysis

To analyze the data from the spectrum studies a simplified multi-parameter detection method was developed with components from section 4.2. This method was designed to have better performance than threshold detection.

The data produced by the spectrum analyzer is the result of integrating power received over a resolution bandwidth (RBW): this envelope detection process eliminates complex signal information. Hence some of the methods described in the previous section 4.2 can not be applied to the data from our spectrum studies.

To develop this multi-parameter detection method, several of the detection methods in section 4.2 were applied to the spectrum study data sets to examine their performance and determine the variables that should be used in their implementation. This data mining process involved processing over 30 GB of data from the urban Atlanta and rural North Carolina spectrum studies. The results of each detection method were compared with threshold detection and *a priori* knowledge of the systems' characteristics present in particular spectrum bands to evaluate performance. Table 4.2 summarizes some of the detection methods used to mine the spectrum study data. This process involved the creation of several thousand plots and expenditure of several hundred CPU hours.

Table 4.2: Summary of detection methods used in data mining.

Threshold 10 kHz Bin	Threshold 100 kHz Bin	Polarization Difference 10 kHz Bin	Polarization Difference 100 kHz Bin
[dB]	**[dB]**	**[dB]**	**[dB]**
1	3	1	1
3	4	3	3
5	5	5	5
6	6	7	7
7	7	10	10
10	10	13	13
13	13	16	16

The simplified multi-parameter detection used to analyze the spectrum studies was limited in the number of data measurements it could use for each determination of spectral usage. This was to produce percent usage information for every frequency segment. For the most accurate detection, all of the data measured would be used for each determination of spectral usage. This data totals 3,600 measurements for each 10 kHz of spectrum measured: azimuth (6 for each frequency), polarization (2 for each frequency), time period (6 for each frequency), and sweeps in time (50 for each frequency). But this would produce only one determination of usage for a given frequency segment. Additionally, the frequency segment over which a determination of usage would be made was specified to be a relatively narrow (100 kHz). This was to provide a fine grain of analysis of the spectrum studies with a frequency segment that is narrower than most of the signals expected in the frequency range from 400 MHz to 7.2 GHz. The multi-parameter detection was also developed to be a generic detector, detecting the presence of all spectral emitters: from radio navigation and communication systems to transmitter phase noise.

The multi-parameter detection method known as generic v10 uses three methods to detect the presence of spectral usage. If any signal in a 10 kHz frequency bin is greater than 10 dB above the calibrated noise floor, then that one frequency bin is determined to have usage. If the difference in power of the horizontal and vertical polarizations averaged over a 100 kHz frequency bin (10 samples for each polarization) is greater than 6 dB, then the complete 100 kHz frequency bin is determined to have usage. If the power averaged over a 100 kHz frequency bin in both polarizations (20 samples) is greater than 4 dB above the calibrated noise floor then the complete 100 kHz frequency bin is determined to have usage. The individual detection methods are very sensitive with respect to their threshold value; changing the threshold value by as little as 1 dB, can produce a ten fold increase in false alarms.

The generic v10 detection method developed is much simpler than was expected to achieve the level of performance that it attains. Furthermore, the integration of additional detection methods to increase its probability of detection was found to have a disproportionately negative effect on false alarm rate performance.

The sliding window method discussed in section 4.2.1 is not used to process the data, because the results produced for probability of detection and false alarm rate would use redundant data, and hence would be statistically inaccurate.

4.4 Results of Generic v10 Detection Method

This section will detail the results of the generic v10 multi-parameter detection method with data from the urban Atlanta and rural North Carolina spectrum studies. The generic v10 method will be compared with threshold detection at 3 dB and 5 dB, since these levels offer similar probability of detection.

Figure 4.11 shows the results of the three detection methods on a region of spectrum measured in rural North Carolina that most likely had an emitter operating on it. The false alarm rate for these methods can be determined from this vacant spectrum. The generic v10 method shows usage at the 0.001 % level, this level represents 0 detections (the plot creation software uses the 0.001 % value to signify 0, because 0 can not be plotted on a log scale), hence the false alarm rate is 0. The threshold methods exhibit false alarm rates at 0.0318 and 0.0013 for the 3 dB and 5 dB levels respectively.

The false alarm rates shown in Table 4.3 were computed by analyzing the portions of the urban Atlanta and rural North Carolina studies where no emitters were expected to be present. The false alarm rate for the generic v10 method was determined to be $< 10^{-6}$. To attain a more definitive value for the false alarm rate of the generic v10 method more measured data is needed.

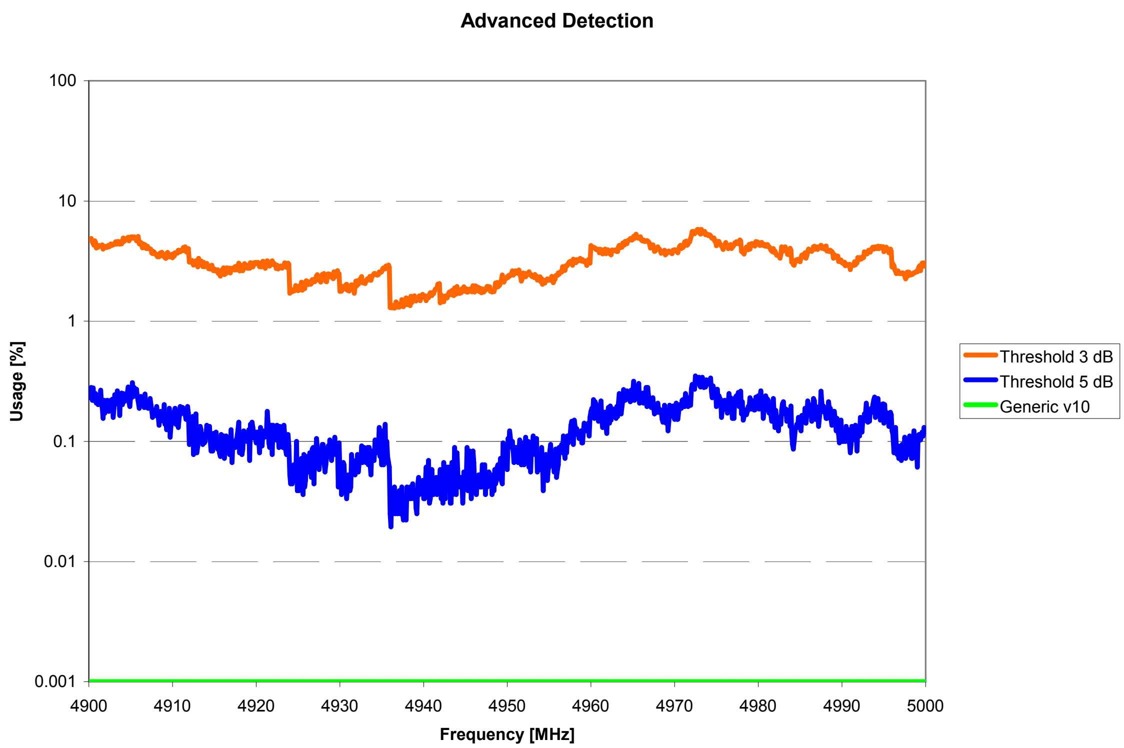

Figure 4.11: Comparison of usage detected with generic v10 detection and threshold detection at 3 dB and 5 dB, from the rural North Carolina spectrum study data from 4900 MHz to 5000 MHz.

Table 4.3: Comparison of false alarm rates for different detection methods.

Detection Method	**False Alarm Rate**
3 dB Threshold	0.04
5 dB Threshold	0.002
Generic v10	$< 10^{-6}$

4.4.1 Broadcast Signals

Figure 4.12 shows the results of the three detection methods used in a region of spectrum occupied by satellite radio broadcast transmitters. All the methods show the same level of usage for the terrestrial repeaters centered at 2326.25 MHz and 2338.75 MHz, because of their high SNR. The lower power satellite signals shown at the sides of the XM band from 2332.5 MHz to 2345 MHz are detected with the generic v10 method at a usage level less than that detected by the 3 dB threshold method and slightly more than that detected by the 5 dB threshold method.

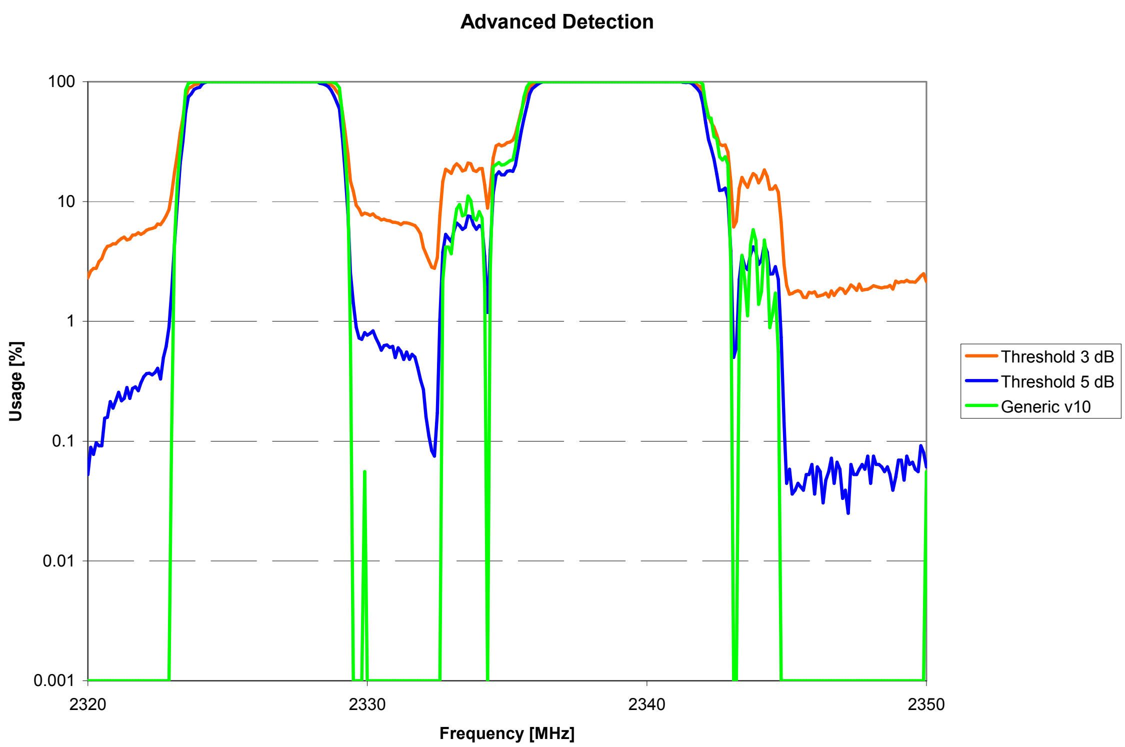

Figure 4.12: Comparison of usage detected with generic v10 detection and threshold detection at 3 dB and 5 dB, from the urban Atlanta spectrum study data from 2300 MHz to 2400 MHz.

4.4.2 Intermittent Communication Signals

Figure 4.13 shows the results of the three detection methods used in a region of spectrum occupied by IEEE 802.11 wireless emitters. These devices intermittently operate on the ISM spectrum from 2400 MHz to 2383.5 MHZ. The generic v10 method offers a higher probability of detection compared with 3 dB threshold detection over the complete ISM band. The generic v10 method at the same frequency (2459 MHz) shows a 24 % higher usage level than the 3 dB threshold detection method and a 40 % higher usage level than the 5 dB threshold detection method. The narrow band signals (2450.7 MHz, 2480.5 MHz) in the ISM spectrum are also detected with the generic v10 method at higher usage levels compared with the threshold methods.

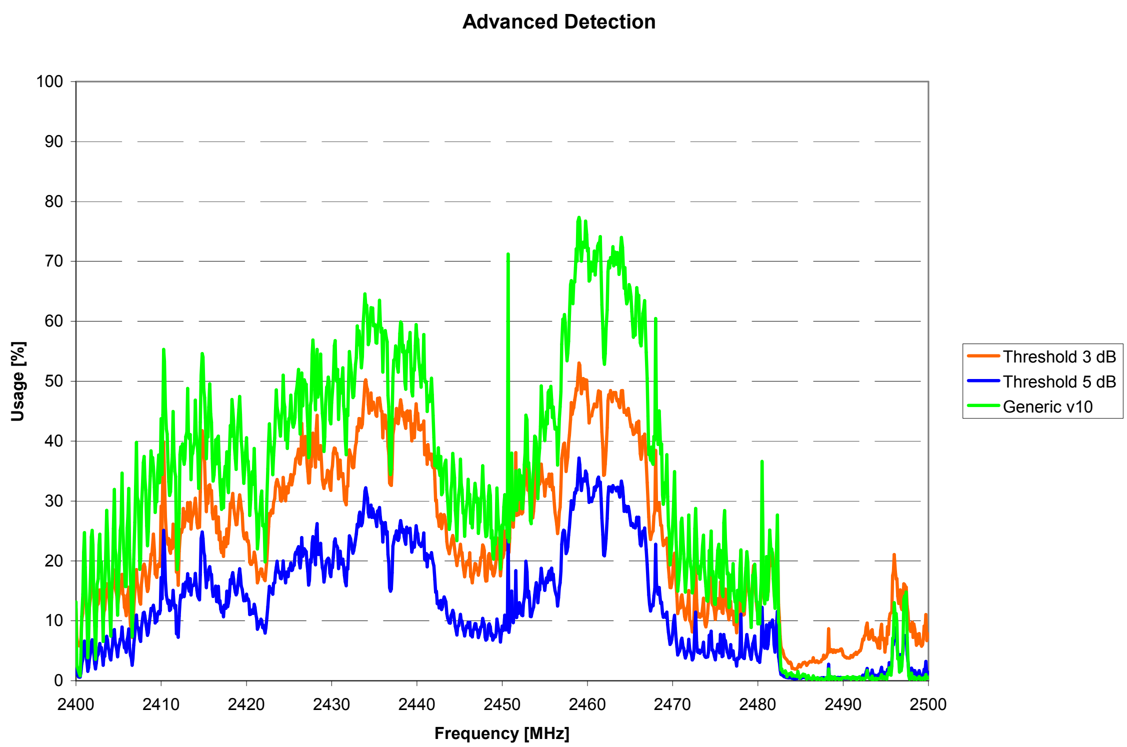

Figure 4.13: Comparison of usage detected with generic v10 detection and threshold detection at 3 dB and 5 dB, from the urban Atlanta spectrum study data from 2400 MHz to 2500 MHz.

4.4.3 Radar Signals

Figure 4.14 shows the results of the three detection methods used in a region of spectrum occupied by several different radar systems. The generic v10 method shows usage levels that are occasionally higher than with 3 dB threshold detection, and always higher than with the 5 dB threshold detection. The generic v10 method detects less usage than the 3 dB threshold detection method, because many of the radars' duty cycles are lower than the false alarm rate for the 3 dB threshold detection method. This figure illustrates the difficulty of identifying signals in the presence of false detections from the threshold methods.

Figure 4.15 shows another area of spectrum occupied by radars. In this figure, the ability of the generic v10 method to identifying signals with vastly greater clarity compared with the threshold detection methods is demonstrated. Several of the radars in this figure are "lost" in the false detections of the threshold detection methods.

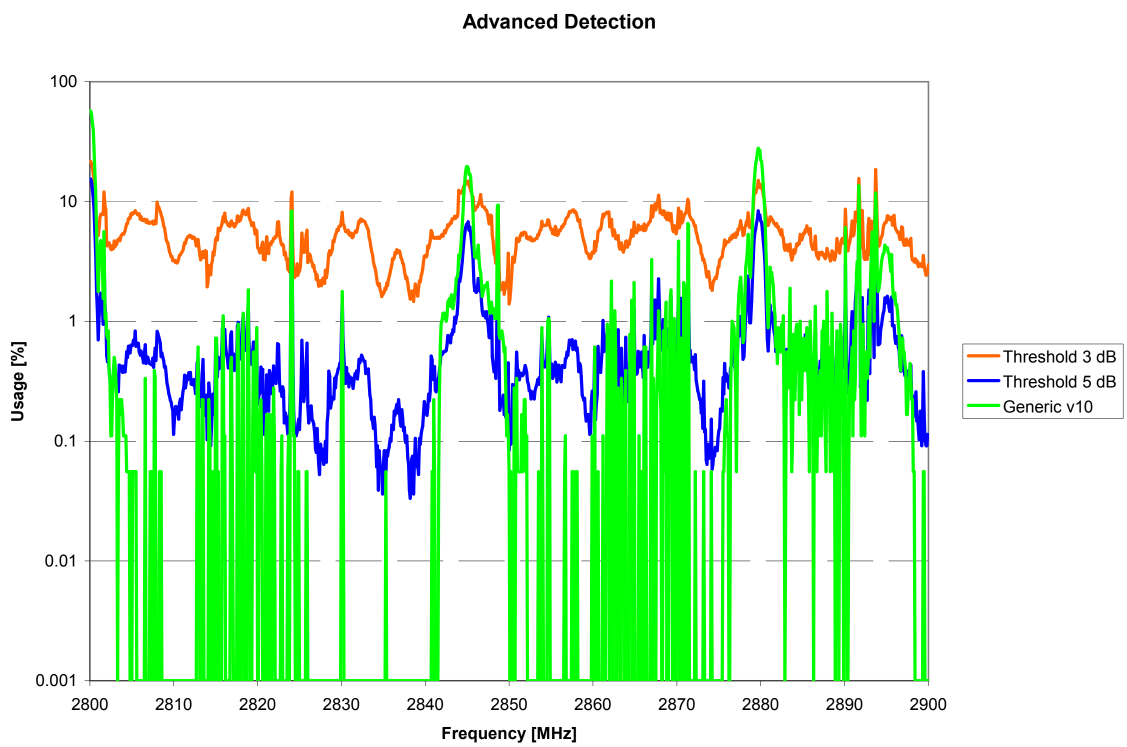

Figure 4.14: Comparison of usage detected with generic v10 detection and threshold detection at 3 dB and 5 dB, from the urban Atlanta spectrum study data from 2800 MHz to 2900 MHz.

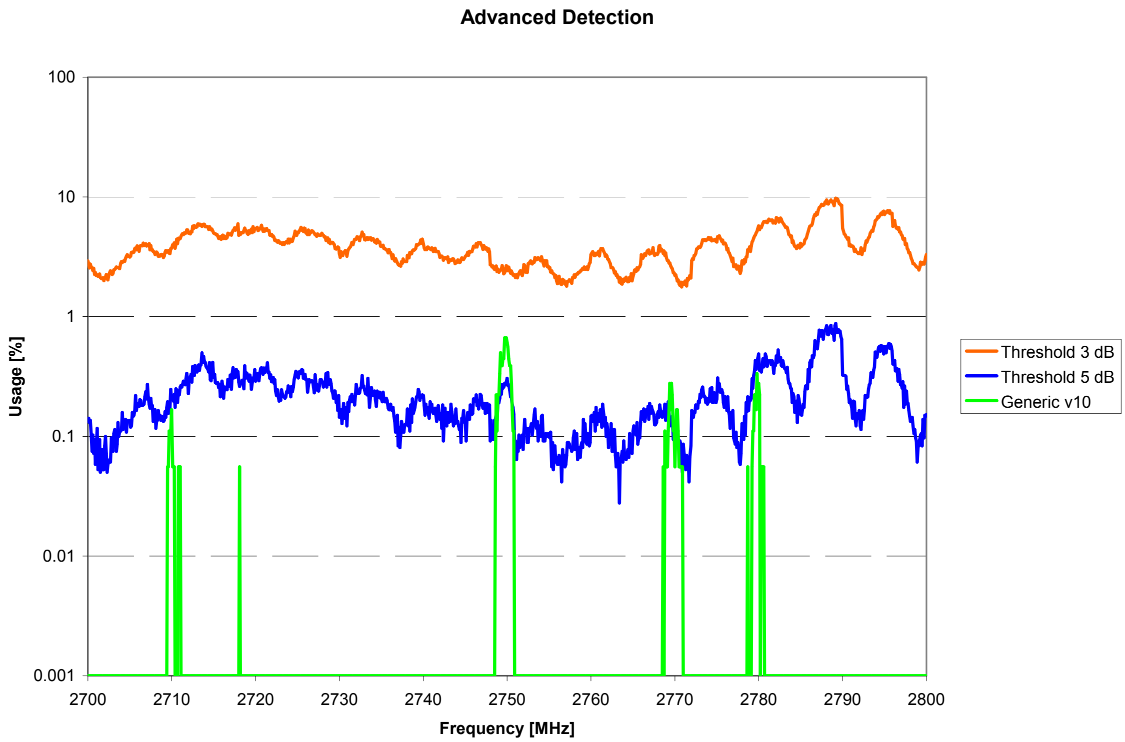

Figure 4.15: Comparison of usage detected with generic v10 detection and threshold detection at 3 dB and 5 dB, from the rural North Carolina spectrum study data from 2700 MHz to 2800 MHz.

4.4.4 Conclusion

The generic v10 method achieves a probability of detection that is better than the 3 dB threshold detector for most signals while exhibiting a false alarm rate that is at least 40,000 times lower.

The performance of the generic v10 method could be improved if additional detection methods discussed in section 4.2 are implemented, although this requires complex signal information, and much higher implementation complexity. Also, a multi-parameter detection method could be targeted to find emitters from a particular system type to further improve performance beyond the generic v10 method.

4.5 Cognitive Radio Implementation of Multi-Parameter Detection Method

The generic v10 detection method could be implemented into a cognitive radio to discover unused spectrum. Table 4.4 shows how often a false alarm would be experienced in a cognitive radio if detection is performed once per second. The generic v10 detection method offers less then three false alarms over the course of a month, compared with a false alarm every 25 seconds for the 3 dB threshold detection method.

4.5.1 Single Decision Determination of Usage

In contrast to the generic v10 detection method, the detection methods discussed in section 4.2 can be combined to provide a single determination of usage based on *all* available spectrum measurements. This multi-parameter detection method will determine usage for spectrum measured at a given frequency (F), over a bandwidth (BW), time segment (TS), antenna pointing azimuth (Az), and time period (TP), using components from equations 4.5, 4.6, 4.7 and 4.12:

$$TH_{Total}(F, BW, TS, TP, Az) <$$

$$\sum_{B} \sum_{F=F_{Start}}^{F_{Start}+BW-B} B_{WF}\left(P(F,B)[dBm] + 174[dBm] - 10LOG_{10}(B[Hz]) - NF[dB]\right)$$

$$+\sum_{B} \sum_{F=F_{Start}}^{F_{Start}+BW-B} Polz_{WF}\left|P_H(F,B)[dBm] - P_V(F,B)[dBm]\right|$$

$$+\sum_{\tau} \sum_{T=0}^{TS-\tau} \tau_{WF}\left(P(T,\tau)[dBm] + 174[dBm] - 10LOG_{10}(B[Hz]) - NF[dB]\right)$$

$$+WF(TP, Az, F) \quad (4.13)$$

where TH_{Total} is the total threshold value, B is a collection of bandwidths that the data is analyzed over, B_{WF} is the weighting factor for each bandwidth, $Polz_{WF}$ is the weighting factor for polarization detection for each bandwidth, τ is a collection of time durations over which measurements are averaged, τ_{WF} is the weighting factor for each time duration, and WF is the weighting factor relative to time period, azimuth, and frequency. When the terms on the right side of the equation exceed TH_{Total} then usage is determined to be present. The values for $TH_{Total,}$ B, B_{WF}, $Ploz_{WF}$, τ, τ_{WF}, and WF can be determined though *a priori* knowledge of the signals to be detected, or by empirical analysis. This method implements a sliding window method to maximize the probability of detecting a signal. However, unlike the generic v10 detection method, percentage usage is no longer determinable.

4.5.2 Multi-node Detection

Several nodes of a cognitive radio network could use their integrated ability to detect spectral emitters to improve the network's performance. The nodes in a network could be spatially distributed, increasing the probability that the network as a whole would detect the presence of signals. If the nodes synchronize their detection process, then the amount of data available for a detection determination could be increased, thus increasing the performance of the detection method especially for pulsed or low duty cycle signals.

A network of cognitive radio nodes can use their spatial distribution to detect the location of transmitters, improving their knowledge of the spectral environment and adding a tool for use by the detection method.

Finally, the analysis of different spectral regions could be distributed among the nodes in cognitive radio network, reducing the amount of time each node dedicates to this task.

Table 4.4: Results of implementing different detection methods in a cognitive radio.

Detection Method	False Alarm Rate	False Alarm Every*
3 dB Threshold	0.04	25 Seconds
5 dB Threshold	0.002	8.3 Minutes
Generic v10	$< 10^{-6}$	> 11.6 Days

* with detection once a second

CHAPTER 5

SPECTRUM STUDY RESULTS

5.1 Analysis Software

The analysis software ProcData, described in section 3.6 was extensively revised to implement the generic v10 detection method. This software (known as v3) has numerous structural changes and additional features. The software was developed in the same environment as the pervious version: Microsoft Visual Studio .NET 2003 with Framework 1.1.

The ProcData software was recomposed into 6 primary classes: Form1, RSESFile, DATFileAccCl, DATDataCl, DetectorCl, and DATXLSCl. All of the classes are written in Visual Basic .NET. The Form1 class is the main object: forming the user interface, initializing the other classes, and initiating high-level events. RSES software also has a class named Form1, which is completely different; the Form1 name is used for consistently, to represent the main object. The RSESFile class is exactly the same class used for the object-oriented database described in section 3.5.1. The DATFileAccCl is used to access and calibrate all the data stored in the object-oriented database. It uses the same calibration method described in section 3.6.

The DATDataCl is used to form an object that stores all the data for ProcData. This runtime data storage method offers a controllable memory footprint, and simplified data access. This data object can be created and destroyed without affecting other components of the ProcData software. Different areas of spectrum or data from different spectrum studies can be analyzed simultaneously with ease, by creating new data objects. Additionally, development of a parallel processing version of ProcData software is simplified by the use this storage structure.

Microsoft Windows XP Processional is limited in the amount of memory is can allocate to a process, because of its 32-bit basis. For software developed with Microsoft's memory manager, there typically is a memory limit of 1 GB. The exact memory limit depends on the structure of memory allocation desired (several data primitives or a large multi-dimension array) and system specific issues. Since the data files to be processed are up to 2 GB in size, the analysis software is memory limited. In the current implementation, the DATDataCl based object stores data in 100 MHz segments, to reduce its memory footprint. After Microsoft releases a 64-bit software development environment and operating system, the ProcData software could be modified to expand its memory footprint. This 64-bit version of ProcData would be able to process data at least twice the speed of the current implementation, if adequate amounts of RAM are available.

The DetectorCl class contains the function to implement the generic v10 detection method, in addition to several other usage detectors. The DATXLSCl class is used to generate all the EXCEL output files. As with the pervious version the plots produced can show: power in dBm normalized to isotropic gain antenna, or spectral power flux density (SPFD) in units of dBW/m^2/Hz. The DATXLSCl class uses Microsoft's EXCEL 2003 and Office 2003 objects to support this task. The creation of EXCEL files accounts for almost half of the time needed for ProcData to process data.

5.1.1 EXCEL File Description

The EXCEL files produced by ProcData v3 contain 13 worksheets with plots, data, and information. As with the previous version of ProcData, each EXCEL file contains data for 100 MHz of spectrum. All the plots are rendered with a reduced frequency resolution of 100 kHz. The plots are 1,001 points wide to overlap one point with each sequential EXCEL file.

All the data plotted in the EXCEL file is stored in a worksheet named "Data." A worksheet named "Info" stores information on how the data was acquired and information that pertains to the entire 100 MHz band. Shown in Table 5.1 is the "Info" worksheet from the EXCEL file. The terms in this table are mostly self explanatory. The "Total Percentage Usage" term refers to the usage determined to exist over the entire 100 MHz band, using the generic v10 detection method. The "Percentage of Bandwidth with No Usage" term refers to the percentage of the 100 MHz band that the generic v10 detection method never detects usage.

ProcData produces 11 plots to show different characteristics of the data and the results of several different usage detection methods. All the data in the plots is calibrated relative to a CW signal.

Figure 5.1 shows the average power compared with the “Noise Floor”. The average power is determined for each point in the plot by averaging 36,000 data measurements, covering 100 kHz of spectrum. The level of the “Noise Floor” is typically 4 dB higher than the level given for “Average Thermal Noise Floor, with 250K Antenna” in the “Info” worksheet. The value for “Average Thermal Noise Floor, with 250K Antenna” is the maximum sensitivity of the system. The “Noise Floor” has been corrected to take into account the positive peak detection method. If it was not corrected then the “Average of All” would always be higher than the “Noise Floor” even when no usage is present.

Figure 5.2 shows the power percentile distribution. The percentile is determined for each point with 36,000 data measurements, covering 100 kHz of spectrum.

Figure 5.3 shows the average power for the two different linear polarizations. The average power for each polarization is determined for each point in the plot by averaging 18,000 data measurements, covering 100 kHz of spectrum.

Figure 5.4 shows the average power for six different time periods, each four hours long. The average power for each time period is determined for each point in the plot by averaging 6,000 data measurements, covering 100 kHz of spectrum.

Figure 5.5 shows the average power for three time regions, each covering 8 hours. The “Day” time region covers from 8 AM to 4 PM, the “Night” time region covers from 8 PM to 12 AM and from 12 AM to 4 PM, and the "Morning & Evening" time region covers from 4 AM to 8 AM and from 4 PM to 8 PM. Data for the time regions is gathered by combining the time periods. The average power for each time region is determined for each point in the plot by averaging 12,000 data measurements covering, 100 kHz of spectrum.

Figure 5.6 shows the average power received for the six different azimuthal pointing directions of the receiving antennas. The average power for each direction is determined for each point in the plot by averaging 6,000 data measurements, covering 100 kHz of spectrum.

Five additional plots show the implementation of different detection methods. The usage level shown is each of these plots is calculated in 100 kHz intervals, to match the plot resolution.

Figure 5.7 shows the polarization difference detection method for varying threshold levels, performed on a single 10 kHz frequency bin.

Figure 5.8 shows the polarization difference detection method for varying threshold levels, performed by averaging 10 frequency bins (100 kHz).

Figure 5.9 shows the threshold detection method for varying threshold levels, performed on a single 10 kHz frequency bin.

Figure 5.10 shows the threshold detection method for varying threshold levels, performed by averaging 10 frequency bins (100 kHz).

Figure 5.11 shows the generic v10 detection method compared with the threshold detection method with 3 dB and 5 dB thresholds, performed on a single 10 kHz frequency bin.

Table 5.1: Information sheet from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

Process With ProcDat V3, Updated Feb 24, 2005			
Location	Urban Atlanta		
Start Date	3/15/2004 11:50 AM		
Stop Date	3/17/2004 9:49 AM		
Start Frequency	800	MHz	
Stop Frequency	900	MHz	
Source Data	800-1200noLNA.RFDat		
Source Calibration	No File, Default Cal.		
Number of Data Points	36,036,000		
Points Over Reference Level	0		
Sweeps per Frequency	50	In one Polz. one Az. one Time Pd	
Total Points per Frequency	3,600		
Data Points for Plot Point	36,000		
Plot Freq. Resolution	100	KHz	
Measurement Version	3	Polz. Switch after several Sweeps	
Antenna	Create 5130-2N		
Gain	8	dBi	
Average NF of RF-Subsystem	32.6	dB	
Average NF of System	34.04	dB	
Average Thermal Noise Floor, with 250K Antenna	-107.4	dBm	
Total Percentage Usage	41.451	%	
Percentage of Bandwidth with No Usage	24.476	%	
Filter	Bandpass: 800 to 1600	MHz	
LNA	None		
Spectrum Analyzer	HP8564E		
Resolution Bandwidth	10	KHz	

Sweep Time	150	ms	
Detector Type	Positive Peak		
Reference Level	-20	dBm	
Attenuation	0	dB	
Time Region			
Day	8AM to 4PM		
Night	8PM to 12AM, 12AM to 4AM		
Morning & Evening	4AM to 8AM, 4PM to 8PM		

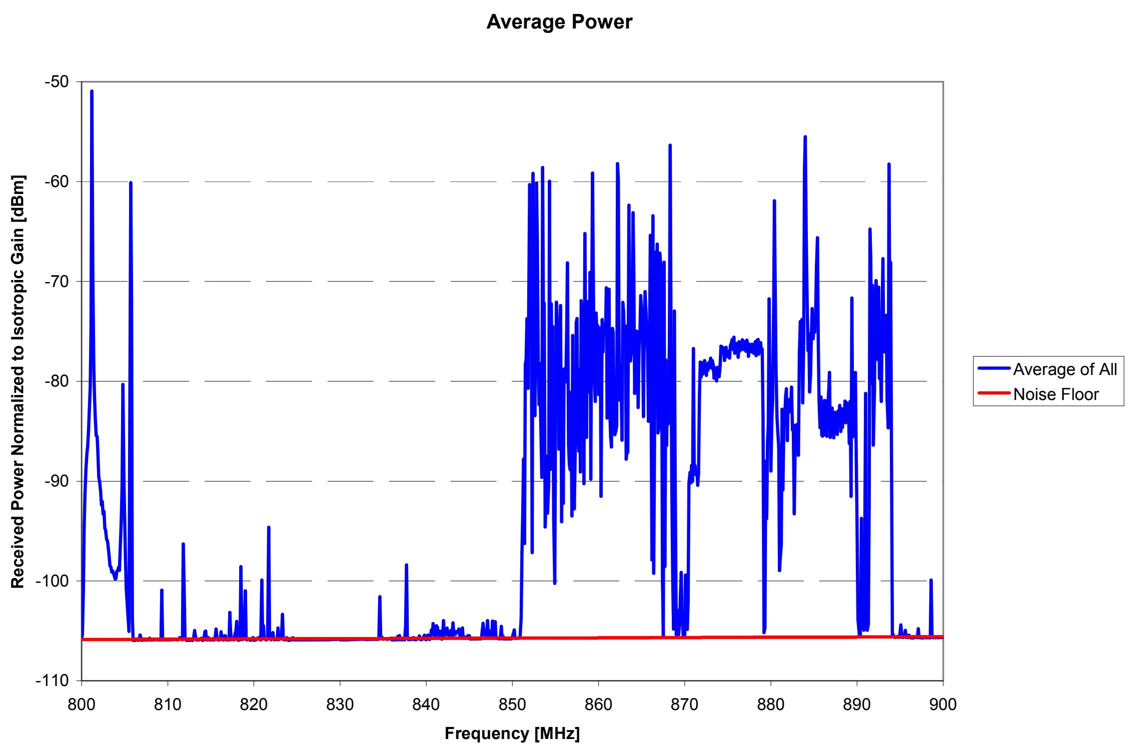

Figure 5.1: Average Power plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

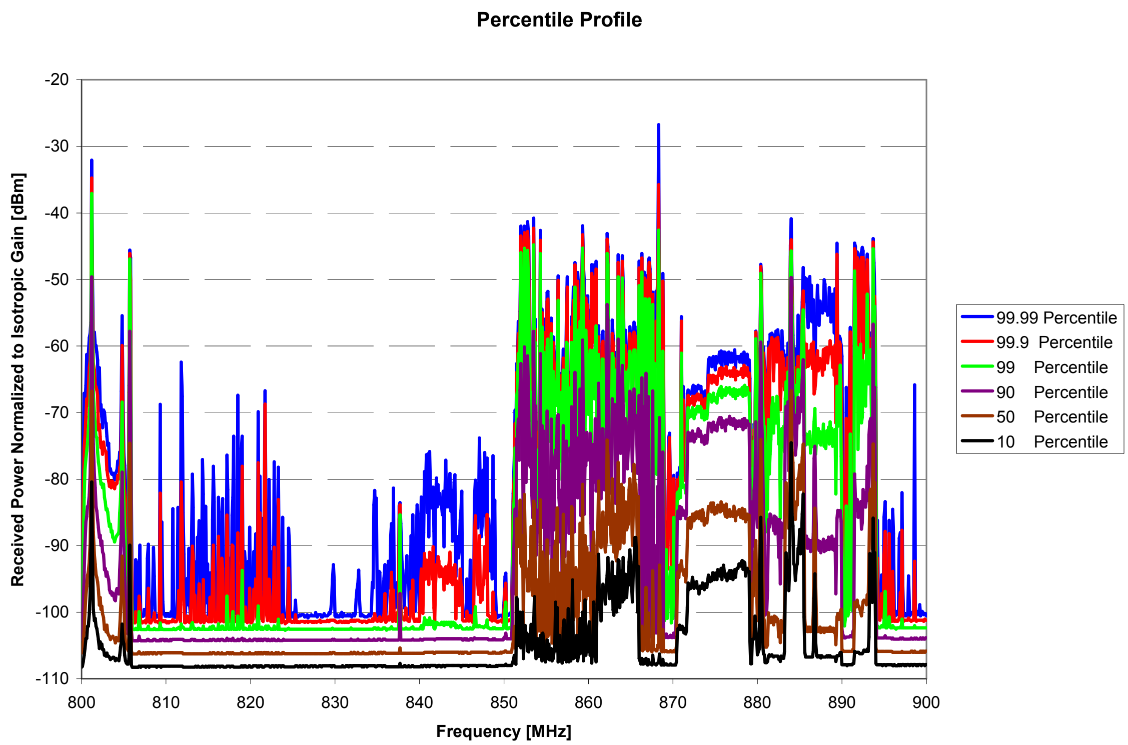

Figure 5.2: Percentile Profile plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

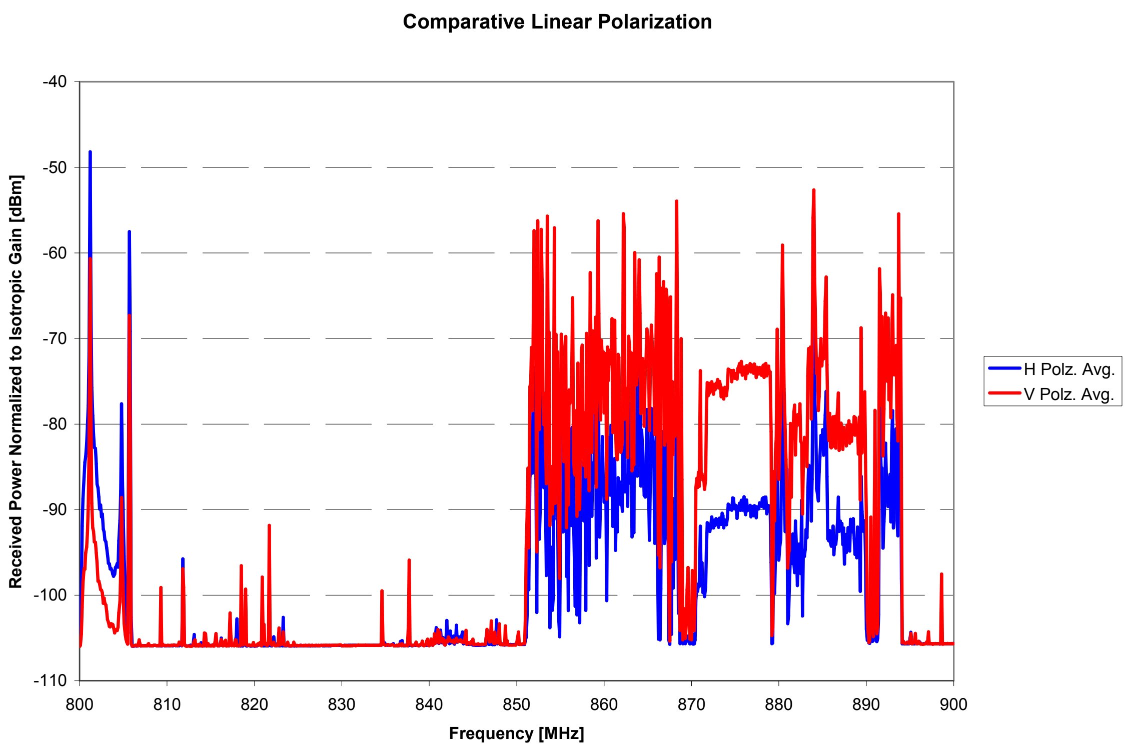

Figure 5.3: Comparative Linear Polarization plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

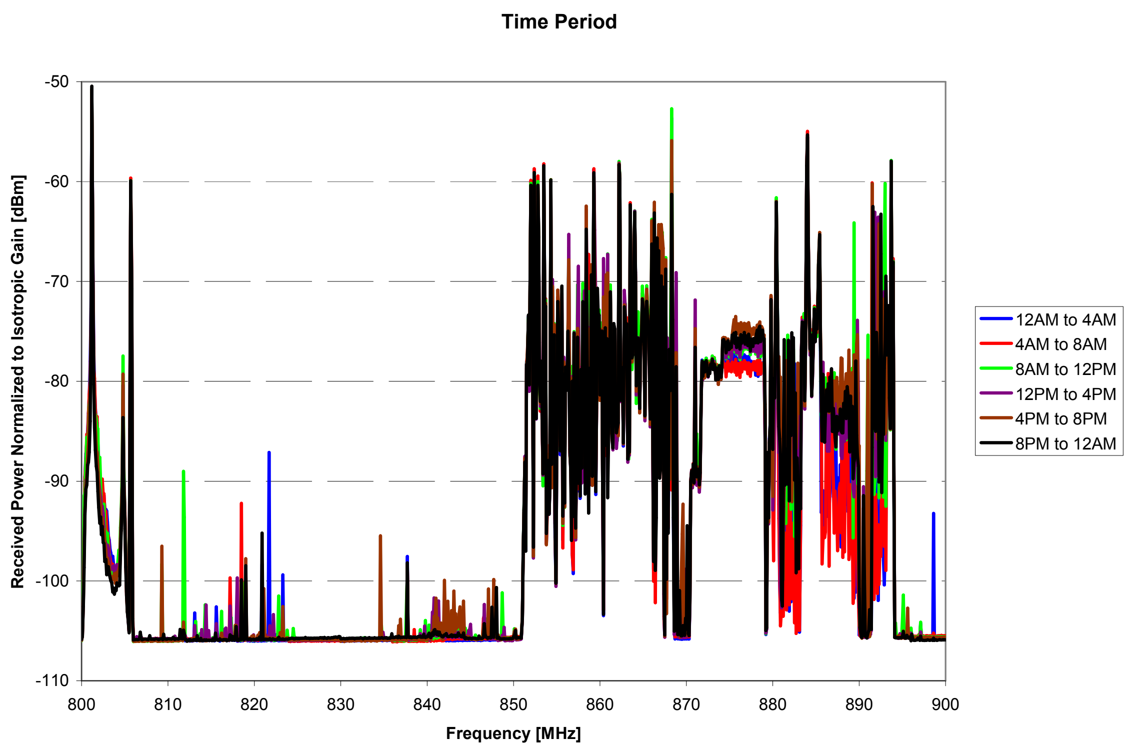

Figure 5.4: Time Period plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

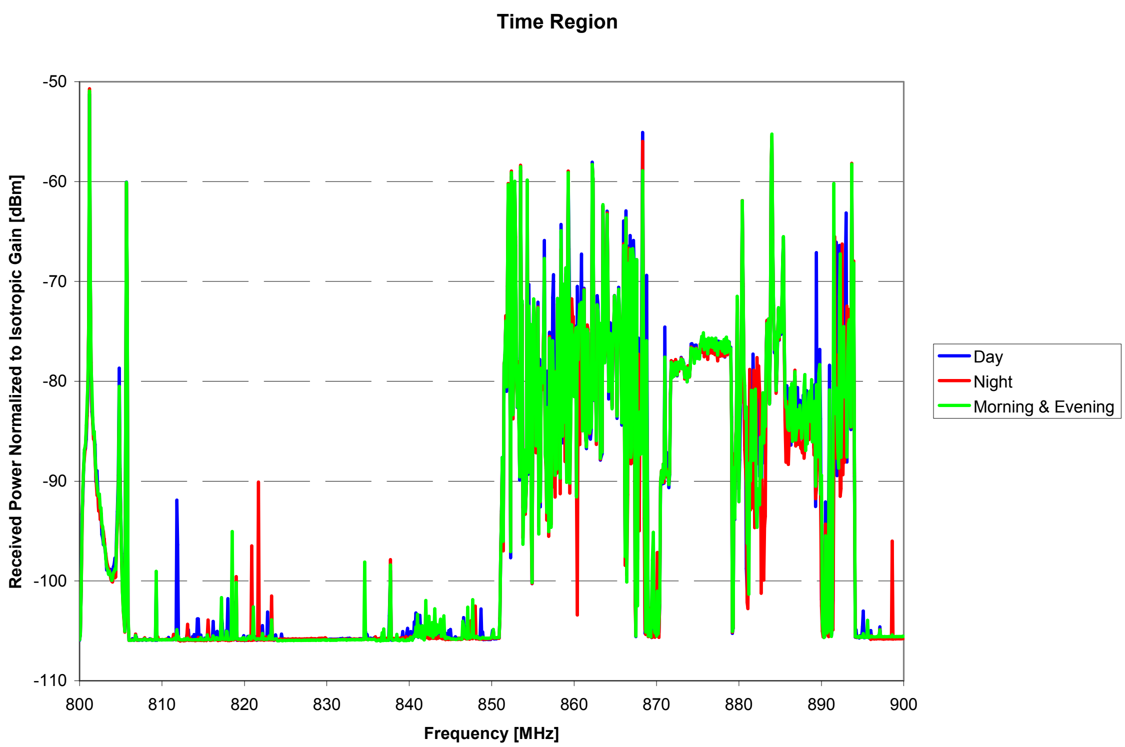

Figure 5.5: Time Region plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

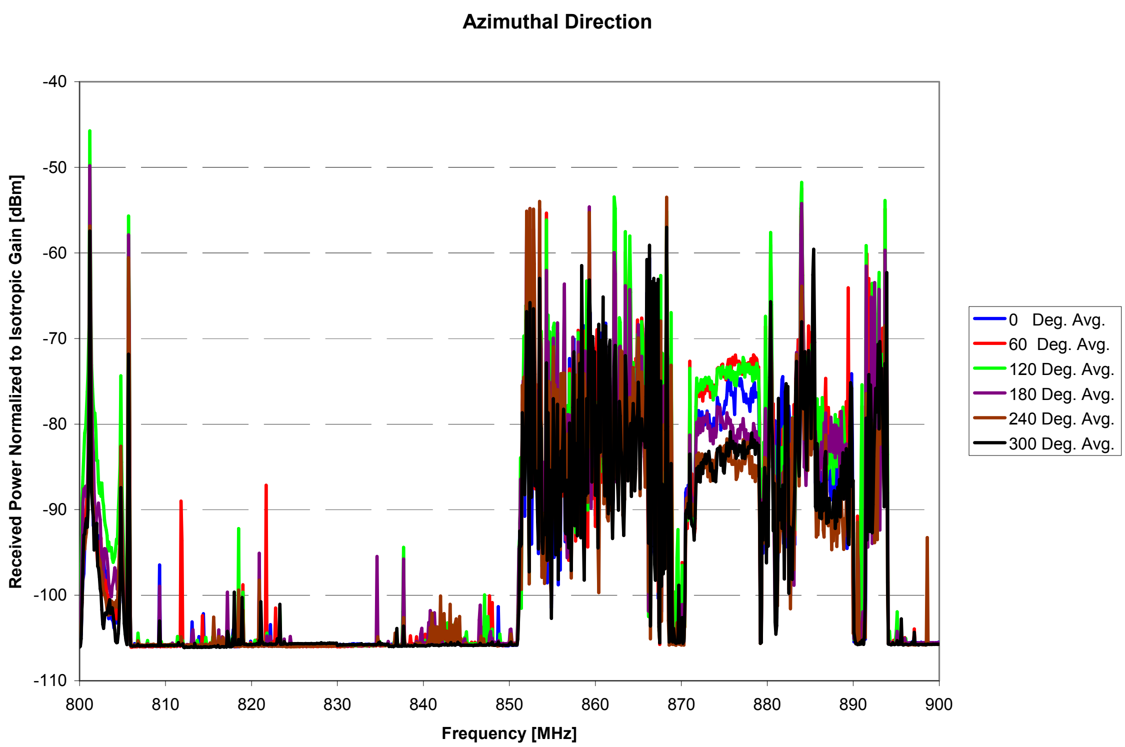

Figure 5.6: Azimuthal Direction plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

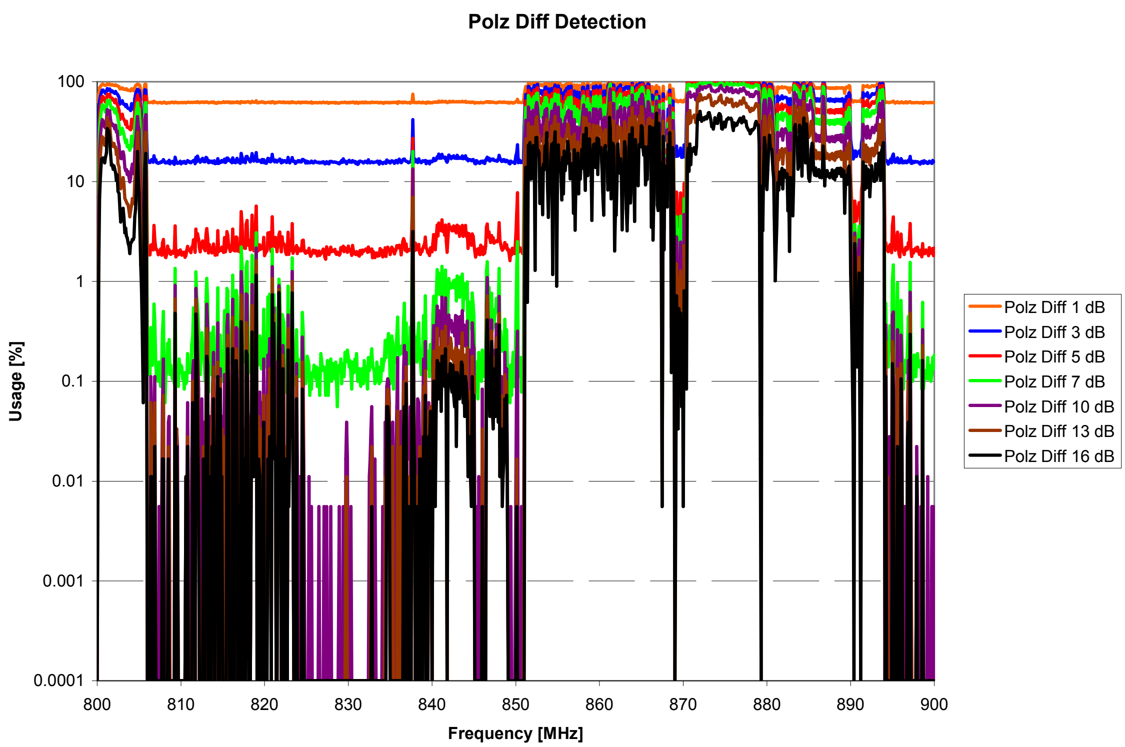

Figure 5.7: Polarization Difference Detection plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

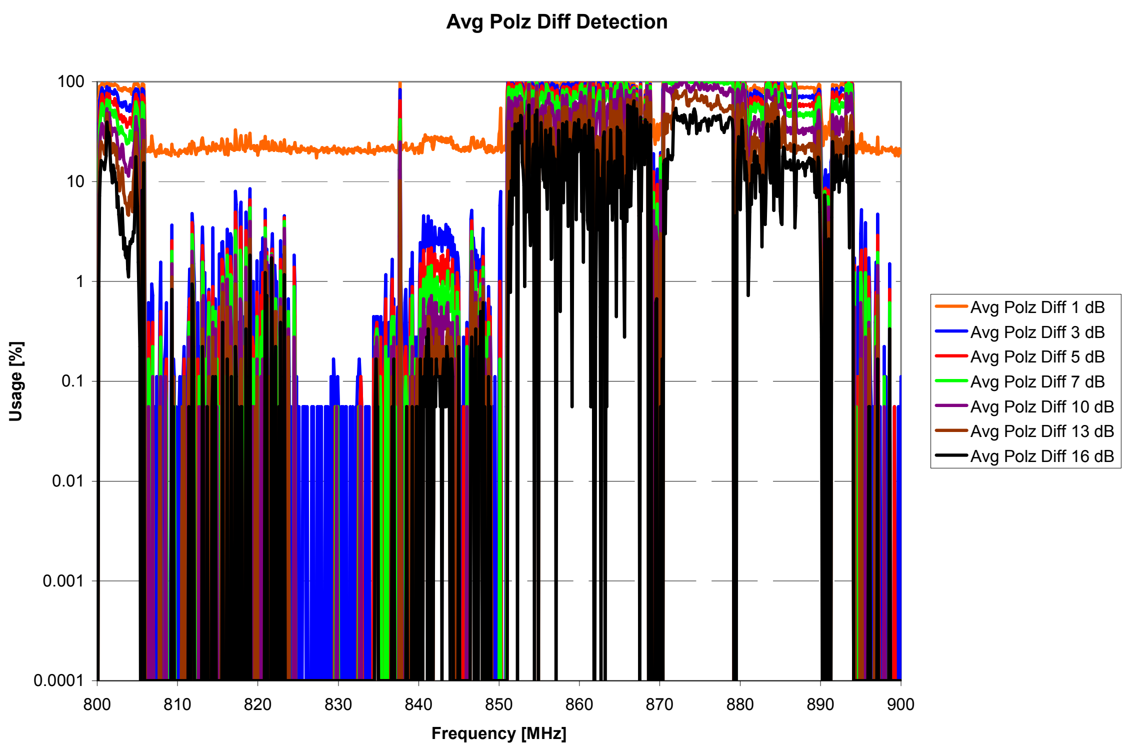

Figure 5.8: Average Polarization Difference Detection plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

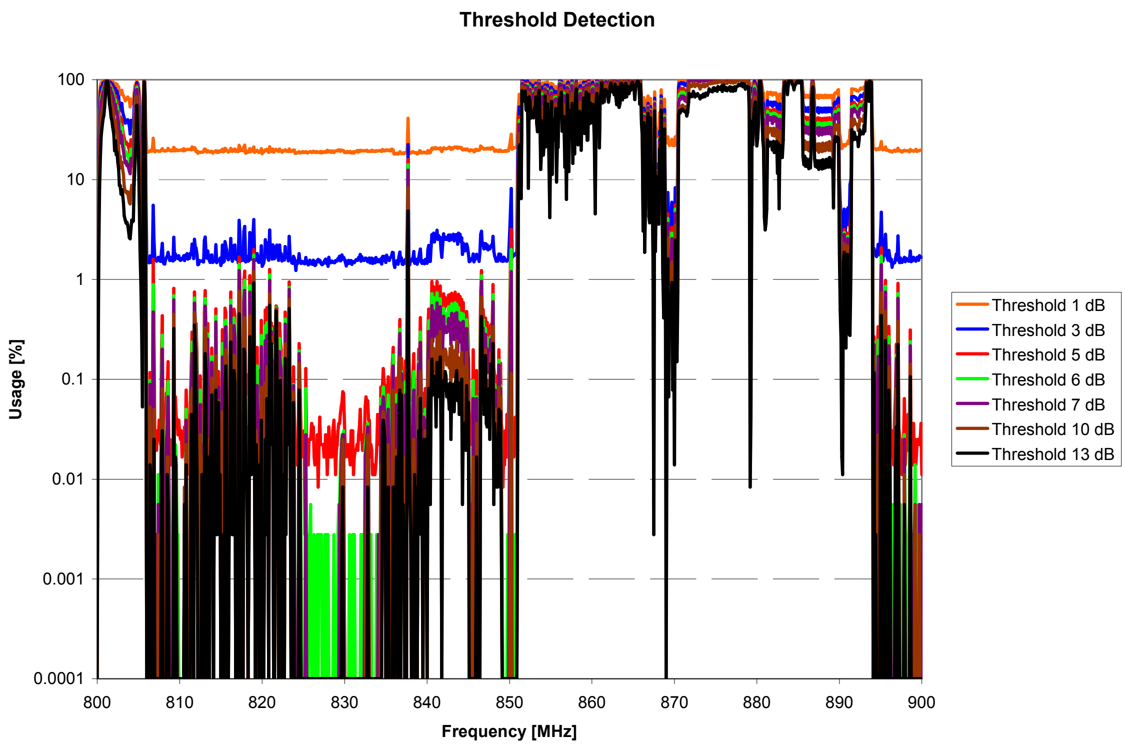

Figure 5.9: Threshold Detection plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

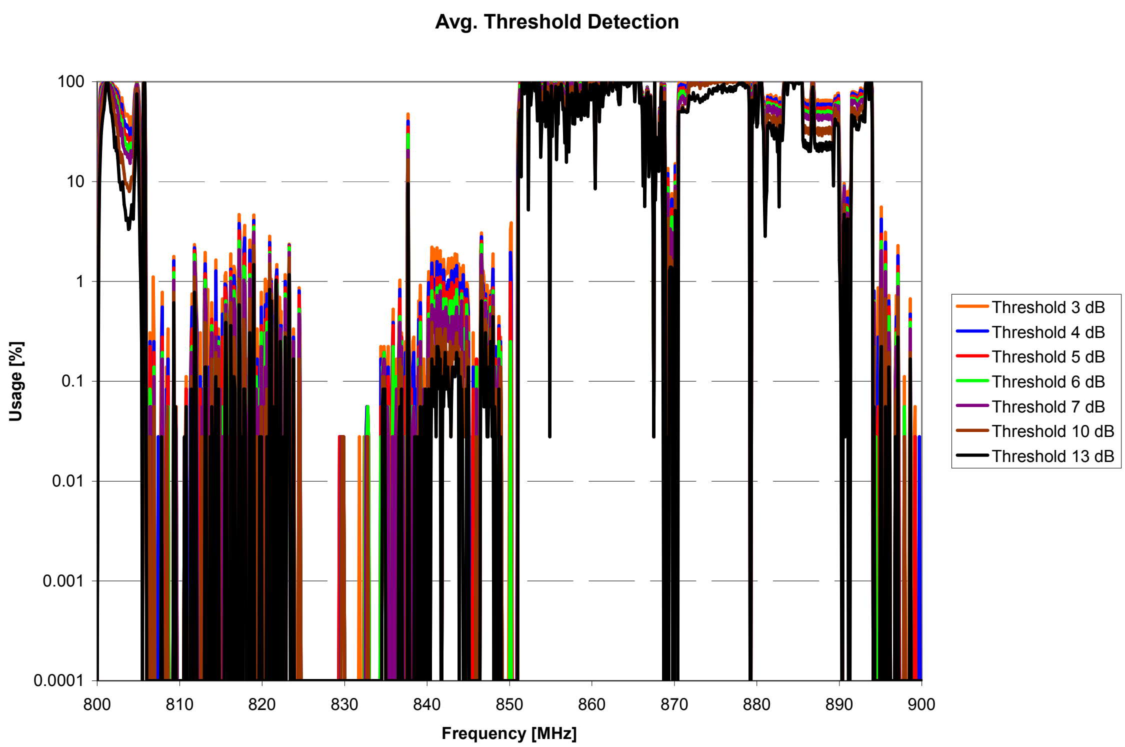

Figure 5.10: Average Threshold Detection plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

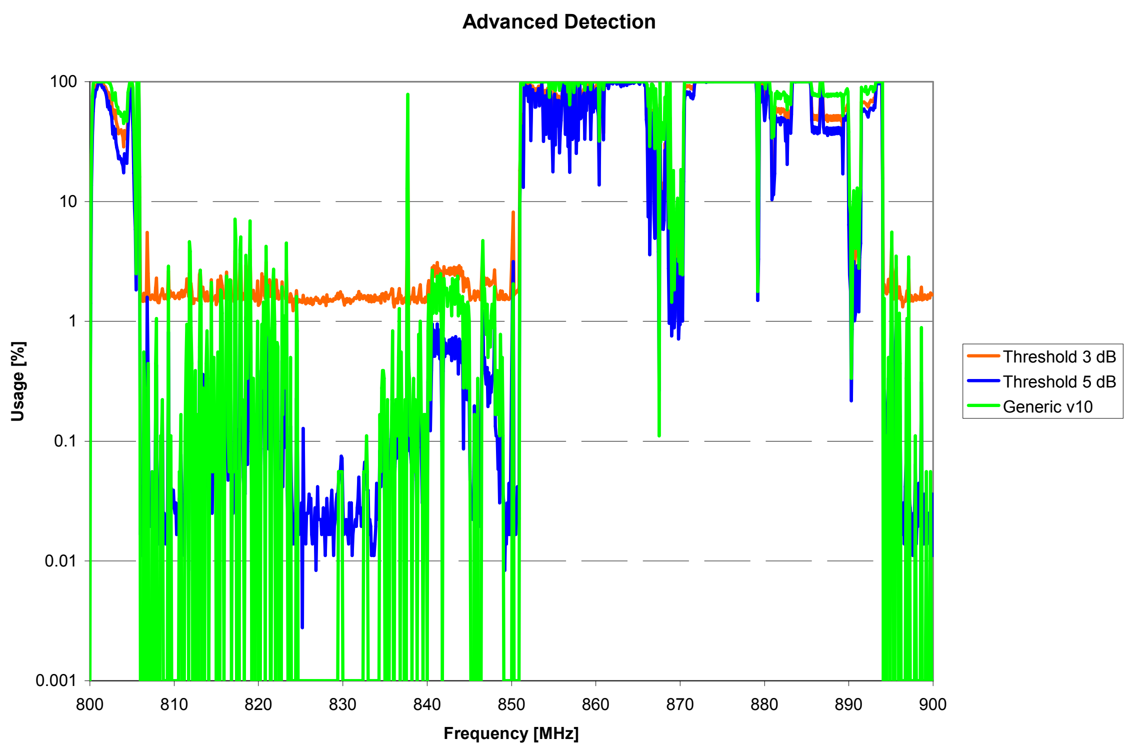

Figure 5.11: Advanced Detection plot from EXCEL file produced with ProcData v3, from the urban Atlanta spectrum study from 800 MHz to 900 MHz.

5.2 Spectrum Occupancy Model

The generic v10 detection method was applied to the urban Atlanta, suburban Atlanta, and rural North Carolina spectrum studies to provide a model of spectrum occupancy.

The generic v10 detection method is unable to reliability detect several signals present in the spectral environment. This includes signals with very low received SNR (satellites) and broadband signals with low power spectral densities (code division multiple access, CDMA). Of course, passive use of the spectrum (radio astronomy and remote sensing) is likewise undetectable.

The spectrum analyzer setting used for the spectrum studies can overstate the usage of the spectral environment, since positive peak detection is employed. The 10 kHz RBW that is used could overstate usage for narrower bandwidth (< 10 kHz) high power signals, of which there are very few.

The results of applying the generic v10 detection method to the urban Atlanta, suburban Atlanta, and rural North Carolina spectrum studies are shown in Table 5.2. In the urban Atlanta spectrum study the level of usage in time and azimuthal space for spectrum from 400 MHz to 7.2 GHz was determined to be only 6.5 %. For the suburban Atlanta and rural North Carolina spectrum studies the usage was determined to be only 5.33 % and 0.8 % respectively. Areas of the spectrum that never experienced usage were determined to be “Vacant”. For the urban Atlanta spectrum study this amounted to 77.60 % of the spectrum measured. For the suburban Atlanta and rural North Carolina spectrum studies

82.26 % and 96.80 % of the spectrum measured respectively was determined to be "Vacant". The term "White Space" is used to quantify the amount of "Vacant" spectrum; for the urban Atlanta spectrum study this amounted to 5.3 GHz. The suburban Atlanta and rural North Carolina spectrum studies were determined to have 5.6 GHz and 6.6 GHz of "White Space" respectively. These results show vast underuse of the spectral environment, and significant opportunities for spectrum reuse.

Table 5.2: Usage detected with the generic v10 method, for spectrum from 400 MHz to 7.2 GHz.

	Urban Atlanta	**Suburban Atlanta**	**Rural North Carolina**
Usage in Time and Azimuth	6.50 %	5.33 %	0.80 %
"Vacant" Spectrum	77.60 %	82.26 %	96.80 %
"White Space"	5.3 GHz	5.6 GHz	6.6 GHz

5.3 Spectrum Interference

Interference has been detected in several protected radio astronomy, passive remote sensing and sensitive radio navigation bands.

Figure 5.12 and Figure 5.13 show the usage detected in the L-band, from 1200 MHz to 1450 MHz for the urban Atlanta and rural North Carolina spectrum studies respectively. The threshold detection method shown in the plots is performed on a single 10 kHz frequency bin. The signals in the L-band spectrum are from Federal Aviation Administration (FAA) Air Route Surveillance Radars (ARSR). Several of the ARSR transmitters are tube based and inadequately filtered; emitting over 100 MHz of phase noise as shown in Figure 5.12.

Interference is detected in urban Atlanta for the GPS L2 band (centered at 1227.6 MHz). This band is presently used only for military P-code (precision) navigation, but a new civilian code, L2C, will soon be transmitted on this band.[97,98,99] Dual-band civilian receivers will use this new signal along with the current signal at the L1 band to improve their accuracy and GPS availability. This interference could seriously impact the values of the new service.

Interference shown in the band from 1400 MHz to 1427 MHz for the urban Atlanta study is of particular concern. This band has been used since the early 1950s for the detection of hydrogen in the cosmos and is protected internationally from any intentional transmission.[100,101,102,103,104,105] Since radio astronomy measures emitters at the jansky (10^{-26} W/m^2/Hz) level, even very low power interfering signals can produce harmful interference.

No interference is detected for the rural North Carolina study in the GPS L2 and 1400 – 1427 MHz radio astronomy bands.

Figure 5.14 and Figure 5.15 show the usage detected from 1650 MHz to 1700 MHz for the urban Atlanta and rural North Carolina spectrum studies respectively. Transmission into the band from 1660 MHz to 1670 MHz is limited internationally, to protect radio astronomers observing OH emissions.[100,104,105,106,107,108,109] A low amount of interference was detected in this protected band for the urban Atlanta spectrum study. No usage was detected in this band for the rural North Carolina spectrum study.

Figure 5.16 and Figure 5.17 show the usage detected from 4900 MHz to 5000 MHz for the urban Atlanta and rural North Carolina spectrum studies respectively. The band from 4990 MHz to 5000 MHz is protected from intentional transmission in the US, to protect radio astronomers performing Very Long Baseline Interferomertry (VLBI).[100,104,105] This band is an example of a properly protected passive band, with no usage detected for both the urban Atlanta and rural North Carolina spectrum studies.

Figure 5.18 and Figure 5.19 show the usage detected in the C-band, from 6400 MHz to 7200 MHz for the urban Atlanta and rural North Carolina spectrum studies respectively. This band, which is not protected from interference, is used by the passive remote sensing community.[110] Significant portions of this band are used by the Advanced Microwave Scanner Radiometer for Earth Observing System (AMSR-E) aboard the National Aeronautics and Space Administration (NASA) Aqua satellite and the Conical Scanning Microwave Imager/Sounder (CMIS) for the proposed National Polar-orbiting Operational Environmental Satellite System (NPOESS).[22,23] This band with is shared with fixed point microwave and satellite uplink ground stations.[111,112,113,114] For the urban Atlanta spectrum study a moderate level of usage is detected, with signals up to -107 dBW/m^2/Hz in intensity. In contrast, only one intermittent signal was detected the rural North Carolina spectrum study for this band.

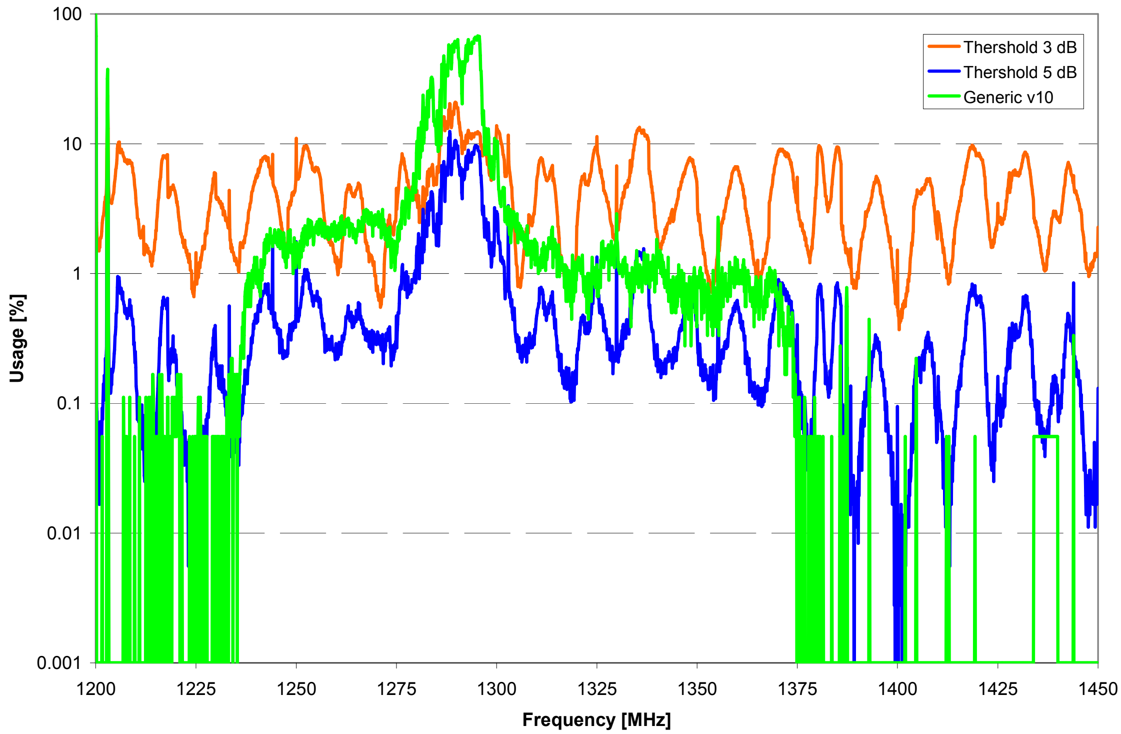

Figure 5.12: Usage detected from 1200 MHz to 1450 MHz for the urban Atlanta spectrum study; system noise floor: -180 dBW/m^2/Hz.

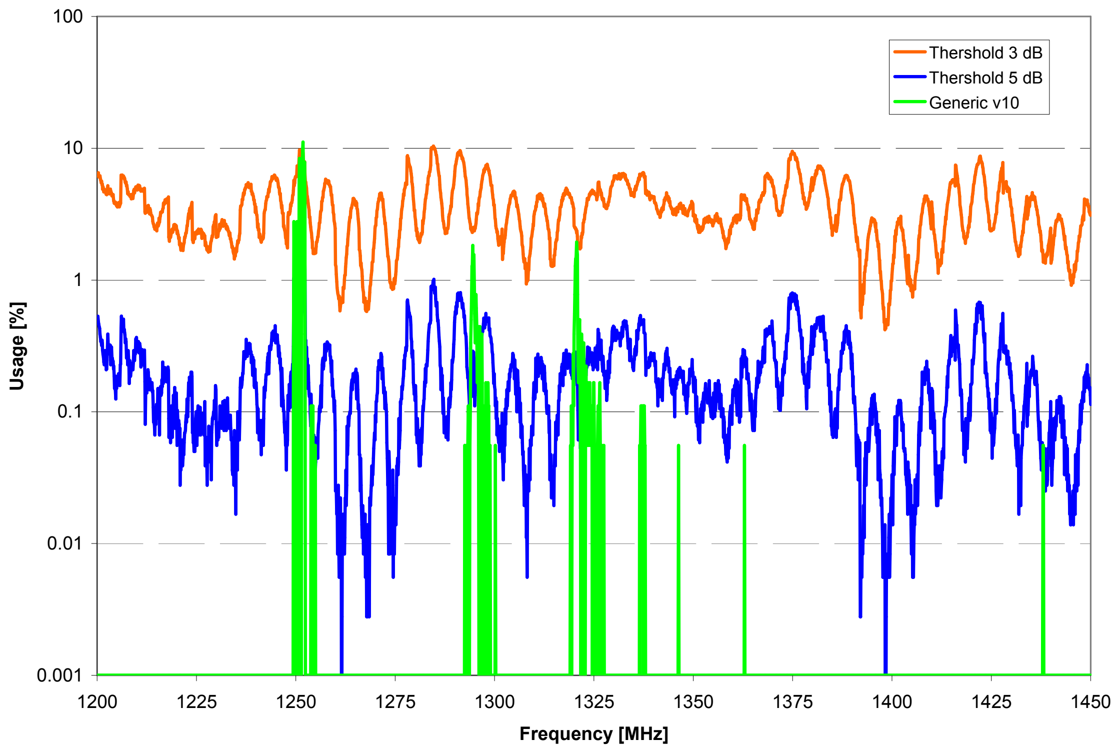

Figure 5.13: Usage detected from 1200 MHz to 1450 MHz for the rural North Carolina spectrum study; system noise floor: -179 dBW/m^2/Hz.

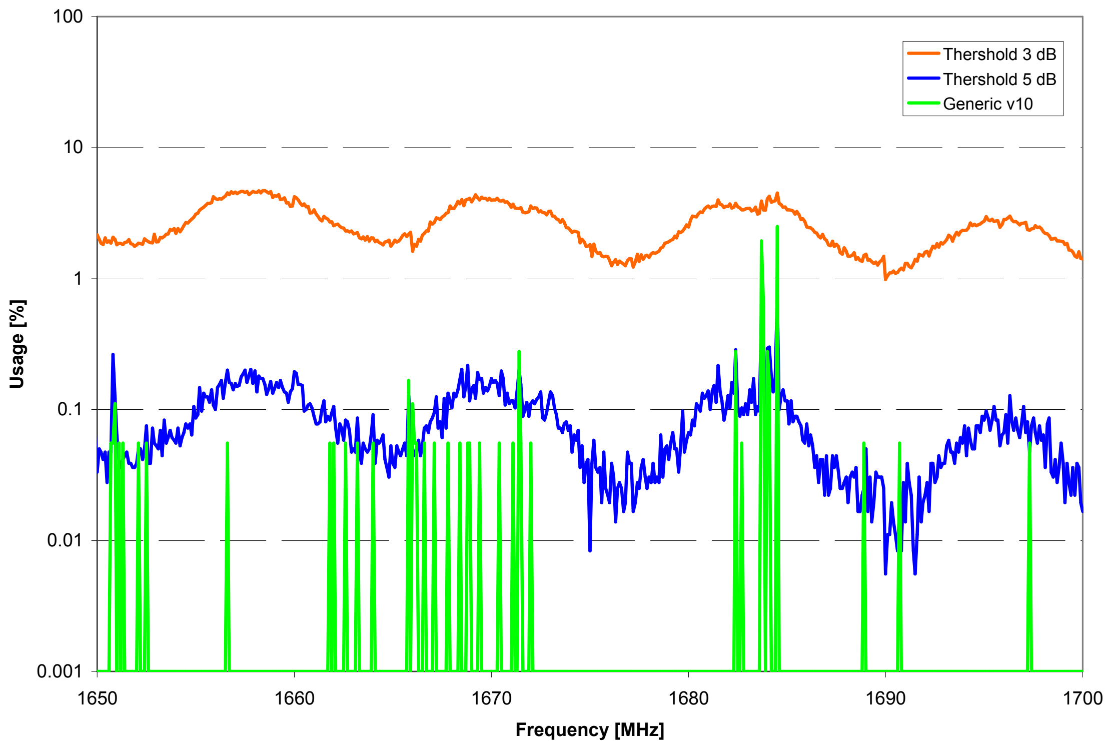

Figure 5.14: Usage detected from 1650 MHz to 1700 MHz for the urban Atlanta spectrum study; system noise floor: -174 dBW/m^2/Hz.

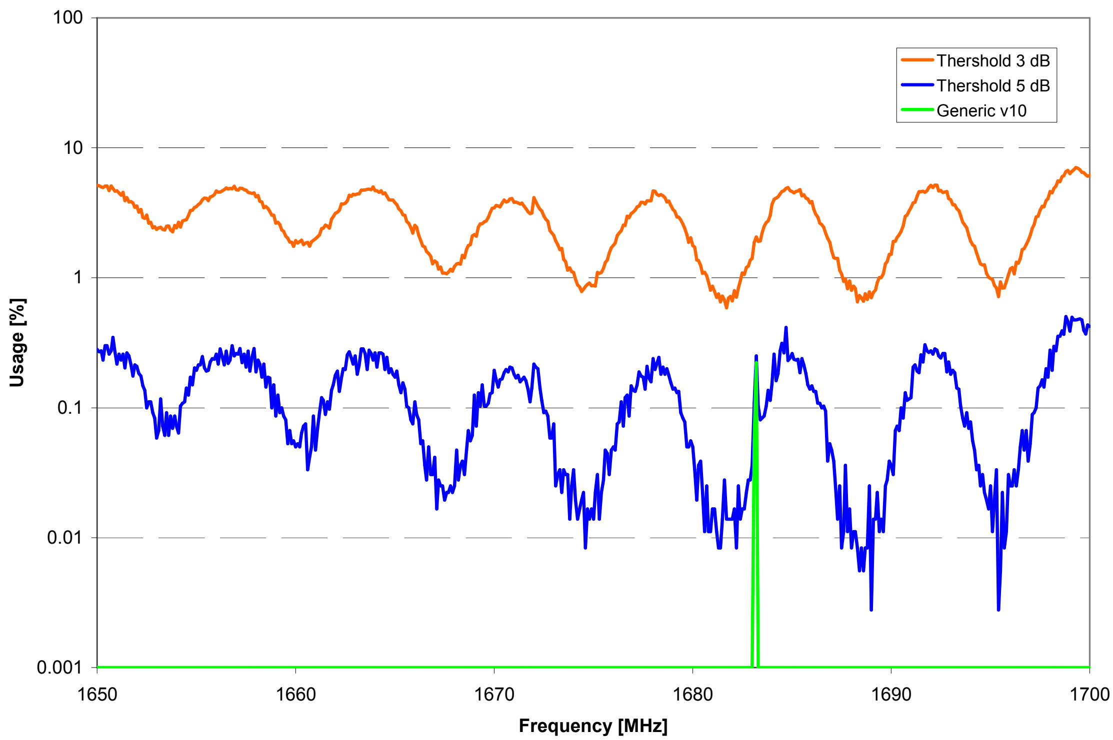

Figure 5.15: Usage detected from 1650 MHz to 1700 MHz for the rural North Carolina spectrum study; system noise floor: -178 dBW/m^2/Hz.

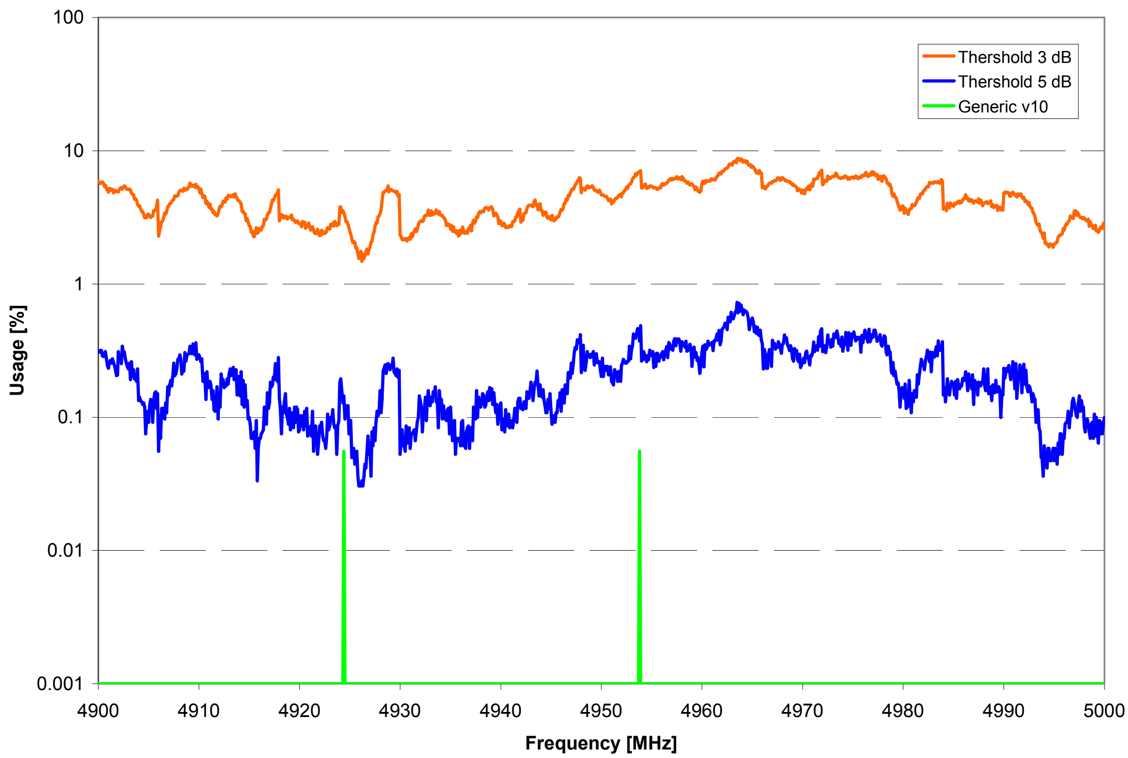

Figure 5.16: Usage detected from 4900 MHz to 5000 MHz for the urban Atlanta spectrum study; system noise floor: -168 dBW/m^2/Hz.

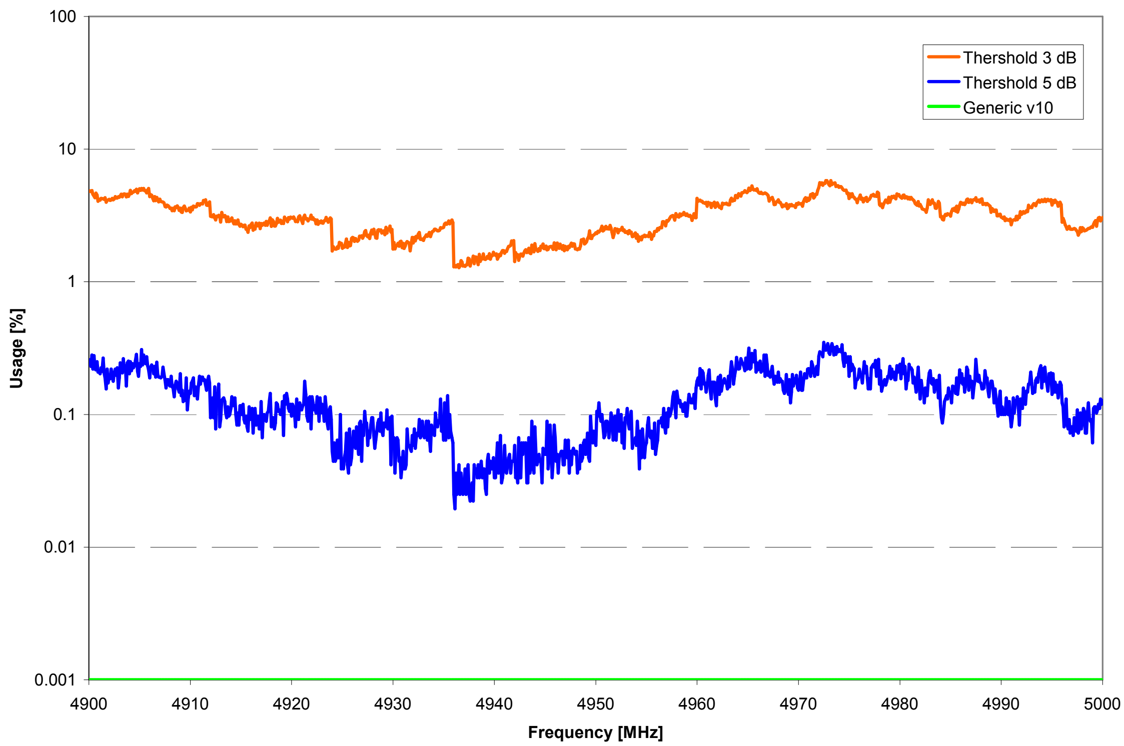

Figure 5.17: Usage detected from 4900 MHz to 5000 MHz for the rural North Carolina spectrum study; system noise floor: -167 dBW/m^2/Hz.

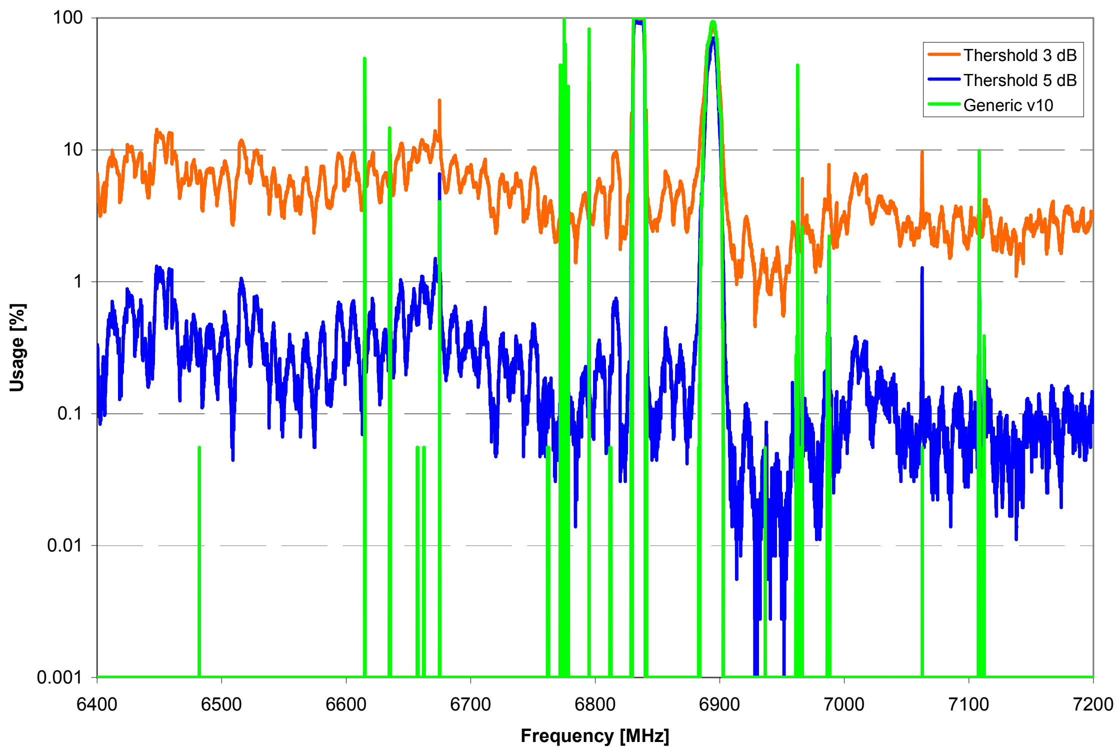

Figure 5.18: Usage detected from 6400 MHz to 7200 MHz for the urban Atlanta spectrum study; system noise floor: -158 dBW/m^2/Hz.

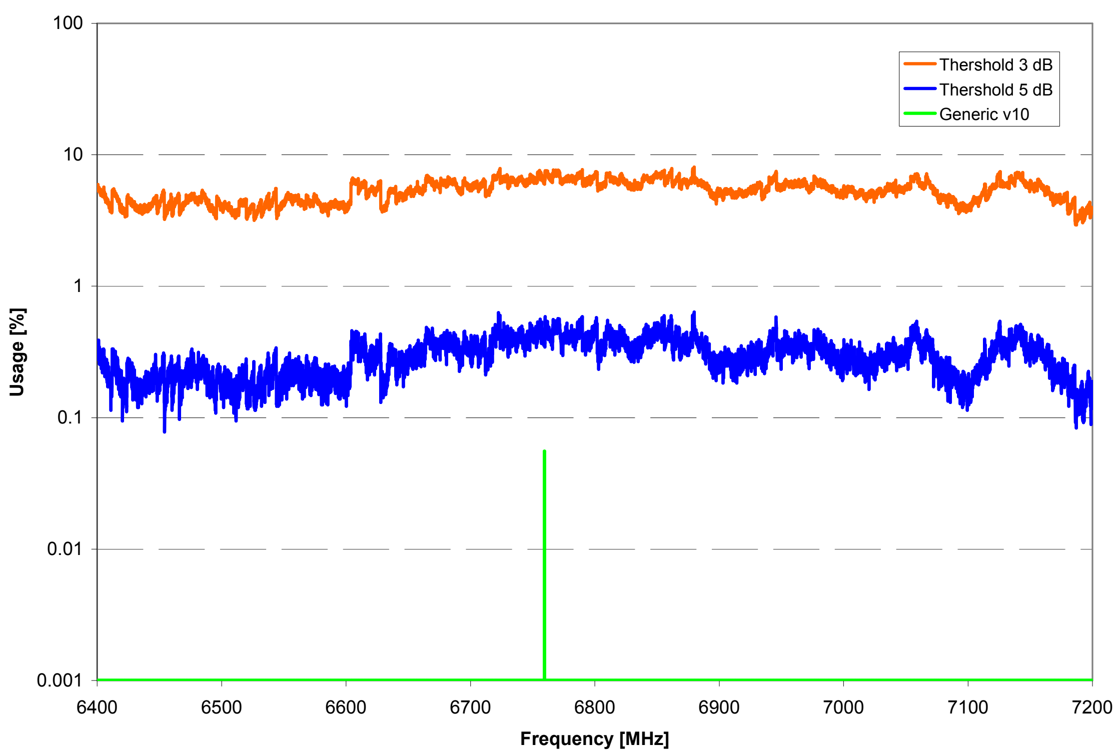

Figure 5.19: Usage detected from 6400 MHz to 7200 MHz for the rural North Carolina spectrum study; system noise floor: -160 dBW/m^2/Hz.

CHAPTER 6

A SPECTRUM SHARING COGNITIVE RADIO NETWORK

A cognitive radio network architecture was developed based on the results of the spectrum studies and characteristics of incumbent spectrum users.

6.1 Spectrum Opportunities

The spectrum that was chosen for the cognitive radio network includes the following bands presently licensed to the fixed microwave services: 5925 to 6425 MHz, 6425 to 6525 MHz, 6525 to 6875 MHz, and 6875 to 7125 MHz. The bandwidth of these bands totals 1200 MHz, offering significant amounts spectrum for use by the cognitive radio network.

These bands were selected because of their present low level of usage, especially in rural areas of the United States. Broadband wireless-based systems could occupy unused and unlicensed portions of spectrum to provided high-speed communication services to rural communities that have been underserved by the present telecommunications infrastructure.[115]

The bands are summarized in Table 6.1, along with their measured levels of usage determined with the generic v10 detection method for the urban Atlanta and rural North Carolina spectrum studies.

Table 6.1: Usage measured for select microwave bands for urban Atlanta, GA and rural North Carolina.

Band	**Percentage Usage Measured**	
[MHz]	**Urban Atlanta**	**Rural North Carolina**
5925 to 6425	0.2 %	0.0 %
6425 to 6525	0.0 %	0.0 %
6525 to 6875	0.2 %	0.0 %
6875 to 7125	2.5 %	0.0 %

6.2 Spectrum Sharing Method

Protection of current and future licensed spectrum from harmful interference is a major objective of the spectrum sharing method that has been developed. This sharing method has several components. First, a spectrum broker will work with the present licensed holders of spectrum in the selected bands in a process similar to that outlined in part 101 of the Radio Regulations; acquiring their system's technical specifications and vulnerabilities to interference.[114] Licenses for the fixed microwave users are unique by requiring licensees to provide information about their system's location, pointing direction, antenna, and transmission power. Information about transmitters and receivers will be integrated with a propagation model to determine paths where spectrum is available for use.[116] These paths will then be offered on a temporary and interruptible basis to the cognitive radio nodes using an online-based process.

Several layers of technology are used to minimize harmful interference to licensed users. Secure communication will be used between the spectrum broker and the wireless node, through the use of encryption and digital signatures. This negates the possibility of a rogue node operating on spectrum without permission. The cognitive radio nodes will have geolocation capability and an integrated ability to sense spectrum usage. This sensing method will be based on the generic v10 detection method. The propagation model that is used will take into account the effects of terrain and structures on radio waves, including possibly harmful reflections. This propagation model will be improved over time for a given geographic region by using the wireless radio network itself to measure the attenuation and reflections of the propagation environment. The wireless nodes may integrate additional technologies to increase this spectral efficiency, including automatic transmit power control and smart antennas.

The online spectrum broker will to respond to licensed users' inquiries of potential interference in seconds, by performing measurements of spectrum usage and switching off paths that are possibly causing unwanted interference. Figure 6.1 illustrates the architecture for this spectrum sharing method.

This cognitive radio network could be based on the IEEE 802.16 standard, commonly referred to as WiMAX. This network technology has the support of over 200 wireless companies that have joined the WiMAX Forum.[117]

This sharing method has several benefits compared to the traditional licensing process. Many potential users of radio spectrum cannot meet the regulatory requirements for fixed point-to-point microwave service; including equipment technical issues and license holder qualifications. The needs of small network service providers and private individuals wishing to deploy low-cost and quick-to-establish wireless networks are not satisfied with the licensing process designed for large private entities that requires long-term access to spectrum with a very high assurance of no harmful interference. The method proposed will enable wireless internet service providers (WISP) and other operators of low-cost and quick-to-establish wireless networks to gain access to spectrum with significantly lower levels of interference compared to unlicensed bands, at a moderate cost to cover the interference prevention services provided by spectrum broker. The access to spectrum and rights of present and future licensed spectrum users will be preserved by interference prevention and the dynamic ability to discontinue use of spectral paths once they are licensed.

This cognitive radio network architecture will serve the public interest by increasing access to spectrum while preserving the rights of current and future licensed spectrum users.

To encourage the establishment of spectrum brokers, a temporary exclusive concession could be granted by the FCC to “pioneer” brokers, improving the risk-to- reward ratio. To ensure a completive marketplace in the long-term, the FCC could thereafter, reclaim and auction off the concession, or grant additional concessions.

This cognitive radio network architecture was formally proposed to the FCC Office of Engineering and Technology in March 2005, after discussions with several of their most senior engineers.

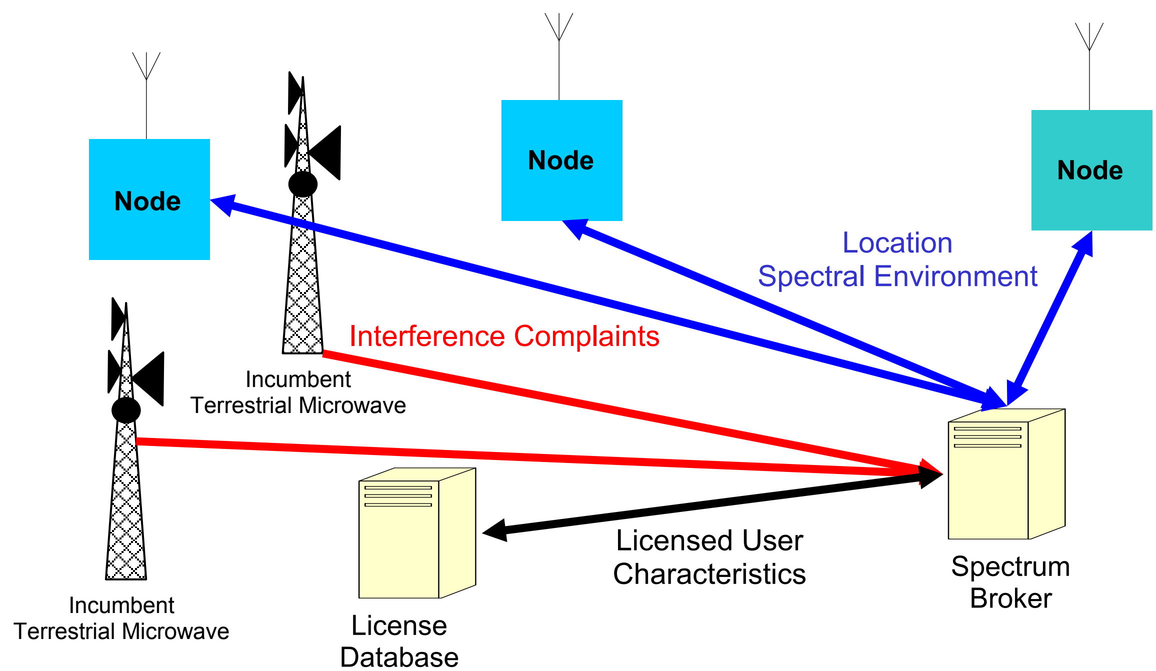

Figure 6.1: Network architecture for spectrum sharing with fixed microwave services.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

7.1.1 Spectrum Measurement System

A radio spectrum measurement system has been designed and developed to measure usage as a function of frequency, time, polarization, and azimuth. It measures the continuous frequency range from 400 MHz to 7.2 GHz with high sensitivity and good intermodulation performance. The complete spectrum measurement system has achieved better than 99.99999 % operational reliability.

7.1.2 Spectrum Studies

Three extensive spectrum studies have been completed, at measurement locations in: urban Atlanta, suburban Atlanta, and rural North Carolina. More than 8 billion spectrum measurements, totaling 56 GB of data, have been taken over several months of observation.

7.1.3 Usage Detection Method

A multi-parameter spectrum usage detection method was developed and analyzed with data from the spectrum studies. This method (known as generic v10) was designed to exploit all the characteristics of spectral information that was available from the spectrum studies.

The multi-parameter detection method was also developed to be a generic detector, detecting the presence of all spectral emitters: from radio navigation and communication systems to unintended emissions from transmitter phase noise.

The generic v10 method achieves a probability of detection that is better than the 3 dB threshold detector for most signals while exhibiting a false alarm rate that is at least 40,000 times lower.

7.1.4 Analysis of Spectrum Studies: Spectrum Occupancy Model & Interference

The generic v10 detection method was applied to the urban Atlanta, suburban Atlanta, and rural North Carolina spectrum studies to provide a model of spectrum occupancy. For the urban Atlanta spectrum study the level of usage in time and azimuthal space for spectrum from 400 MHz to 7.2 GHz was determined to be only 6.5 %. For the suburban Atlanta and rural North Carolina spectrum studies the usage was determined to be only 5.33 % and 0.8 % respectively. Areas of the spectrum that never experienced usage were determined to be “Vacant”. For the urban Atlanta spectrum study this amounted to 77.60 % of the spectrum measured. For the suburban Atlanta and rural North Carolina spectrum studies 82.26 % and 96.80 % of the spectrum measured respectively was determined to be “Vacant”. The term “White Space” is used to quantify the amount of “Vacant” spectrum; for the urban Atlanta spectrum study this amounted to 5.3 GHz. The suburban Atlanta and rural North Carolina spectrum studies were determined to have 5.6

GHz and 6.6 GHz of “White Space” respectively. These results show vast underuse of the spectral environment, and significant opportunities for spectrum reuse.

Interference was detected in several protected radio astronomy and sensitive radio navigation bands.

7.1.5 Cognitive Radio

A cognitive radio network architecture to share spectrum with fixed microwave systems was developed. The architecture uses a broker-based sharing method to control spectrum access and investigate interference issues. The nodes in the network have the potential to access up to 1200 MHz of spectrum, enabling high data rates.

7.2 Summation of Original Work Completed

- Radio Spectrum Measurement System
    - Designed, built, and tested a broadband RF-subsystem with low noise, good intermodulation performance, and built-in calibration.
    - Designed, built and tested an antenna matrix.
    - Designed, coded, and tested remote control system and data collection software.
    - Designed, coded, and tested a proprietary object-oriented database.
    - Achieved 99.99999 % operational reliability for the completed system.

- Spectrum Studies
    - Performed three broadband spectrum studies in urban Atlanta, suburban Atlanta area, and rural North Carolina over the course of several months.
    - Collected over 8 billion measurements of spectrum usage.

- Usage Detection Method
  - Developed, coded, and tested a spectrum usage detection method than offered an 40,000 fold reduction in false alarms compared with threshold detection.

- Analysis of Spectrum Studies
  - Designed, coded, and tested automated data analysis software.
  - Analyzed spectrum study data to examine spectrum usage in multiple dimensions.
  - Archived spectrum study information with several hundred files in EXCEL format.
  - Determined current levels of spectrum usage for both the urban Atlanta, suburban Atlanta and rural North Carolina spectrum studies.
  - Identified interference into passive radio astronomy and remote sensing bands.
  - Identified portions of the spectrum that can be opportunistically reused with cognitive radios.

- Cognitive Radio
  - Developed a cognitive radio network architecture to share spectrum with fixed microwave systems.

7.3 Publications List

7.3.1 Professional Presentations and Conference Papers

A. Petrin and P.G. Steffes, "Spectrum Monitoring," National Science Foundation Future Spectrum Technology and Policy Workshop, Arlington, VA, May 25 2005 **(invited)**.

A. Petrin and P.G. Steffes, "Analysis and Comparison of Spectrum Measurements performed in Urban and Rural Areas to Determine the Total Amount of Spectrum

Usage," Proceedings of the 2005 International Symposium on Advanced Radio Technologies, *NTIA Special Publication SP-05-418*, 2004, pp. 9-12. Presented at the 2005 International Symposium on Advanced Radio Technologies, Boulder, CO, March 1, 2005.

A. Petrin, "Cognitive Radio: The Next Wireless Frontier," *Presentation,* Atlanta Chapter of the IEEE Vehicular Technology Society, Atlanta, GA February 15, 2005 **(invited)**.

A. Petrin and P.G. Steffes, "Maximizing the Utility of Radio Spectrum," *Presentation,* Federal Communications Commission, Washington, DC February 2, 2005 **(invited)**.

A. Petrin and P.G. Steffes, "Comparison of Radio Spectrum Usage in Urban and Rural Environments for Radio Astronomy and Passive Remote Sensing Bands," International Union of Radio Science Programs and Abstracts: 2005 National Radio Science Meeting, pp. 217. Presented at the 2005 URSI National Radio Science Meeting, Boulder, CO, January 7, 2005.

A. Petrin and P.G. Steffes, "Radio Spectrum Occupancy Model," Proceedings of the 2004 Software Defined Radio Technical Conference, vol. B, pp. 111. Presented at the 2004 Software Defined Radio Technical Conference, Scottsdale, AZ, November 17, 2004.

P.G. Steffes and A. Petrin, "Study of Spectrum Usage and Potential Interference to Passive Remote Sensing Activities in the 4.5 cm and 21 cm Bands," 2004 International Geoscience and Remote Sensing Symposium Proceedings, vol. III, pp. 1679-1682. Presented at the 2004 International Geoscience and Remote Sensing Symposium, Anchorage, AK, September 23, 2004 **(invited)**.

A. Petrin, "Spectrum Measurement," *Presentation,* National Academies Committee on Wireless Technology Prospects and Policy Options 5th Committee Meeting, San Diego, CA, July, 22, 2004 **(invited)**.

A. Petrin and P.G. Steffes, "Radio Spectrum Engineering," *Presentation,* National Spectrum Managers Association's Spectrum Management 2004 Conference, Arlington, VA, May 18, 2004 **(invited)**.

A. Petrin and P.G. Steffes, "Radio Spectrum Engineering Research at Georgia Tech," *Presentation,* National Science Foundation Division of Astronomical Sciences, North Arlington, VA, May 14, 2004 **(invited)**.

A. Petrin and P.G. Steffes, "Measurement and Analysis of Urban Spectrum Usage," Proceedings of the 2004 International Symposium on Advanced Radio Technologies, *NTIA Special Publication SP-04-409*, 2004, pp. 45-48. Presented at the 2004 International Symposium on Advanced Radio Technologies, Boulder, CO, March 3, 2004.

A. Petrin and P.G. Steffes, "Study of Spectrum Usage and Potential Interference in the UHF and Microwave Radio Astronomy Bands," Bulletin of the American Astronomical Society, vol. 35, no. 5, 2003, pp.1268. Presented at the 203rd Meeting of the American Astronomical Society, Atlanta, GA, January 6, 2004.

A. Petrin and P.G. Steffes, "A Spectrum Study of Usage in and Adjacent to Passive Scientific Bands," URSI Digest – 2003 IEEE International Antennas and Propagation Symposium and USNC/CNC/URSI North American Radio Science Meeting, pp. 648. Presented at the 2003 IEEE International Antennas and Propagation Symposium and USNC/CNC/URSI North American Radio Science Meeting, Columbus, OH, June 26, 2003.

A. Petrin and P.G. Steffes, "System Architecture for a Dynamic-Spectrum Radio," Proceedings of the 2003 International Symposium on Advanced Radio Technologies, *NTIA Special Publication SP-03-401*, 2003, pp. 47-53. Presented at the 2003 International Symposium on Advanced Radio Technologies, Boulder, CO, March 5, 2003.

A. Petrin and P.G. Steffes, "Potential Usability of Allocated but Unused Spectrum in the United States of America," 27th Triennial General Assembly of the International Union of Radio Science, August 2002.

A. Petrin and P.G. Steffes, *Presentation,* Technology Policy Advisory Council of the Georgia Center for Advanced Telecommunications Technology "Using Assigned but Unlicensed Spectrum (Float) to Provide High Bandwidth Communication Services to Rural Areas," Atlanta, GA, September 27, 2001.

A. Petrin and P.G. Steffes, *Presentation,* Georgia Technology Broadband Institute "Dynamic End User Pricing for Mobile Communication Services to Achieve Policy and Technical Goals," and "Using Assigned but Unlicensed Spectrum (Float) to Provide High Bandwidth Communication Services to Rural Area," Atlanta, GA, April 15, 2001.

7.3.2 Federal Filings

Proposal for Spectrum Sharing, Spectrum MAX LLC, 6 pages. Submitted to the FCC March 11, 2005.

In the Matter of Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing Cognitive Radio Technologies (ET Docket No. 03-108). 34 Pages. Filed May 5, 2004.

In the Matter of Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band (ET Docket No. 02-380). 17 Pages. Filed April 7, 2003.

7.4 Future Work

7.4.1 Suburban Atlanta Area Spectrum Study

Analyze the suburban Atlanta spectrum study for interference into protected radio astronomy and sensitive radio navigation bands.

7.4.2 Analysis Software

After Microsoft releases a 64-bit software development environment and operating system, the ProcData software should be modified to expand its memory footprint. This 64-bit version of ProcData would be able to process data at least twice the speed of the current implementation, if adequate amounts of RAM are available.

7.4.3 Targeted Detection Method

A targeted detection method could be developed to improve probability of detection and false alarm performance. Such a method could be targeted to a class of spectral emitters: radar, terrestrial communication, satellite, or to specific systems: GSM, digital TV.

7.4.4 Additional Spectrum Studies

7.4.4.1 Study of the Environmental Noise Floor

Recent FCC rulemaking on the topics of UWB systems and “interference temperature” has brought attention to the concept of “environmental noise”.[33,118] A presumption in the current rulemaking by the FCC is the existence of an artificially-generated environmental noise floor, significantly exceeding the thermal noise across the spectrum.[33,118]

Additional spectrum measurements can be made to determine the level of the environmental noise floor. These measurements could be performed in the passive radio astronomy and radio navigation bands, since these bands are portions of the spectrum that are largely free of active users, or have active uses a at very low power level, providing a "white space" to measure environmental noise. The radio astronomy bands designated for passive use only at 1400 – 1427 MHz, 2690 – 2700 MHz, and 4990 – 5000 MHz would be appropriate choices. The radio navigation bands at the GPS frequencies L1, L2, and L5 (1575, 1227 and 1176 MHz respectively), each with a bandwidth of 20MHz would also be candidate bands. GPS satellites currently transmit on both the L1 and L2 bands, but since the signals are from distant satellites, and are CDMA modulated, their power flux density is approximately 20dB below the sensitivity of the measurement system. Past measurements have shown interference in the L2 GPS band at high power levels. Starting in 2005, the L5 GPS frequency will be used for civilian geolocation, which will provide accuracy greater than the signals currently available at the L1 and L2 frequencies.[119] This signal will introduce military GPS precision to the civilian user community. Measuring these radio astronomy and GPS bands will provide information about the environmental noise floor in general, and provide interference information to the individual band user.

To conduct these measurements the existing spectrum measurement system will need to be upgraded to improve its sensitivity, increase speed of spectrum measurements, and improve its ability to detect pulsed noise signals. The RF-subsystem could be upgraded with additional narrow-band filters targeted only at the bands under examination and LNA, with lower noise figures and higher dynamic range. This will lower the system's thermal noise and reduce intermodulation generated in the LNA and spectrum analyzer. Ideally the spectrum analyzer would be replaced with a fast Fourier transform (FFT) based model, such as the Agilent PSA E4440A.[120] This analyzer has a lower noise figure (10dB less than the current one), better intermodulation performance (10 dBc lower than the current system), wider maximum resolution bandwidth (8 MHz), and faster data acquisition performance (up to 10x faster than the current system speed). The wider resolution bandwidth will allow for the detection of sub-microsecond pulses. The improved data acquisition speed will permit the collection of larger data sets, which have greater statistical significance.

7.4.4.2 Long-Term Spectrum Measurements

The spectrum studies were conducted by sampling each frequency 3,600 times, over the period of about a week. A more statistically relevant model for spectrum occupancy would perform millions of measurements for a band under investigation. A single band could be observed for several weeks, to measure spectrum with improved time resolution. To measure spectrum occupancy faster than past studies, we plan on using FFT analysis. An 8 MHz-wide band with moderate dynamic usage could be selected for study. The data set produced from the study could also be used to simulate the operation of frequency agile radios in software, discussed in a latter section.

7.4.5 Frequency-Agile Radio Network Simulation Software

Basic technical and viability questions for FAR networks can be investigated with simulation software: How long an observation is needed in a certain band to have a desired confidence that transmitting spectrum users are not present? What is the efficiency of a FAR network in the presence of incumbent users? What is the probability and magnitude of interference to incumbent spectral users produced by a FAR network? What frequency bands have usage patterns which are opportunistic for sharing? What is the long term reliability of a FAR network? What is the possibility and consequences of different FAR networks interfering with each other?

Many of these issues have been raised in FCC rulemaking on Cognitive radio and from developers of FAR networks.[48,121] The simulation software could incorporate the data sets from the past and proposed spectrum studies, and be used to investigate these issues and in the development of FAR network protocols. These protocols could use a typology that links the physical layer (PHY) closely with the media access control layer (MAC). Software simulations could test the concept of a FAR network acting as a sensor network to image the spectral environment. The desired attribute of this network typology is improved sensitivity and spatial knowledge with reduced observation time for each node. The simulation software could also be used to develop FAR protocols that are optimized for different attributes (e.g. efficiency vs. emitting interference). The protocols developed could be implemented in the prototype hardware FAR network, discussed in the next section.

7.4.6 Frequency Agile Radio Hardware Test Bed

A hardware prototype frequency-agile radio network could test concepts and implement the protocols developed with the FAR network simulation software. A heterogeneous architecture could be used that incorporates several fixed nodes and mobile nodes that have different capabilities and responsibilities. Figure 7.1 depicts a possible FAR network test-bed. The fixed nodes could offer better sensitivity than the mobile nodes; with both retaining the same IF level components to reduce cost and simplify the design. The fixed nodes could observe spectrum over long time periods to obtain its usage characteristics, which could be used to optimize the network protocols implemented. The network using a distributed model could collectively identify opportunities for spectrum reuse and search from incumbent spectral users to avoid inference.

The technical and viability issues for FAR networks discussed in the simulation software section could be investigated with the prototype hardware network. Prevention of interference and long term reliability could also be examined.

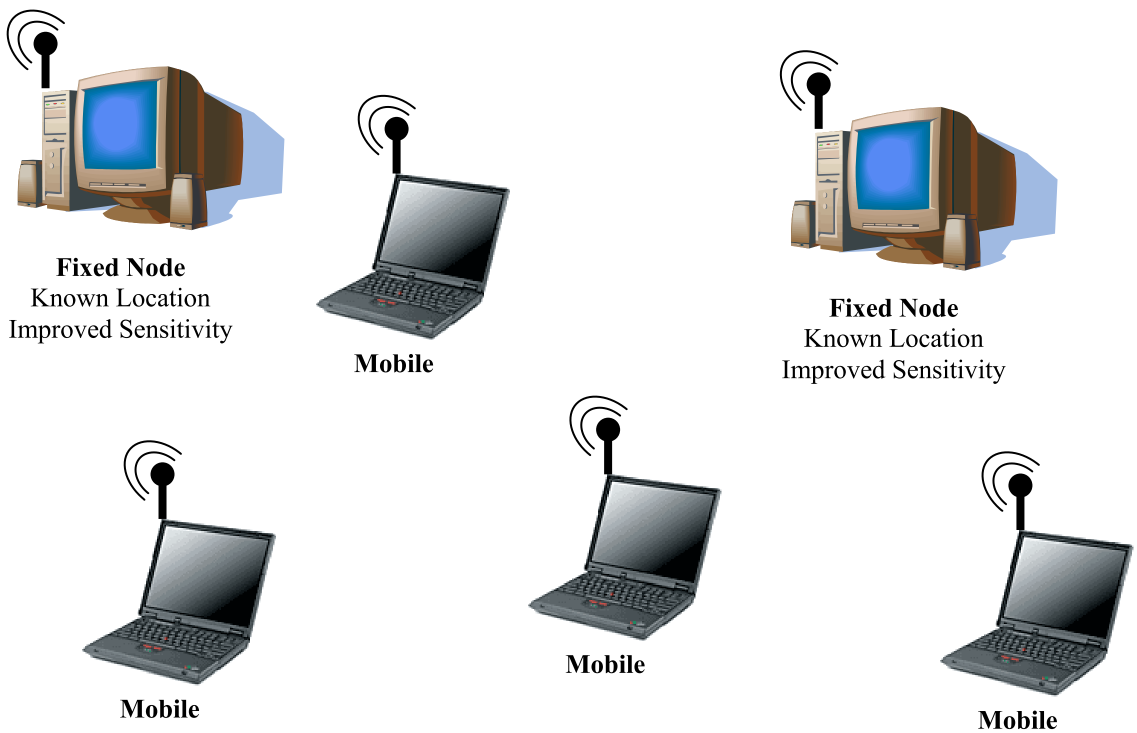

Figure 7.1: Heterogeneous frequency agile radio system.

APPENDIX A

DATABASE CLASS DESCRIPTION

```
<Serializable()> Public Class RSESFile

    Private inlocation As LocationTp
    Private indatetime As DateTime
    Private intimepd As TimePd
    Private inantenna As AntennaTp
    Private indirection As Integer 'same as angle
    Private infilter As FilterTp  'change for different freq
    Private inamp As AmpTp
    Private ingaincorr As GainCorrTp
    Private inunits As UnitsTp
    Private insweeptime As Double 'in seconds
    Private indet As DetectorTp
    Private inrl As Double 'in dBm
    Private insaatt As Double 'in dB
    Private infastart As Double 'in ver 1 was infstart, and property
startfreq, in Hz
    Private inrbw As Double 'in Hz
    Private invaliddatapts As Integer 'pos or negative
    Private indatapts() As Single = New Single(599) {} ' a 600 pt
array, with index from 0 to 599
    Private inversion As Integer 'Version of RSESfile, in Version 2
    Private instartfreq As Double 'Start Freq of complete data set, in
Hz, in Version 2
    Private instopfreq As Double 'Stop Freq desired, in Hz, in Version
2
    Private insweepsforbw As Integer 'number of sweeps needed to cover
the BW
    Private insweepsper As Integer 'sweeps per polz, direction, and
time period, in Version 2



#Region "Enums"

    Enum TimePd
        TPNA = 0   ' Time Period Not Available
        TIME1OF6 = 1 '12AM to  4AM
        TIME2OF6 = 2 ' 4AM to  8AM
        TIME3OF6 = 3 ' 8AM to 12PM
        TIME4OF6 = 4 '12PM to  4PM
        TIME5OF6 = 5 ' 4PM to  8PM
        TIME6OF6 = 6 ' 8PM to 12AM
    End Enum

    Enum AntennaTp
        UHFH = 1 ' UHFH
        UHFV = 2 ' UHFV
        GHZH = 3 ' 1 to 8 GHz H
        GHZV = 4  ' 1 to 8 GHz V
        NDON = 5  'noise diode port, with ND on
```

```
        NDOFF = 6 'noise diode port, with ND off
    End Enum

    Enum FilterTp
        FNONE = 0   ' none
        CF600 = 1   ' Lark 400-800 MHz
        CF1200 = 2 'Lark 800-1600 MHz
        CF1400 = 3 'Reactel 1175-1625 MHz
        CF2400 = 4 'Lark 1600-3200 MHz
        CF4800 = 5 'Lark 3200-6400 MHz
        HPF3000 = 6 'Minicircuits VHP-26
    End Enum

    Enum AmpTp

        AMPNONE = 0 ' none
        JCA08417 = 1 'JCA 08-417
    End Enum

    Enum DetectorTp

        DETNORMAL = 1 'Normal
        DETPOS = 2   'Positive Peak
        DETNEG = 3   'Negative Peak
        DETSAMPLE = 4 'Sample
    End Enum

    Enum GainCorrTp
        GNONE = 0   'none, SA reading
        GRSES = 1   'up to RSES input port
        GANTC = 2   'up to antenna cable
        GANTENNA = 3 'all including antenna
    End Enum

    Enum LocationTp
        RURAL = 0 'Rural, new: changed for rural measurements
        URB = 1 'Urban
        SUBR = 2 'Suburban
        'RURAL = 3 old version, do not use
    End Enum

    Enum UnitsTp
        UDBM = 1 'dBm
        UDBW = 2 'dBW
        USPFD = 3 'Spectral Power Flux Density, dBW/m^2/Hz
    End Enum

#End Region

#Region "Properties"

    Public Property location() As LocationTp
        Get
            Return inlocation
        End Get
        Set(ByVal Value As LocationTp)
            inlocation = Value
```

```
        End Set
    End Property

    Public Property vbdatetime() As Date
        Get
            Return indatetime
        End Get
        Set(ByVal Value As Date)
            indatetime = Value
        End Set
    End Property

    Public Property timepeiod() As TimePd
        Get
            Return intimepd
        End Get
        Set(ByVal Value As TimePd)
            intimepd = Value
        End Set
    End Property

    Public Property antenna() As AntennaTp
        Get
            Return inantenna
        End Get
        Set(ByVal Value As AntennaTp)
            inantenna = Value
        End Set
    End Property

    Public Property direction() As Integer
        Get
            Return indirection
        End Get
        Set(ByVal Value As Integer)
            indirection = Value
        End Set
    End Property

    Public Property filter() As FilterTp
        Get
            Return infilter
        End Get
        Set(ByVal Value As FilterTp)
            infilter = Value
        End Set
    End Property

    Public Property amp() As AmpTp
        Get
            Return inamp
        End Get
        Set(ByVal Value As AmpTp)
            inamp = Value
        End Set
    End Property
```

```
Public Property gaincorr() As GainCorrTp
    Get
        Return ingaincorr
    End Get
    Set(ByVal Value As GainCorrTp)
        ingaincorr = Value
    End Set
End Property

Public Property units() As UnitsTp
    Get
        Return inunits
    End Get
    Set(ByVal Value As UnitsTp)
        inunits = Value
    End Set
End Property

Public Property sweeptime() As Double
    Get
        Return insweeptime
    End Get
    Set(ByVal Value As Double)
        insweeptime = Value
    End Set
End Property

Public Property detector() As DetectorTp
    Get
        Return indet
    End Get
    Set(ByVal Value As DetectorTp)
        indet = Value
    End Set
End Property

Public Property ReferenceLevel() As Double
    Get
        Return inrl
    End Get
    Set(ByVal Value As Double)
        inrl = Value
    End Set
End Property

Public Property SAAttenuation() As Double
    Get
        Return insaatt
    End Get
    Set(ByVal Value As Double)
        insaatt = Value
    End Set
End Property

Public Property FAStart() As Double
    Get
        Return infastart
```

```
    End Get
    Set(ByVal Value As Double)
        infastart = Value
    End Set
End Property

Public Property RBW() As Double
    Get
        Return inrbw
    End Get
    Set(ByVal Value As Double)
        inrbw = Value
    End Set
End Property

Public Property ValidDataPts() As Int16
    Get
        Return invaliddatapts
    End Get
    Set(ByVal Value As Int16)
        invaliddatapts = Value
    End Set
End Property

Public Property DataPts() As Single()
    Get
        Return indatapts
    End Get
    Set(ByVal Value As Single())
        indatapts = Value
    End Set



End Property

Public Property startfreq() As Double
    Get
        Return instartfreq
    End Get
    Set(ByVal Value As Double)
        instartfreq = Value
    End Set
End Property

Public Property stopfreq() As Double
    Get
        Return instopfreq
    End Get
    Set(ByVal Value As Double)
        instopfreq = Value
    End Set
End Property

Public Property version() As Integer
    Get
        Return inversion
```

```
        End Get
        Set(ByVal Value As Integer)
            inversion = Value
        End Set
    End Property

    Public Property SweepsPer() As Integer
        Get
            Return insweepsper
        End Get
        Set(ByVal Value As Integer)
            insweepsper = Value
        End Set
    End Property


    Public Property SweepsForBW() As Integer
        Get
            Return insweepsforbw
        End Get
        Set(ByVal Value As Integer)
            insweepsforbw = Value
        End Set
    End Property
#End Region

End Class ' RSESFile
```

APPENDIX B

SETUP AND OPERATION OF SPECTRUM MESURMENT CONTROL SYSTEM

There are several steps to operating the spectrum measurement control system. The control computer to be used should have an installation of Microsoft Windows XP Professional and Microsoft Studios .Net 2003 with Framework 1.1 or backward compatible versions

The RSES software requires a Virtual Instrument Software Architecture (VISA) driver library for the GPIB hardware interface. This library is supplied by the GPIB hardware interface manufacturer (National Instruments for our system) and has to be called visa32.dll. For National Instruments this library is not installed with their default driver installation procedure; the custom option must be used. The address of the GPIB controller card and spectrum analyzer must match the identification number is the RSES software. This information is located in the saopen function of the SAHDF class.

The serial port numbers assigned by Windows must match the pre-assigned vales in the RSES software for use with the RF-subsystem and rotator controller. This information is located in the SysSetup function of the Form1 class.

The procedures for batch data collection are located in the DoJob function of the Form1 class. When the number of batch jobs to be completed is changed the corresponding information in the TimerBatch_Tick function must also be updated.

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VITA

Allen John Petrin was born in northern New Jersey in 1978. He grew up in Cedar Grove, New Jersey, and attended the subpar local public schools, until his graduation from high school. He has worked near continuously since he was 14, with his first job in a dog kennel. At 16 he got his first experience with management by supervising over 30 people, with many of them over twice his age. In May 1996 he started his collegiate education at New Jersey Institute of Technology located in the city of Newark. His original goal was to become a chemical engineer, but computers and electronics spurred his interest more. While an undergraduate he worked as an assistant in academic research labs and participated in several engineering internships. After four years of study he received a Bachelors of Science in Computer Engineering.

In August 2000 he began his graduate studies at Georgia Institute of Technology with naive enthusiasm, boundless energy, and the goal of changing the world. On the path to a PhD he was awarded a Masters of Science in Electrical and Computer Engineering in August 2003. He has been a pioneer in maximizing the usage of the radio spectrum though the development of Cognitive Radio technologies. This work included several broadband multi-dimensional spectrum studies to examine usage characteristics and interference in the radio spectrum environment. His work has been presented over a dozen times to academic conferences (IEEE, ISART, and URSI), government bodies (NSF, FCC), defense contractors, and a panel of the National Academies. In August 2005 he will receive his doctorate in Electrical and Computer Engineering for his contributions in this area. After defending, he will join Northrop Grumman in Fairfax, Virginia as a Communications Systems Engineer.