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Measurements to Characterize Land Mobile Channel Occupancy for Federal Bands 162–174 MHz and 406–420 MHz in the Washington, D.C., Area

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ACRONYMS

ADC	analog-to-digital converter.
ACPR	adjacent channel power ratio.
APD	amplitude probability distribution.
CW	continuous wave.
dB	decibel.
dBc	dB relative to carrier power.
FFT	fast Fourier transform.
FM	frequency modulation.
HOC	high occupancy channel.
IM	intermodulation.
ITS	Institute for Telecommunication Sciences.
kHz	kilohertz.
LMR	Land Mobile Radio.
LO	local oscillator.
MHz	megahertz.
NOAA	National Oceanic and Atmospheric Administration.
NTIA	National Telecommunications and Information Administration.
OSM	Office of Spectrum Management.
PSWAC	Public Safety Wireless Advisory Committee.
RF	Radio Frequency.

RSMS Radio Spectrum Measurement Science.

RSMS-4 Radio Spectrum Measurement Science 4th generation measurement system.

DEFINITIONS

Adjacent Channel Power Ratio: The ratio in decibels (dB) between the total transmitter power that lies within its authorized channel bandwidth and the part of the output power that falls within the bandwidth centered around the frequency assignment of the adjacent channel (expressed in units of dBc).

Amplitude Probability Distribution: A cumulative probability distribution plot representing the probability of exceeding a given level of power, where the y-axis displays power and the x-axis displays the probability expressed on a Rayleigh scale. A detailed description of APDs is given in a tutorial located in Appendix A of [1].

Area Assignments: Frequency assignments in the Government Master File that do not have specific coordinates and authorize base and/or mobile stations to operate anywhere within a defined geographic area (e.g., United States and Possessions).

Average of Busiest Usage by Hour: Determined by computing the average of the *Busiest Usage by Time-of-Day for Each Channel* values across all channels in the band, resulting in a single value for the entire band. The *Average of Busiest Usage by Hour* values are displayed in Tables A-1, A-2, A-5, and A-6.

Band Occupancy by Time-of-Day: Determined by taking the *Hourly Band Usage* values for each hour of the day, and computing the average for the corresponding hours of the measurement period. *Band Occupancy by Time-of-Day* values are displayed in Figures 29 through 31 and 41 through 43.

Busiest Usage by Time-of-Day for Each Channel: Determined for each channel by identifying the *Usage by Time-of-Day* value that is the largest out of the 24 values. There is only one *Busiest Usage by Time-of-Day* value for each channel. The *Busiest Usage by Time-of-Day for Each Channel* values are summarized in Figures 34 and 46.

Busiest Hour of the Week for Each Channel: Determined for each channel by identifying the time and date at which the highest *Hourly Channel Percent Occupancy* value occurs. During the week, channels will typically have a different date and time when the usage is busiest. *Busiest Hour of the Week for Each Channel* values are displayed in Figures 27 and 39.

Channel Percent Occupancy: Computed for each channel by determining the percent of *Channel Power Values* that exceed a detection threshold for each 1-second acquisition every day of the measurement period. For example, if 2,280 out of the 76,000 total *Channel Power Values* for a specific channel are above the detection threshold, then the channel occupancy is 3 percent at that detection level, for the specified channel. *Channel Percent Occupancy* values are summarized in Figures 33 and 45.

Channel Power Readings: The amount of received power on an individual channel measured using an Agilent E4440A Spectrum Analyzer in a resolution bandwidth of 5.5 kHz. Five of these basic measurements are used to compute a *Channel Power Value*, which is the building block for all further analysis and computations.

Channel Power Value: Determined by computing the median of five consecutive individual *Channel Power Readings* measured within a 1-second measurement period. The median value of the 5 independent measurements made for each channel is selected as the single value of measured power for that channel during that 1-second measurement period. All further processing of measured data is based on this median-of-five measurement technique. For example, if the five individual *Channel Power Readings* are -77, -70, -75, -69, and -73 dBm, the median value is -73 dBm. This value is computed for each channel at 1-second intervals, in the 4-minute measurement period for each 5-MHz frequency block. *Channel Power Values* are summarized in Figures 35, 36, 47, and 48.

Channel Power Values in an Hour: A set of individual *Channel Power Values* measured over a 1-hour period. This is represented by a set of data that typically contains either 240 (162–174 MHz band) or 480 (406–420 MHz band) median-of-5 *Channel Power Values* for that hour of that day for a specific channel.

Erlangs: A traffic equivalent to full time occupancy of a channel for an hour – for instance, one channel used continuously for 60 minutes, or two channels with a combined occupancy of 60 minutes. In this report, the number of Erlangs is determined by multiplying the percent usage by the total number of channels in the band.

High Occupancy Channel: A channel that exceeds the detection threshold for a large percent of the time (defined in this paper as > 80% of time).

Hourly Band Usage: Determined by averaging all of the *Hourly Channel Percent Occupancy* values in a given hour of a given day for all of the channels in the band. The *Hourly Band Usage* is displayed in Figures 26, 28, 38, 40, A-1, and A-2.

Hourly Channel Percent Occupancy: Computed for each channel by determining the number of *Channel Power Values in an Hour* for a given channel that exceed a detection threshold. For example, if 14 out of 480 total *Channel Power Values in an Hour* are above the detection threshold, then the channel occupancy is 3 percent at that detection level, for the specified hour and channel. *Hourly Channel Percent Occupancy* values are summarized in Figures 32, 37, 44, and 49.

Maximum Band Occupancy: The maximum of all *Band Occupancy by Time-of-Day* values. This can be identified in Figures 30 and 42.

Occupancy: Channels are considered to be occupied (i.e., in use) whenever the channel contains Radio Frequency (RF) power above a certain received detection threshold level. By some definitions a channel may be considered "in use" even if no traffic is being carried during the time of measurement. For instance, a channel being used by a Secret Service agent protecting the President may not carry traffic (not occupied) unless there is an emergency. However, the channel is "in use" in the sense that personnel are monitoring the channel and ready to take action should a situation require it. In this report, "usage" is used interchangeably with the term "occupancy," which means "carrying traffic" – not simply being monitored.

Percent Band Usage: Determined by computing the mean of all *Hourly Channel Percent Occupancy* values for all channels during the measurement period. The measurement periods examined include all days, weekdays only, weekend days, and Election Day. *Percent Band Usage* values are shown in Tables A-1 through A-8.

Specific Location Assignments: Frequency assignments in the Government Master File that have specific coordinates (latitude and longitude) for the location of the base station and a radius of operation for the associated mobile and portable stations.

Trunking: The method used in some modern communications systems in which frequency channels are assigned dynamically as communication is required, usually when there are more users than available frequency channels. This allows time sharing of the same frequencies by multiple users, thus improving channel usage efficiency. Typically, a control channel is used to make initial contact, after which a frequency channel is assigned and automatically tuned to by the user's radio device during the course of the connection. This technique is utilized in most modern cellular phone services since there are far more users than available frequencies.

Usage by Time-of-Day for Each Channel: Determined for each channel by computing the average of the *Hourly Channel Percent Occupancy* values for each specific hour of the day for the corresponding measurement period (e.g., all days, weekdays, weekend days, and Election Day). For example, channel 1 will have 24 different *Usage by Time-of-Day for Each Channel* values, each for a different hour of the day. These 24 values represent the mean usage for that specific time of day over the course of the several days of the measurements.

Usage: Refer to the definition for "Occupancy".

EXECUTIVE SUMMARY

In May 2003, President Bush established the Spectrum Policy Initiative to promote the development and implementation of a United States spectrum policy for the 21st century. In response to the Spectrum Policy Initiative, the Secretary of Commerce established a Federal Government Spectrum Task Force and initiated a series of public meetings to address policies affecting spectrum use by the Federal, state, and local governments, and the private sector. The recommendations resulting from these activities were included in two reports released by the Secretary of Commerce in June 2004. Based on the recommendations contained in these reports, the President directed the Federal Agencies on November 30, 2004, to plan the implementation of the 24 recommendations contained in the reports. One of the recommendations directed the National Telecommunications and Information Administration (NTIA) to develop analytic approaches, software tools, and engineering techniques for evaluating and improving the efficiency and effectiveness of Federal spectrum use.

To satisfy one of the goals of that recommendation, NTIA's Institute for Telecommunication Sciences (ITS) undertook a series of channel occupancy measurements in the Washington, D.C., area from October 26 to November 3, 2004 in the Land Mobile Radio (LMR) bands 162–174 and 406–420 MHz. The purpose of these measurements was twofold: first, to develop channel occupancy measurement techniques for LMR bands and secondly, to gather actual data on the usage of these bands in the Washington, D.C., area. The measurement techniques can be used at other metropolitan locations when the need arises to measure the LMR channel usage. The data gathered for this area and these bands will be used for further analyses of other aspects of the Presidential Spectrum Policy Initiative.

The measurements were conducted on the grounds of the partially abandoned Saint Elizabeth's Hospital, centrally located in the Washington, D.C., area, using the fourth generation of the Radio Spectrum Measurement Science (RSMS) system. The measurements were conducted 24 hours per day over the course of 8 consecutive days which included the Presidential Election Day. The measured data were post processed at the ITS Laboratory in Boulder, Colorado.

The measurement system was designed to have a coverage area of approximately 100-km radius for base stations, 50-km radius for mobile units, and 25-km radius for portable units. The measurement results are reported in terms of channel usage for designated LMR channels, irrespective of whether the individual channels have been assigned or not. The data, which was based on sampling the received power on individual LMR channels over an eight-day period of time and comparing those values to specific detection thresholds, was used to identify whether or not the LMR channels are being used at that location and to what extent.

Four types of data are presented in this report: 1) mean channel usage statistics, 2) mean busiest-hour usage statistics, 3) power level statistics, and 4) statistics on percent of channels (and hourly channel usage) exceeding a given percent usage.

The measured data contains information on channel usage for two types of frequency assignments: Specific Location Assignments and Area Assignments. Specific Location Assignments have specific coordinates (latitude and longitude) for the location of the base station and a radius of operation for associated mobile and portable stations. Area Assignments do not have specific coordinates and authorize base and/or mobile stations to operate anywhere within a specific geographic area (e.g., United States and Possessions). These two types of frequency assignments were not distinguished during analyses; therefore the usage statistics are based on both types of assignments.

For the 162–174 MHz band, the mean percent time that all of the channels in the band are being used for each hour (referred to in this report as *Band Occupancy by Time of Day*) varied between 0.5 and 1.6 percent, with the busiest hours being between 7 am and 5 pm. For the 406–420 MHz band, the value was 1.2 to 3.6 percent with the busiest hours being between 5 am and 8 pm.

The *Band Occupancy by Time of Day* for conventional LMR systems can be compared to allowable call-blockage (typically defined as Grade of Service) as recommended in the Final Report of the Public Safety Wireless Advisory Committee (PSWAC). In that report, the PSWAC recommends that call-blockage not exceed "one call for service per one hundred attempts during the average busy hour." That translates to no more than 1 percent usage for multi-user conventional systems where channels are assigned statically. Since the existing systems measured in the 162–174 MHz band are conventional systems, the measured channel usage during the busiest hour of 1.6 percent is consistent with the recommendations made by the PSWAC.

Each of the two measured bands show approximately the same diurnal pattern of usage, irrespective of the measurement period (e.g., all days, weekdays, weekends, or Election Day), with slight variations between them. In the 162–174 MHz band, the highest usage occurs during the weekdays, exceeding the other time scenarios by about 1 percent. In the 406–420 MHz band, the usage was about the same for all of the time scenarios, except for about a 1 percent less usage on the weekend mornings, and about a 1 percent greater usage on the afternoon of the Presidential Election Day.

It should be noted that most of the channels in these bands are statically assigned to networks or individual users, in contrast to dynamically assigned as is the case with trunked systems, where there is time sharing of each frequency channel by multiple users. Some of these assigned channels are reserved for high priority usage in which communication must be available at all times for a limited number of users, thus resulting in low percent usage. In addition, none of these measurements were made during a major emergency that might have greatly increased the use of radio channels.

The data can be used for specifying the overall performance objectives of a hypothetical communications system using a different technology (e.g., trunking). By designing the hypothetical system to provide the same overall communications capability as the existing LMR systems, the existing and hypothetical systems could then be compared to examine relative total spectrum usage (number of channels required for each system).

The intent of the measurements was not to examine details of performance and use for the characterization of individual channels. This individual channel information, as well as more extensive measurements, may be required for a detailed engineering design for a next generation system.

Measurements to Characterize Land Mobile Channel Occupancy for Federal Bands 162–174 MHz and 406–420 MHz in the Washington, D.C., Area

J. Randy Hoffman, Robert J. Matheson, and Roger A. Dalke[1]

This report describes field measurements to characterize Land Mobile Radio (LMR) channel occupancy of Federal bands 162–174 MHz and 406–420 MHz at a single central location in the Washington, D.C., area. This is part of the National Telecommunications and Information Administration effort to evaluate the spectrum efficiency in the Federal frequency bands. Measurements of the received signal levels in LMR frequency bands 162–174 MHz and 406–420 MHz were performed over an eight day period for the purpose of determining channel usage within the measurement system's coverage area of approximately 100-km radius for base stations, 50-km radius for mobile units, and 25-km radius for portable units. The measurements were made using new equipment and techniques that digitize as much as a 5-MHz segment of spectrum and process it to obtain simultaneous signal levels of up to 400 individual LMR channels. These techniques provided faster measurements, but also allowed enhanced post-processing of the data to remove effects of impulsive noise.

Key words: channel occupancy; channel usage; Federal radio usage; Land Mobile Radio (LMR); measurements; spectrum efficiency

1 INTRODUCTION

In May 2003, President Bush established the Spectrum Policy Initiative to promote the development and implementation of a United States spectrum policy for the 21st century. In response to the Spectrum Policy Initiative, the Secretary of Commerce established a Federal Government Spectrum Task Force and initiated a series of public meetings to address policies affecting spectrum use by the Federal, state, and local governments, and the private sector. The recommendations resulting from these activities were included in two reports released by the Secretary of Commerce in June 2004. Based on the recommendations contained in these reports, the President directed the Federal Agencies on November 30, 2004, to plan the implementation of the 24 recommendations contained in the reports. One of the recommendations directed the National Telecommunications and Information Administration (NTIA) to develop analytic approaches, software tools, and engineering techniques for evaluating and improving the efficiency and effectiveness of Federal spectrum use.

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As discussed in the Spectrum Policy Initiative reports, the radio frequency spectrum is a critical resource that is used by the Federal Government to perform congressionally mandated missions. Efficient use of the spectrum is one of the cornerstones for obtaining maximum usage of the available spectrum. NTIA and the other Federal Agencies realize that the primary way to satisfy the growing demands for spectrum in the Land Mobile Radio (LMR) frequency bands is to employ more spectrum efficient technologies.

As part of the effort to meet these objectives, NTIA performed a study that created a database of frequency assignments from the Government Master File (GMF) in the 162–174 MHz band within a 100-mile radius of Washington, D.C. The Washington, D.C., metropolitan area was selected because it is believed to be representative of a spectrally congested environment. Licensed data from Federal Agency radio systems and agency interviews were used to understand the services provided by Federal radio systems in this frequency band, including the coverage areas and other aspects of each radio system. This information was used to produce "signal capacity" maps that showed the cumulative coverage areas of all Federal radios in this band, including the number of simultaneous messages that could be carried at various locations within 100 miles of Washington, D.C. Results of this work were compiled in a report titled "Federal Land Mobile Operations in the 162-174 MHz Band in the Washington, D.C., Area" [2].

NTIA's Institute for Telecommunication Sciences (ITS) then undertook a series of channel occupancy and usage measurements in Washington, D.C., in the LMR bands of 162–174 and 406–420 MHz, the results of which are described in this report. The results of these channel occupancy measurements can further be used to specify the overall performance objectives of LMR systems employing different technologies (e.g., trunking).

1.2 Objective

There were two objectives for this project. The first objective was to monitor each assignable 12.5- and 25-kHz channel in the 162–174 MHz and 406–420 MHz bands in the Washington, D.C., area to determine the amount of time those channels contained power above specific thresholds, and to present statistical analysis of channel occupancy based on number of occurrences exceeding the threshold. The second objective was to develop channel occupancy and usage measurement techniques for LMR bands using the latest in technology.

1.3 Approach

Using the Radio Spectrum Measurement Science 4th generation measurement system (RSMS-4), the measurements were performed during the course of eight consecutive days, including the Presidential Election Day (October 26 to November 3, 2004). The measurement system was designed for a receiver coverage of approximately 100-km radius for base stations and repeaters, 50-km radius for mobile units, and 25-km radius for portable units.[2] Data were acquired continuously, 24 hours per day, over the course of the eight-day period and then analyzed for Federal bands 162–174 MHz and 406–420 MHz to furnish channel loading statistics.

The measurements were made using new equipment and techniques that digitize as much as a 5-MHz segment of spectrum and process it to obtain simultaneous signal levels of up to 400 individual LMR channels. These techniques provided faster measurements, but also allowed enhanced post-processing of the data to remove effects of impulsive noise.

In this report, channels are considered to be occupied (i.e., in use) whenever the channel contains Radio Frequency (RF) power above a certain received threshold level. The measurements were made and recorded so that variable threshold levels could be used for purposes of analyzing the effects of external noise and other factors. This definition of occupancy is generally consistent with other definitions of usage, although the choice of received power detection threshold levels is not necessarily uniform among researchers. By some definitions a channel may be considered "in use" even if no traffic is being carried during the time of measurement. For instance, a channel being used by a Secret Service agent protecting the President may not carry traffic (not occupied) unless there is an emergency. However, the channel is "in use" in the sense that personnel are monitoring the channel and ready to take action should a situation require it. In this report, "usage" is used interchangeably with the term "occupancy," which means carrying traffic – not simply being monitored.

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[2] Typical reuse distances for base stations and repeaters is approximately 100 km.

2 LMR SIGNAL CHARACTERISTICS AND EMISSION ENVIRONMENT

This section provides an overview of the LMR signal characteristics and the other emissions in the RF environment that were a factor in determining the parameters of the system for measuring the 162–174 MHz and 406–420 MHz frequency bands. The two LMR signal characteristics that determine measurement parameters are: channelization (how the frequencies are assigned in each band), and adjacent channel power ratio (how much a signal must be attenuated at the adjacent channel). The former determines preselector filter characteristics, center frequency assignments, the degree of decimation of digitized data, and the manner in which frequencies are grouped for acquisition. The latter determines the windowing requirements and data acquisition length (which ultimately determine the resolution of individual LMR signals that can be measured). The other environmental emission factors that must be considered in determining the measurement system parameters, include the range of in-band signal levels, out-of-band signal levels, and the nature of RF noise.

2.1 Channelization

Table 1 summarizes the center frequencies of possible channel assignment in the 162–174 MHz and 406–420 MHz bands. While frequencies in these bands were originally assigned using a 25-kHz channel spacing scheme (referred to in this report as "the old 25-kHz channels"), frequencies assigned in these bands are now required to use a 12.5-kHz channel spacing (referred to in this report as "the new 12.5-kHz channels"). To do so requires that the emission bandwidth of any existing LMR systems be reduced to half the original bandwidth so that the new 12.5-kHz channels can be inserted between the original channels, spaced 25 kHz apart. In the 406–420 MHz band, the center frequencies of the old 25-kHz channels are assigned according to the following equation:

$$(406.125 \text{ MHz}) + (N \text{ x } .025), \text{ where } N = 0 \text{ to } 554.$$

The new 12.5-kHz channelization scheme adds channels midway between the old 25-kHz channels so that these channels occur at:

$$(406.1125 \text{ MHz}) + (N \text{ x } .025), \text{ where } N = 0 \text{ to } 555.$$

In the 162–174 MHz band, the center frequencies of the old 25-kHz channels and the new 12.5-kHz channels are assigned according to the equations given in Table 2 and Table 3 respectively [3].

Table 1. Center Frequencies for LMR Measurements

Frequency	Measurement Center Frequencies
162–174 MHz	Multiples of 12.5 kHz starting at 162.0125 MHz
406–420 MHz	Multiples of 12.5 kHz starting at 406.1125 MHz

Table 2. Old 25-kHz Channel Assignments in the 162–174 MHz Band

162.025 MHz + N x 0.025, where N = 0–22
162.6125 MHz + N x 0.025, where N = 0–7
162.825 MHz + N x 0.025, where N = 0–22
163.4125 MHz + N x 0.025, where N = 0–7
163.625 MHz + N x 0.025, where N = 0–6
163.8125 MHz + N x 0.025, where N = 0–7
164.05 MHz + N x 0.025, where N = 0–31
164.8625 MHz + N x 0.025, where N = 0–37
165.825 MHz + N x 0.025, where N = 0–23
166.4375 MHz + N x 0.025, where N = 0–8
166.675 MHz + N x 0.025, where N = 0–20
167.2125 MHz + N x 0.025, where N = 0–23
167.825 MHz + N x 0.025, where N = 0–135
171.2375 MHz + N x 0.025, where N = 0–6
171.425 MHz + N x 0.025, where N = 0–70
173.4125 MHz + N x 0.025, where N = 0–23

Table 3. New 12.5-kHz Channel Assignments in the 162–174 MHz Band

162.0125 MHz + N x 0.025,	where N = 0–23
162.6 MHz + N x 0.025,	where N = 0–7
162.8375 MHz + N x 0.025,	where N = 0–22
163.425 MHz + N x 0.025,	where N = 0–7
163.6125 MHz + N x 0.025,	where N = 0–7
163.825 MHz + N x 0.025,	where N = 0–6
164.0375 MHz + N x 0.025,	where N = 0–32
164.85 MHz + N x 0.025,	where N = 0–37
165.8375 MHz + N x 0.025,	where N = 0–23
166.45 MHz + N x 0.025,	where N = 0–7
166.6625 MHz + N x 0.025,	where N = 0–21
167.225 MHz + N x 0.025,	where N = 0–22
167.8375 MHz + N x 0.025,	where N = 0–135
171.25 MHz + N x 0.025,	where N = 0–5
171.4125 MHz + N x 0.025,	where N = 0–71
173.425 MHz + N x 0.025,	where N = 0–22

2.2 Adjacent Channel Power Ratio

Adjacent channel power ratio (ACPR) is the ratio in decibels (dB) between the total transmitter power that lies within its authorized channel bandwidth and the part of the output power that falls within the bandwidth centered around the frequency assignment of the adjacent channel (expressed in units of dBc). Chapter 5 of the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management specify the ACPR standards for Federal LMR systems in the 162–174 MHz and 406–420 MHz bands [4]. The ACPR standards are specified for analog and digital wideband (25 kHz channels) and narrowband (12.5 kHz channels) operations as shown in Table 4. The NTIA ACPR standards are consistent with those specified by the Telecommunications Industry Association for analog [5] and digital [6] LMR systems.

Table 4. Minimum ACPR Requirements for Analog and Digital Federal LMR Systems

	Channel Spacing	
Frequency Range	Wideband Operation	Narrowband Operation
162–174 MHz	50 dBc	70 dBc
406–420 MHz	70 dBc	70 dBc

2.3 Emission Environment

Factors associated with the RF emission environment must also be taken into consideration in determining the parameters for the measurement system. These factors include range of in-band signal levels, out-of-band signal characteristics, and the nature of RF noise. Because LMR systems by their very nature are mobile, the signal power received at the measurement system can be time varying and span a range as great as 100 dB in received power – the weakest signals coming from distant transmissions and the stronger signals coming from nearby base stations and local mobile and hand-held units that approach the measurement system. Not only can a single frequency assignment vary greatly in power from time to time, but power can vary greatly between adjacent frequencies. Because of this broad range of received signal powers, depending upon the degree of sensitivity of the measurement system, the system must have a wide instantaneous dynamic range (i.e., be able to resolve the individual signals without varying the sensitivity of the measurement system across the band of acquisition).

To prevent overload of the measurement system front-end amplifiers, out-of-band emissions must be attenuated through proper filtering. The most significant out-of-band emissions that affect the measurement system requirements are those due to TV station channel 7; this channel occupies the spectrum between 174 and 180 MHz. This is a very strong signal, and not only can it saturate the front-end amplifiers of a sensitive system, but it also has strong enough adjacent channel emissions within the 162–174 MHz LMR band to be detected significantly above the noise floor of the measurement system (10 dB or more depending upon the measurement system noise figure).

The other factor in the emission environment that has to be addressed is RF noise. Preliminary investigation shows that in the spectrum region of interest, the mean of the Gaussian RF background noise power usually lies well enough below the measurement system noise power so as not to be detected. However, impulsive noise can occur well above the measurement system noise, and therefore techniques have to be employed to differentiate this emission source from the LMR signals.

3 FIELD MEASUREMENTS DESCRIPTION

This section describes the measurement method and requirements, system configurations, and calibrations.

3.1 Measurement Requirements

The major objective in making these LMR measurements was to determine, for various detection thresholds, the proportion of time that a given channel (or group of channels) is carrying traffic. To meet these objectives, several requirements, as described in Table 5, were imposed with regard to sensitivity, antenna characteristics, dynamic range, frequency resolution, out-of-band rejection, noise suppression, speed of acquisition, and location.

Table 5. Measurement Requirements

Parameters	Requirement
Threshold	Minimum threshold for signal detection set as low as possible, which for this measurement system is 8 dB above median system noise. This translates to a field strength of approximately 8 dB μV/m. (The noise figure referenced to the output of the antenna terminals for the 162-174 MHz and 406-420 MHz systems is 13.9 dB and 11.9 respectively.)
Instantaneous Dynamic Range	84 dB between point of measurement system front-end compression and arithmetic mean system noise power.
Channel Resolution	12.5 kHz, 70 dB below the channel center frequency.
Out-of-band Rejection	Preselection filtering to reduce total passband power so that sensitivity and dynamic range requirements can be maintained.
Noise Suppression	Process data to achieve a probability of no greater than 0.01% that an instantaneous system noise level will exceed the median system noise by more than 8 dB.
Speed of Acquisition	Acquire and store data every 1 second.
Antenna Characteristics	Omnidirectional; vertically polarized; Gain = 1 dBi.
Location	Place measurements system in the center of the city with the highest elevation possible.

The measurement of LMR signal usage can be technically very demanding. The detection of very weak LMR signals transmitted by distant transmitters requires the use of a very good system noise figure. However, the possible presence of relatively strong signals from close-in transmitters means that strong signals can occasionally push the measurement system amplifiers into a non-linear region of operation and produce intermodulation (IM) products. These IM products appear like real signals to a measurement system. To minimize the undesired generation of unwanted signals from IM effects, a measurement system that has a large instantaneous dynamic range is required.

Strong signals can also mix with local oscillator (LO) noise sidebands (what is left after the pure sinusoidal signal is subtracted from a local oscillator). These LO noise sidebands create a region of higher system noise for many channels on either side of the strong signal. To minimize the effects of LO noise sidebands, it is necessary to obtain "cleaner" LO signals or to somehow avoid strong signals in the receiver. Sideband noise can also be due to jitter in the analog-to-digital converter (ADC), and sidebands created when applying a window function to the raw digitized data; therefore, a high quality ADC and a carefully chosen window function are required.

Because of the numerous unwanted effects of very strong LMR signals, great care is taken to keep strong signals out of the measurement receivers. Measurement sites are selected on the basis of having at least a minimum geographical separation from known sites with strong transmitters. The measurement system is often used with narrowband preselection filters, whose function is to limit the frequency range over which strong signals can enter the measurement system. Known strong signals (e.g., transmitted from a nearby transmitting tower) can be specifically rejected by tunable notch filters or other techniques. Unfortunately, some of these techniques to control unwanted strong signals also tend to increase the measurement system noise figure. Therefore, the actual performance of the measurement system is often determined by a difficult set of compromises and adjustments that depend partly on the specific characteristics of the local signal environment.

3.2 Site Selection

These LMR channel occupancy measurements were made using NTIA's Radio Spectrum Measurement Science (RSMS) mobile laboratory at a site on the grounds of the partially-abandoned Saint Elizabeth's Hospital located at coordinates N38° 51.427', W77° 0.013' (Figure 1). The measurements were conducted 24 hours per day over the course of 8 consecutive days (Tuesday, October 26 to Wednesday, November 3, 2004), which included the Presidential Election Day. The site was chosen for several reasons. It is centrally located in Washington, D.C., and is elevated above the surrounding area. Because it is partially abandoned, there is little LMR activity in close proximity. In addition, there are relatively few strong base stations nearby that could overdrive the measurement system.

Figure 2 shows an aerial view of the Washington, D.C., area with a marker designating the location of the measurement system. Figures 3 and 4 show coverage plots using the Longley-Rice irregular terrain model (maximum receiver sensitivity) for three different transmitter scenarios: 1) a 100-W transmitter with 3-dBi gain and a 30-meter antenna height (typical base station), 2) a 50-W transmitter with 0-dBi gain and a 1.5-meter antenna height (typical mobile unit), and 3) a 10-W transmitter with -3-dBi gain and a 1.0-meter antenna height (typical portable unit).[3] Figures 3 and 4 are for frequency bands 162–174 MHz and 406–420 MHz respectively.

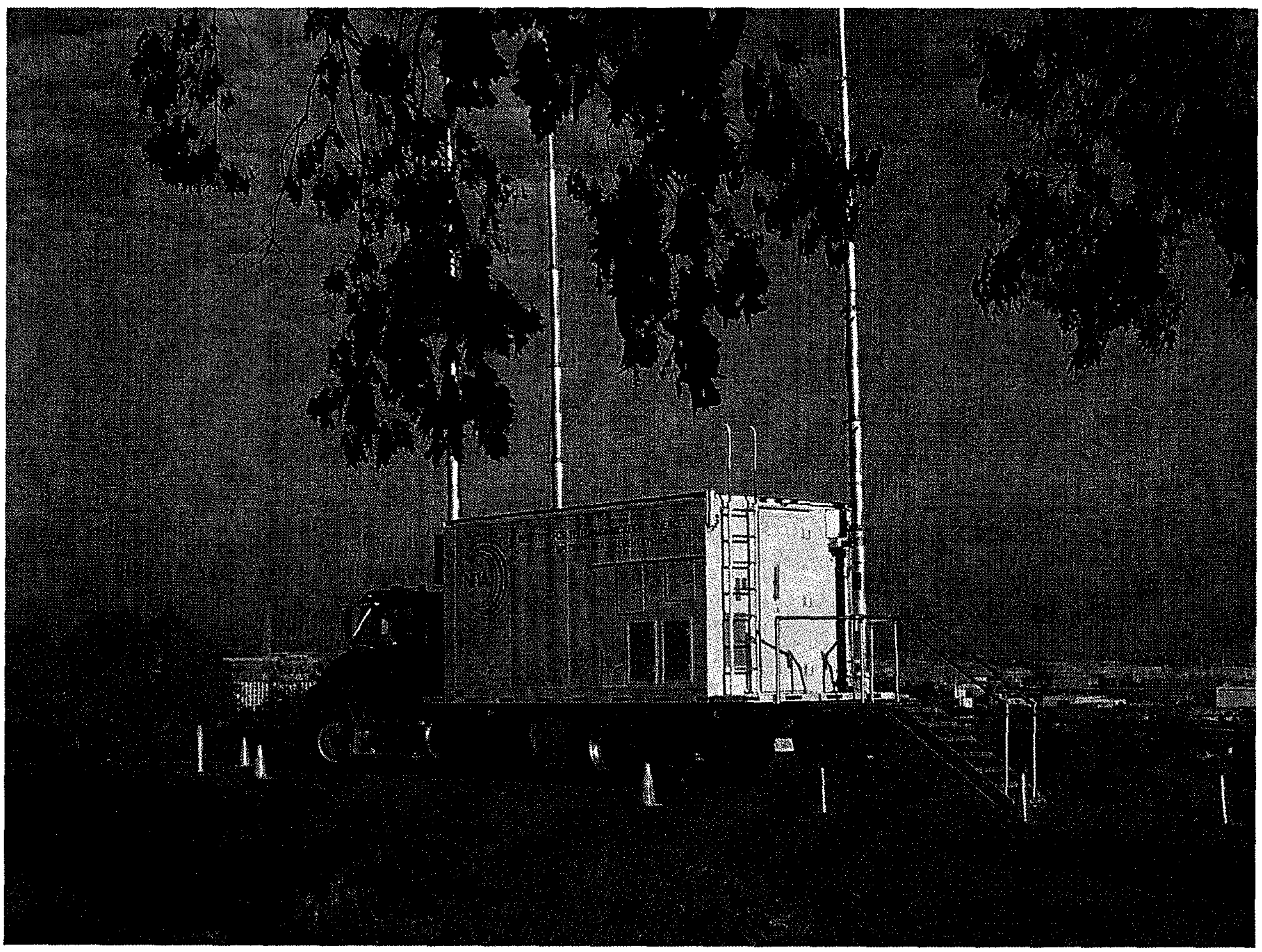

Figure 1. RSMS mobile lab at the St. Elizabeth's Hospital site.

[3]More realistically, portable units have a maximum output of 5–6 W, and therefore, the coverage plot for portable units may be slightly less than that shown in the diagrams.

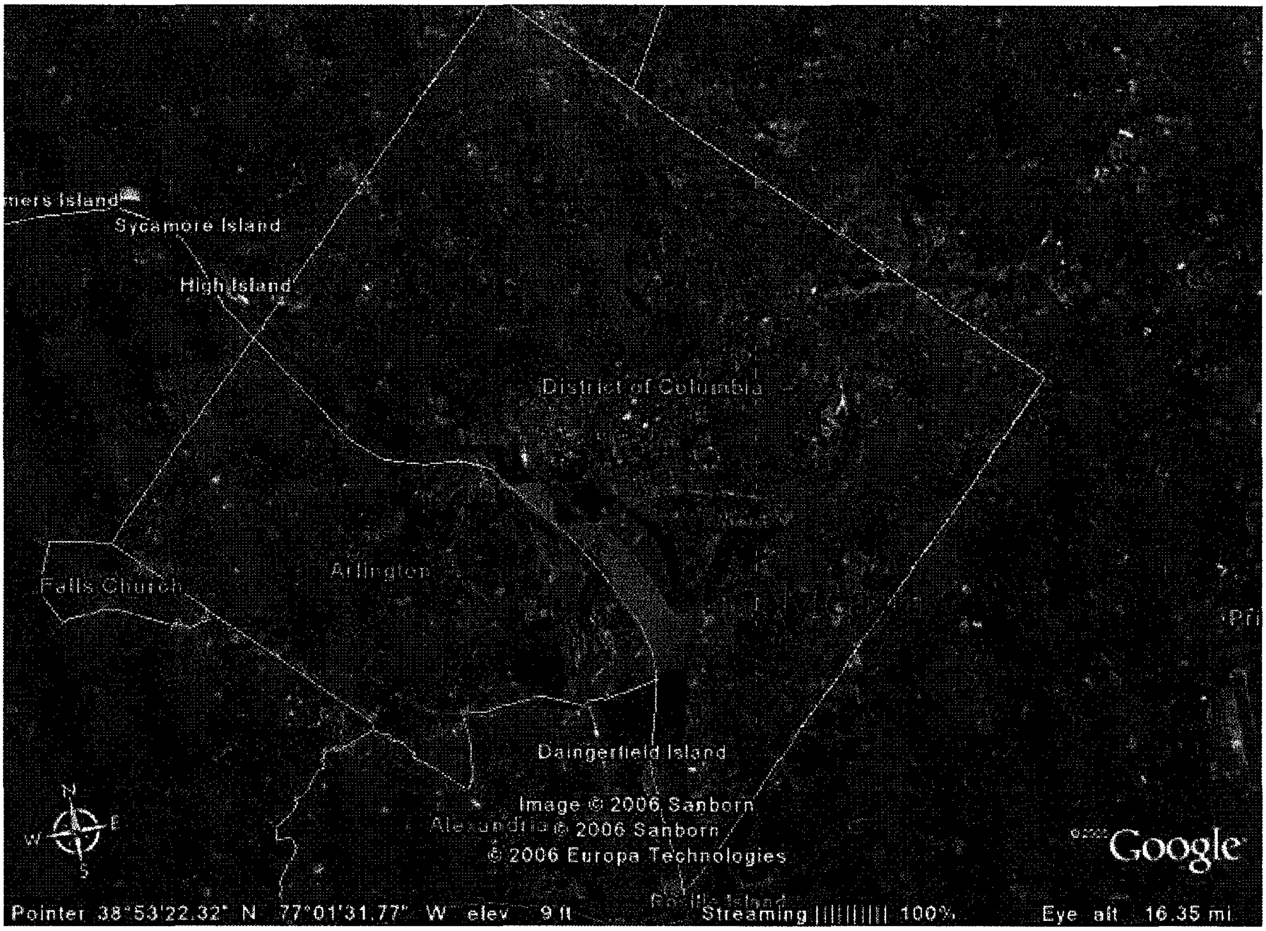

Figure 2. Aerial view of Washington, D.C., area showing location of measurement system.

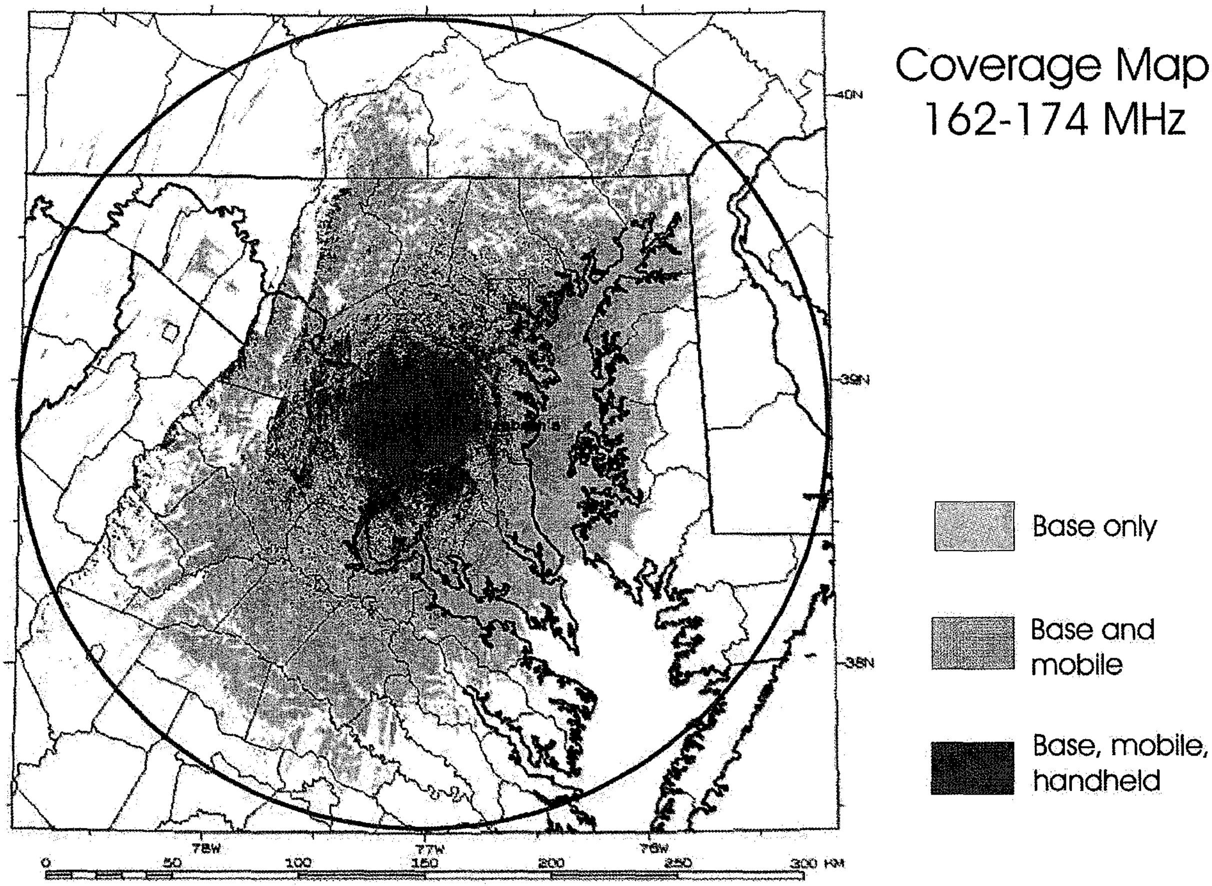

Figure 3. Coverage plots for the 162–174 MHz band using the minimum receiver threshold.

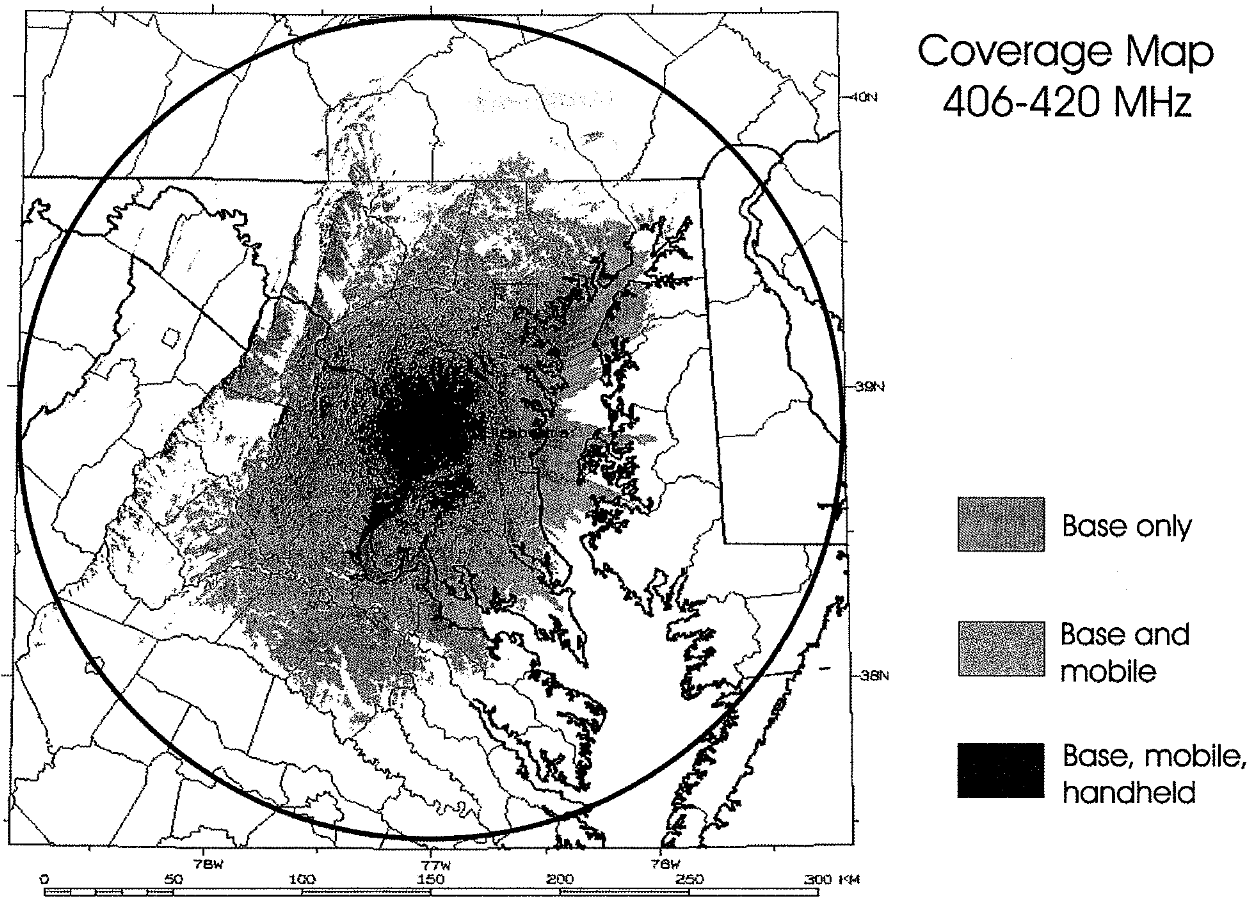

Figure 4. Coverage plots for the 406–420 MHz band using the minimum receiver threshold.

3.3 System Hardware Components

A generic block diagram of the measurement system is shown in Figure 5. Two separate fully automated systems were run simultaneously, one to collect data in the 162–174 MHz band and the other to collect data in the 406–420 MHz band. Two separate vertically polarized discone antennas, one optimized for each measurement frequency band, were positioned on top of 10-meter masts. The preselector unit consists of a variable attenuator to reduce system sensitivity in cases of strong local in-band signals, bandpass filters to reduce strong signals outside the measurement band so that sensitivity and dynamic range requirements can be maintained, and a low-noise amplifier to improve the system sensitivity by reducing the noise figure. The output of the preselector is passed to an Agilent E4440A spectrum analyzer that downconverts and digitally processes the signal in a specialized "Base" mode configuration.[4] A computer controls the spectrum analyzer and the preselector. The computer also processes the data and saves it to storage for further post processing and analysis. The preselector filters for the 162–174 MHz band consist of 3 separate bandpass filters in the following 1-dB bandwidths: 159–164 MHz, 164–169 MHz, and 169–174 MHz. The filters are inserted into the path through an automated switching routine controlled by the acquisition software. The 406–420 MHz system has a single bandpass filter with cutoff frequencies at the edges of the band.

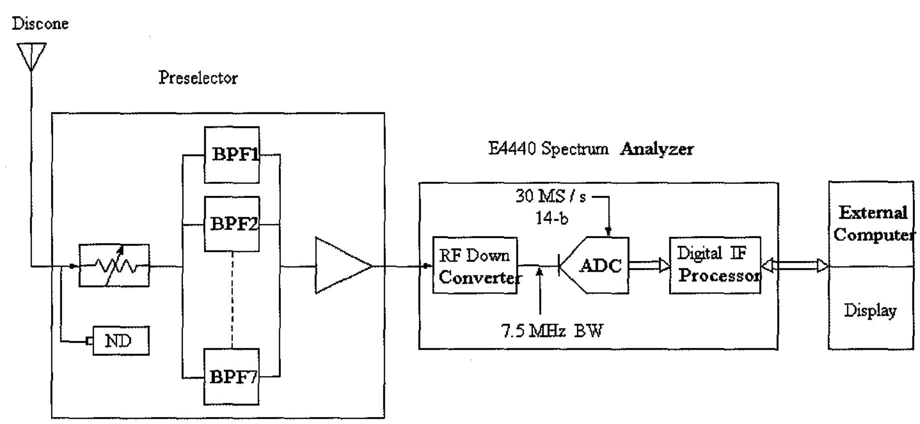

Figure 5. Block diagram of measurement system.

[4]"Base" mode on an Agilent E4440A spectrum analyzer provides FFT spectrum analysis, as opposed to swept frequency analysis typically utilized for most spectrum analyzers.

3.4 Measurement Procedures

The 162–174 MHz band and the 406–420 MHz band were each measured in contiguous several-MHz-wide blocks, beginning at the lowest frequency block, continuing in several-MHz steps until the highest frequency block in the band was reached, and then restarting at the lowest frequency block in the band. Within each block, signals were measured at 12.5-kHz channel spacings so that the data could be analyzed for both the old 25-kHz channels and the new 12.5-kHz channels by processing with the frequencies assigned to the respective channelization schemes (described in Section 2.1). The 162–174 MHz band was measured in 3 separate frequency blocks: 162–164 MHz (158 channels), 164–169 MHz (400 channels), and 169–174 MHz (400 channels). Though there is only one bandpass filter that covers the entire frequency range of the 406–420 MHz band, the measurements were divided into 3 separate frequency blocks, with each having a span no greater than 5 MHz; these consist of the blocks 406–411 MHz (400 channels), 411–416 MHz (400 channels), and 416–420 MHz (319 channels). As with the 162–174 MHz band, signals in the 406–420 MHz band were measured at 12.5-kHz channel spacings.

By setting the proper acquisition time period and using a Flattop window [7], a 1-dB resolution bandwidth of 5.5 kHz is achieved. This results in a 70-dB suppression for signals outside a 15-kHz range, as demonstrated in Figure 6 which shows a fast Fourier transform (FFT) of a continuous wave (CW) signal with the same settings used in the LMR measurements. Figure 7 shows multiple FFT traces of a carrier signal FM-modulated with 3-kHz band-limited Gaussian noise and a ±3-kHz maximum frequency deviation. Figure 8 shows the same thing but with a ±6-kHz maximum frequency deviation.[5] The digital acquisition time is short enough that, for any one acquisition, the signal is relatively stationary at a very narrow range of frequencies. For the different traces, the carrier is shifted in frequency by the modulating signal but with a shift no greater than the maximum frequency deviation. However, because there is still a small shift in frequency during the acquisition, the spectrum of any single trace is "spread," as compared to that seen with a CW signal. Using this measurement scheme, it can be seen, therefore, that for two adjacent channels (*C1* and *C2*) and an FM modulated signal *S* with a center frequency at *C1*, essentially no power from *S* is detected at *C2* by as much as 70 dB below the peak power of *S* when the channel separation is greater than 12.5 kHz for a ±3-kHz maximum frequency deviation and 15 kHz for a ±6-kHz maximum frequency deviation. Therefore, irrespective of the channel spacing, this resolution bandwidth can resolve adjacent FM modulated, LMR-type channels as specified in the measurement requirements (Table 5).

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[5] Frequency deviation for all FM or PM station classes are not to exceed 5 kHz for analog wideband emissions, 2.5 kHz for analog narrowband emissions, and 3.11 kHz for digital emissions.

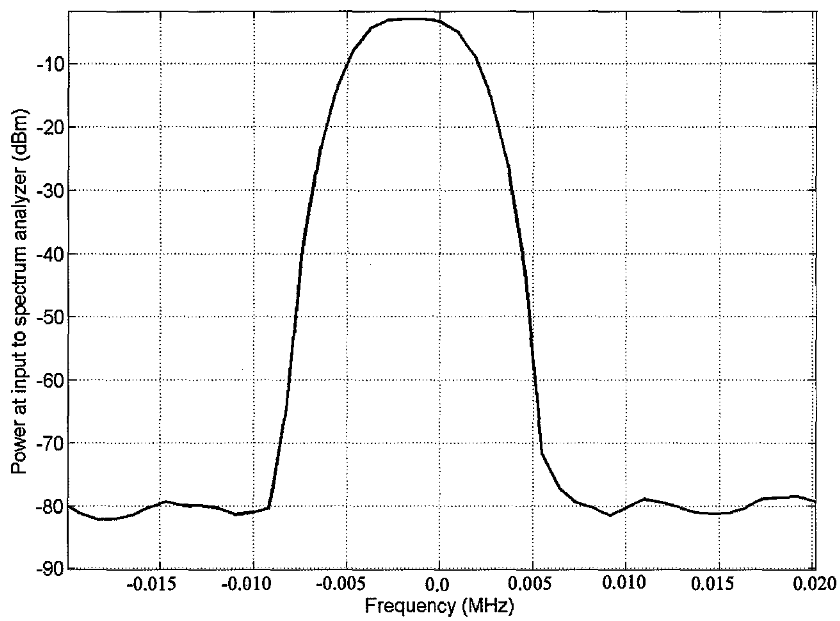

Figure 6. FFT of CW signal using LMR measurement parameters.

Since a typical conversation on these Federal channels will last several seconds or more, there is little advantage in measuring each channel more often than once every second (since most of the additional measurements will give statistically-redundant information). In most (but not all) of these LMR systems, the transmitter will be turned on only when the channel is carrying a message. For these signals, the presence of a message can be detected by tuning to the channel and noting whether a transmitted signal is present. Usually, this can be done most easily by simply measuring the amount of RF energy received within the channel bandwidth, and inferring the presence of a signal if the measured received power is larger than the power that could reasonably be present from measurement system noise only. Based on the measurement system noise figure and the windowing bandwidth, a specific "detection threshold" is calculated, such that any measured channel power higher than the detection threshold is assumed to indicate the presence of a transmitted signal.

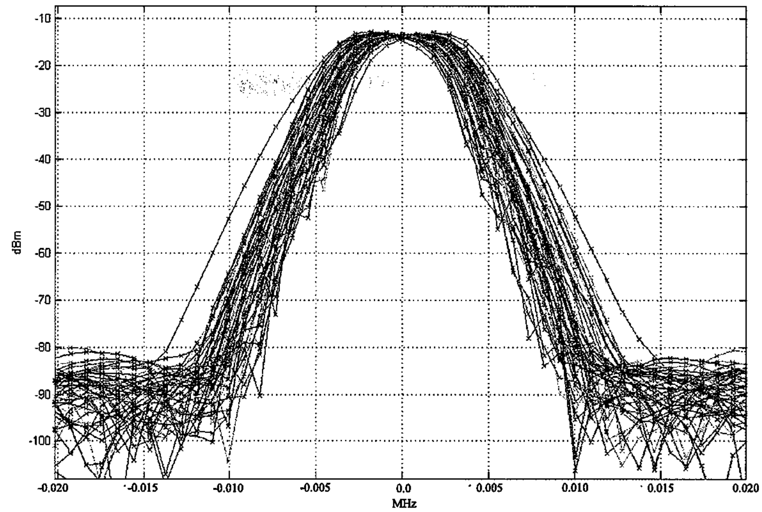

Figure 7. Multiple FFT traces of a carrier signal FM modulated with 3-kHz band-limited Gaussian noise and a 3-kHz maximum frequency deviation.

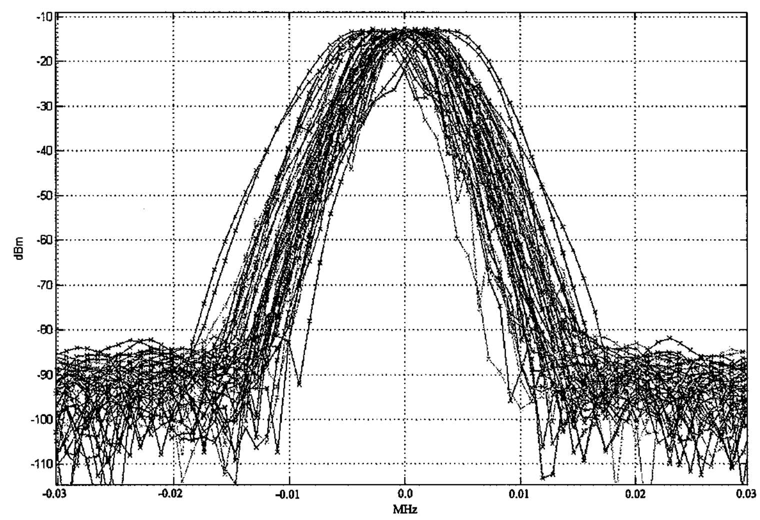

Figure 8. Multiple FFT traces of a carrier signal FM modulated with 3-kHz band-limited Gaussian noise and a 6-kHz maximum frequency deviation.

The actual percentage of time that a given LMR channel is in use will be expected to change, depending upon the specific function served by that channel, the time-of-day and day-of-week, and the random occurrence of specific individual emergencies and other important events. Therefore, a minimum set of measurements for LMR channel usage should include data acquisition on each channel over a period of at least one week (including weekends) on a 24-hr per day basis. Although it is not required that each channel be measured continuously, it is desirable to include sufficient measurements to characterize every channel on at least an hourly basis.

As diagramed in Figure 9, all the channels in a given several-MHz frequency block were measured for 4 minutes, giving 240 measurements on each channel. At the end of 4 minutes, measurement frequencies were shifted to the next-higher frequency block. Each frequency block was re-measured every 36 minutes for the 162–174 MHz band and every 12 minutes for the 406–420 MHz band.[6] Thus, although a given frequency block was not measured continuously, it was sampled for a 4-minute period interleaved with either 32 or 8 minutes with no measurement (while other frequency blocks were being measured). This was continued for 24 hours per day throughout the 8-day period. Thus each frequency in the 162–174 MHz band was measured 240 x 40 = 9600 times per day, spread out over 24 hours, giving 76,800 total measurements over an 8-day period. Frequencies in the 406–420 MHz band were measured about three times more often. The resulting measurement data were saved for further analysis in the NTIA/ITS laboratory in Boulder, Colorado.

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[6]There is an hourly synchronization (± 4 minutes) of data acquisition for the 406-420 MHz band, This could skew the mean usage (either up or down) if a significant number of transmissions are keyed up at specified times each hour – though we have no knowledge of this type of timed usage.

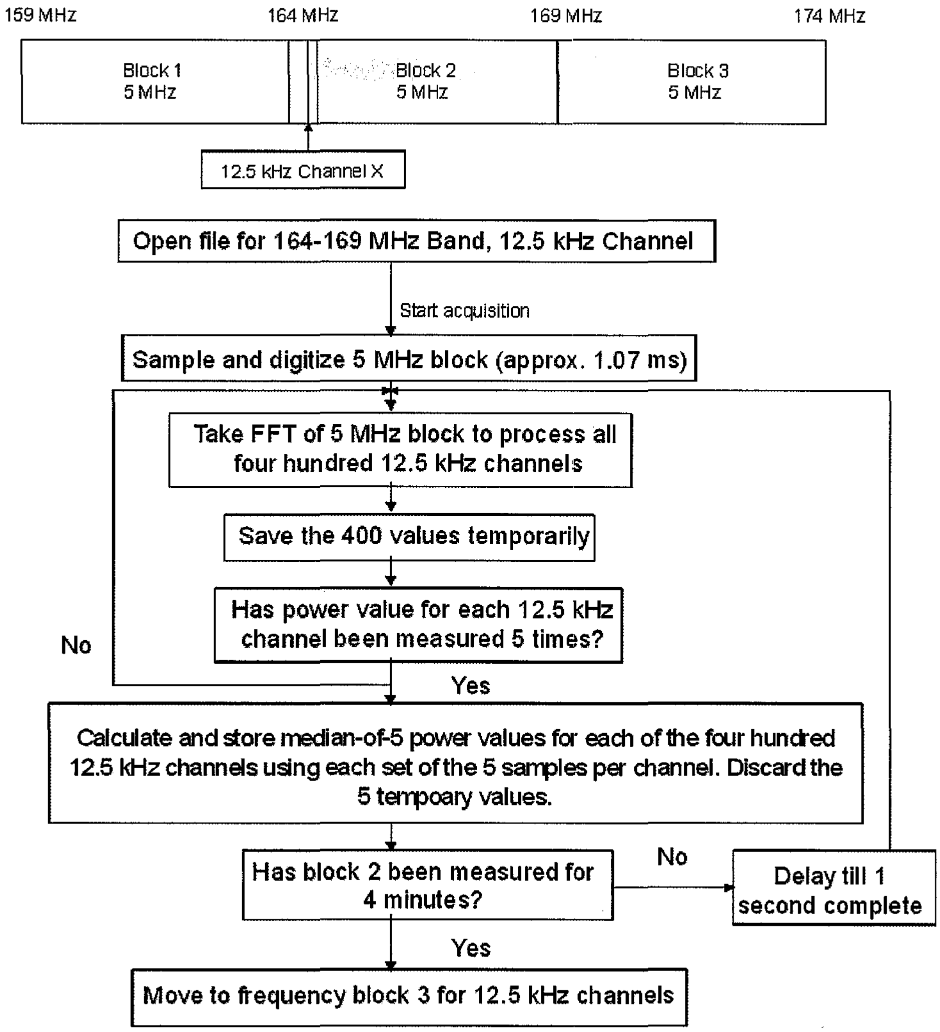

Figure 9. Flow diagram of channel power measurements.

3.5 Real-time Signal Processing

The measurements were performed using some of the specialized hardware and software features of the Agilent E4440A spectrum analyzer. The spectrum analyzer provides high-dynamic-range down-conversion to an IF signal with a bandwidth up to 8 MHz wide. The 8-MHz bandwidth IF signal is digitized with 14 bits of resolution at a 30 MS/s sample rate. Using the "Base" mode software package, the digital data were processed on a real-time basis, using a library of software signal processing routines.

The hardware-software package typically produced a measurement of the estimated received power in each of 400 channels in a 5-MHz band during each 1-second period in a 4-minute measurement block. The process used to produce these 400 measurements each second is described in the following paragraphs.

Once the spectrum analyzer is tuned to the center frequency of the 5-MHz frequency band, the 14-bit digitizer acquires ADC readings for 1.07 ms, producing a digital record containing about 32 kilo-samples (where sample size is dependent upon resolution bandwidth specifications). These 32 kilo-samples are processed inside the spectrum analyzer with firmware that produces a reading for the RF power at the center frequency of each of the 400 channels in the frequency block. The system has an 84-dB dynamic range, but if a strong signal overloads the digitizer (approximately -22 dBm at the antenna terminals), an alarm flag causes the 32 kilo-samples to be discarded and the digitizing process will repeat. The digital data is windowed and then processed with an FFT to give a resolution bandwidth of 5.5 kHz, after which the data is decimated[7] to give a power reading at the center frequency of each of the 400 LMR channels (spaced at 12.5 kHz).

These 400 *Channel Power Readings* are displayed on the front panel of the spectrum analyzer and also transferred via an ethernet local area network to an external controller/computer. The process of digitizing, computing, and transferring data for the frequency block requires about 150 ms, with a majority of the time used by the data transfer process. The digitizing, computing, and transfer process is repeated five times, ending when 5 sets of 400 data points are obtained, representing five *Channel Power Readings* of each channel in the frequency block. At this point, the computer determines the median value from the 5 measurements for each channel, and the set of 400 median values for each channel – also referred to as the *Channel Power Values* – becomes the data output set for that respective 1-second measurement period. The system then waits until the beginning of the next 1-second measurement period, when the median-of-5 measurement cycle begins again to produce another set of *Channel Power Values.*

The median-of-5 processing was selected to minimize the effect of amplitude variations caused by signal modulation, measurement system noise, and external impulsive noise. The importance of this processing for minimizing errors in determining channel occupancy is discussed in more detail in section 4.

The *Channel Power Values* for each of the channels in the frequency block are also incorporated into a continuously updated (every second) data display on the external computer as shown in Figure 10. This external display shows the most recent 1-second *Channel Power Value* (referenced to the spectrum analyzer input) for each measured channel (blue "+" symbols), as well as a peak value for each channel updated over the current 4-minute frequency block (black "+" symbols). The operator can position a cursor over a particular frequency and obtain readouts of these quantities, as well as the exact frequency of

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[7]Decimation, in this case, is the process of eliminating unnecessary data points that occur between center frequencies of the channels.

the selected channel (e.g., this allows a receiver/demodulator to be tuned to a channel-of-interest). The display on the external computer is continually updated with data from the most recent 1-second *Channel Power Value,* while the spectrum analyzer shows a display of the current 5-per-second instantaneous *Channel Power Reading* from the measurement process.

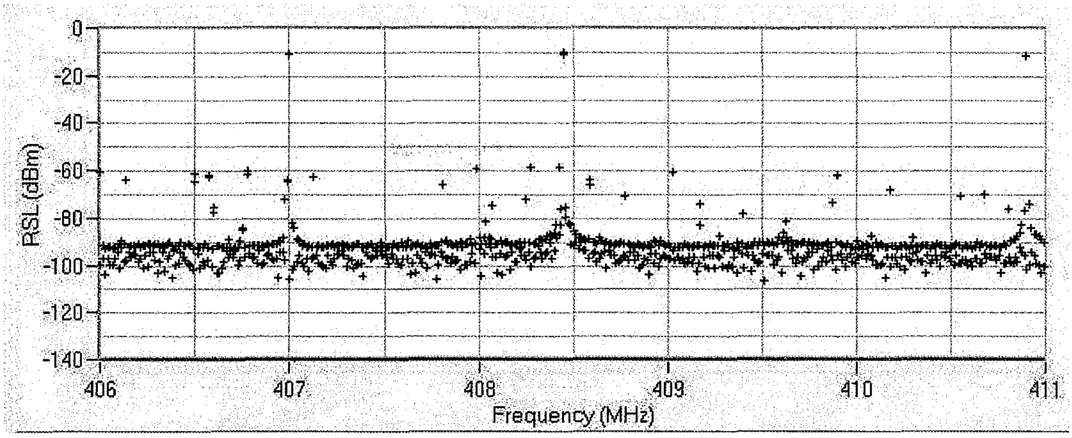

Figure 10. "Data display" as viewed on the computer (power referenced to spectrum analyzer input).

3.6 Calibrations

System calibrations using the noise source Y-factor method were performed immediately prior to the measurements and again at the end of the week.[8] Certain signals of known power and 100 percent usage were also checked on a daily basis to monitor the integrity of the system. Gain factors, as determined by the calibration, were later subtracted from the measured power levels to reference the power to the output of the antenna terminals. Noise-figure values were used to determine detection thresholds for signal-occupancy processing.

All of the antennas were calibrated at a certified laboratory within 6 months of the measurements. Antenna correction factors were then used to determine the field strength based on the received power at the input.

[8]The Y-factor calibration technique is used here to determine the noise factor and gain of the system [8].

4 POST-MEASUREMENT PROCESSING

This section describes post processing techniques used to extract channel occupancy statistics. This includes setting the proper detection threshold levels, as well as removing the effects of impulsive noise and measurement system sideband noise.

Although very significant efforts were made in hardware design and field measurement procedures to minimize measurement defects caused by IM, LO noise sidebands, broadband impulsive noise, and other problems, the raw measurement data still contains certain defects from these sources that, for the most part, can be corrected. Since techniques that would have eliminated these defects completely would also have decreased the ability to measure weaker signals, we chose to operate with better sensitivity – anticipating that we could adequately remove most defects with further post-measurement processing. This section describes those efforts to identify and remove the most common types of measurement defects.

All of the post-measurement defect-reduction processing is performed on the saved 1-second, median data (*Channel Power Values*). A key factor in being able to distinguish some of these defects from the good data that they are embedded in is that the entire set of 1-second data is measured simultaneously across an entire 8-MHz IF bandwidth. The 8-MHz bandwidth completely captures the 5-MHz sample of signals that can pass through the 5-MHz (typically) RF bandpass filters in the preselector. That means that the processed data would be expected to include all of the high-amplitude signals that could have caused IM products to appear in the computed *Channel Power Values* – which means that proper modeling could remove most of the IM effects. However, initial analysis of the data showed that IM products from strong signals occurred so infrequently during these measurements that removing them using specialized processing techniques was not warranted.

4.1 Broadband Impulsive Noise

Broadband impulsive noise from electrical machinery or automobile ignition systems is usually seen on scanning spectrum analyzers as a sequence of impulses appearing at more-or-less regularly spaced frequencies across the analyzer display. Actually, the noise impulses are very broadband, but they show up on swept analyzers at whatever frequency the spectrum analyzer was measuring at the instant when the noise impulse occurred. However, the "simultaneous" nature of the 8-MHz IF digital sampling used in these LMR measurements means that either all frequencies show the noise, or none of them do. If the noise impulse occurs during the 1-ms digitizing period, the effect of the broadband noise will be generally present at each of the frequencies in the band of measurement. If the noise impulse does not occur during the 1-ms digitizing period, it will occur in none of the frequencies.

Therefore, impulsive noise can be eliminated in two very effective ways. The first "line-of-defense" against impulsive noise is from the median-of-5 measurement algorithm. Unless at least three of the five independent measurements taken in a 1-second period are contaminated by impulsive noise, the noise will be almost completely eliminated by the median-of-5 processing because these higher power levels occupy the places of the 2 highest readings and are ignored (along with the 2 lowest readings). Therefore, most impulsive noise is eliminated on a real-time basis by the measurement algorithm and is never seen in the recorded median-of-5 *Channel Power Values.*

If the median-of-5 *Channel Power Values* are contaminated with noise, all channels will tend to be similarly contaminated. This allows contaminated *Channel Power Values* to be easily recognized and removed from further data analysis. The noise-contamination algorithm checks to see whether at least 75%[9] of the frequencies in the measured band were 5 dB or more above the arithmetic mean[10] system noise power. If so, that set of *Channel Power Values* is judged contaminated by broadband noise and removed from further processing. Figures 11 and 12 show two sequential measurements, one without impulsive noise and one with, taken 1 second apart (the threshold being 8 dB above the median system noise). The impulsive noise in Figure 12 appears as a substantial momentary increase in system noise, causing that data set to be rejected from any further processing.

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[9] 75% was chosen because it is highly unlikely that 75% of all channels in the band would simultaneously come on line. Because the signal power for each of the channels is measured simultaneously, the impulsive noise is likely to raise the noise floor for, at least, 75% of the channels in the band.

[10] For median-of-5 traces of Gaussian noise there is a 1.5-dB difference between the arithmetic mean and median power – mean being the higher of the two. In this report, both mean and median are used under different circumstances, but each may be translated to the other using the 1.5-dB correction factor.

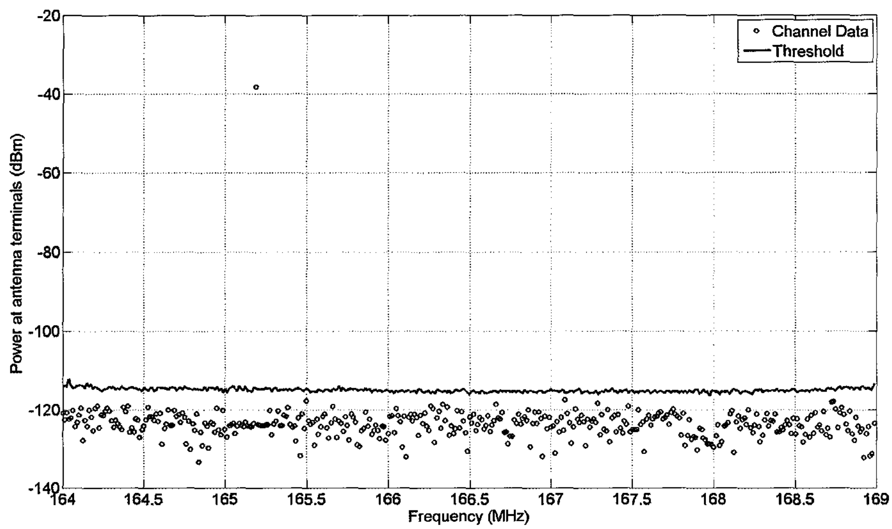

Figure 11. One-second sample without impulsive noise.

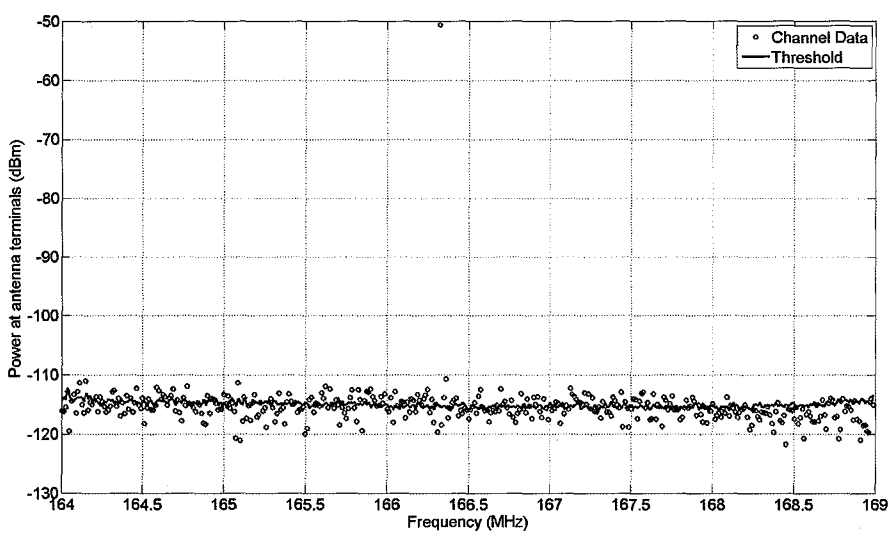

Figure 12. One-second sample with impulsive noise.

While every effort was made to minimize the effects of noise, there were occasional periods when impulsive noise raised the power in the entire band enough for individual channels to exceed the detection threshold but not high enough to trigger a "data discard." It is difficult to determine precisely how often this occurred but it may have occurred enough to skew the mean usage values somewhat towards higher than expected usage values.

4.2 Noise Sidebands

Noise sidebands, due to either the measurement system local oscillator phase noise, jitter of the ADC, or sideband characteristics of the windowing function (and sometimes transmitter phase noise), can cause apparent signals adjacent to the channel occupied by a strong signal. In the case of these measurements, the noise sidebands produce additional apparent adjacent-channel signals for any real signal at least 60–70 dB above the system noise level. These additional responses decrease at the rate of about 0.5–1.0 dB per channel, for channels further away from the strong signal, and eventually these additional responses disappear below the measurement system noise. Because of the nature of these additional responses, they cannot be removed by using real hardware IF bandpass filters.

Since the noise sideband responses can affect a large number of additional channels, it is especially important to remove these false signals. These noise sideband responses are eliminated by measuring the levels of a typical noise sideband response and generating a "mask" that shows how much signal power to subtract (in linear form) from each channel located adjacent to a strong signal. Fortunately, this mask is typically quite stable and predictable. Unfortunately, the mask is probabilistic – having an amplitude distribution similar to Gaussian noise instead of giving a single value at each frequency. This means that 5–10 dB extra power must be subtracted to reliably discard the noise sideband responses. The major problem with subtracting so much additional signal power is that this process may also discard some real (but weak) signals located near the strong signal. Figure 13 shows the effect of noise sideband responses on measured signal levels, as well as the effectiveness of the algorithm in removing this signal contamination.

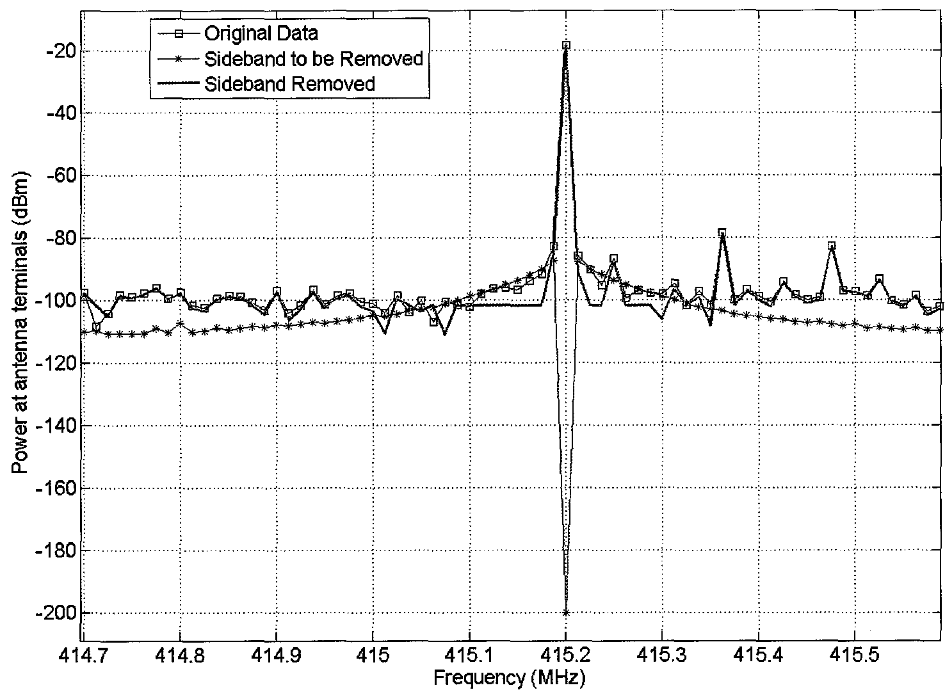

Figure 13. Removal of LO noise sidebands.

4.3 Detection Thresholds

Once imperfections due to impulsive noise, and sideband noise are removed, the next step is to determine the presence of real LMR signals. Determining channel traffic reduces to the problem of determining the portion of time that a signal is detected on the channel. The obvious way to determine whether a signal is present on a channel is to measure the received signal power. If the measured received signal power is substantially higher than some appropriately-selected threshold value, the channel must contain a signal. If it is substantially lower than this threshold value, the channel probably contains only system noise – or possibly noise plus a very weak signal. For our purposes, a signal below system noise is not likely to provide usable service to the LMR user, and therefore it should not be counted as real traffic at the measurement site.

The selection of an exact detection threshold presents some trade-offs. If a very low detection threshold is selected (i.e., close to system noise), some statistically expected noise bursts will occasionally exceed the selected threshold and cause a certain amount of usage to appear on all radio channels (even unused channels). On the other hand, if a much higher detection threshold is chosen, some weak (but functionally usable) signals may be left uncounted by the analysis program. The actual threshold level selected for determining channel usage is therefore a compromise between noise-caused false usage (low detection thresholds) and missed usage of weaker signals (high detection thresholds). In some cases, local external background noise can exceed the system noise, changing the optimal detection threshold level. Some quantitative insights to the selection of a detection threshold can be obtained by considering the amplitude probability distribution (APD) [1] for measurement system noise only. Figure 14 shows an APD for multiple single samples of system noise (solid line) and for multiple noise samples processed as median-of-5 values (dashed line). The solid line shows the expected straight line for Gaussian noise, using the "Rayleigh" graph scaling. The vertical scale is in "dB, relative to the median power." Therefore, both lines cross the "0 dB value" at the 50% point. The arithmetic mean level of power for the unprocessed system noise is about 2 dB above the median value. The graph shows how much of the time system noise is found at various amplitudes. For example, the graph shows that system noise will be 10 dB above the median value about 0.1% of the time. This means that if a detection threshold was selected at 10 dB above the median noise value (8.5 dB above the arithmetic mean noise power), a channel with no real signals would be expected to show a usage of about 0.1% – since the system noise alone exceeds the 10-dB level 0.1% of the time.

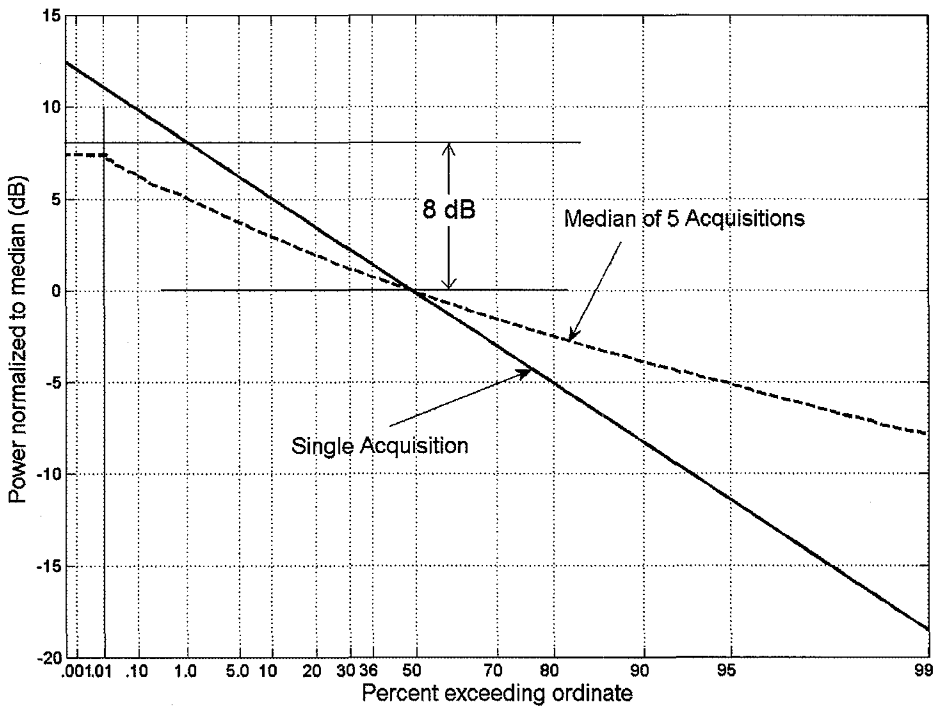

Figure 14. APD of system noise.

On the other hand, if all measurements are processed with a "median-of-5" routine, system noise appears to have an APD described by the dashed line. (The horizontal left-hand part of the curve is an anomaly caused by an insufficient number of measurements; assume that the actual dashed curve extends the general shape of the remainder of the line.) The dashed line is more horizontal (i.e., has fewer high-dB or low-dB samples), because the median-of-5 process requires that at least 3 of the 5 measurements be as large as the indicated value (versus only 1 of the 5 measurements for the single-measurement statistics). Therefore, large variations are less likely for the median-of-5 process. This allows the detection threshold value to be set closer to the median noise value without increasing the probability of false usage readings. For example, allowing 0.1% of false usage readings, the median-of-5 data occupancy threshold could be set near 6 dB, nearly a 4-dB improvement over the individual readings.

Presumably, this detection threshold could be improved even more by taking the median of even more readings – possibly a median-of-11 or median-of-21 readings. However, this would have considerably increased the measurement time and would eventually cause some problems with measurement of short messages. It should be noted that this median-of-5 process is also believed to have removed much of the amplitude variation due to signal modulation techniques and to have almost completely removed any effects from external impulsive noise which might otherwise be falsely detected as LMR signals.

In order to achieve a probability of no greater than 0.01% that an instantaneous system noise level will exceed the median system noise (as specified in Table 5), a minimum threshold of 8 dB above the median system noise was chosen for processing. This means that, at the minimum threshold, there is a probability of only 0.01% that system noise could give a false indication of an LMR signal. Additional higher thresholds were also chosen for processing for the purpose of displaying statistics on multiple threshold levels.

Due to TV Channel 7 out-of-band emissions, a correction to the minimum detection threshold is applied in the spectral region between 170.7–174 MHz. Figure 15 shows the median of multiple median-of-5 *Channel Power Values* in the frequency range 169–174 MHz. Because some of the out-of-band emissions from TV Channel 7 have a power as much as 10 dB above the threshold, the minimum detection threshold (where the threshold is 8 dB above the median system noise – square symbols in Figure 15) is not sufficient to exclude noise that could be falsely construed as LMR signals. Therefore, in the region between 170.7–174 MHz, the minimum detection threshold is determined by adding 9 dB to arithmetic mean noise power that is due to TV channel 7. This modified threshold is represented in Figure 15 by the solid line. Analysis of the TV out-of-band emission statistics showed that this modified detection threshold would allow the TV out-of-band emissions to be mistaken for LMR signals only in 0.01% of the measurements.

Throughout the analysis, statistics are reported for various thresholds – the minimum threshold, as well as several thresholds at 10 db intervals above the minimum. Because the minimum detection threshold in the region between 170.7–174 MHz has been increased by as much as 15 dB due to Channel 7 out-of-band emissions, all thresholds above the minimum detection threshold are set so that at no point is the threshold less than any other preceding "lesser" threshold for the same frequency channel. Because the detection threshold, especially the minimum threshold, is not constant across the frequency channels, threshold values given for statistical analysis are stated in terms of "mean" threshold power.

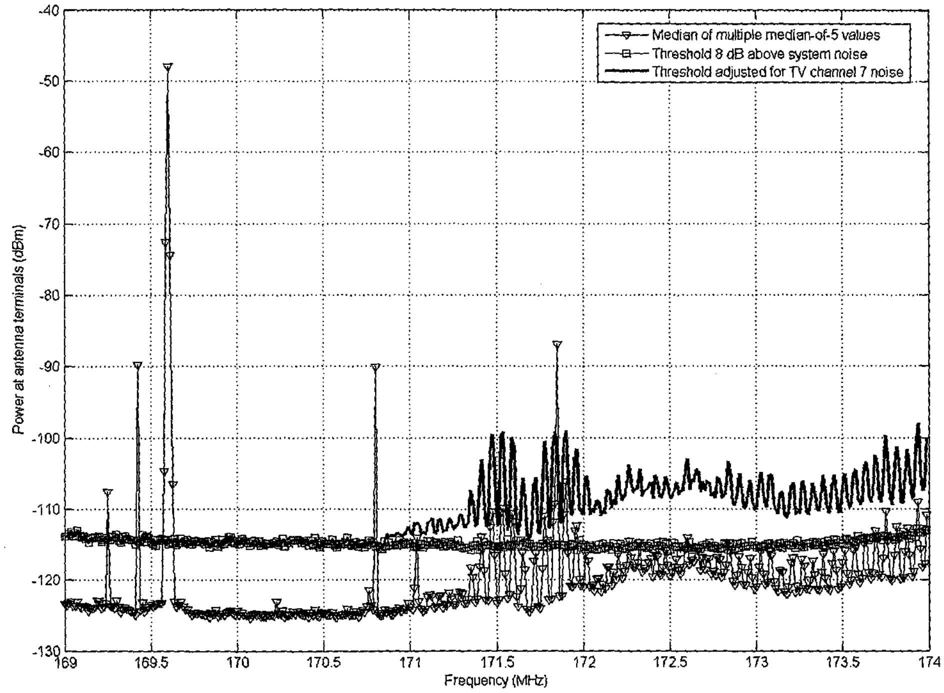

Figure 15. Thresholds and median of multiple median-of-5 data acquisitions.

5 ANALYSIS AND RESULTS

This section discusses the various methods of statistical analysis employed to summarize the channel usage in various LMR bands. Graphs and tables summarizing the usage for the different bands are included in the latter half of this section, as well as in Appendix A.

5.1 Frequency Groupings

Two primary frequency groupings were analyzed as follows:

1. 162–174 MHz (excluding NOAA[11] weather radio channels located at 162.400, 162.425, 162.450, 162.475, 162.500, 162.525, and 162.550 MHz).
2. 406–420 MHz.

5.2 Channelization

As described in Section 2.1, channel assignments in these bands are now required to migrate toward a 12.5-kHz channelization; however, some LMR systems are still operating under the 25-kHz channelization scheme. To get an understanding of how much the newly created channels (spaced 12.5 kHz between the old assignments) are being used, analysis was performed on the following sets of channels:

1. all channels spaced 12.5 kHz apart.
2. channels assigned under the old 25-kHz channelization (spaced 25 kHz apart) – referred to in this report as "the old 25-kHz channels."
3. channels earmarked for the 12.5-kHz channelization (spaced 25 kHz apart and located halfway between the old 25-kHz channels) – referred to in this report as "the new 12.5-kHz channels."

5.3 Time Scenarios

Each of the 2 frequency groupings were analyzed according to 6 different time scenarios as follows:

1. **Entire week**: Data analyzed as a whole for the entire week Tuesday, October 26, 2004 at 2:00 PM through Wednesday, November 3, 2004 at 4:00 PM, independent of time or date.
2. **Date and time of day**: Data analyzed according to the date and time in one-hour blocks.

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[11]National Oceanic and Atmospheric Administration.

3. **Time of day for any day**: Data analyzed according to time in one-hour blocks between 12:00 midnight and 12:00 midnight 24 hours later, independent of date or type of day (e.g., weekend day).
4. **Time of day for Election Day**: Data analyzed according to time in one-hour blocks between 12:00 midnight and 12:00 midnight 24 hours later only on Election Day (November 2).
5. **Time of day for weekdays**: Data analyzed according to time in one-hour blocks between 12:00 midnight and 12:00 midnight 24 hours later only for weekdays, independent of the type of weekday.
6. **Time of day for weekends**: Data analyzed according to time in one-hour blocks between 12:00 midnight and 12:00 midnight 24 hours later only for weekend days, independent of the type of weekend day.

5.4 High Occupancy Channels

In addition to the frequency and time groupings, data were also analyzed under two scenarios with regard to high occupancy channels (HOCs). HOCs, as defined for analysis under these measurements, are channels where the received signal level is above the detection threshold greater than 80% of the time (other than the NOAA weather radio channels, which were always excluded from analysis). Known examples of HOCs include channels used for telemetry (such as hydrology sensors) and control channels used in LMR trunked systems. Since these HOC channels differ greatly from the much lower percent usage of LMR channels, HOCs represent "outliers" that would substantially skew the mean LMR channel usage statistics. For this reason the data were sometimes processed with HOCs both included and excluded in the analysis, the latter providing a method for determining the usage for LMR channels that represent the overwhelming majority of signals in the LMR bands. These HOCs represent 1.1% of channels in the 162–174 MHz band, and 0.5% of channels in the 406–420 MHz band.

5.5 Busiest Hour Statistics

Several of the statistical summaries are reported for "busy hours," or a similar term, as applied to the usage of single channels or groups of channels. There are several distinct definitions for these processed statistics, which we will carefully describe here (as well as in sections 5.7) since substantially different numerical results can arise from slightly different processing algorithms.

The quantity that is loosely called "hourly usage" does not actually contain the results from 60 minutes of measurements. Instead, it represents the averaged results from whatever measurements were sampled during that hour. Typically, the hourly data were derived from two 4-minute measurement periods (separated by 32 minutes without measurements) for frequencies in the 162–174 MHz band and from five 4-minute measurement periods (each separated by 8 minutes without measurements) for frequencies in the 406–420 MHz band. In about 12% of the hourly blocks in the 162–174 MHz band, the data were derived from a single 4-minute measurement. Sampling for less than the full hour can skew any of the "busy hour" results because a shorter sample period gives a greater statistical spread of percent usage for each channel. Typical usage in many of these channels tends to cluster into short periods of high activity, possibly with several almost-continuous exchanges between base and mobile stations, followed by a period of less usage. For a sample time shorter than a typical message, a given channel will tend to be used 100% of the time or not used at all. In a longer sample time, the short very-busy periods tend to be more smoothly averaged-out by the idle periods. Therefore, when looking at any of the busy-hour results, a shorter sample period tends to skew the data towards higher usage percentages.

In the following descriptions, we observe that the word "hour" has at least two distinct meanings: 1) a 60-minute period, and 2) a time of the day (e.g., "the hour is late"). In the "busy-hour" statistics, we will use "hour" only in the sense of an arbitrary 60-minute period, i.e., any hour of the day, week, or year. Whenever a specific time of the day is described, the term "time-of-day" will be used. Unless otherwise indicated, "time-of-day" will refer to the set of 24 one-hour time blocks that has been used to categorize the measurement data.

The *Hourly Channel Percent Occupancy* is computed for each channel, each hour of each day, by taking all of the *Channel Power Values* in an hour for a channel, comparing them to the detection threshold, and then determining the percent of values that exceed the threshold during that one-hour period.

The *Busiest Hour of the Week for Each Channel* is the specific 60-minute time block within the entire 1-week measurement period when the average usage on a given channel was highest. The *Busiest Hour of the Week for Each Channel* is determined by examining the *Hourly Channel Percent Occupancy* every hour of every day over the course of the measurements for each channel and identifying the "busiest hour" as the date and hour for the *Hourly Channel Percent Occupancy* with the largest value for each channel. Different channels will typically have a different date and time when the usage is highest.

The *Busiest Usage by Time-of-Day for Each Channel* is the highest average usage measured for a single channel during a particular time-of-day hourly block, over the course of the pertinent measurement period. There are 24 time-of-day hourly blocks, each lasting one hour and beginning and ending exactly on the hour. The *Busiest Usage by Time-of-Day for Each Channel* is computed by grouping into 24 separate time-of-day groups all of the *Hourly Channel Percent Occupancy* values within the pertinent measurement period (which could be a day or multiple days). The weighted average for each channel of all of the *Hourly Channel Percent Occupancy* values within each one-hour period is then determined. They are weighted because not all one-hour-periods have the same amount of acquired data. The highest of these 24 average values is called the *Busiest Usage by Hour for Each Channel.*

Figure 16 is a diagram of fictitious data used to represent the difference between these two different types of "busiest hour" statistics. This diagram shows the average usage for each hour of the day of a single channel, with each of the thin lines representing a different day during the course of the measurements. The green dot represents the *Busiest Hour of the Week for a Specific Channel* since it is the one hour out of all of the single-day plots for a specific channel that has the highest value. The thick black line represents an hourly average by time-of-day over the entire measurement period. The red dot represents the *Busiest Usage by Time-of-Day for a Specific Channel* since it is the largest value of the 24 time-of-day averages. One can say that, in this diagram, the *Busiest Hour of the Week for the Specific Channel* occurs at 6:00 AM on Day 1 and the *Busiest Usage by Time-of-Day for the Specific Channel* occurs at 3:00 PM.

The *Busiest Hour of the Week for Each Channel* method is used to determine the time of occurrence of the busiest hour for each channel (Figures 27 and 39), described later, which may help show whether "events" may cause high usage in multiple channels within the same hour. The *Busiest Usage by Time-of-Day for Each Channel* data is used to compile statistics showing how many channels were at various levels of usage during their busiest hour (e.g., Figures 34 and 46).

The *Average of Busiest Usage by Hour* is a single value that is computed by determining the average of all the usage values corresponding to the *Busiest Hour of the Week for Each Channel* across all channels in a band. These values are displayed in Tables A-1, A-2, A-5, and A-6 as "Busy Hour Usage (24 hours)."

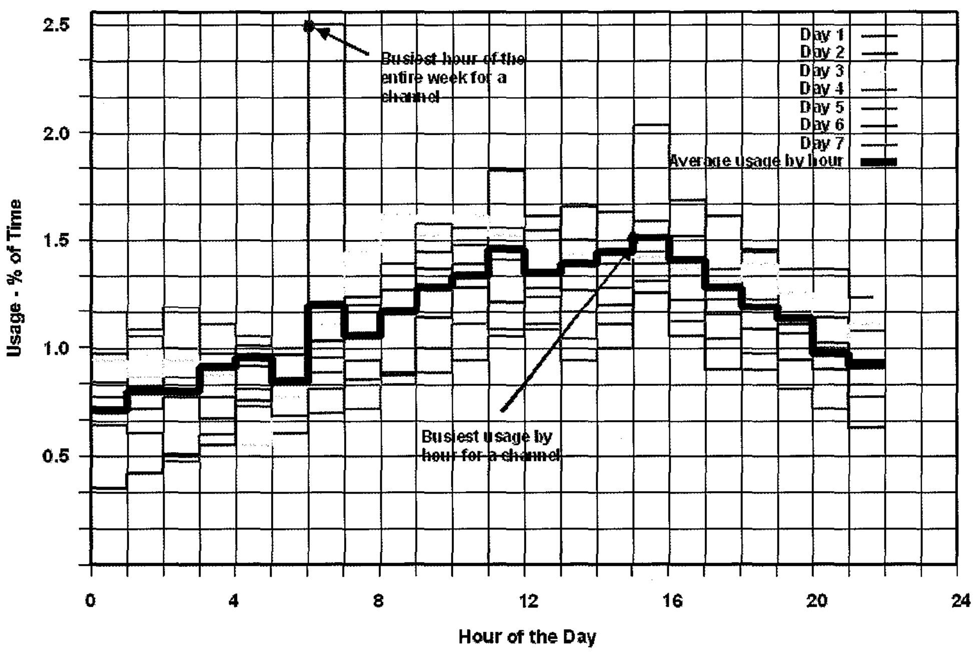


Figure 16. Diagram of fictitious data showing the difference between "busiest hour of the week" and "busiest usage by hour."

5.6 General Description of Analysis

The data is summarized with variations on 6 types of analysis:

(1) graphs of *Hourly Band Usage* during different 1-hour time periods.
(2) graphs of the *Busiest Hour of the Week for Each Channel.*
(3) APD graphs of *Channel Power Values* for all channels across the band.
(4) cumulative distribution graphs of the percent of channels (or hourly channel usage) exceeding a given percent usage.
(5) cumulative distribution graphs of the percent of channels that exceed a given percent of hours at greater than or equal to a given percent usage.
(6) tables of *Percent Band Usage* (during 24 hours and during the hours of 8:00 AM to 5:00 PM) and *Average of Busiest Usage by Hour* (during 24 hours).

Hourly Band Usage is determined by computing the *Hourly Channel Percent Occupancy* of each channel and then determining the mean usage of all the channels in the band. A graph of *Hourly Band Usage* is demonstrated in Figure 17, which shows both the *Hourly Band Usage* of channels in the band and total Erlangs (where Erlangs are determined by multiplying the *Hourly Percent Usage* by the total number of channels in the band – Table 6). Tic marks identify midnight. Each *Hourly Band Usage* represents a different hour and day.

Figure 18 shows *Band Occupancy by Time-of-Day*, which is determined by taking the *Hourly Band Usage* values for each hour of the day, and computing the average for the corresponding hours of the measurement period. Results in these example graphs are summarized for multiple mean threshold power levels (expressed in power at the antenna terminals and field strength at the input to the antenna), whereby a channel is considered to be occupied only if (as described in Section 4.3) the power exceeds the given threshold. As an example, Figure 18 shows that *Band Occupancy by Time-of-Day* of this sample data is approximately 2.8% at 10:00 AM when using a mean field-strength threshold of 12 dB μV/m. Variations of the *Hourly Band Usage* and *Band Occupancy by Time-of-Day* plots (summarized in Tables 7 and 8) consist of different frequency groupings, time scenarios, channelization schemes, and detection threshold levels.

While the *Band Occupancy by Time-of-Day* in Figure 18 varies between approximately 1-3%, readers are cautioned against drawing the conclusion that, because the channels in these bands were used 1-3% during the course of these measurements, 97-99% of the channels can be relinquished for other use. Because most of the channels in these bands are statically assigned to receivers, as opposed to dynamically assigned as is the case with trunked systems (see Definitions), many of these channels are reserved for high priority usage in which communication must be available at all times for a limited number of users, thus resulting in low percent usage. The Public Safety Wireless Advisory Committee (PSWAC) recommends in a report [9] that call-blockage (typically defined as Grade of Service) should not exceed "one call for service per one hundred attempts during the average busy hour." That translates to no more than 1 percent usage for multi-user conventional (non-trunked) systems where channels are assigned statically.

It should also be noted that while the *Band Occupancy by Time-of-Day* in this band varies between approximately 1-3%, individual agencies may have averages that deviate from these values - either to a greater or lesser extent. Likewise, none of these measurements were made during a major emergency that might have greatly increased the use of radio channels.

Table 6. Total Number of Statistically Analyzed Channels Spaced 12.5 kHz Apart

Frequency Band	Number of Channels Analyzed
162–174 MHz – including HOCs	944
162–174 MHz – excluding HOCs	934
406–420 MHz – including HOCs	1119
406–420 MHz – excluding HOCs	1113

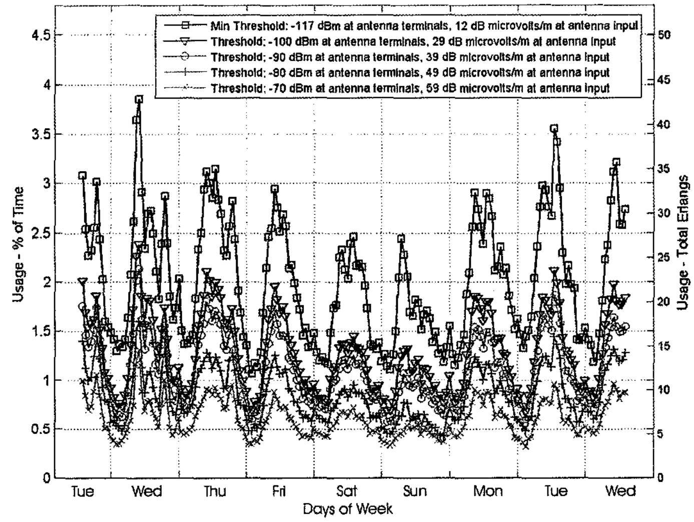


Figure 17. Sample graph (reference to Figure A-2) of *Hourly Band Usage* (percent of time and total Erlangs).

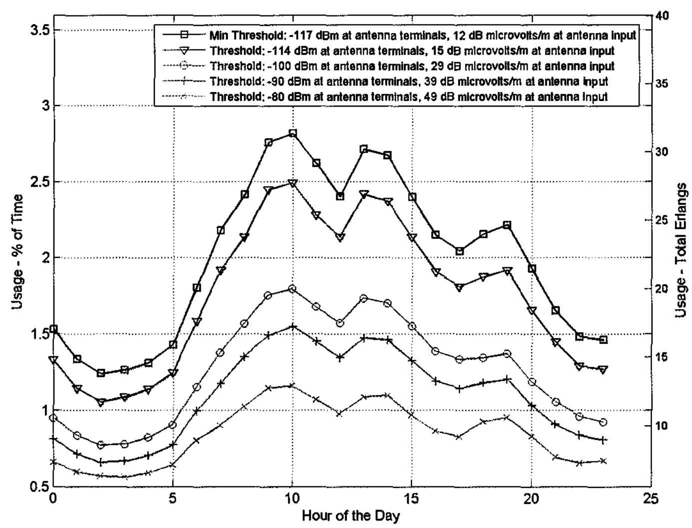


Figure 18. Sample graph (reference to Figure 42) of *Band Occupancy by Time-of-Day* (percent of time and total Erlangs).

As previously explained in Section 4.3, the detection threshold values in these figures are mean threshold values, where the average is determined across the appropriate range of frequencies.

An example of the *Busiest Hour of the Week for Each Channel* is displayed in the graph in Figure 19. The x-axis is divided into one-hour blocks throughout the week and the y-axis represents the individual channel frequencies. One-hour time slots in which anomalies occurred (as described in the latter part of this section) were excluded from processing. The purpose of this type of graph is to display the distribution of channel usage throughout the passage of time to identify possible aggregation of channel usage at certain time blocks. For instance, there are diurnal patterns where the use is heaviest at certain hours of the day, and during those heaviest-use times, certain groups of adjacent channels were simultaneously busy. For instance, multiple channels between 173–174 MHz had the heaviest usage at approximately 3:00 AM on Saturday morning (point A). It should be kept in mind, however, that whenever large numbers of adjacent frequencies appear to become busy at the same time, there is a possibility that the measurements were being affected by broadband RF energy, radiated intentionally or accidentally. Also note that data on different groups of frequency channels (3 groups for each of the two bands) were acquired at different blocks of time. Therefore, correlation between these different blocks may not exist since the heavy use may have occurred during the acquisition of one frequency group but not the others. Correlation within the frequency groups of simultaneously acquired data could exist if a significant event triggered multiple use of channels in that group.

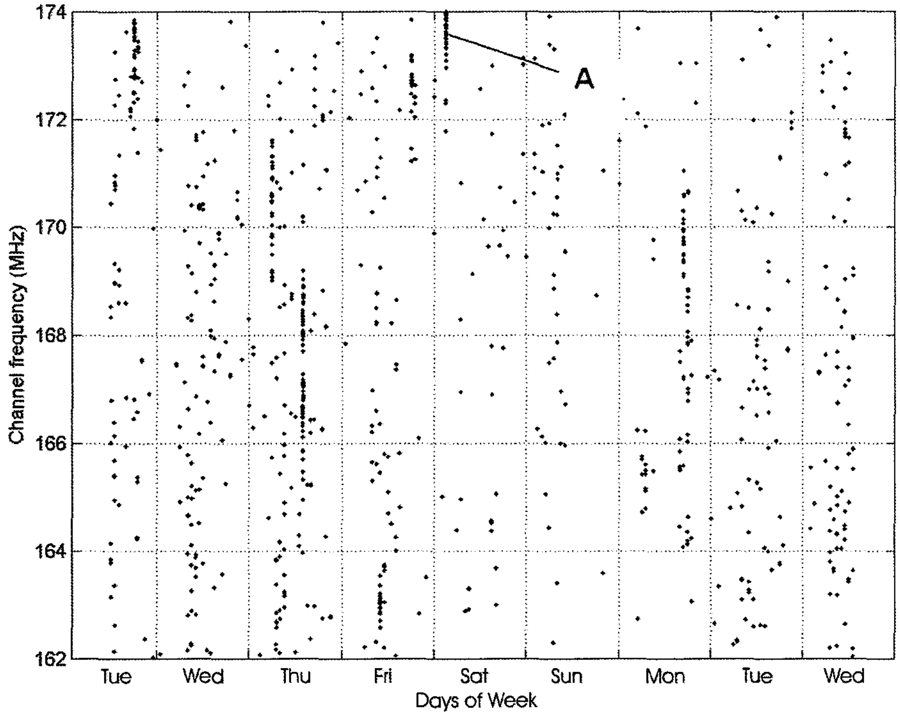


Figure 19. Sample graph (reference to Figure 27) of the *Busiest Hour of the Week for Each Channel.*

APD graphs of *Channel Power Values* are cumulative probability distribution plots representing the percent probability of a channel exceeding a given *Channel Power Value* at any one moment, where the y-axis displays power and the x-axis displays the probability expressed on a Rayleigh scale. A detailed description of APDs is provided in a tutorial located in Appendix A of [1].

Figure 20 shows an APD plot of *Channel Power Values* for all channels in a band. There are two lines on the plot, one that shows the percent probability of a channel exceeding a given *Channel Power Value* and the other showing the percent probability of exceeding a given power due only to Gaussian system noise (represented by the slightly sloped horizontal line). Points on the first line that deviate from the latter line are due to either LMR signals and/or RF noise that exceeds the system noise. Because most of the impulsive noise was removed using the techniques described in Section 4.1, points deviating from the system noise curve are believed to be due primarily to LMR signals. The y-axis is displayed in both *Channel Power Value* at the antenna terminals in dBm and field strength in dB μV/m. For example, Figure 20 shows that there is a 1 percent chance that the *Channel Power Values* for the channels in the band exceed a field strength of 44 dB μV/m at the measurement antenna input or -85 dBm at the antenna output.

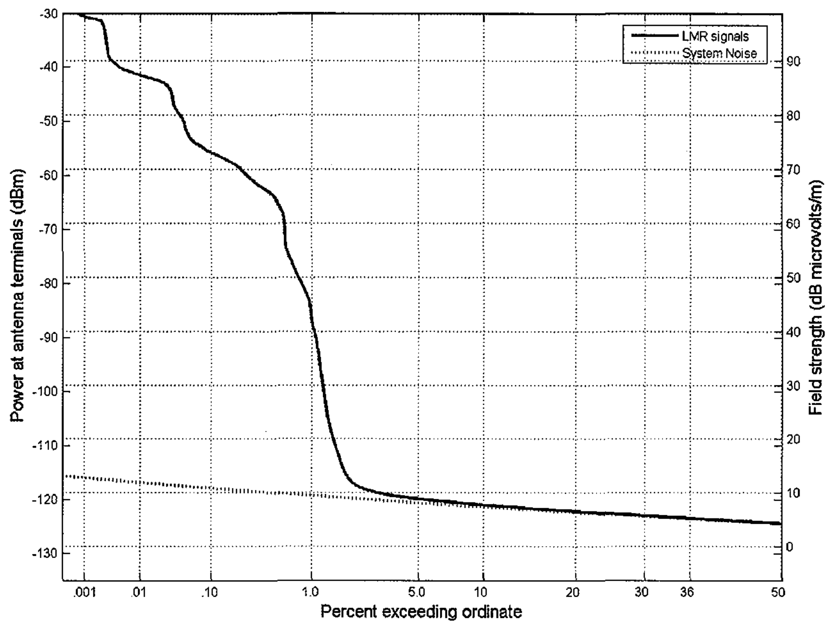


Figure 20. Sample APD (reference to Figure 47) of *Channel Power Values* for all channels in a given band.

Figure 21 shows a representative cumulative distribution graph of *Hourly Channel Percent Occupancy* values that exceed a given percent usage for different channelization and HOC scenarios, whereby a channel is considered to be "occupied" whenever (as described in Section 4.3) the measured power exceeds a given detection threshold (-113 dBm, in this example). In this figure, for the case of all channels spaced 12.5 kHz apart with the HOCs excluded, it can be seen that 13 percent of the *Hourly Channel Percent Occupancy Values* have a percent usage of greater than 1 percent, or conversely that 87 percent of all 12.5-kHz channels have a usage less than 1 percent. Similar conclusions can be determined for the other channelization cases presented in Figure 21. Note that a channel was considered to be an HOC when the measurements showed an 80 percent or more mean usage over the 8-day measurement period. However, it is possible for a channel with mean weekly usage of less than 80 percent to have some hourly periods where that value is exceeded. Those periods are still included in these statistics.

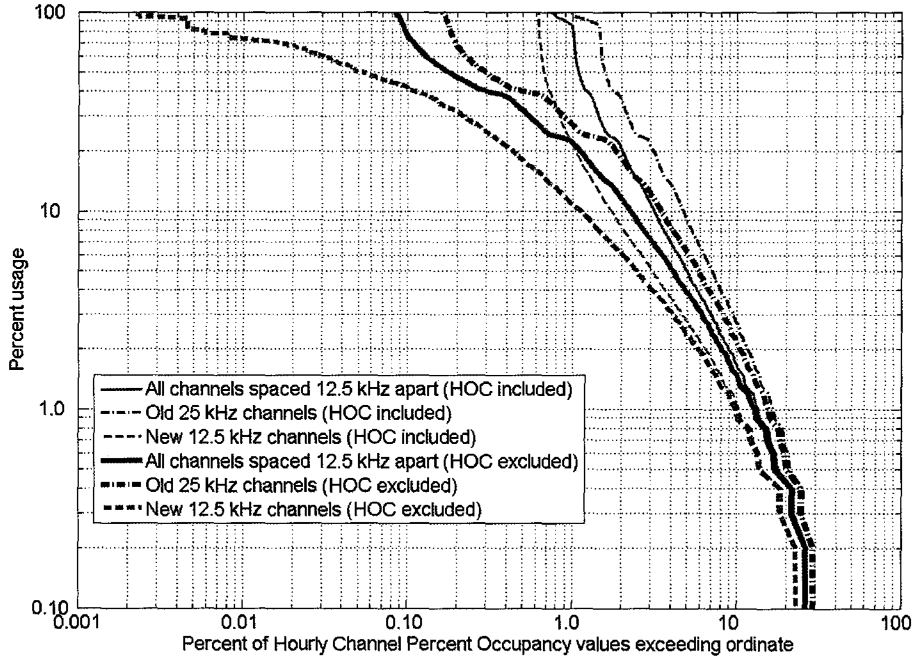


Figure 21. Sample graph (reference to Figure 32) of the percent of *Hourly Channel Percent Occupancy* values exceeding a given percent usage.

Figure 22 shows the *Channel Percent Occupancy* for the week of measurements. This is computed for each channel by taking every *Channel Power Value* for each 1-second acquisition every day and comparing that to the detection threshold to determine an overall percent occupancy for the specific channel. As shown in Figure 22, for the case of all channels spaced 12.5 Hz apart with HOC excluded, 15 percent of the *Channel Percent Occupancy* values have a mean percent-usage of greater than or equal to 1%, or conversely, that 85 percent of the *Channel Percent Occupancy* values have a usage less than 1%. Similar conclusions can be determined for the other channelization cases presented in Figure 22. For this figure, note that typical measured hourly usage values for a given channel may vary greatly, with occasional hourly periods of unusually high or low usage. The effect of averaging the hourly usage values into a weekly channel usage value causes the weekly values to have much less variability than the corresponding hourly values. This effect is clearly shown by comparing the case of all channels spaced 12.5 kHz apart (HOC excluded) in Figures 21 and 22.

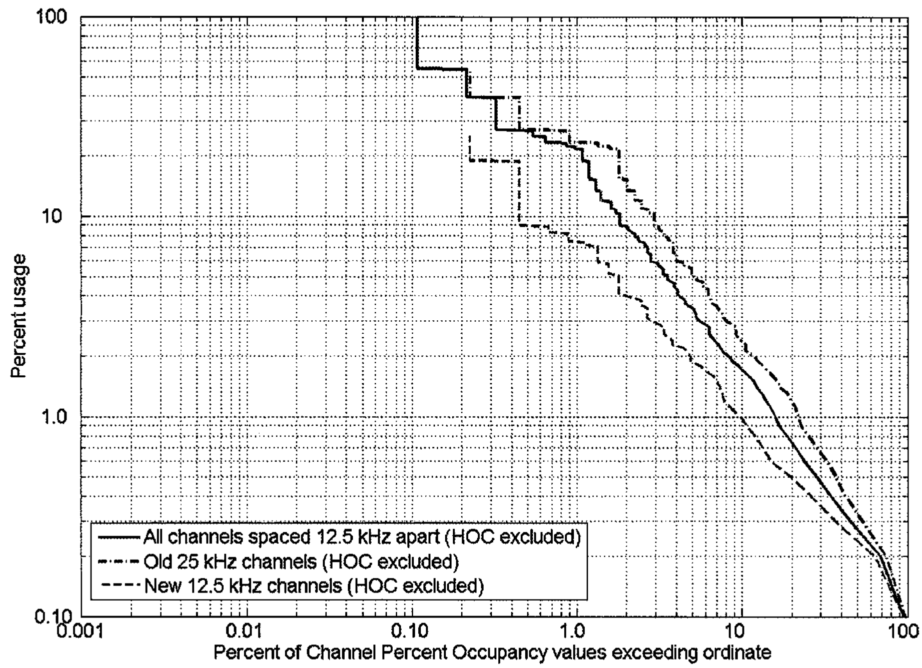


Figure 22. Sample graph (reference to Figure 33) of the percent channels exceeding a given percent usage for *Channel Percent Occupancy*.

The cumulative distribution of usage is also presented in one final form. Figure 23 shows the percent of channels exceeding a given percent usage for the *Busiest Usage by Time-of-Day for Each Channel*. In this figure, for the case of all channels spaced 12.5 kHz apart with HOC excluded (weekdays only), 60 percent of the channels have a *Busiest Usage by Time-of-Day* greater than 1%, 10 percent of the channels have a usage greater than 7 percent and 1 percent of the channels have a usage greater than 34%.

Much of the data presented in this report is represented in the form of "mean usage" which is meant to convey "typical" usage by a channel. However, because the percent usage statistics are not Gaussian distributed, and because, as shown in Figure 23, there are a few channels with relatively high usage (20 percent of the channels with greater than 2 percent usage) but there are far more channels with relatively low usage (80 percent with less than 2 percent usage) the mean is skewed, due to outliers, towards a larger value than what one might think of as "typical." This is because the overwhelming majority of usage value are around 1-3% but there are individual values much greater than this that tend to computationally bias the mean to a higher value. In this case, the median may be more representative of what is a "typical" channel usage – depending upon how the statistic is used. This median value can be easily determined by looking at the 50% point along the x-axis of the cumulative distribution graphs and finding the corresponding percent-usage on the usage plot. In Figure 23, as an example, the median of *Busiest Usage by Time-of-Day* is 1.3 percent.

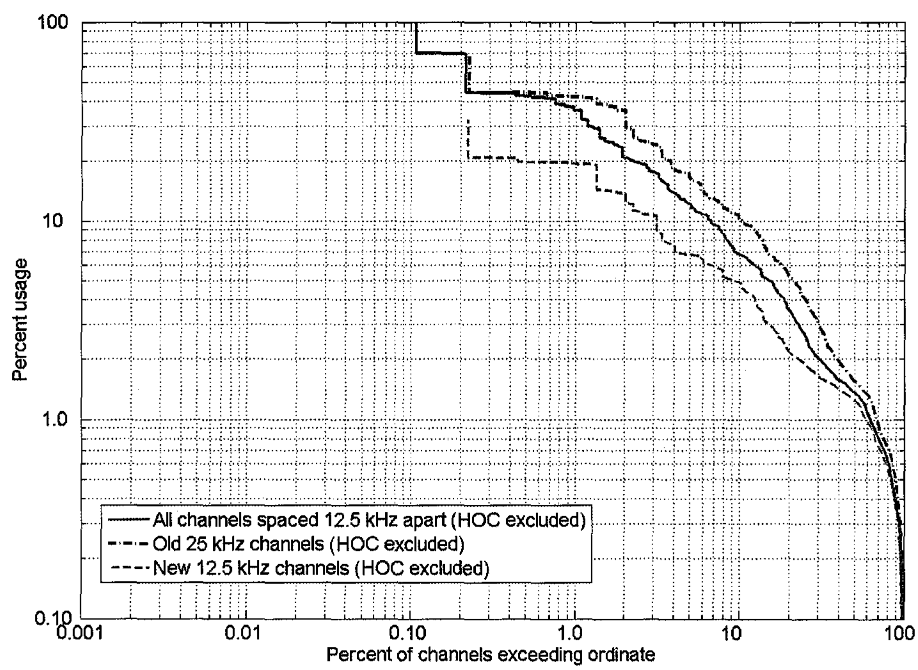


Figure 23. Sample graph (reference to Figure 34) for percent of channels exceeding a given percent usage for the *Busiest Usage by Time-of-Day* during weekdays only.

Note that Figures 21 and 22 are based on the entire week of measurements, while Figure 23 is based on weekday measurements only. This was done because the busiest hours occurred during the weekdays.

Figure 24 shows a representative cumulative distribution graph of the percent of channels that exceed a given percent time at greater than or equal to a given usage for the entire 8-day period of the measurements, where time is broken into 1-hour segments for which average usage is determined. In this case, usage refers to *Hourly Channel Percent Occupancy* as defined in Section 5.5. Each hour time-slot represents an average of 6.7 minutes of data acquisition in the 162-174 MHz band and 15 minutes of data acquisition for the 406-420 MHz band. Each line in the graph represents a unique percent-usage (*Hourly Channel Percent Occupancy*) as noted in the graph legend. For example, consider the case of the line that represents the percent usage of 1 percent. Point A (annotated on the 1 percent usage line) shows that for this case, approximately 33 percent of the channels have 10 percent or more of the 1-hour periods in which the usage is 1.0 percent or greater. Conversely, 67 percent of the channels have less than 10 percent of the 1-hour periods in which the usage is 1.0 percent or greater. Or 67 percent of the channels have 90 percent or more of the 1-hour periods in which the usage is less than 1.0 percent. Another example is the case of the line that represents the usage being 5 percent. Point B (annotated on the 5 percent usage line) shows that for this case, approximately 20 percent of the channels have 3 percent or more of the 1-hour periods in which the usage is 5.0 percent or greater. Conversely, 80 percent of the channels have less than 3 percent of the 1-hour periods in which the usage is 5.0 percent or greater. Or 80 percent of the channels have 97 percent or more of the 1-hour periods in which the usage is less than 5.0 percent. Note that discrete steps occur in the "percent of hourly periods" lines because there are a discrete number of one-hour time slots over the course of the measurement. Since there were approximately 196 hours of measurement during the course of the 8 days, a single one-hour time slot represents a "percent of hourly periods" of 0.51%, two hours is 1%, and three hours represents 1.5% (consistent with the discrete steps seen in Figure 24).

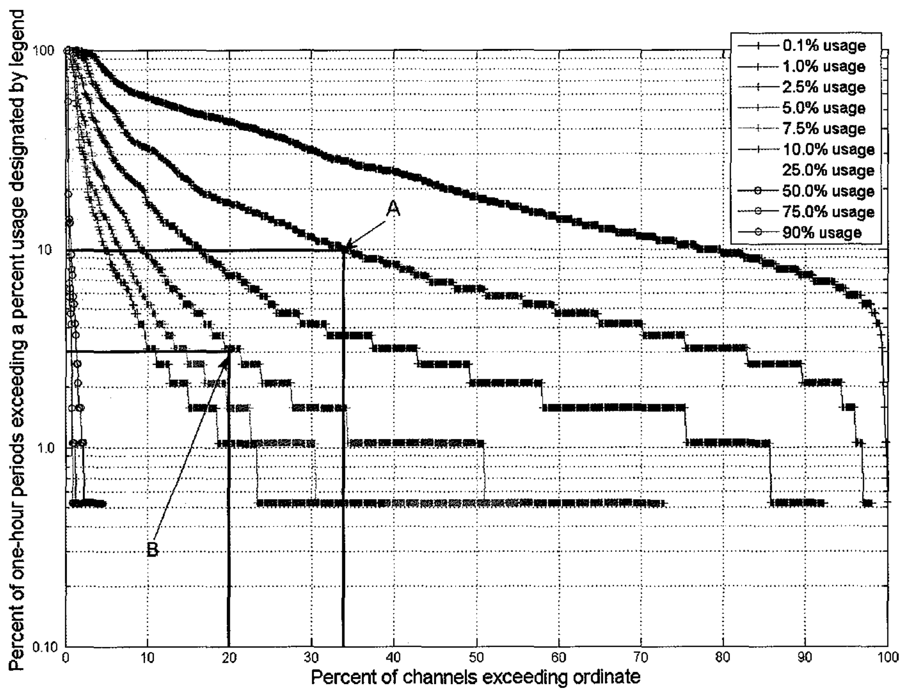


Figure 24. Sample (reference to Figure 37) cumulative distribution graphs of the percent of channels that exceed a given percent of hours at greater than or equal to a given usage (*Hourly Channel Percent Occupancy).*

Table 7 is a representative table showing *Percent Band Usage* and *Average of Busiest Usage by Hour* expressed in percent usage. *Percent Band Usage* is determined by computing the mean of all *Hourly Channel Percent Occupancy* values for all channels during the measurement period. *Average of Busiest Usage by Hour* is defined in Section 5.5. The table shows *Percent Band Usage* over a 24-hour period, as well as between 8 AM to 5 PM, and *Average of Busiest Usage by Hour* over a 24-hour period. The associated values are given for 5 different detection threshold levels represented both by power in dBm at the antenna terminal for the particular antenna and field strength in dB μV/m at the antenna input. Ninety-nine percent confidence intervals, the derivation of which is described in Appendix A, are given for percent usage values determined at the minimum detection threshold. The mean usage values for *Average of Busiest Usage by Hour* are only reported for the minimum detection threshold, since the minimum threshold is used to determine which hour of the day is the busiest. It is not valid to use other thresholds to calculate the

Average of Busiest Usage by Hour. Variations of Table 7 (provided in Appendix A) consist of different frequency groupings and time scenarios.

Table 7. Sample Table Showing Mean Percent Usage and Mean Erlangs for 934 Channels (Reference to Table A-1)

All Days	**Mean Detection threshold**				
Threshold (dBm)	-113	-100	-90	-80	-70
Threshold (dBμV/m)	8	21	31	41	51
Timescale	**Percent Band Usage**				
Percent Band Usage (24 hours)	1.08±0.01[12]	0.63	0.5	0.27	0.21
Average of Busiest Usage by Hour	2.72±0.08[12]	Not applicable			
Percent Band Usage (8am–5pm)	1.42±0.02[12]	0.76	0.6	0.37	0.3
Note: Mean Erlangs can be calculated by multiplying the Percent Band Usage for any threshold by the number of channels. For example, Mean Erlangs for a threshold of -113 dBm is 10.95 (1.08 * 934).					

The relationship between the cumulation distributions (Figures 21 and 22) and the values in Table 7 can be understood better by considering how Figure 21 can be crudely analyzed to give the data shown in Table 7. Figure 25 shows the principles of this analysis, using the corresponding data in each figure. The solid black line in Figure 25 (all channels spaced 12.5 kHz apart, HOC excluded) corresponds to the "1.08" mean percent usage in Table 7 (-113 dBm threshold, 24 hours per day usage). Figure 25 illustrates the process of converting Figure 21 data into an entry in Table 7.

The area under the solid black cumulative distribution line in Figure 25 (see arrow) can be approximated by a series of rectangular areas. The leftmost of these areas represents the point on the line that says .09% of all channels have a usage of approximately 100%. The general approach will be to see what proportion of channels have what values of usage, to give a total percent usage for the entire band. The following table summarizes the values used in the rectangular approximations.

[12] 99% confidence level – assuming an **average** message length of no greater than 5 seconds.

The derived answer of 1.007% compares to the answer in Table 7 of 1.08%, which is a reasonable accuracy considering the approximations used.

Table 8. Summary of values used in the rectangular approximations of mean percent usage

Percent of channels			Mean usage	Total usage
min	max	net	(% usage)	(channels x usage)
0	0.09	0.09	100%	1.000 x 0.09% = 0.090%
0.09	0.2	0.11	60%	0.600 x 0.11% = 0.066%
0.2	0.5	0.3	40%	0.400 x 0.30% = 0.120%
0.5	1	0.5	25%	0.250 x 0.50% = 0.125%
1	2	1	16%	0.150 x 1.00% = 0.150%
2	5	3	7%	0.070 x 3.00% = 0.210%
5	10	5	3%	0.030 x 5.00% = 0.150%
10	22	12	0.8%	0.008 x 12.0% = 0.096%
				Total usage = 1.007%

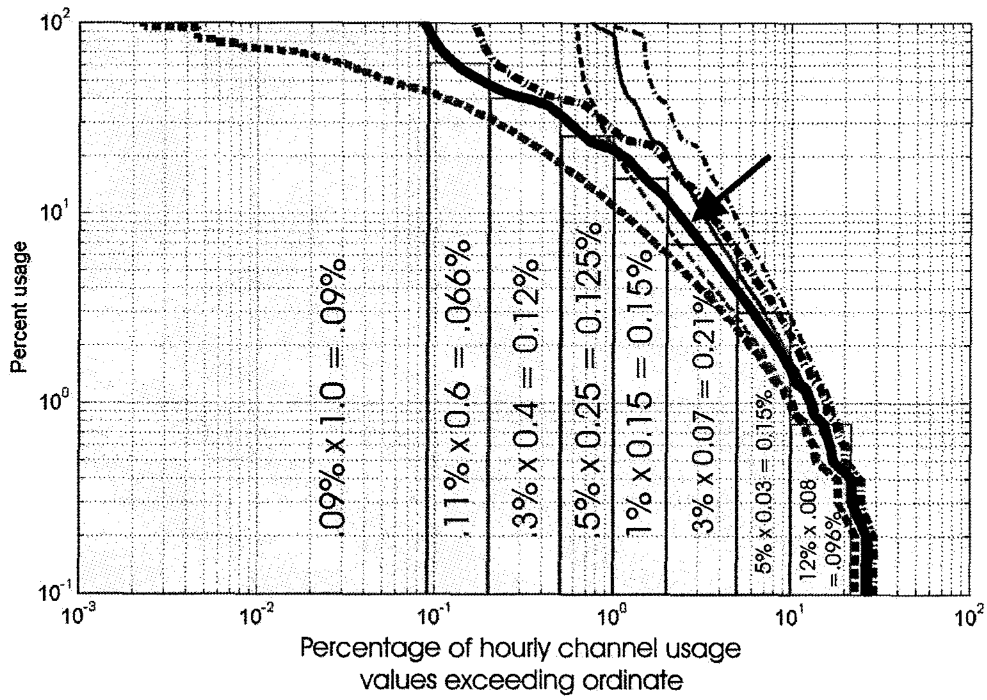
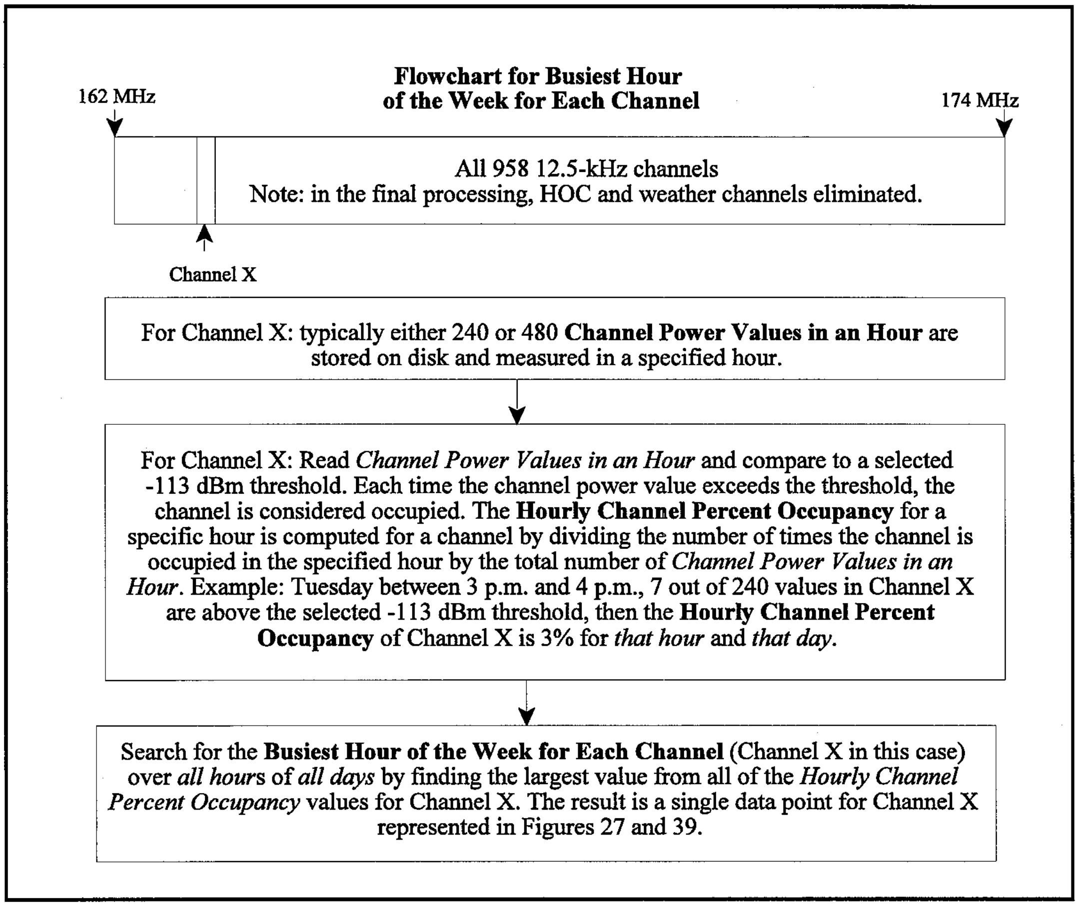


Figure 25. Calculating mean hourly channel usage.

5.7 Summary of Processing

The flowcharts in this section summarize the process that was used for obtaining the following statistics: *Busiest Hour of the Week for Each Channel, Busiest Usage by Time-of-Day for Each Channel, Average of Busiest Usage by Hour, Band Occupancy by Time-of-Day,* and *Maximum Band Occupancy.*



Flowchart for Busiest Usage by Time-of-Day and Average of Busiest Usage by Hour

162 MHz — 174 MHz

All 958 12.5-kHz channels
Note: in the final processing, HOC and weather channels eliminated.

Channel X

For Channel X: typically either 240 or 480 **Channel Power Values in an Hour** are stored on disk and measured in a specified hour.

↓

For Channel X: Read *Channel Power Values in an Hour* and compare to a selected -113 dBm threshold. Each time the channel power value exceeds the threshold, the channel is considered occupied. The **Hourly Channel Percent Occupancy** for a specific hour is computed for a channel by dividing the number of times the channel is occupied in the specified hour by the total number of *Channel Power Values in an Hour*. Example: Tuesday between 3 p.m. and 4 p.m., 7 out of 240 values in Channel X are above the selected -113 dBm threshold, then the **Hourly Channel Percent Occupancy** of Channel X is 3% for *that hour* and *that day*.

↓

Compute **Usage by Time-of-Day for Each Channel** during the entire week by summing the weighted *Hourly Channel Percent Occupancy* for a given hour using the minimum threshold. **Usage by Time-of-Day for Each Channel** is given by

$$u_{ij} = \frac{\sum_{k=1}^{D} c_{ijk} w_{jk}}{D},$$

where u_{ij} is the **Usage by Time-of-Day for Each Channel** for the i^{th} channel and the j^{th} hour of the day, c_{ikj} is the *Hourly Channel Percent Occupancy* for the i^{th} channel, the k^{th} day of the measurement, and the j^{th} hour of the day, w_{kj} is the weight factor for the the k^{th} day of the measurement and the j^{th} hour, and D is the number of days during the course of the measurement. The respective hourly values are weighted proportional to the number of measurements used in computing the hourly values since not all *Hourly Channel Percent Occupancy* values contain data based on an equal number of measurements.

↓

Determine the **Busiest Usage by Time-of-Day for Each Channel** by finding, for each channel, the *Usage by Time-of-Day for Each Channel* value that is the largest out of the 24 values. There is only one *Busiest Usage by Time-of-Day* value for each channel.

↓

Compute the **Average of Busiest Usage by Hour** by averaging, across all channels, the values for *Busiest Usage by Time-of-Day for Each Channel.* Example: Channel 1, Hour 4, 1.2%; Channel 2, Hour 2, 18.6%; ....Channel 958, Hour 24, 5.3%. **Average of Busiest Usage by Hour** (p) is given by

$$p = \frac{\left(\sum_{i=1}^{N} b_i\right)}{N},$$

where b_i is the *Busiest Usage by Time-of-Day* for the i^{th} channel, and N is the number of channels. The result is a single data value for the entire band, displayed in Tables A-1, A-2, A-5, and A-6 as the "Average of Busiest Hour."

Flowchart for Band Occupancy by Time of Day and Maximum Band Occupancy

162 MHz — 174 MHz

All 958 12.5-kHz channels
Note: in the final processing, HOC and weather channels eliminated.

Channel X

For Channel X: typically either 240 or 480 **Channel Power Values in an Hour** are stored on disk and measured in a specified hour.

↓

For Channel X: Read *Channel Power Values in an Hour* and compare to a selected -113 dBm threshold. Each time the channel power value exceeds the threshold, the channel is considered occupied. The **Hourly Channel Percent Occupancy** for a specific hour is computed for a channel by dividing the number of times the channel is occupied in the specified hour by the total number of *Channel Power Values in an Hour*. Example: Tuesday between 3 p.m. and 4 p.m., 7 out of 240 values in Channel X are above the selected -113 dBm threshold, then the **Hourly Channel Percent Occupancy** of Channel X is 3% for *that hour* and *that day.*

↓

Compute the **Hourly Band Usage** by taking all of the *Hourly Channel Percent Occupancy* values in a given hour of a given day and averaging across all of the channels in the band. **Hourly Band Usage** (h_{jk}) for the j^{th} hour of the k^{th} day is given by

$$h_{jk} = \left(\sum_{i=1}^{N} c_{ijk}\right) \Big/ N ,$$

where c_{ijk} is the *Hourly Channel Percent Occupancy* for the i^{th} channel, the k^{th} day of the measurement, and the j^{th} hour of the day, and N is the number of channels. The result of this processing is displayed in Figures 26, 28, 38, 40, 50, 52, A-1, and A-2.

↓

Compute the **Band Occupancy by Time-of-Day** by taking the *Hourly Band Usage* values for each hour of the day and averaging together the values for corresponding hours of the day across all days of the measurement. **Band Occupancy by Time-of-Day** (d_j) for the j^{th} hour of the day is given by

$$d_j = \left(\sum_{k=1}^{M} h_{jk}\right) \Big/ M .$$

where h_{jk} is the *Hourly Band Usage* for the k^{th} day of the measurement, and the j^{th} hour of the day, and M is the number of days during the measurement. The result of this processing is displayed in Figures 29, 30, 31, 41, 42, and 43.

↓

The ***Maximum Band Occupancy*** is the maximum of all the ***Band Occupancy by Time-of-Day*** values for a day. It is represented by a single data point on Figure 30 (as annotated).

5.8 Measurement Results

Figures 26 through 49 summarize results using the various graphs described in the previous section. As a quick reference, Tables 9 and 10 provide figure numbers for various plot types. For statistics that do not provide results for multiple threshold levels, only the minimum threshold is used, the values of which are listed in Table 11.

Table 9. Figure Numbers for Graphs in the 162–174 MHz Band

Hourly Band Usage	X		X										X
Busiest Hour of the Week for Each Channel		X											
Band Occupancy by Time-of-Day				X	X	X							
% Hourly Channel Percent Occupancy Values Exceeding % Usage							X						
% Channels Exceeding % Usage for Channel Percent Occupancy								X					
% Channels Exceeding % Usage for Busiest Usage by Time-of-Day for Each Channel									X				
APD of Channel Power Values										X	X		
% Channels Exceeding a Given % of Hours at Greater than or Equal to a Given % Usage												X	
Multiple Thresholds						X							X
Mult Channelization Scenarios	X		X		X		X	X	X	X			
Multiple HOC Scenarios							X				X		
Multiple Time Scenarios				X									
Including HOC		X	X				X				X		
Excluding HOC	X			X	X	X	X	X	X	X	X	X	X
Entire Week							X	X	X	X	X	X	
Date and Time of Day	X	X	X										X
Time for Any Day				X	X	X							
Election Day				X									
Weekdays				X									
Weekend Days				X									
All Channels	X	X	X	X	X	X	X	X	X	X	X	X	X
25-kHz Channelization	X		X		X		X	X	X	X			
12.5-kHz Channelization	X		X		X		X	X	X	X			
Figure Number	26	27	28	29	30	31	32	33	34	35	36	37	A-1

Table 10. Figure Numbers for Graphs in the 406–420 MHz Band

Hourly Band Usage	X		X										X
Busiest Hour of the Week for Each Channel		X											
Band Occupancy by Time-of-Day				X	X	X							
% Hourly Channel Percent Occupancy Values Exceeding % Usage							X						
% Channels Exceeding % Usage for Channel Percent Occupancy								X					
% Channels Exceeding % Usage for Busiest Usage by Time-of-Day for Each Channel									X				
APD of Channel Power Values										X	X		
% Channels Exceeding a Given % of Hours at Greater than or Equal to a Given % Usage												X	
Multiple Thresholds						X							X
Mult Channelization Scenarios	X		X		X		X	X	X	X			
Multiple HOC Scenarios							X				X		
Multiple Time Scenarios				X									
Including HOC		X	X				X				X		
Excluding HOC	X			X	X	X	X	X	X	X	X	X	X
Entire Week							X	X	X	X	X	X	
Date and Time of Day	X	X	X										X
Time for Any Day				X	X	X							
Election Day				X									
Weekdays				X									
Weekend Days				X									
All Channels	X	X	X	X	X	X	X	X	X	X	X	X	X
25-kHz Channelization	X		X		X		X	X	X	X			
12.5-kHz Channelization	X		X		X		X	X	X	X			
Figure Number	38	39	40	41	42	43	44	45	46	47	48	49	A-2

Table 11. Minimum Detection Threshold Values

Frequency Band	dBm at antenna terminals	dB μV/m field strength
162–174 MHz	-113	8
406–420 MHz	-117	12

Several of the channel-usage graphs show anomalies that require further explanation (anomaly, meaning data that does not reflect what is truly happening). As can be seen in Figure A-1 in Appendix A, as well as Figures 26 and 28, there are three different times (at the beginning, midway, and at the end of the week) in which all of the usage values go to zero. The reason for this is that, during this time, no data were collected in the bands of interest, and therefore usage erroneously appears to be zero. This anomaly occurs only in the 162–174 MHz band. Another anomaly that occurs – but only in the 162–174 MHz band (as seen in Figures A-1, 26, and 28) – can be seen at approximately 10:00 AM on Thursday, in which usage values for all data plots exceed 2.5 percent usage. Upon examining the usage data in greater detail it was determined that this was due to an incomplete data set where the data collected was in a small section of the spectrum that had greater usage than the average. A third anomaly occurs at midday on Sunday and Monday in which only the data for the minimum detection threshold exceed 2.5 percent usage. This occurs in the 162–174 MHz band and can be seen in Figures A-1, 26, and 28. Examining the usage data in greater detail revealed periods of increased noise that were high enough to raise the statistics for mean usage on the minimum detection threshold plot but were not high enough to be detected and removed by the processing techniques described in Section 4.1. This phenomenon also has an impact on the 24-hour plot shown in Figure 31, in which only the minimum detection threshold plot appear to have this anomaly. For APD plots, time periods during which this aberrant noise condition occurred were excluded from analysis. To improve readability of the week-long plots, the latter anomalies are often cut off by the top of the graphs, since this data is not relevant to the usage analysis. As shown in Figure A-2 of Appendix A, none of the anomalies occurred in the 406–420 MHz band.

To give some indication of the degree to which assignments have migrated to the 12.5-kHz channel spacing, several of the graphs show statistical summaries for 3 different channelization schemes as described in section 2.1. These include the following:

1. all channels spaced 12.5 kHz apart.
2. the old 25-kHz channels (spaced 25 kHz apart).
3. the new 12.5-kHz channels (spaced 25 kHz apart and located halfway between the old 25-kHz channels).

Statistics for each of the three categories are determined only for the channel frequencies indicated. However, because ACPR requirements, as specified in Section 2.2, require 25-kHz channels only to be attenuated in the adjacent 25-kHz channel, there is likely to be significant signal power in the adjacent channel spaced 12.5 kHz away. Therefore, some of the new 12.5-kHz channels are likely to show usage even though the power simply comes from an adjacent old 25-kHz channel. From the standpoint of percent-usage of all channels spaced 12.5 kHz apart, a channel 12.5 kHz away from the center frequency of a wider bandwidth transmission in an old 25-kHz channel is considered to be occupied, even though the power comes from an adjacent channel; however, because the two adjacent channels 12.5 kHz away from the center frequency of the wider bandwidth transmission will show less power, the mean for percent usage of all channels spaced 12.5 kHz apart is likely to be slightly low since their values may, at times, fall below the threshold. On the other hand, statistics for usage of the new 12.5-kHz channels are likely to show mean-usage values slightly higher than the true value because the channel is not being used for a transmission as a new 12.5-kHz channel but is simply showing usage because there is sideband power in the channel from an adjacent old 25-kHz channel.

5.8.1 Results for 162–174 MHz Band

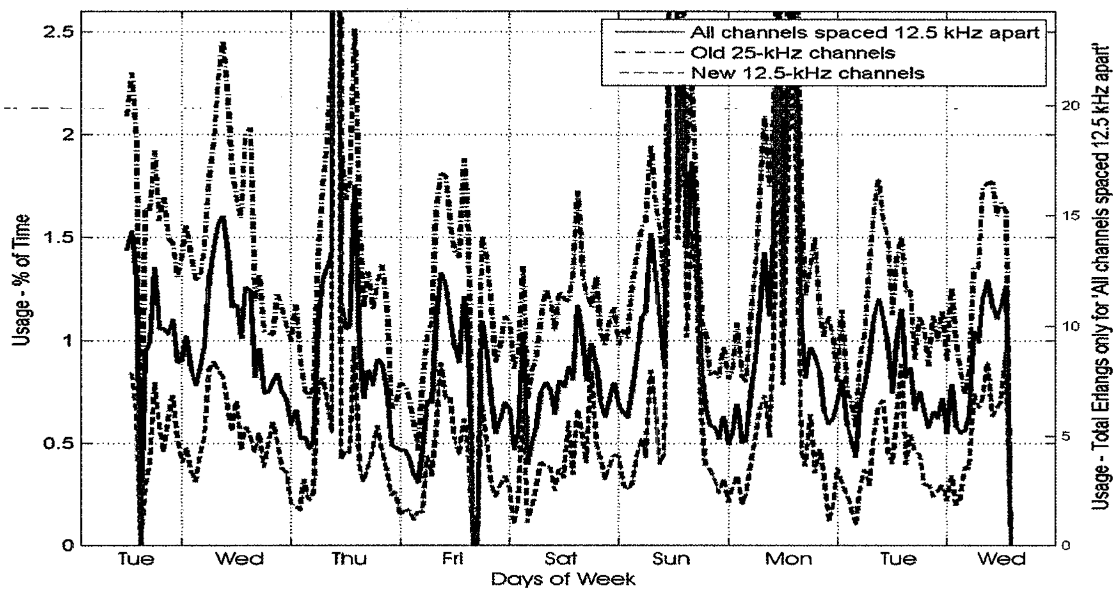


Figure 26. *Hourly Band Usage* (percent of time and total Erlangs) during the course of the measurements for the 162–174 MHz band (excluding HOCs; minimum thresholds).

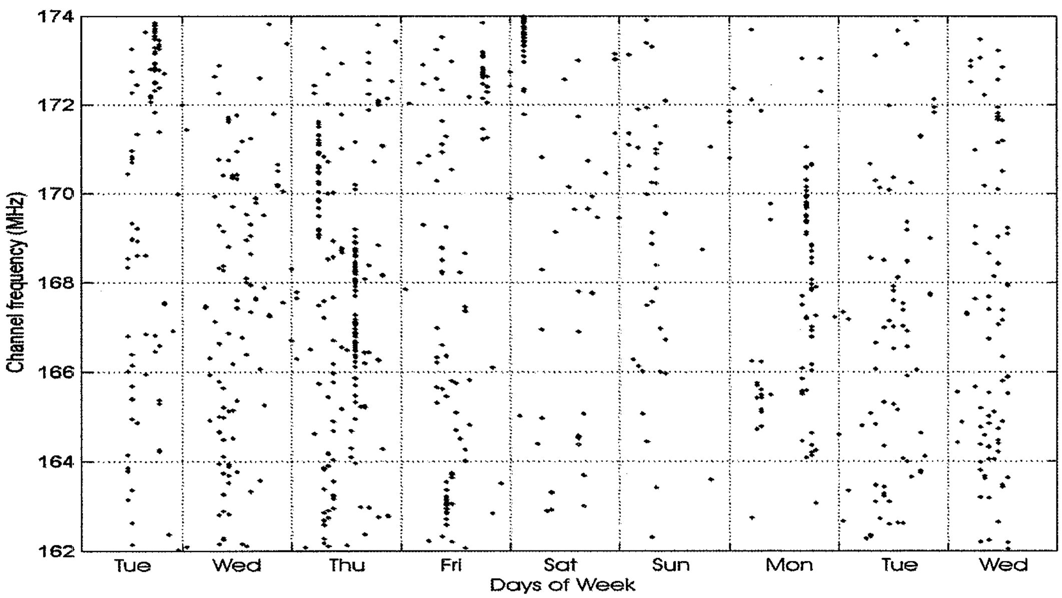


Figure 27. *Busiest Hour of the Week for Each Channel* in the 162–174 MHz band.

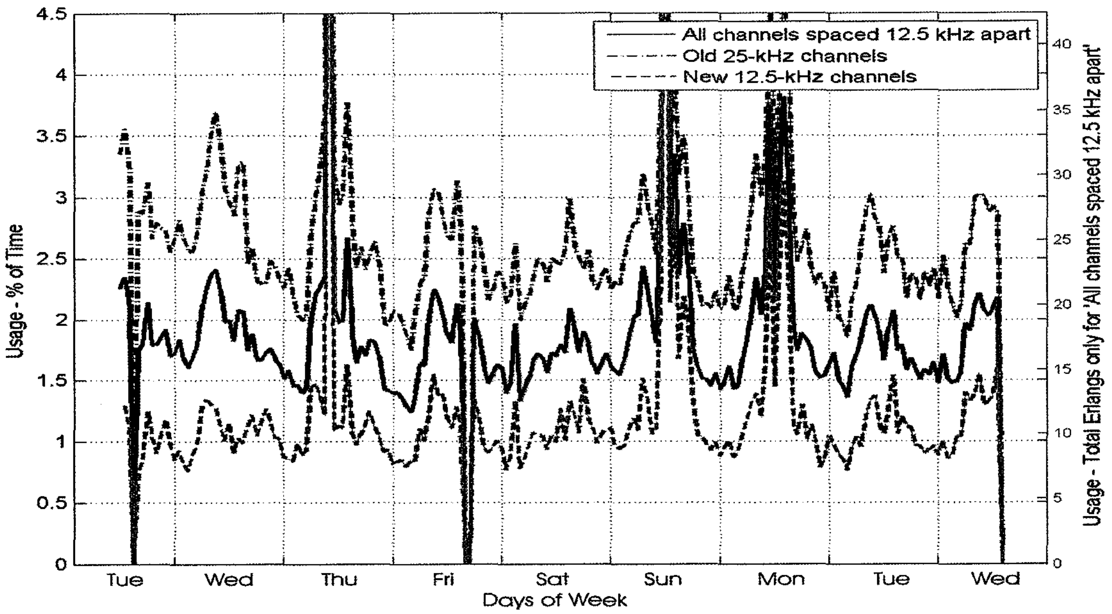


Figure 28. *Hourly Band Usage* (percent of time and total Erlangs) during the course of the measurements for the 162–174 MHz band (including HOCs; minimum threshold).[13]

[13] As previously noted, both Figures 26 and 28 have some anomalies that require explanation. There are three different times (at the beginning, midway, and at the end of the week) in which all of the plot values go to zero. The reason for this is that, during this time, no data were collected in the bands of interest, and therefore usage erroneously appears to be zero. Another anomaly can be seen at approximately 10:00 AM on Thursday, in which all data plots exceed 4 percent usage. Upon examining the data in greater detail it was determined that this was due to an incomplete data set in which the data collected was a small section of the spectrum that had greater usage than the average. A third anomaly occurs at midday on Sunday and Monday in which only the data for the minimum threshold exceed 2.5 percent usage. Examining this data in greater detail revealed periods of increased noise that were high enough to raise the statistics for mean usage on the minimum threshold plot but were not high enough to be detected and removed by the processing techniques described in Section 4.1. This phenomenon also has an impact on the 24-hour plot shown in Figure 31, in which only the minimum threshold plots appear to have this anomaly. To improve readability of the week-long plots, the latter anomalies are cut off by the top of the graphs, since this data is not relevant to analysis.

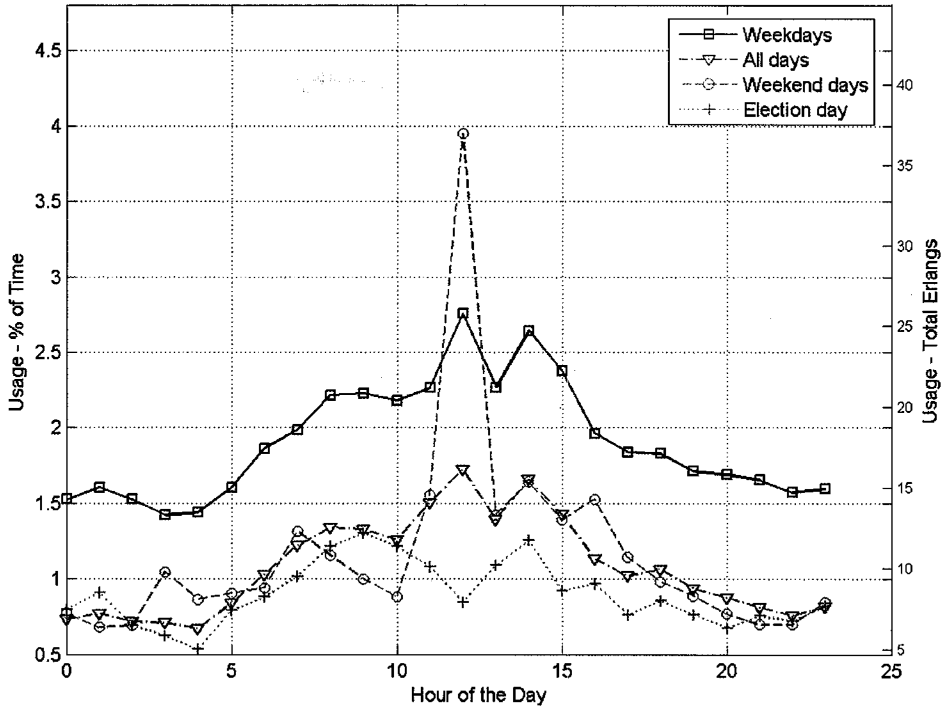


Figure 29. *Band Occupancy by Time-of-Day* (percent of time and total Erlangs) during different 24-hour time scenarios in the 162–174 MHz band (excluding HOCs; minimum threshold).[14]

[14] An anomaly occurs at midday on weekend days in which the data approaches 4 percent usage. Examining this data in greater detail revealed a period of increased noise on Sunday that was high enough to raise the statistics for mean usage on the minimum threshold plot but were not high enough to be detected and removed by the processing techniques described in Section 4.1.

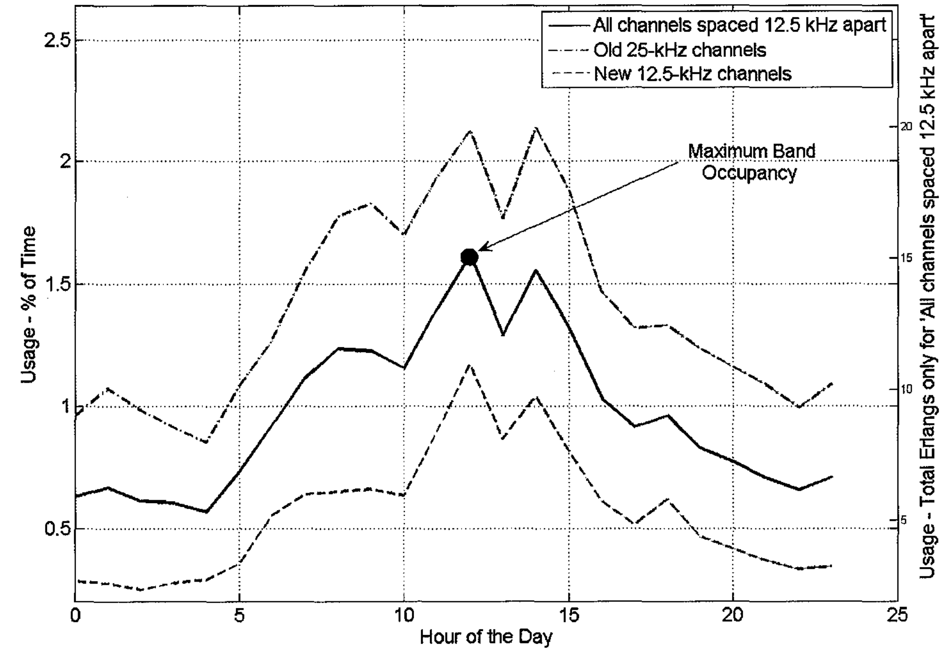


Figure 30. *Band Occupancy by Time-of-Day* (percent of time and total Erlangs) during the course of 24 hours, independent of the date, for different channelization scenarios in the 162–174 MHz band (excluding HOCs; minimum threshold).[15]

[15] As discussed earlier, the processed data in Figures 30 and 31 contain measurements on both Specific Location Assignments and Area Assignments. The *Maximum Band Occupancy* in Figure 30, which includes both types of assignments, is about 1.6 percent at 12 noon. The *Maximum Band Occupancy* associated with each type of assignment ("Specific Location" vs "Area") will be different, since Area Assignments may or may not have been active during the measurement period within the measurement coverage area. A search of the GMF by OSM revealed that the number of Specific Location Assignments deemed to be visible to the measurement system is 511, and when the measured data were examined on a channel-by-channel basis for that specific time (12 pm), it was determined that total number of Erlangs for Specific Location Assignments was 10.98. Therefore, the *Maximum Band Occupancy* for Specific Location Assignments was determined to be 2.1 percent.

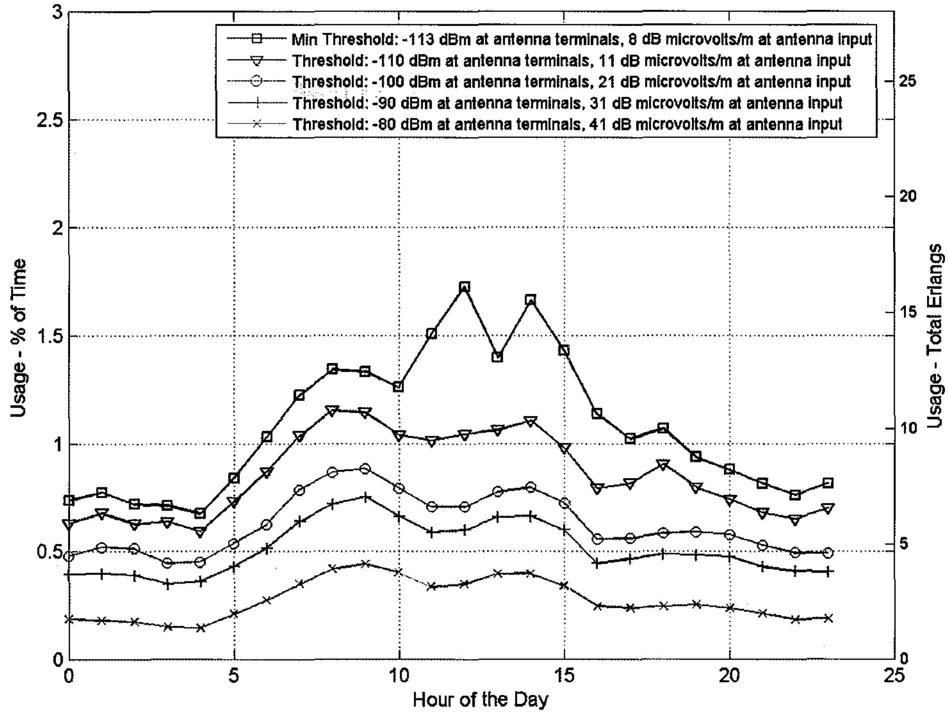


Figure 31. *Band Occupancy by Time-of-Day* (percent of time and total Erlangs) using different thresholds, independent of the date, for all 934 channels in the 162–174 MHz band (excluding HOCs).

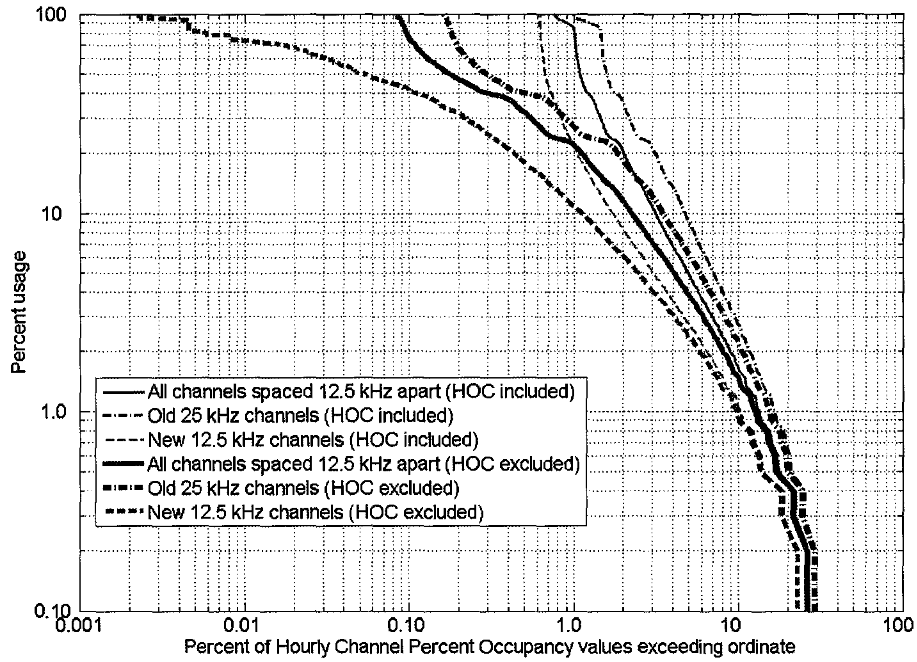


Figure 32. Percent of *Hourly Channel Percent Occupancy* values exceeding a given percent usage over the course of the measurements for the 162–174 MHz band (minimum threshold).

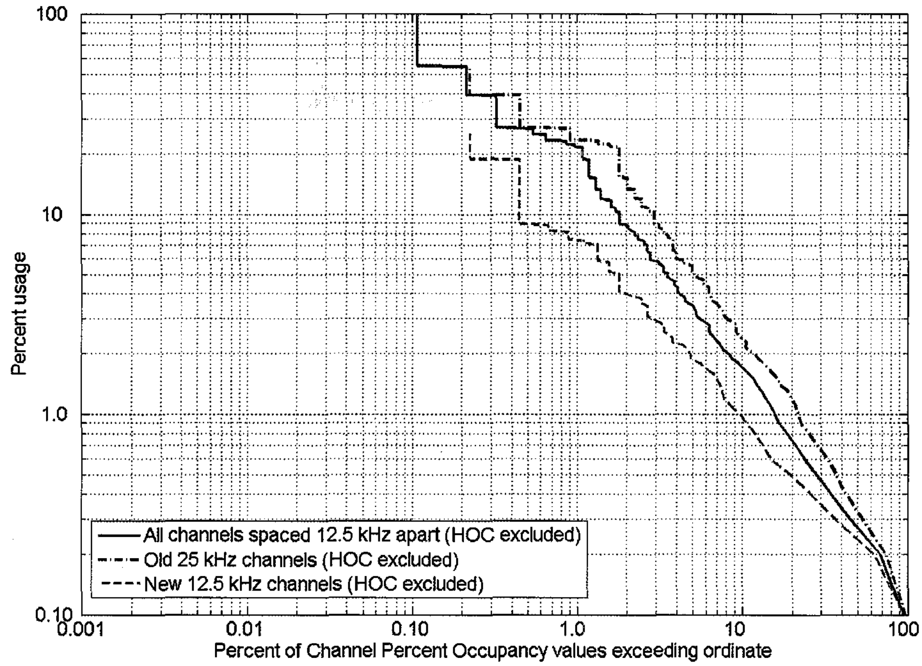


Figure 33. Percent of channels exceeding a given percent usage for *Channel Percent Occupancy* over the course of the measurements for the 162–174 MHz band (minimum threshold).

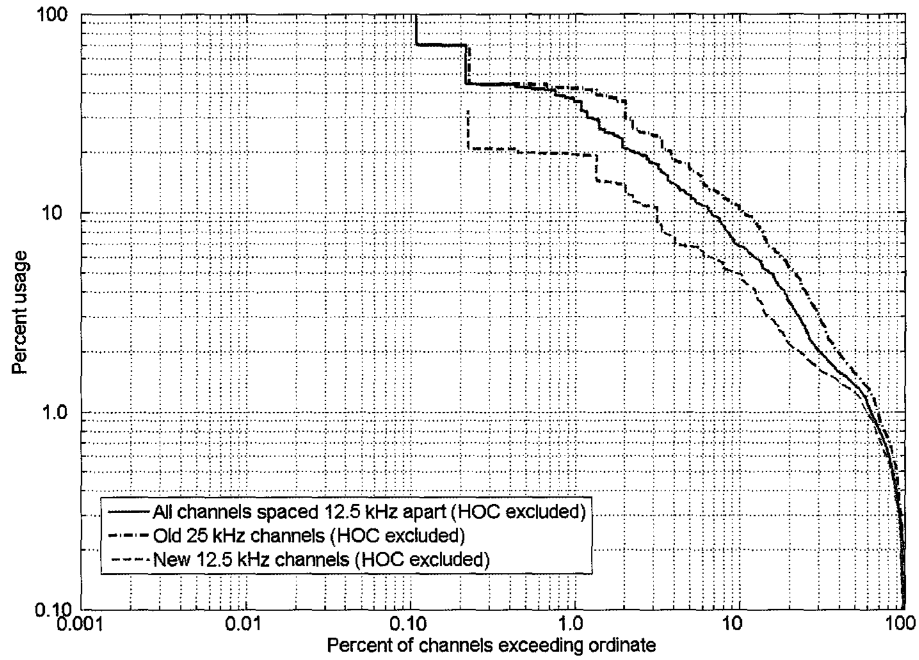


Figure 34. Percent of channels exceeding a given percent usage for the *Busiest Usage by Time-of-Day for Each Channel* during weekdays only in the 162–174 MHz band (minimum threshold).

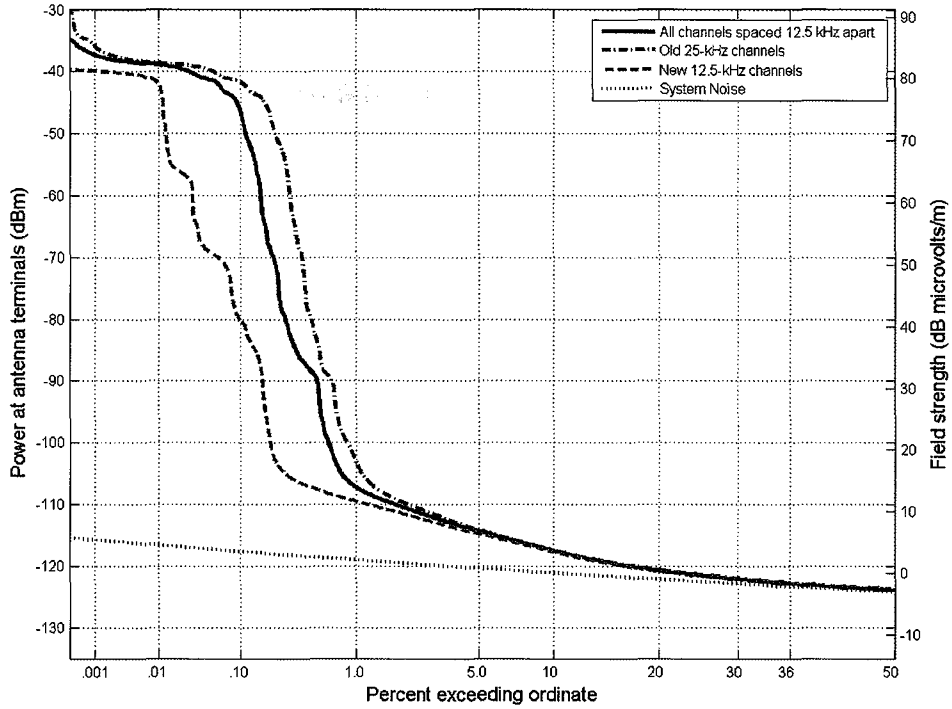


Figure 35. APDs of *Channel Power Values* for channels in the 162–174 MHz band – entire week, independent of date or time for different channelization (excluding HOCs; minimum threshold).

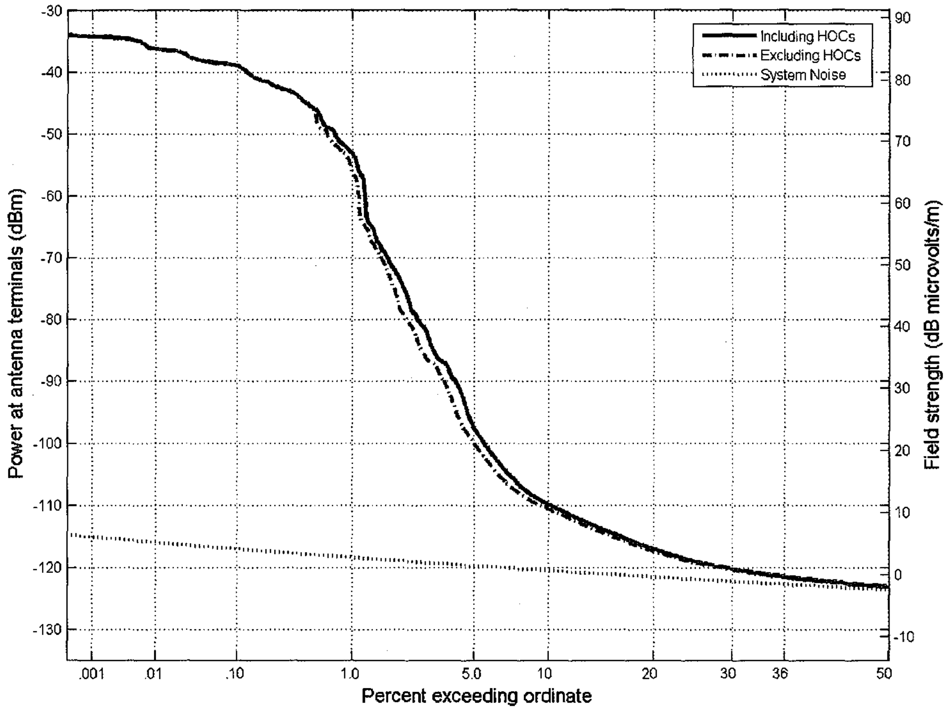


Figure 36. APDs of *Channel Power Values* for all channels spaced 12.5 kHz apart in the 162–174 MHz band for the busiest hour during the entire week independently for each frequency for different HOC scenarios (minimum threshold).

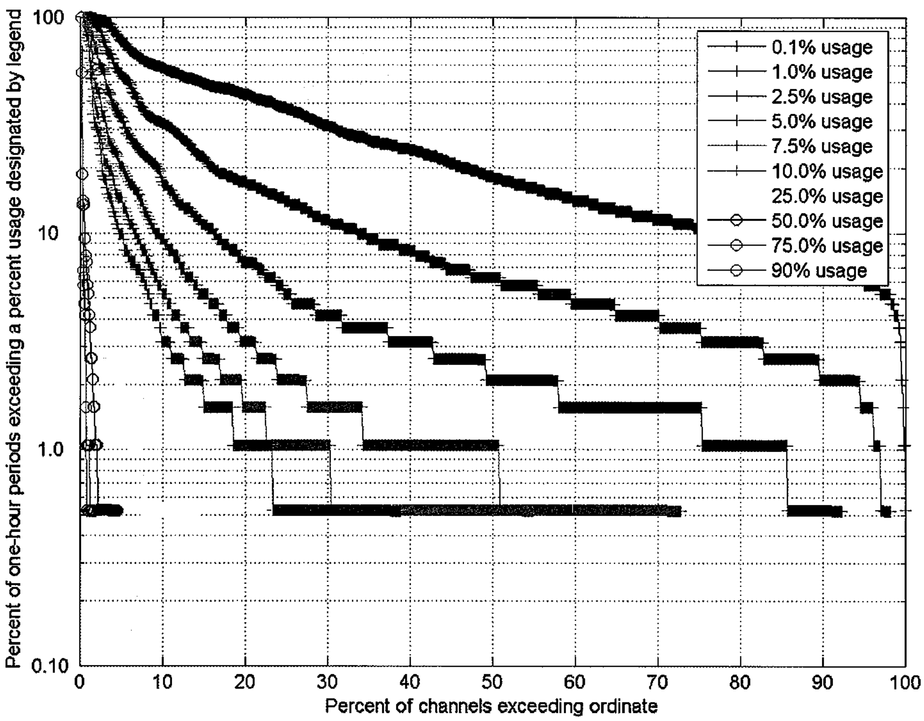


Figure 37. Cumulative distribution of the percent of channels that exceed a given percent of hours at greater than or equal to a given *Hourly Channel Percent Occupancy* (designated by legend) for all channels in the 162–174 MHz band (excluding HOCs; minimum threshold, entire week).[16]

[16] Discrete steps in the "percent of hourly periods" occur because there are a discrete number of one-hour time slots over the course of the measurement. Since there were approximately 196 hours of measurement during the course of the 8 days, a single one-hour time slot represents a "percent of hourly periods" of 0.51%, two hours represents 1%, and three hours represents 1.5% (consistent with the discrete steps seen in the figure above).

5.8.2 Results for 406–420 MHz Band

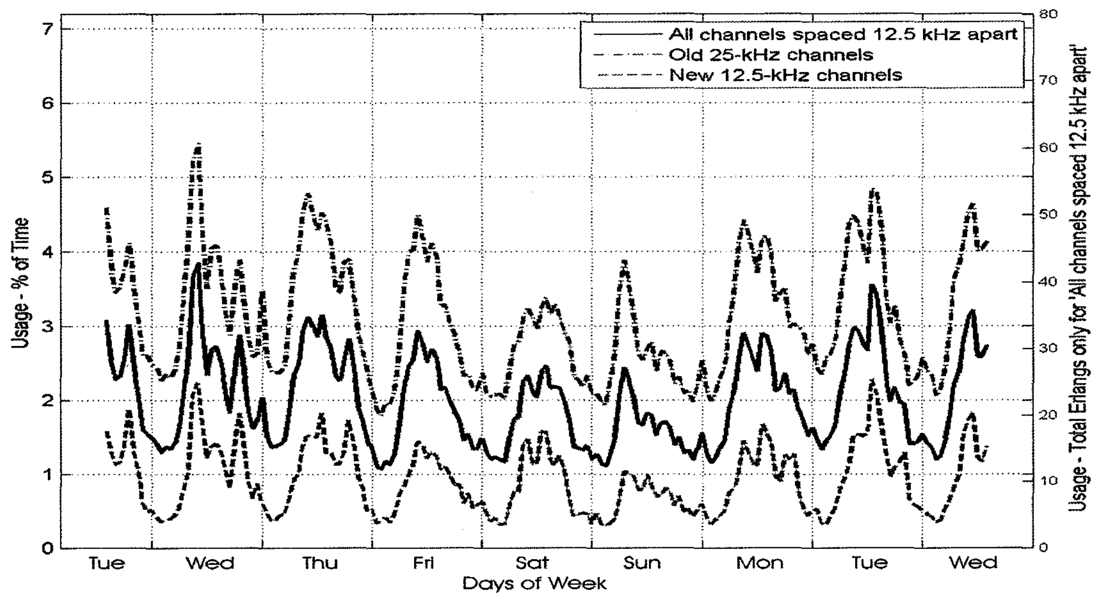


Figure 38. *Hourly Band Usage* (percent of time and total Erlangs) during the course of the measurements for the 406–420 MHz band (excluding HOCs; minimum threshold).

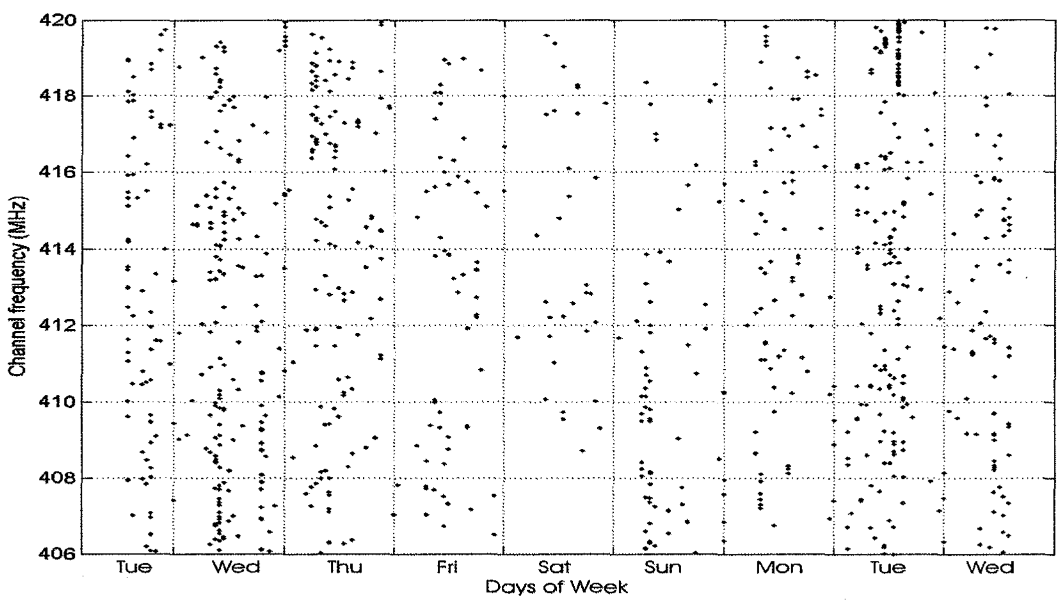


Figure 39. *Busiest Hour of the Week for Each Channel* in the 406–420 MHz band.

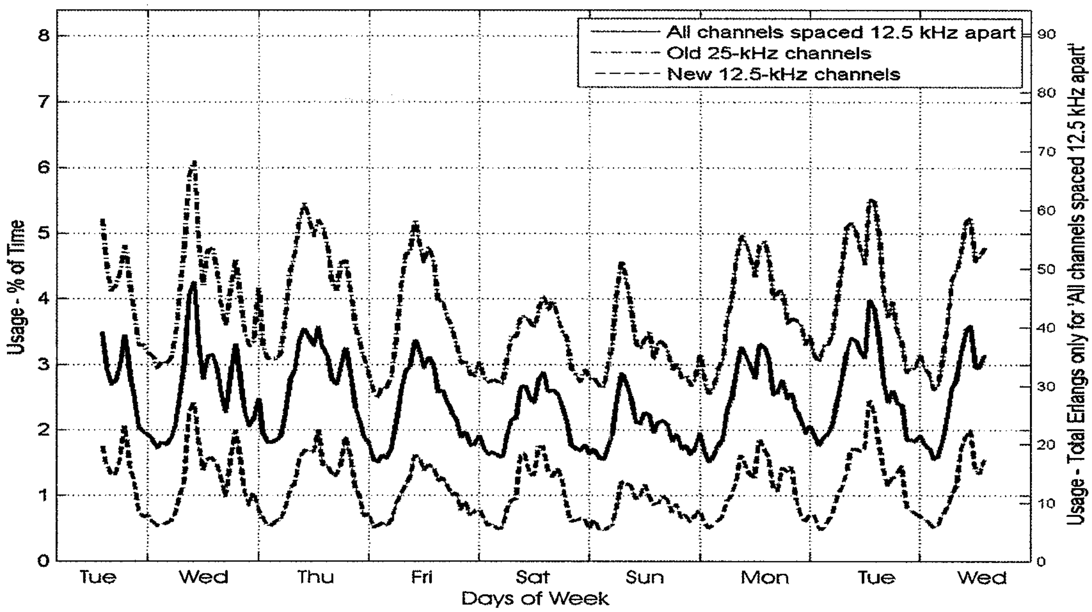


Figure 40. *Hourly Band Usage* (percent of time and total Erlangs) during the course of the measurements for the 406–420 MHz band (including HOCs; minimum threshold).

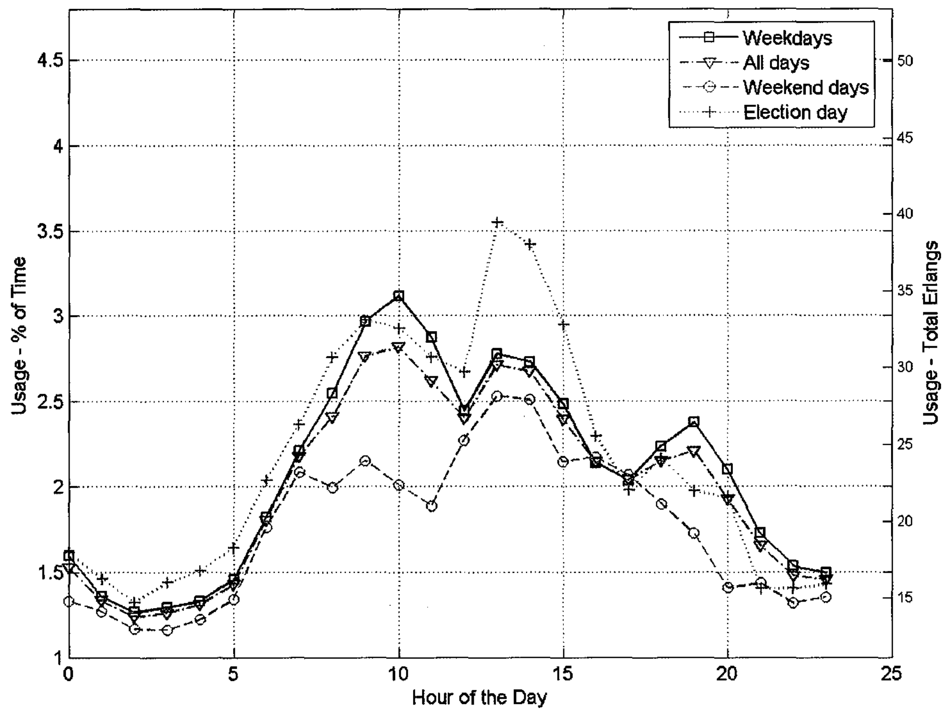


Figure 41. *Band Occupancy by Time-of-Day* during different 24-hour time scenarios in the 406–420 MHz band (excluding HOCs; minimum threshold).

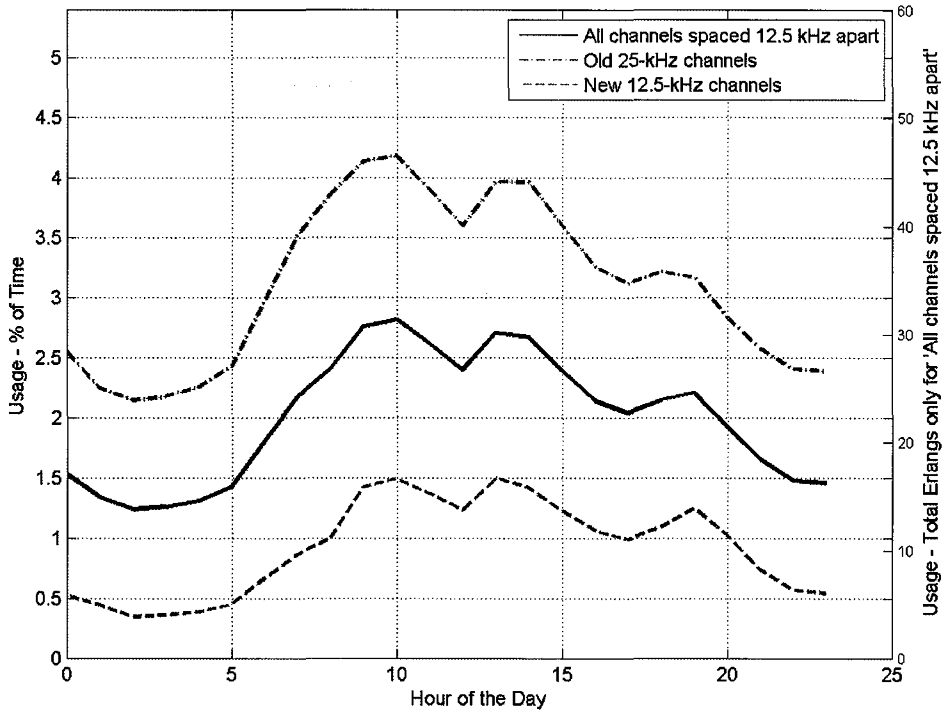


Figure 42. *Band Occupancy by Time-of-Day* (percent of time and total Erlangs) during the course of 24 hours, independent of the date, for different channelization scenarios in the 406–420 MHz band (excluding HOCs; minimum threshold).

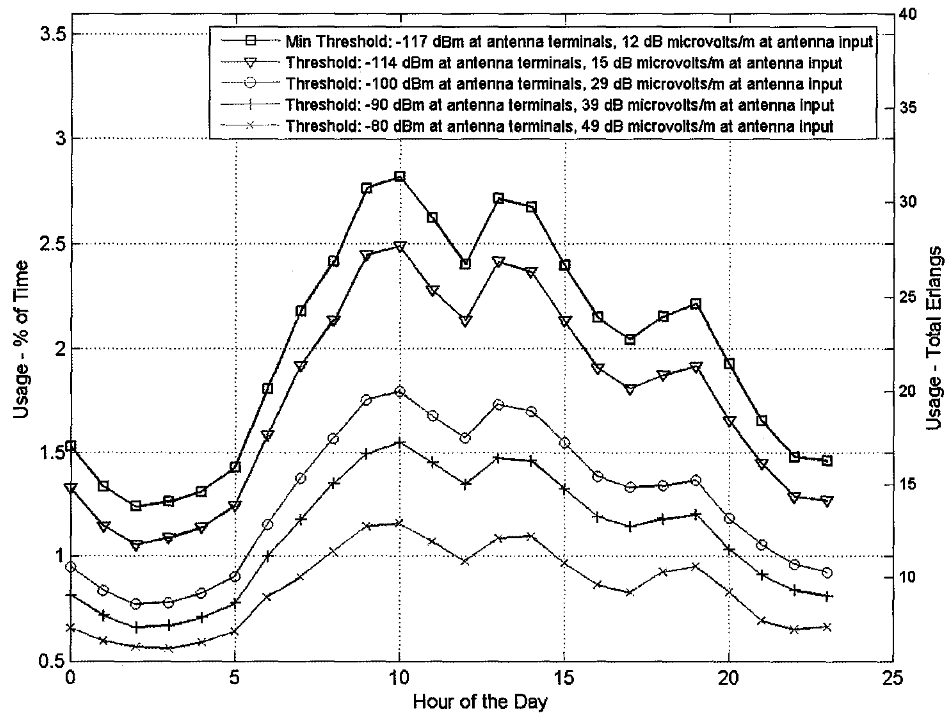


Figure 43. *Band Occupancy by Time-of-Day* (percent of time and total Erlangs) using different thresholds, independent of the date, for all 1113 channels in the 406–460 MHz band (excluding HOCs).

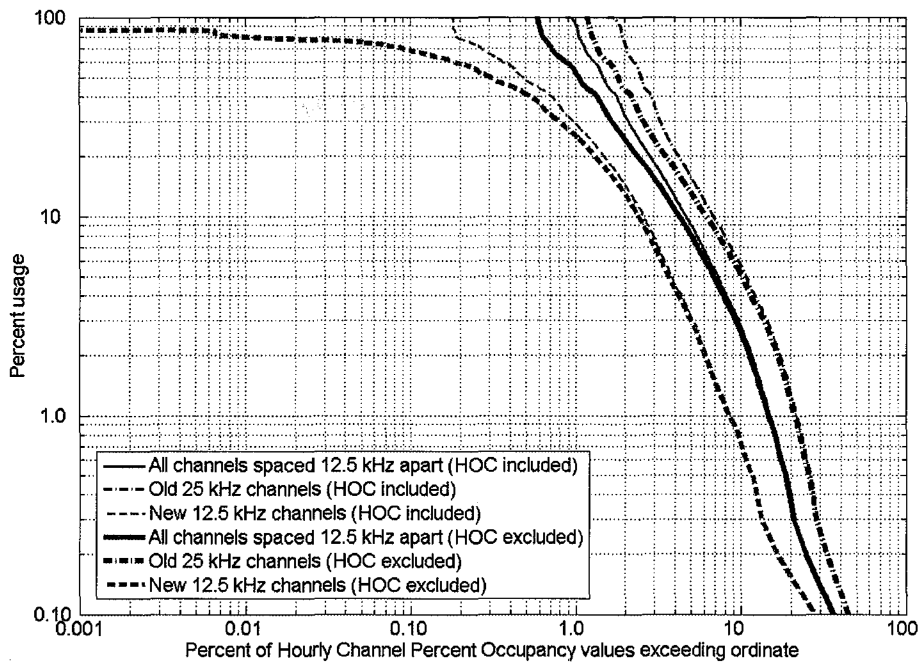


Figure 44. Percent of *Hourly Channel Percent Occupancy* values exceeding a given percent usage over the course of the measurements for the 406–420 MHz band (minimum threshold).

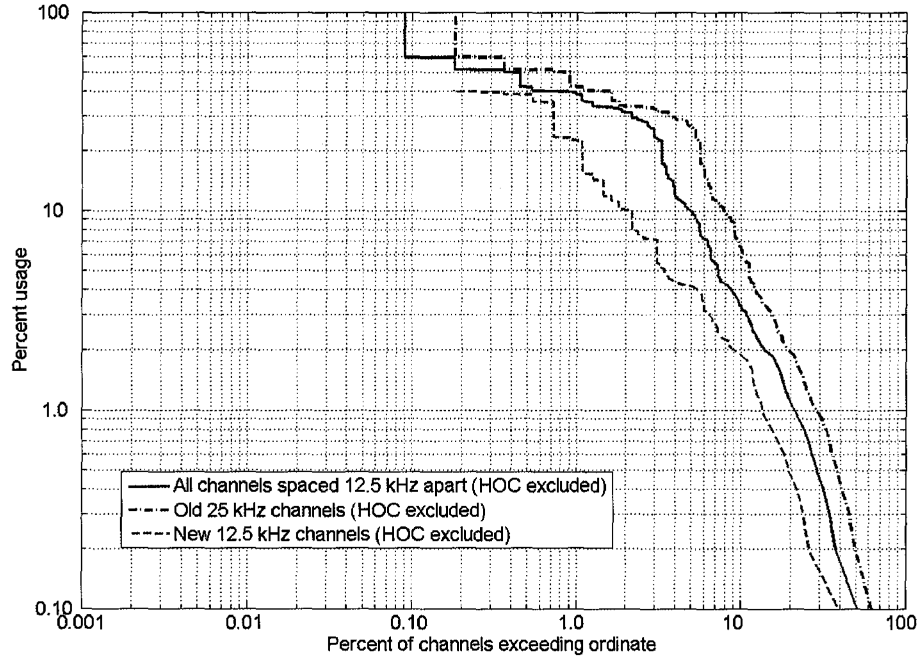


Figure 45. Percent of channels exceeding a given percent usage for *Channel Percent Occupancy* over the course of the measurements for the 406–420 MHz band (minimum threshold).

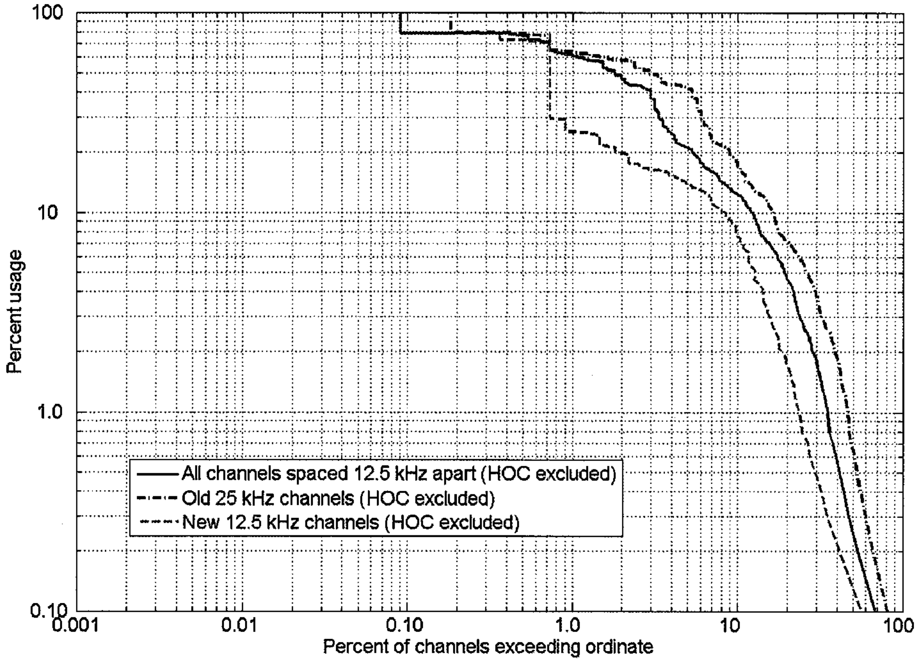


Figure 46. Percent of channels exceeding a given percent usage for the *Busiest Usage by Time-of-Day for Each Channel* during weekdays only in the 406–420 MHz band (minimum threshold).

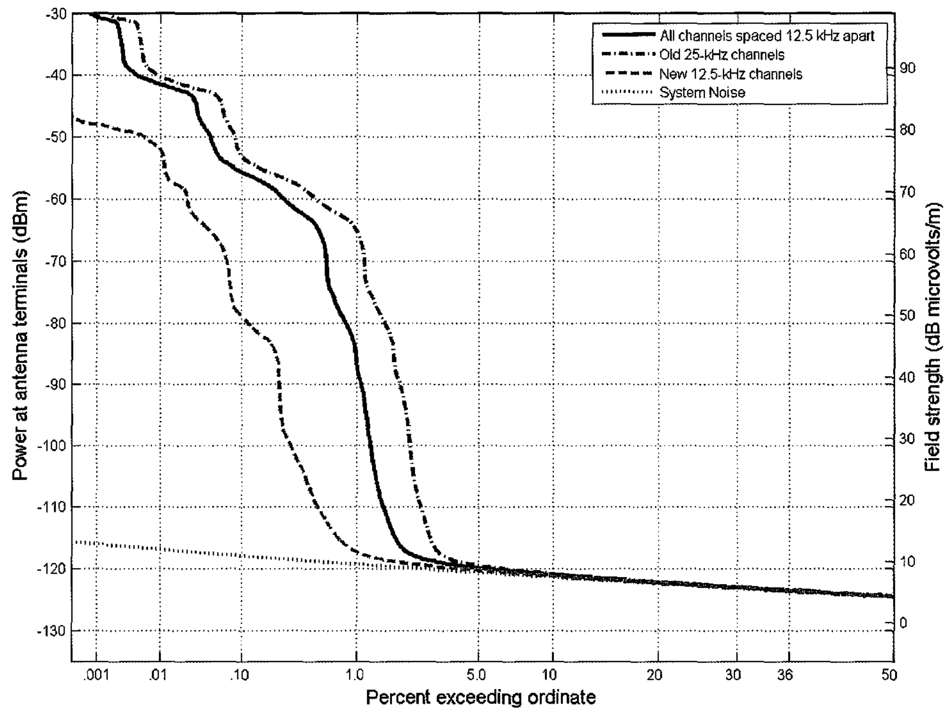


Figure 47. APDs of *Channel Power Values* for channels in the 406–420 MHz band – entire week, independent of date or time for different channelization (excluding HOCs; minimum threshold).

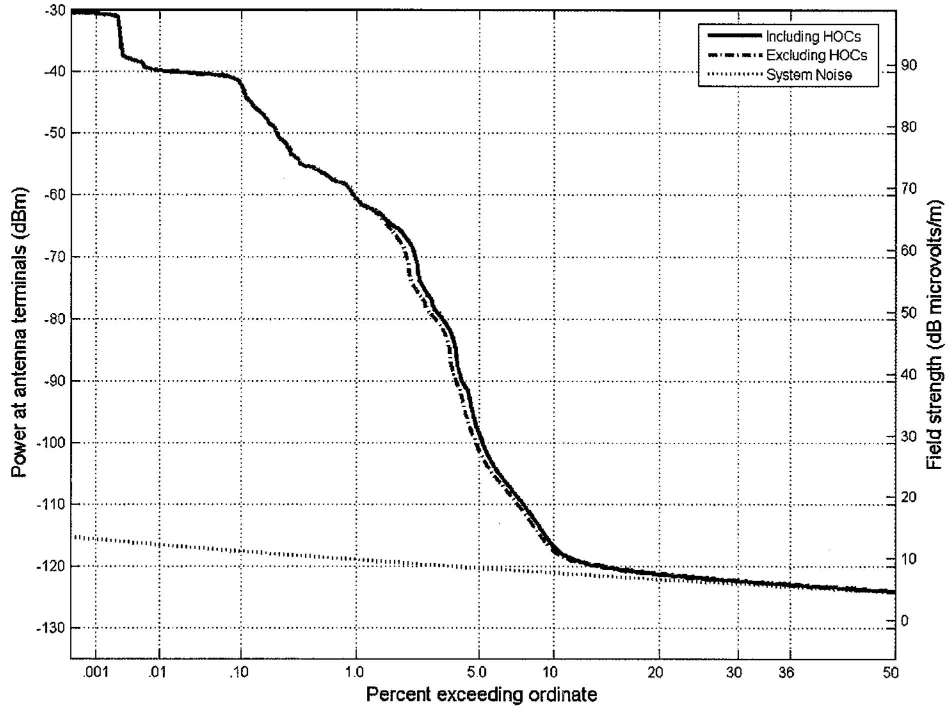


Figure 48. APDs of *Channel Power Values* for all channels spaced 12.5 kHz apart in the 406–420 MHz band for the busiest hour during the entire week independently for each frequency for different HOC scenarios (minimum threshold).

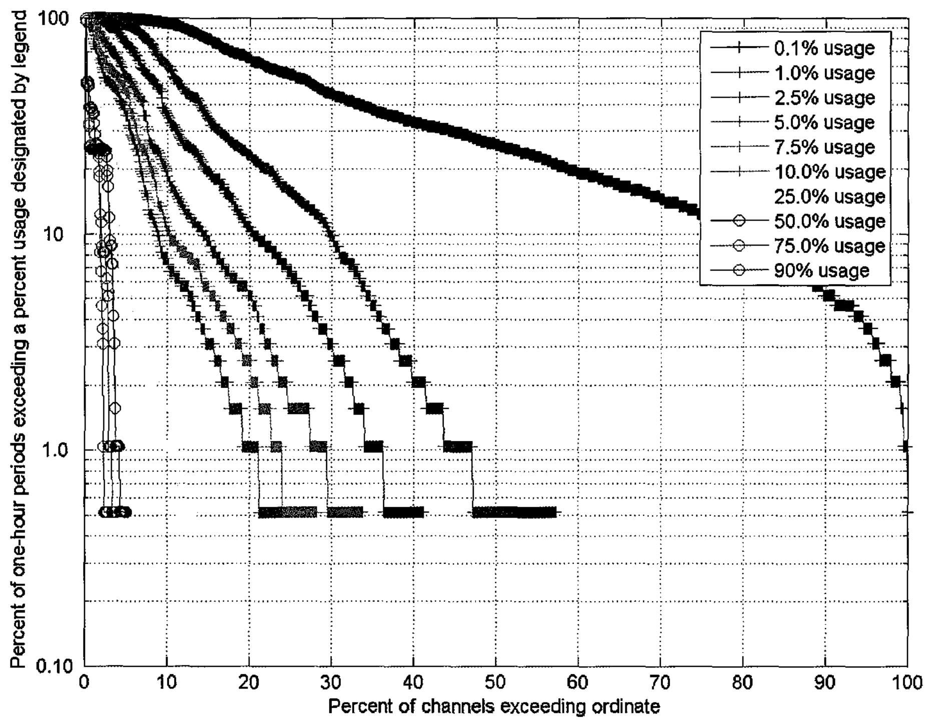


Figure 49. Cumulative distribution of the percent of channels that exceed a given percent of hours at greater than or equal to a given *Hourly Channel Percent Occupancy* (designated by legend) for all channels in the 406–420 MHz band (excluding HOCs; minimum threshold).

6 SUMMARY OF MEASUREMENT RESULTS

The measured data presented in this report characterizes channel usage of LMR systems operating in the 162–174 and 406–420 MHz frequency bands in the Washington, D.C., area. The analysis of the data is used to present the percent usage for a typical or representative channel during an 8-day measurement period using sampling procedures for the measurements.

A summary of the measurement results for channel usage for each band is given in the following sections along with a description of the diurnal patterns. There are several limitations to the measurements, however, that need to be considered, as follows.

Because the measurement system coverage area for mobile and portable stations is not as extensive as for base stations and repeaters, and because terrain and structural obstruction may prevent adequate reception of these mobile radio signals by the measurement system, the usage statistics may not fully reflect the usage within the bands. However, for each transmission by a portable or mobile station there is usually a corresponding transmission response from a base station or repeater that reflects that usage; therefore, for the worst case, where no portable and mobile station transmissions are detected, the measured usage would need to be doubled (assuming no talk-around). In reality, the usage statistics lie somewhere in between these two extremes, since some of the signals from mobile and portable stations were detected by the measurement system. It is also possible that the measurement system coverage area for base stations is extensive enough to detect frequency reuse, thus reflecting a higher than expected average usage.

There are some assignments that, while included in the overall statistical analysis, in reality are not used for LMR transmissions or cannot be detected. Some cannot be detected for the reasons described in the previous paragraph. The received power from some assignments may be below the measurement system sensitivity. Some channels may be assigned for "listening only" in the sense that they infrequently carry traffic but are monitored continually for emergency transmissions. In every case, the result is that the usage statistics may show usage less than what would be expected if the analysis were performed only on channels that are reserved for transmission and can be detected within the measurement receiver coverage. Furthermore, any 12.5-kHz channel that has a wideband assignment adjacent to it cannot generally be used within the measurement system coverage area, and therefore would not show any activity.

Only 2 out of 36 hydrology channels in the 162–174 MHz band exceeded 80 percent usage and therefore were excluded from analysis – when HOCs were excluded (see Section 5.4). None of the 12 hydrology channels in the 406–420 MHz band exceeded the 80 percent usage level and therefore, none were excluded from analysis. This means that the hydrology channels with less than 80 percent usage (some with very little, if any, usage) were included in the overall LMR occupancy statistics. Upon closer examination, it was determined that the non-HOC hydrology channels in the 162–174 MHz band had a mean usage of 3.7% and the non-HOC hydrology channels in the 406–420 MHz band had a mean usage of 5.1%. Because the non-HOC hydrology channels are few in number and the mean usage values are only slightly above the overall LMR band usage, they had little effect upon skewing the results upward.

While every effort was made to minimize the effects of noise, as described in Section 4.1, there were occasional periods when impulsive noise raised the power in the entire band enough for individual channels to exceed the detection threshold but not high enough to be identified as corrupted data and discarded from the analysis. It is difficult to determine precisely how often this occurred but it may have occurred enough to skew the mean usage values somewhat towards higher than expected usage values.

Much of the data presented in this report is represented in the form of "mean usage" which is meant to convey "typical" usage by a channel. However, because the percent usage statistics are not Gaussian distributed, and because, as shown in Figure 34, there are a few channels with relatively high usage (20 percent of the channels with greater than 2 percent usage) but far more channels with relatively low usage (80 percent with less than 2 percent usage) the mean is skewed, due to outliers, towards a larger value than what one might think of as "typical." This is because the overwhelming majority of usage values are around 1-3% but there are individual values much greater than this that tend to computationally bias the mean to a higher value. In this case, the median may be more representative of what is a "typical" channel usage and can be extracted from the cumulative distribution plots as described in Section 5.6.

Because most of the channels in these bands are statically assigned to networks or individual users, as opposed to dynamically assigned as is the case with trunked systems (see Definitions), many of these channels are reserved for high priority usage in which communication must be available at all times for a limited number of users. It should also be noted that agencies may have channel usage that deviates from these values – either to a greater or lesser extent. Likewise, none of these measurements were made during a major emergency that might have greatly increased the use of radio channels.

The channel occupancy measurements in this report provide a measure of the level of communications traffic in the 162–174 MHz and 406–420 MHz LMR bands. The results can be used for specifying the overall performance objectives of a hypothetical communications system using a different technology (e.g., trunking). By designing the hypothetical system to provide the same overall communications capability as the existing LMR systems, the existing and hypothetical systems could then be compared to examine relative total spectrum usage (number of channels required for each system).

The intent of the measurements was not to examine details of performance and use for the characterization of individual channels. This individual channel information, as well as more extensive measurements, may be required for a detailed engineering design for a next generation system.

6.1 Overall Results

Hourly Band Usage within the measurement system coverage area varies between 0.3–3.8% (Figures 26 and 38) for the two measured bands, but show the busiest hours to be between 7 AM and 5 PM, with the minimum usage near midnight. Results also show that the newly created 12.5-kHz channels are not yet used as much as the old 25-kHz channels. Note that these are average statistics, and usage for individual channels and agencies may deviate significantly (higher or lower) from the overall band usage.

6.1.1 Results for 162–174 MHz Band

For a mean detection threshold of -113 dBm, in the 162–174 MHz band (HOCs excluded), *Band Occupancy by Time-of-Day* within the measurement system coverage area is between 0.6–1.6% for all channels spaced 12.5 kHz apart, 0.9–2.2% for the old 25-kHz channels, and 0.2–1.2% for the new 12.5-kHz channels (see Figure 30). The highest value of the *Band Occupancy by Time-of-Day* represents the *Maximum Band Occupancy*, which is 1.6% for all channels spaced 12.5 kHz apart and includes both Specific Location and Area frequency assignments. When the *Maximum Band Occupancy* for channels spaced 12.5 kHz apart is calculated based on only the Specific Location assignments, the value is 2.1 percent.

The *Band Occupancy by Time-of-Day* for conventional LMR systems can be compared to allowable call-blockage (typically referred to as Grade of Service) as recommended in the Final Report of the PSWAC. In that report the committee recommends that blockage not exceed "one call for service per one hundred attempts during the average busy hour." That translates to no more than 1 percent usage for multi-user conventional systems where channels are assigned statically. Since the systems measured in the 162–174 MHz band are conventional systems, the measured usage during the busiest hour of 1.6 percent is relatively consistent with the recommendations by the PSWAC. [9]

For a mean detection threshold of -113 dBm, the overall *Percent Band Usage* for the 162–174 MHz band (HOCs excluded) during weekdays is 1.11% over a 24-hour period, 1.53% between 8 AM and 5 PM, and 3.14% for the *Average of Busiest Usage by Hour* (see Table A-2). For *Busiest Usage by Time-of-Day*, 60% of the channels exceed a usage of 1%, while 10% of the channels exceed 7%, and 1% of the channels exceed 34% (see Figure 34).

6.1.2 Results for 406–420 MHz Band

For a mean detection threshold of -117 dBm, in the 406–420 MHz band (HOCs excluded), *Band Occupancy by Time-of-Day* within the measurement system coverage area varies between 1.3–2.7% for all channels spaced 12.5 kHz apart, 2.2–4.1% for the old 25-kHz channels, and 0.4–1.5% for the new 12.5-kHz channels (see Figure 42).

For a mean threshold level of -117 dBm, overall *Percent Band Usage* for the 406–420 MHz band during weekdays is 2.08% over a 24-hour period, 2.67% between 8 AM and 5 PM, and 4.29% for the *Average of Busiest Usage by Hour* (see Table A-6). For *Busiest Usage by Time-of-Day*, 44% of the channels have a usage that exceeds 1%, while 10% of the channels exceed 13%, and 1% of the channels exceed 60% (see Figure 46).

6.2 Diurnal Patterns for Both Bands

Each of the two bands show about the same diurnal pattern of usage, irrespective of the whether they were measured for all days, weekdays, weekends, or Election Day (see Figures 29 and 41). However, there are slight variations between the bands. In the 162–174 MHz band, the highest usage occurs during the weekdays, exceeding the other time scenarios by about 1%. The other time scenarios show about the same usage except for about a 0.5% less usage in the midday for Election Day. In the 406–420 MHz band, the usage is about the same for all of the time scenarios, except for about a 1% less usage on the weekend mornings, and about a 1% greater usage on the afternoon of Election Day.

For both bands, the times and dates for *Busiest Hour of the Week for Each Channel* (see Definitions) are distributed fairly evenly over time-of-day and day-of-week, with the exception that busiest hours are broadly grouped more in the daytime hours (see Figures 27 and 39). There are a few occurrences where blocks of adjacent frequencies appear to have the busiest hour all at the same time. However, such occurrences are not typical. Whenever large numbers of adjacent frequencies appear to become busy at the same time, there is a possibility that the measurements were being affected by broadband RF energy, radiated intentionally or accidentally.

7 ACKNOWLEDGMENTS

This project required technical contributions by various individuals at the Institute for Telecommunication Sciences. The authors recognize Dr. William Kissick for his vision and leadership, Brent Bedford for his technical and theoretical support, as well as his leadership and skills at making the measurements, Iris Tobias for her support and help with the measurements, Yeh Lo for his work on the preselectors, as well as other system development, Rick Statz and Steve Engelking for software development, and Margaret Luebs for editorial review.

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8 REFERENCES

[1] W.A. Kissick, Ed., "The temporal and spectral characteristics of ultrawideband signals," Appendix A, NTIA Report 01-383, Jan. 2001, Available: <http://www.its.bldrdoc.gov/pub/ntia-rpt/01-383/>.

[2] G. Patrick, C. Hoffman, R.J. Matheson, F. Najmy, and R. Wilson, "Federal land mobile operations in the 162-174 MHz band in the Washington, D.C. area, Phase 1: Study of agency operations," NTIA Report 06-440, 2006.

[3] *Manual of regulations and procedures for Federal radio frequency management*, May 2003 Edition, September 2005 Revision (NTIA Manual), Sections 4.3 and 5.3. Available: <http://www.ntia.doc.gov/osmhome/redbook/redbook.html>.

[4] NTIA Manual, Sections 5.3.5.1 and 5.3.5.2.

[5] TIA/EIA-102.CAAA, *Digital C4FM/CQPSK Transceiver Measurement Methods.*

[6] TIA/EIA-603, *Land Mobile FM or PM Communications Equipment Measurement and Performance Standards.*

[7] A.V. Oppenheim, and R.W. Schafer, *Discrete-time Signal Processing*, 2nd ed., Upper Saddle River, NJ: Prentice-Hall Inc., 1998, pp. 465-478.

[8] F.H. Sanders, B.J. Ramsey, and V.S. Lawrence, "Broadband spectrum survey at San Diego, California," Appendix D, NTIA Report 97-334, Dec. 1996, Available: <http://www.its.bldrdoc.gov/pub/surv_sdg/>.

[9] Public Safety Wireless Advisory Committee (PSWAC) Report, Spectrum Requirements Subcommittee (SRSC) Final Report, Volume 2, Appendix D, Page 76, Sept. 1996.

APPENDIX A: SUPPLEMENTAL MEASUREMENT RESULTS

This appendix provides additional results. The first section shows, for the purpose of discussing anomalies, usage data for each one-hour block during the course of the measurements. The remaining two sections provide mean usage within the receiver's spatial coverage for the two frequency bands.

A.1 Usage for Each One-hour Block During the Course of the Measurements

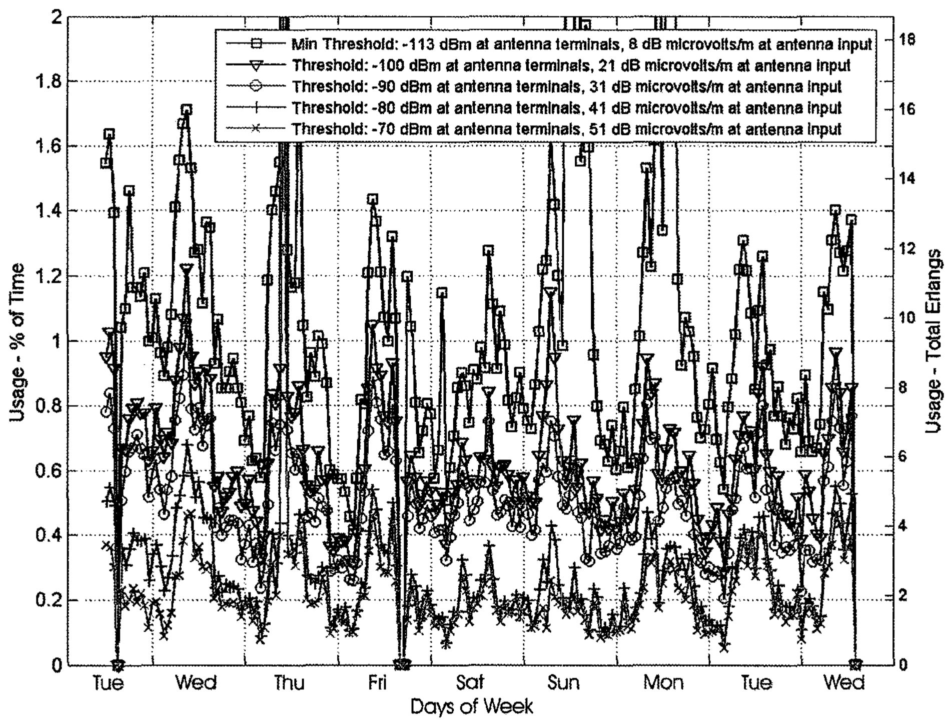

Figure A-1. *Hourly Band Usage* (percent of time and total Erlangs) during the course of the measurements for all 934 channels in the 162–174 MHz band (excluding HOCs).

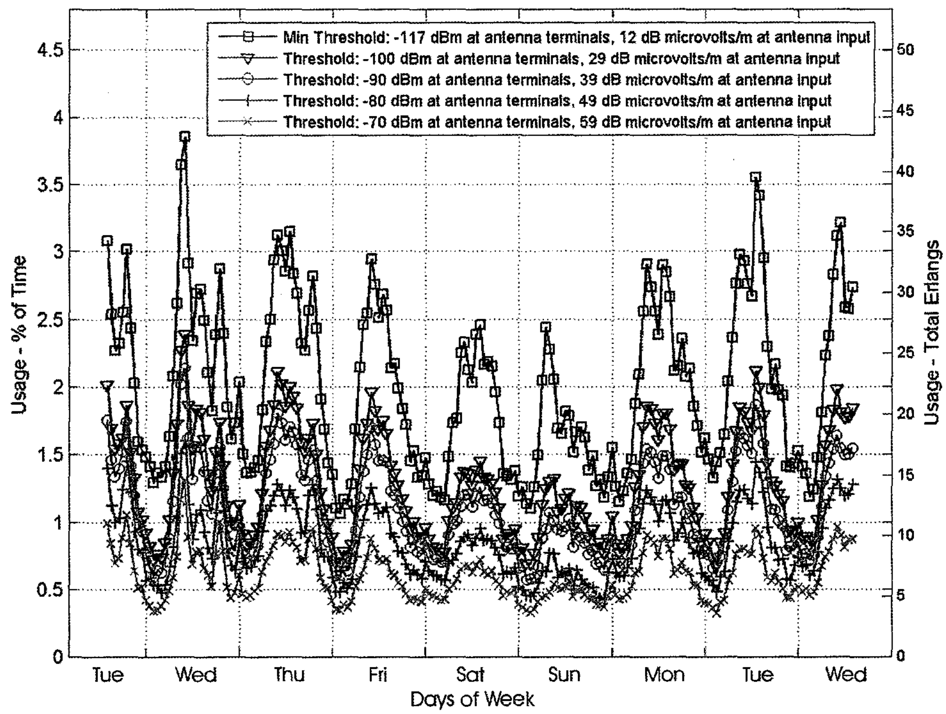

Figure A-2. *Hourly Band Usage* (percent of time and total Erlangs) during the course of the measurements for all 1113 channels in the 406–420 MHz band (excluding HOCs).

A.2 Percent Band Usage for the 162–174 MHz Band

Tables A-1 through A-4 contain the *Percent Band Usage* data for the 162–174 MHz band for the *entire week*, *weekdays* only, *weekends* only and *Election Day* only. As described in greater detail in Section 5.6, the data is presented in terms of a 24 hour period and a period of 8 AM to 5 PM for each table for that measurement time. Note that for the *entire week* and *weekdays only* tables, data is included for the *Average of Busiest Usage by Hour.* That information is not relevant to the *weekend* only and *Election Day* tables and is not included for those measurement times since the busiest times happen during the weekdays.

Table A-1. *Percent Band Usage* and *Average of Busiest Usage by Hour* During the Entire Week for All 934 Channels in the 162–174 MHz Band (Excluding HOCs)

All Days	**Mean Detection Threshold**				
Threshold (dBm)	-113	-100	-90	-80	-70
Threshold (dBμV/m)	8	21	31	41	51
Timescale	**Percent Band Usage**				
Percent Band Usage (24 hours)	1.08±0.01[17]	0.63	0.5	0.27	0.21
Average of Busiest Usage by Hour	2.72±0.08[17]	Not applicable			
Percent Band Usage (8am–5pm)	1.42±0.02[17]	0.76	0.6	0.37	0.3
Note: Erlangs can be calculated by multiplying the Percent Band Usage for any threshold by the number of channels. For example, Mean Erlangs for a threshold of -113 dBm is 10.09 ((1.08 / 100) * 934).					

[17] 99% confidence level - assuming an **average** message length of no greater than 5 seconds.

Table A-2. *Percent Band Usage* and *Average of Busiest Usage by Hour* During Weekdays Only for All 934 Channels in the 162–174 MHz Band (Excluding HOCs)

Weekdays Only	**Mean Detection Threshold**				
Threshold (dBm)	-113	-100	-90	-80	-70
Threshold (dBµV/m)	8	21	31	41	51
Timescale	**Percent Band Usage**				
Percent Band Usage (24 hours)	1.11±0.01[18]	0.63	0.52	0.29	0.22
Average of Busiest Usage by Hour	3.14±0.10[18]	Not applicable			
Percent Band Usage (8am–5pm)	1.53±0.02[18]	0.79	0.66	0.4	0.32

Note: Erlangs can be calculated by multiplying the Percent Band Usage for any threshold by the number of channels. For example, Mean Erlangs for a threshold of -113 dBm is 10.37 ((1.11 / 100) * 934).

[18] 99% confidence level - assuming an **average** message length of no greater than 5 seconds.

Table A-3. *Percent Band Usage* During *Weekend Days* for All 934 Channels in the 162–174 MHz Band (Excluding HOCs)

Weekend Days	**Mean Detection Threshold**				
Threshold (dBm)	-113	-100	-90	-80	-70
Threshold (dBµV/m)	8	21	31	41	51
Time Scale	**Percent Band Usage**				
Percent Band Usage (24 hrs)	1.16±0.02[19]	0.59	0.49	0.2	0.16
Percent Band Usage (8am–5pm)	1.62±0.04[19]	0.64	0.53	0.24	0.2

Note: Erlangs can be calculated by multiplying the Percent Band Usage for any threshold by the number of channels. For example, Mean Erlangs for a threshold of -113 dBm is 10.83 ((1.16 / 100) * 934).

Table A-4. *Percent Band Usage* During *Election Day* for All 934 Channels in the 162–174 MHz Band (Excluding HOCs)

Election Day	**Mean Detection Threshold**				
Threshold (dBm)	-113	-100	-90	-80	-70
Threshold (dBµV/m)	8	21	31	41	51
Percent Band Usage (24 hours)	0.90±0.02[19]	0.56	0.45	0.25	0.22
Percent Band Usage(8am–5pm)	1.10±0.04[19]	0.72	0.62	0.37	0.33

Note: Erlangs can be calculated by multiplying the Percent Band Usage for any threshold by the number of channels. For example, Mean Erlangs for a threshold of -113 dBm is 8.41 ((0.9 / 100) * 934).

[19] 99% confidence level - assuming an **average** message length of no greater than 5 seconds.

A.3 Percent Band Usage for the 406–420 MHz Band

Tables A-5 through A-8 contain the *Percent Band Usage* data for the 406–420 MHz band for the *entire week, weekdays* only, *weekends* only and *Election Day* only. As described in greater detail in Section 5.6, the data is presented in terms of a 24 hour period and a period of 8 AM to 5 PM for each table for that measurement time. Note that for the *entire week* and *weekdays* only tables, data is included for the *Average of Busiest Usage by Hour.* That information is not relevant to the *weekend* only and *Election Day* tables and is not included for those measurement times since the busiest times happen during the weekdays.

Table A-5. *Percent Band Usage* and *Average of Busiest Usage by Hour* During the Entire Week for All 1113 Channels in the 406–420 MHz Band (Excluding HOCs)

All Days	**Mean Detection Threshold**				
Threshold (dBm)	-117	-100	-90	-80	-70
Threshold (dBμV/m)	12	29	39	49	59
Timescale	**Percent Usage**				
Percent Band Usage (24 hours)	2.00±0.01[20]	1.3	1.1	0.84	0.6
Average of Busiest Usage by Hour	3.79±0.04[20]	Not applicable			
Percent Band Usage (8am–5pm)	2.55±0.01[20]	1.6	1.41	1.04	0.75
Note: Erlangs can be calculated by multiplying the Percent Band Usage for any threshold by the number of channels. For example, Mean Erlangs for a threshold of -113 dBm is 22.26 ((2.0 / 100) * 1113).					

[20] 99% confidence level - assuming an **average** message length of no greater than 5 seconds.

Table A-6. *Percent Band Usage* and *Average of Busiest Usage by Hour* During Weekdays for All 1113 Channels in the 406–420 MHz Band (Excluding HOCs)

Weekdays Only	**Mean Detection Threshold**				
Threshold (dBm)	-117	-100	-90	-80	-70
Threshold (dBμV/m)	12	29	39	49	59
Timescale	**Percent Usage**				
Percent Band Usage (24 hours)	2.08±0.01[21]	1.3	1.14	0.89	0.63
Average of Busiest Usage by Hour	4.29±0.05[21]	Not applicable			
Percent Band Usage (8am–5pm)	2.67±0.01[21]	1.7	1.49	1.1	0.79
Note: Erlangs can be calculated by multiplying the Percent Band Usage for any threshold by the number of channels. For example, Mean Erlangs for a threshold of -113 dBm is 23.15 ((2.08 / 100) * 1113).					

[21]99% confidence level - assuming an **average** message length of no greater than 5 seconds.

Table A-7. *Percent Band Usage* During *Weekend* Days for All 1113 Channels in the 406–420 MHz Band (Excluding HOCs)

Weekend Days	**Mean Detection Threshold**				
Threshold (dBm)	-117	-100	-90	-80	-70
Threshold (dBμV/m)	12	29	39	49	59
Time Scale	**Percent Band Usage**				
Percent Band Usage (24 hours)	1.76±0.01[22]	1.11	0.96	0.72	0.52
Percent Band Usage (8am–5pm)	2.19±0.02[22]	1.37	1.18	0.87	0.63
Note: Erlangs can be calculated by multiplying the Percent Band Usage for any threshold by the number of channels. For example, Mean Erlangs for a threshold of -113 dBm is 19.59 ((1.76 / 100) * 1113).					

Table A-8. *Percent Band Usage* During *Election* Day for All 1113 Channels in the 406–420 MHz Band (Excluding HOCs)

Election Day	**Mean Detection Threshold**				
Threshold (dBm)	-117	-100	-90	-80	-70
Threshold (dBμV/m)	12	29	39	49	59
Time Scale	**Percent Band Usage**				
Percent Band Usage (24 hours)	2.17±0.02[22]	1.3	1.15	0.88	0.59
Percent Band Usage (8am–5pm)	2.92±0.03[22]	1.79	1.59	1.21	0.79
Note: Erlangs can be calculated by multiplying the Percent Band Usage for any threshold by the number of channels. For example, Mean Erlangs for a threshold of -113 dBm is 24.15 ((2.17 / 100) * 1113).					

[22] 99% confidence level - assuming an **average** message length of no greater than 5 seconds.

APPENDIX B: CONFIDENCE INTERVALS FOR OCCUPANCY MEASUREMENTS

B.1 Introduction

This appendix describes a method for calculating confidence intervals for channel occupancy measurements. Typically, a channel occupancy measurement involves random samples of the signal strength. The channel is deemed occupied if a predetermined threshold is exceeded and hence each measurement is a realization of a binary random variable. The probability of exceeding the threshold gives the fraction of time the channel is occupied.

B.2 Statistical Character of Channel Occupancy Measurements

We wish to estimate the probability p that given a random observation, the signal strength exceeds our predetermined threshold. Let the binary random variable ξ_i represent the i^{th} observation, then

$$\xi_i = \begin{cases} 1 & \text{with prob, } p \\ 0 & \text{with prob, } q = 1 - p \; . \end{cases}$$

To estimate channel occupancy, we make n observations and obtain a realization of the random variable

$$\upsilon = \sum_{i=1}^{n} \xi_i \qquad (1)$$

and estimate of channel occupancy $\hat{p} = \upsilon / n$. Note that this estimate has the desirable property of being unbiased (i.e. $\mathcal{E}\{\hat{p}\} = p$).

To further understand the statistical nature of our estimate it is useful to determine its probability distribution. Some simplifying assumptions are needed to make this exercise tractable as described below.

B.2.1 Characterization of the Process

The sequence of observations is a realization of a discrete random process. We assume that in general the samples are not independent and are reasonably characterized as a regular first-order Markov chain as discussed in [1].

For our purposes, the regular Markov chain is characterized by a 2 x 2 transition matrix **P** and the relation

$$(q,p)\mathbf{P} = (q,p). \tag{2}$$

In terms of p, q and the transition probability $\eta = P\{\xi_i = 0 \mid \xi_{i-1} = 1\}$ we have

$$\mathbf{P} = \begin{pmatrix} 1 - \eta p/q & \eta p/q \\ \eta & 1 - \eta \end{pmatrix}.$$

When n is large, we can use the Central Limit Theorem for Markov Chains [2], which gives the limiting normal distribution for υ

$$P\{r < \frac{\upsilon - np}{\sqrt{n\beta}} < s\} \rightarrow \frac{1}{\sqrt{2\pi}} \int_r^s e^{-x^2/2}\,dx \tag{3}$$

where $n\beta$ is the *limiting variance* for the number of times that $\xi_i = 1$ and

$$\beta = pqL \tag{4}$$

where

$$L \approx \left(\frac{1 + \lambda}{1 - \lambda} \right)$$

and $\lambda = 1 - \eta = P\{\xi_i = 1 \mid \xi_{i-1} = 1\}$ and $p \ll 1$.

The limiting distribution of the channel occupancy estimate is

$$P\{r < \frac{\hat{p} - p}{\sqrt{\beta / n}} < s\} \rightarrow \frac{1}{\sqrt{2\pi}} \int_r^s e^{-x^2/2}\,dx. \tag{5}$$

B.2.2 Confidence Intervals

Since our measurement is an estimate, we would like to make some intelligent remarks about its accuracy. A commonly used methodology is to calculate the endpoints of an interval that with probability $1 - \epsilon$ contains the actual value of the population statistic. Thus, given a small quantity ϵ we need to calculate r and s so that

$$P\{p + r\sqrt{\beta/n} \le \hat{p} \le p + s\sqrt{\beta/n}\} = 1 - \epsilon, \tag{6}$$

where it is customary to set $s = -r = \gamma_\epsilon$. By writing $\hat{p} = p \pm \gamma_\epsilon\sqrt{pqL/n}$ and solving for p, it can be shown that the probability that $\hat{p}$ lies between the limits $p \pm \gamma_\epsilon\sqrt{pqL/n}$ is equivalent to the probability that p lies between the limits

$$\left(1 + \frac{\gamma_\epsilon^2 L}{n}\right)^{-1} \left(\hat{p} + \frac{\gamma_\epsilon^2 L}{2n} \pm \gamma_\epsilon \sqrt{\frac{\hat{p}\hat{q}L}{n} + \frac{\gamma_\epsilon^2 L^2}{4n^2}}\right) \tag{7}$$

as described in [3]. For large n, we can use the normal distribution given in Equation 5 to calculate γ_ϵ

$$\frac{1}{\sqrt{2\pi}} \int_{\gamma_\epsilon}^{\infty} e^{-x^2/2}\,\mathrm{d}x = \frac{\epsilon}{2}. \tag{8}$$

Note that the determination of L in Equation 7 requires that we know the transition probability λ. A method for estimating λ is given in [1]. This method assumes that the time duration T of a transmitted signal is random with an exponential distribution. Denoting the mean duration as t_0 and the time between samples as τ, the following expression is used to estimate the transition probability:

$$\lambda \approx P\{T \ge \tau\} = \frac{1}{t_0} \int_{\tau}^{\infty} e^{-t/t_0}\,\mathrm{d}t = e^{-\tau/t_0}. \tag{9}$$

B.2.3 Example

Assume we obtain $n = 4000$ samples and observe that $\hat{p} = 0.02$ using a sample rate that is twice the average time duration of the transmitted signal $(\tau = t_0/2)$. For the 90% confidence level we have $\epsilon = 0.1$ and using Equation 8, $\gamma_\epsilon = 1.64$. From Equation 9, $\lambda = 0.6$ and $L = 4$. Substituting into Equation 7 gives an upper limit of 0.0286 and a lower limit of 0.0139.

B.3 Average Occupancy for a Band of Channels

Previous sections have addressed calculating the occupancy of a single channel. We now turn our attention to calculating the average occupancy of a group or band of N channels, the calculation of which is described as follows

$$\bar{p} = \frac{1}{N}\sum_{i=1}^{N} \hat{p}_i \tag{10}$$

where $\hat{p}_i$ is the probability of occupancy of each channel as described above. When the number of measurements for the i^{th} channel n_i is large, $\hat{p}_i$ is approximately normal with variance $p_i q_i L_i / n_i$.

Assuming the individual channels are independent, $\bar{p}$ is approximately normal with variance

$$\sigma^2 = \frac{1}{N^2}\sum_{i=1}^{N} \frac{p_i q_i L_i}{n_i}. \tag{11}$$

Since we have sampled from several different populations, it is difficult to obtain exact confidence intervals. However, for large n_i the observed values of the i^{th} channel statistics

($\hat{p}_i$, $\hat{q}_i = 1 - \hat{p}_i$, and $\hat{L}_i$ from estimates of λ_i) can be used to approximate the variance

$$\sigma^2 \approx \frac{1}{N^2}\sum_{i=1}^{N} \frac{\hat{p}_i \hat{q}_i \hat{L}_i}{n_i}. \tag{12}$$

We can then say with $(1 - \epsilon)100\%$ confidence that the mean probability of occupancy over a band is between the following limits

$$\bar{p} \pm \gamma_{\epsilon}\sigma \tag{13}$$

where γ_{ϵ} is calculated as before and σ is calculated using Equation 12.

B.4 References

[1] A.D. Spaulding, and G.H. Hagn, "On the definition and estimation of spectrum occupancy," *IEEE Trans. on EMC*, vol. 19, no. 3, pp. 269-280, Aug. 1977.

[2] J.G. Kemeny, and J.L. Snell (1960), *Finite Markov Chains*, Princeton, New Jersey: D. Van Nostrand Company, Inc., 1960, p. 89.

[3] H. Cramer, *Mathematical Methods of Statistics*, Princeton, New Jersy: Princeton University Press, 1946, pp. 514-515.

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15. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This report describes field measurements to characterize Land Mobile Radio (LMR) channel occupancy of Federal bands 162–174 MHz and 406–420 MHz at a single central location in the Washington, D.C., area. This is part of the National Telecommunications and Information Administration effort to evaluate the spectrum efficiency in the Federal frequency bands. Measurements of the received signal levels in LMR frequency bands 162–174 MHz and 406–420 MHz were performed over an eight day period for the purpose of determining channel usage within the measurement system's coverage area of approximately 100-km radius for base stations, 50-km radius for mobile units, and 25-km radius for portable units. The measurements were made using new equipment and techniques that digitize as much as a 5-MHz segment of spectrum and process it to obtain simultaneous signal levels of up to 400 individual LMR channels. These techniques provided faster measurements, but also allowed enhanced post-processing of the data to remove effects of impulsive noise.

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