Chicago Spectrum Occupancy Measurements & Analysis and a Long-term Studies Proposal

Mark A. McHenry
Peter A. Tenhula
Dan McCloskey
Shared Spectrum Company, 1595 Spring Hill Road, Suite 110, Vienna, Virginia, USA
Tele: 703-761-2818x103, Fax: 703-761-2817
www.sharedspectrum.com
and
Dennis A. Roberson
Cynthia S. Hood
IIT Wireless Interference Lab, Illinois Institute of Technology
3300 South Federal Street, Chicago, IL 60616-3793
Tele: 312-567-3032, Fax: 312-567-3950
www.wemi.ece.iit.edu

Abstract
This paper describes spectrum occupancy measurements performed in Chicago, IL in November 2005 and proposes long-term studies in multiple locations. The Chicago project consisted of deploying a high dynamic range spectrum measurement system, a data collection and processing system and conducting spectrum occupancy measurements in all bands between 30 MHz and 3,000 MHz (see Figure 1). These measurements were taken over a two-day period and are added to an existing body of data compiled in other cities and regions including Washington, D.C., and New York City. While these studies are critical in determining what bands have low utilization, longer-term studies are crucial in developing new spectrum access technologies such as cognitive radio algorithms related to Dynamic Spectrum Sharing (DSS). The observed low spectrum occupancy in a business center like Chicago indicates that a DSS radio system could access a huge amount of “prime” spectrum. The unoccupied, large contiguous spectrum blocks show that DSS radios can use conventional contiguous waveforms and that high temporal agility may not be required to significantly expand the data capacity of an accessible section of spectrum. From both short-term and long-term spectrum occupancy studies, candidate bands for spectrum sharing can be readily identified along with unique signal characteristics within these bands. The most important use of the data will be to support senior U.S. (and non-U.S.) government officials in taking action to enhance the use of the currently under utilized RF spectrum resources and to make the R&D investments and policy changes needed to support the development of dynamic spectrum sharing radios.

Figure 1: Antenna Array with Chicago Loop
1. Introduction
As the popularity of new wireless applications and devices continues to grow, the demand for spectral capacity is becoming insatiable. Over the past few years such applications as data centric smart phones, Bluetooth headsets, keyboards and mice, broadband WiFi internet connections, satellite radios, and GPS navigation systems (to name only a few) have moved from obscure gadgets for the wealthy to standard devices and capabilities used by the masses. Demand for spectral capacity is fundamentally experiencing a "Quadruple Whammy" composed of the dramatic increase in the number of discrete applications, the rapid rise in the deployment of these applications, the growth in the amount of time each application is utilized, and the radical growth in the data rates used when these applications are operating. These trends are placing enormous demands on the finite spectral capacity. At the same time, it is observed in this, and related studies, that most of the spectrum, in most of the places, most of the time is completely unused. These observations scream for an enhancement to the current block auction system to fundamentally include the time domain in the allocation and command and control regulatory systems to facilitate new dynamic spectrum sharing (DSS) technologies to be developed and deployed to help ameliorate the current untenable situation.

1.1 Importance of Spectrum Measurements
Dramatic changes are taking place in both the sophistication of wireless technologies and in the policies regulating wireless networking and communications. The U.S. Government is already investing significant research and development dollars to develop spectrum sharing technology. Programs such as the NSF NeTS-Pro-WIN Program and the DARPA XG Program are prime examples. Unfortunately, these investments may be miss-applied if they don't address the current and future spectrum use situation. At the same time government policy initiatives are expanding unlicensed spectral bands facilitating dynamic spectrum access technologies such as cognitive radios and considering how to afford access to the "white spaces" in the television bands. These investments and initiatives require quantitative support and a deeper understanding of the characteristics of the current and projected spectrum usage by the research community and the related development and regulatory entities. Understanding the current utilization trends in the spectrum, especially in major commercial centers, is required for the knowledgeable furtherance of these efforts. It is critical to immediately initiate long term spectrum occupancy and related analysis studies to insure that the government's R&D investments target the real and evolving technical issues.

1.2 Previous Spectrum Occupancy Studies
There have been several previous broadband spectrum surveys [1][2], before the series of which this specific measurement is a part [3 – 8], but they lasted only a few hours and did not provide the needed temporal spectrum use information and could not be used to provide spectrum "white-space" estimates. The more recent studies along with this study are extremely useful in determining first that there is considerable spectrum that is unused and in identifying the specific bands that have low utilization.

1.3 Future Spectrum Occupancy Studies
Additional, long term (many months) spectrum occupancy studies would identify the current spectral bands that have low or no active utilization, the seasonal variations in this usage, and begin to identify the long term trends in the use of various spectral bands. From these future studies, candidate (and non-candidate) bands for spectrum re-farming, and sharing can be readily identified. These studies also provide information on the unique signal characteristics associated with these bands, which are needed to properly design spectrum sharing algorithms.

2.0 Chicago Spectrum Occupancy Study
This section describes spectrum occupancy measurements performed by Shared Spectrum Company (SSC) in conjunction with IIT’s Wireless Interference Lab in Chicago, IL in November 2005. This site was intentionally selected as an urban setting with a presumed high level of wireless activity. The research was funded by the NSF under its Computer and Information Sciences & Engineering organization and specifically its NeTS-ProWIN program.

2.1 Project Goals
The project goal was to perform a band by band measurement of the spectrum occupancy in the spectral region between 30 MHz from 3,000 MHz. In the ideal case this would provide information on:
- What bands have low (and high) utilization,
- How the spectrum is being used (what types of modulation schemes, data rates, equipment characteristics, where, when, mobile or fixed, …),
- The existing user’s aggregate equipment parameters (signal bandwidth, modulation, power levels, etc),
- The spectrum occupancy gap width and duration statistics,
- The number and location of transmitters in each band and
- The background noise level.

These parameters are critical to developing cognitive radio algorithms related to dynamic spectrum sharing. Some of the above parameters come directly from the spectrum data. Other parameters need to be interpreted
using models, hypothesis, and observations and investigations outside the scope of the initial measurement activity. Additional analysis and identification efforts will be required to obtain the full range of desired information.

2.2 Measurement Locations and Equipment
The measurement location for this study was the top of the 22 story IITRI Tower located at 35th St and South State Street roughly three miles south of the Chicago Loop, the business center of the city. Figure 1 shows the antenna array with the Chicago Loop in the background and Figure 2 shows the top of the Tower. Figure 3 shows a map of the Chicago area illustrating the location of the Tower relative to the Chicago Loop.

The equipment used for measurement in this study consisted of a spectrum analyzer, an SSC-designed high linearity pre-selector, an omni-directional discone antenna, a small log periodic array (LPA) for frequencies greater than 1000 MHz (see Figure 4), and a laptop computer. The antennas were connected to the pre-selector. A long RF cable, a control and power cable, and a pre-selector power cable connected the pre-selector box to a shielded Faraday cage enclosure (Figure 5). The shielded enclosure contained a 3 GHz spectrum analyzer, a laptop computer, and power supplies. Power was provided to the equipment using an extension cord plugged into a 120 volt AC outlet.

2.3 Pre-selector Description and Data Collection and Calibration.
A Pre-selector was used to improve the measurement sensitivity and dynamic range. The Pre-Selector configuration is illustrated in the block diagram shown in Figure 6. It is composed of filters, RF switches, pre-amplifiers and programmable RF attenuators. The upper path is used for signals from 30 MHz to 1000 MHz, and the lower path is used for 1000 MHz to 3000 MHz. The Pre-selector was located at the base of the antennas and sealed in a plastic bag for weather protection.

Prior to measurement, the pre-selector attenuation values, filters and spectrum analyzer RF attenuation values were manually adjusted in each band. The settings that obtained the lowest distortion and noise for each band were used in the input file that controlled the equipment. During the measurements, separate files were created for each spectrum analyzer trace.

The plotted spectrum data are calibrated to the power level at the antenna input using the following procedure:
- The recorded power levels measured by the spectrum analyzer are provided in dBm relative to the analyzer input.
- The difference between the power level at the analyzer input and the power level at the antenna due to the losses of the RF cables, filters, and the gain associated with the Pre-selector versus frequency is recorded in a calibration file.
- The calibration values (in dB) where then added to the measured values (via an interpolation process) when plotting the spectrum data in this report. Thus, the plotted power level values are the absolute value in dBm at the antenna input.

2.4 Spectrum Occupancy Plots and Observations
Each of the spectrum occupancy plots in this section has three spectrum occupancy sub-plots. The upper sub-plot is the maximum power value versus frequency measured during the period. The power values are corrected for cable losses, filters, amplifier gain and attenuators (as described above), and represent the received power level at the antenna terminals. The time in the plot title is the measurement start time.

The middle sub-plot is a waterfall-type plot with occupancy plotted versus time and frequency. Occupancy is determined when the power level exceeds a threshold. One overall threshold value was intentionally selected for each run, and is shown as a dotted line on the upper plot. In some cases, the noise level exceeded the threshold, causing inflated occupancy levels. This was not corrected because it would have been necessary to manually select the threshold for each plot. The time shown on the right side vertical axis of each figure is the measurement time.

The last sub-plot is the fraction of time the signal is above the threshold versus frequency. A fraction of time value of “1” means that the signal was measured above the threshold for the entire duration of the measurement period. The title of this third plot contains the average duty cycle for the entire period.

With this structure in mind we now selectively look at samples of the collected data starting with Figure 7 which shows the spectrum occupancy from 54 to 88 MHz (the band housing broadcast television channels 2 through 6) measured in Chicago during a 24-hour period from 4:17 pm, 16 November 2005 to roughly 4:15 pm the following day. This is the most heavily utilized spectrum observed in the study with an average duty cycle of 70.9%.

Figure 8 shows the spectrum occupancy for the main cell phone band in Chicago, 806 to 904 MHz. This band has a high average duty cycle of 55%. However, in the mobile side of the spectrum, there appears to be still considerable unused bandwidth. This might be an affect of the data collection approach itself since the
transmit power of the subscriber units is considerably less than the base stations, and therefore some of the handset signals were likely not detectable, especially those used in the glass and steel canyons of Chicago.

Figure 9 shows an example of a set of FCC allocated and auctioned spectral bands which appear to be completely unused. This is a great example of a band where DSS radios might be effectively deployed for an extended period without impact in the Chicago area.

Figure 10 shows the spectrum occupancy for the spectral region containing the two satellite radio operators (XM and Sirius) from 2300 MHz to 2360 MHz. Here we note a much lower average duty cycle of less than 20%. We clearly see the space available for at least one additional satellite radio carrier which would increase the usage of the spectrum to some degree. The bulk of this spectrum, while auctioned for “Wireless Communications Services” (WCS), appears to be completely unused at this point.

Figure 11 shows the well-known unlicensed Industrial, Scientific and Medical (ISM) band used for such applications as WiFi, Bluetooth, microwave ovens, baby monitors, portable phones, etc. This band shows a reasonably heavy utilization at 31%. It is interesting to note that in a similar study in New York this usage rate was only about 15%. Beyond the utilization level it is interesting to note the relative uniformity of the usage with only a narrow window between roughly midnight and 6:00 am when the usage slightly declines.

2.5 Spectrum Occupancy Summary
As noted in Table 1, the spectrum occupancy for the two day measurement period was 17.4%. That means that 82.6% of this completely allocated spectrum was unused for this period. This information is displayed in bar graph form in Figure 9 graphically showing the actual utilization of the spectrum over the various bands in Chicago. As noted in the table and figure, the spectrum usage ranges from 70.9% in the 54 to 88 MHz frequency band, highlighted above, to virtually no usage in the large swath of bands located between 1240 and 1850 MHz, or 610 MHz of effectively empty spectrum.

Figure 13 provides a graphic comparison of the by band occupancy in Chicago with the results of an earlier study performed in New York City in August / September 2004 [6]. The aggregate results of this comparison shows that Chicago’s spectrum utilization exceeds New York’s by roughly one third (17.4% vs. 13.1%). While it could be suggested that this is attributable to the fact that the people in Chicago work roughly one third longer and harder than the people in New York, there may be other explanations. For example, since the measurements in Chicago were taken 14 months later than the New York study, and since they were taken in different seasons (fall vs. late summer), these factors may be significant contributors.

3 Conclusions
We have now collected and summarized a considerable body of data. The following attempts to focus these findings to draw a set of useful observations from the Chicago spectrum measurement project and propose future work that this and related efforts suggest.

3.1 Measurements Show That There is Significant Spectrum “Whitespace”
The goal of this study was to determine the spectrum occupancy in each band at multiple locations. The bar graphs in Figure 13 provide the measured occupancy for each band for Chicago and for comparison New York City, arguably two of the most intensive users of wireless technology in the United States. As noted earlier, the over-all usage for the cities were 13.1% for New York and 17.4% for Chicago. These low occupancy levels show that there is significant spectrum for a DSS radio to provide service. As shown in other studies [3][7], in rural areas, there is a great deal more spectrum available, enough in fact to allow a DSS based radio to provide ten to one hundred times the capacity of all existing wireless devices in those regions.

The policy implication of the low occupancy period depends on the measurement duration period. One issue is the "assuredness" of significant unused spectrum available for a dynamic spectrum sharing system use. Low occupancy during a 24 hour period constitutes a case that a DSS radio system would have a high probability of spectrum access when using one or two spectrum bands. Measurements over several months are required to obtain DSS link access probabilities (i.e. how many spectrum bands does a DSS radio need to operate over to obtain at least one channel 99.99% of the time?).

Another policy issue is that if a spectrum band has continuous low usage over weeks or months, then the resource is not being put to good use. The FCC should reassign the frequencies or reallocate the band. Alternatively, they could allow extensive DSS operations with reduce DSS performance requirements because the probability of causing harmful interference is insignificant. In this case, several months of measurements at multiple locations would determine wide spread low utilization.
3.2 A Low Agility, Contiguous DSS Radio Can Provide High Utility

The detail spectrum occupancy plots show that there is a significant amount of spectrum available in continuous blocks that are 1 MHz and wider. An example is the TV Auxiliary band, where there is large, contiguous spectrum segments not used for hours at a time. This shows that a frequency agile, non-contiguous waveform is not necessary for a DSS Radio. The key DSS technical challenge is to reliably detect signals with high sensitivity to decide what channels can be used without causing interference to the existing users. Similarly, the ability to rapidly vacate a channel when an incumbent user chooses to transmit is critically important.

3.3 An Extensive Spectrum Occupancy Dataset is Available for Future Analysis

We have collected an extensive spectrum occupancy data set that is available for others to investigate. The areas for further investigation include analysis of the spectrum gaps statistics, the transmitter mobility and number (using the amplitude probability distribution), the signal bandwidths, and other existing user parameters. It is critical for DSS radios to be able to know what transceiver types actually use spectrum and how they are operated. An additional area to investigate is to compare the NTIA/FCC allocation tables and assignment databases with the measurements to determine what spectrum is used by GPS and other hard to detect signals to understand why band-by-band the measurement occupancy is so low.

3.4 Future Plans

This study and the related studies referenced earlier [3-8] provide a wealth of information about the spectrum occupancy in Chicago, New York, Washington D.C. and a few rural locations. The conclusively point out the fact that there is an abundance of unused spectral capacity in all locations at this time. This is an enormously helpful finding. At the same time, these studies have ultimately generated many new questions (some of which we have highlighted earlier).

To better assess the comparisons of not only these two cities, but Washington, D.C. and Seattle as well, a proposal has been submitted to the NSF to perform a two-year study to continuously monitor the spectrum occupancy in these cities. This study would involve the authors organizations (Shared Spectrum and IIT), along with Stevens Institute of Technology and the University of Washington. This study should enable us to truly compare contemporaneous results. It is also hoped that this study will provide an initial view on any seasonality in the visible spectrum usage, potentially an early hint on the over-all trends in spectrum utilization and possibly any increase in the over-all noise floor as well.

We now need to take advantage of this momentum and the learnings to date to mount a more aggressive study to be able to first generate comparable and contemporary findings across a broader set of cities, suburban, and rural. We need to compare the results from these studies with one another and with the expected results from local spectrum allocation information. We also need longer studies to begin to be able to identify seasonal trends and potentially longer term trends in band by band spectrum utilization. We may also be able to detect changes in the over-all interference noise floor as the growth in wireless devices utilization (the Quadruple Whammy), and use of electronic equipment in general continues to accelerate.

To support these needs, measurements should provide a band-by-band analysis of the:

- Spectrum occupancy in bands with low occupancy (because they represent a policy failure and are the best opportunity for dynamic spectrum access use) and in bands with variable occupancy (to characterize the white space spatial and temporal properties).
- Detected signal parameters (transmission gap statistics, transmitter mobility, number of transmitters, the signal bandwidths, and other parameters)
- FCC/NTIA rules to determine reasons why signals were not detected (i.e. not present, very low duty cycle, or too weak to detect)

To be useful, this information needs to be consistently and contemporaneously collected over a wide range of locations and over an extended period of time (measured in years) to assess the variations in spectrum usage in environments that have different user profiles, varied geographic characteristics and a variety of population densities (urban, suburban, and rural).

The challenge of distributed spectrum measurements is cost (equipment and deployment). A large number of measurement locations (5-10) are required to provide significantly more insight compared to a single location measurement. High-performance, general purpose spectrum equipment is expensive. Specific purpose equipment would have lower recurring costs, but developing this type of equipment is expensive and is not cost effective unless the number of measurement sites is much larger than planned for our study. Other distributed measurement requirements (remote control and precise scan time alignment) are straightforward to achieve using Internet-based connectivity and GPS 1 PPS timing.

There needs to be a systematic measurement framework to collect distributed spectrum occupancy data. The
sensitivity/occupancy results are dependent on the detector type used, the antenna height and other factors. These factors need to be made identical or normalized out to cross compare results between different locations. Also, the spectrum scan rate needs to be "tuned" to the experimental issue.

The results from the different measurements must be consistently analyzed and plotted because of the complex nature of the spectrum use problem and because of the often contentious points of view related to spectrum issues.

4 Acknowledgments
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5 References
Figure 2: Top of the IITRI Tower

Figure 3: Map showing the location of the measurement site.

Figure 4: Rooftop Antenna Array and Pre-Selector
Figure 5: The RF shielded enclosure in which all the data collection equipment is placed.

Figure 6: Pre-Selector block diagram
Figure 7: 54 MHz to 88 MHz Television Band

Figure 8: 806 MHz to 902 MHz Cell Phone Band
Figure 9: 1700 MHz to 1850 MHz Fixed / Mobile Band

Figure 10: 2300 MHz to 2360 MHz Satellite Radio Band
Table 1: Summary of Spectrum Occupancy by Band

<table>
<thead>
<tr>
<th>Start Freq (MHz)</th>
<th>Stop Freq (MHz)</th>
<th>Bandwidth (MHz)</th>
<th>Spectrum Band Allocation</th>
<th>Chicago Day 1 Spectrum Fraction Used</th>
<th>Chicago Day 2 Spectrum Fraction Used</th>
<th>Chicago Avg Spectrum Fraction Used</th>
<th>Chicago Occupied Spectrum (MHz)</th>
<th>Average Percent Occupied</th>
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<td>24</td>
<td>PLM, Amateur, others</td>
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<td>102</td>
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<td>0.70831</td>
<td>0.70002</td>
<td>21.11</td>
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<td>0.70831</td>
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<td>70.9%</td>
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<td>134</td>
<td>174</td>
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<td>0.04540</td>
<td>4.9%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Total</td>
<td>2850</td>
<td></td>
<td></td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>494.00</td>
<td>17.4%</td>
</tr>
</tbody>
</table>

Total Available Spectrum: 2850.00 MHz
Average Spectrum Use (%): 17.4%
Figure 12: Average Spectrum Occupancy by band in Chicago

Figure 13: Average spectrum occupancy by band – Chicago vs. New York