Long-term Spectral Occupancy Findings in Chicago

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***Abstract*—This paper summarizes some of the results of measurements and related analysis efforts at the Illinois Institute of Technology (IIT) Spectrum Observatory in Chicago over the past three years. The results are unique in the sense that the spectral occupancy estimates are based on multiple years of observations, whereas previous studies produced occupancy numbers based on short term snapshot measurements, often of a few hours duration or at most spanning a few days or weeks. The measurements are also presented in a novel way: the occupancy data in a band of interest during a one year span is graphed as a 2-dimensional image that visually reveals daily, weekly, and yearly trends and anomalies. The main objective of this paper is to present year by year first-order statistics about the spectral occupancy across multiple bands, but more details are presented about radio usage in a few bands like the TV band. In particular, we examine the spectral opportunities that are seen in the newly available "TV White Space". The results illustrate occupancy trends and notable spectral events, such as the 2009 broadcast television transition and the related vacating of the 700 MHz band, which have created significant spectrum opportunities in the 30 - 1000 MHz region. The trends reported are applicable to long term spectrum modeling, spectrum planning, and regulatory decision-making efforts applicable to dynamic spectrum access networks.**

***Index Terms*—spectrum occupancy; spectrum usage trends; spectrum management; dynamic spectrum access; TV white space**

I. Introduction

The development and deployment of wireless technologies have experienced rapid growth in the last 2 decades. A majority of the world's population are now connected on-the-go and at all times, due to the proliferation of highly capable, yet affordable wireless portable devices. National and global economies have become highly dependent on wireless technologies like broadcast radio and TV, public safety radio, cell phone systems, GPS, Wi-Fi and Bluetooth. All these technologies rely on a finite natural resource– the radio spectrum. Decades ago, when mobile wireless usage was less common, most of the spectrum was divided into application-specific bands such as the radio bands (AM and FM) and the various television bands, explicitly allocating the bands to specific users or groups of users [KOB01]. This waveform allocation was established either through the promulgation of rules by the national regulatory agencies to serve a particular policy objective, or by providing a license to a specific entity. This framework for static allocations was intended to prevent the various radio licensees from harmfully interfering with each other. Since then, the intensity of radio usage has grown by orders of magnitude in certain frequencies, like the cellular bands, to the extent that high utilization is common; in other bands, observations indicate a much lower usage level [BAC08].

Wireless occupancy studies that map how radio spectrum is utilized in different bands are useful for planning purposes and developing new regulations to support and sustain the growth and value of radio related technologies and applications. Spectrum also has a high economic value [KEL08]. The results of spectral occupancy studies are useful for making decisions on the reallocation of spectrum and/or valuation estimation. Several short duration studies [ROB06, MCH05, ISL08] have audited spectrum occupancy in the past, but long term studies are needed to track trends to develop a comprehensive picture of radio usage over time, and to enable the development of empirical time and frequency domain models of spectrum use [WEL09]. Illinois Institute of Technology's (IIT) Spectrum Observatory has been (to the authors' knowledge) the center of the longest running study of wide band terrestrial RF spectrum utilization ever performed. Fortunately, the observatory has been conducting its measurements during a particularly exciting period of time for the wireless industry: for example, major regulatory changes recently freed up significant spectrum in the TV bands; new wireless services such as WiMAX and LTE have been introduced in other bands; and we have witnessed a period of dramatic growth and expansion in the use of cellular and Wi-Fi technologies.

In order to free up 100+ MHZ spectrum in the 700 MHz region (formerly a part of the broadcast TV band in the U.S.) and in the TV bands in general, the FCC had mandated a switchover of terrestrial broadcast television from analog NTSC transmission to digital ATSC. The switchover took place at 11.59 pm on June 12, 2009. Many TV stations in Chicago had already switched to digital prior to that date but were also broadcasting on separate analog channels; on June 12th these analog stations were switched off (a special exemption was made for low-power analog stations to continue transmission, however). Based on the need for coordinated spectrum transitions, other stations waited until the June 12th deadline to convert from analog to digital broadcasting. Since the ATSC standard allows multiple digital TV (DTV) signals to share the same 6 MHz television bandwidth, the switchover to ATSC freed up significant spectrum in the TV bands. More importantly, this opened up the 698-806 MHz region for other uses as TV broadcast was suspended in this frequency range and relocated to lower frequency channels freed up by the transition. The Spectrum Observatory captured the moment of this important historical transition, and the results are presented in this paper. Licenses to blocks of the freed up 700-800 MHz spectrum were auctioned to wireless providers by the FCC for the impressive sum of over $19 billion dollars [FCC08].

In concert with the DTV transition, in 2008 the FCC voted unanimously to open up the TV "white spaces" for unlicensed radio usage. TV white space refers to the spectrum in a certain geographical location that is not being used for either TV broadcast or licensed wireless microphone transmissions [WYG09]. The (new) unlicensed "white space" transmitters should not interfere with any of the active TV broadcast channels, and the devices must consult geographic databases to determine which TV channels can be safely used without interference in a particular region. Although the initial FCC rules required that white space devices perform local spectrum sensing in addition to database look up, in September 2010 the FCC removed this requirement [GRE10]. Since spectrum sensing adds significant hardware and software complexity to a radio device, the new FCC regulation should stimulate a more affordable and faster path of adoption for unlicensed TV white space use.

It is envisioned that more standards like the IEEE 802.22 [STE09] wireless regional area network (WRAN) in the TV white space or proprietary devices will begin to use the spectrum, in view of the large unoccupied bandwidths that are now available in many areas. In this paper, we present initial results that indicate how much spectral opportunity is available in the TV white spaces of Chicago.

The paper is organized as follows: the Spectrum Observatory measurement system is described in Section II; Section III describes how the measurement data was processed and analyzed; Section IV summarizes the spectral occupancy findings in Chicago over several years; Section V examines the occupancy data in more detail and explores daily and weekly trends in certain bands; Section VI estimates spectrum opportunities in Chicago's TV white space. Conclusions and lessons-learned from operating a long-term observatory follow in Section VII.

II. Spectrum Observatory Overview

The IIT Spectrum Observatory has been monitoring the 30 - 6000 MHz radio activity of the city of Chicago since July 2007 from its location at the top of the 22 story IIT Tower on IIT's main campus on the south side of Chicago. This building is located 5.3 km south of the Willis (formerly Sears) Tower and has the advantage of an unobstructed view of downtown Chicago from its roof, where the antennas of the Spectrum Observatory are situated. The major components of the base Spectrum Observatory data acquisition system are shown in the diagram in Figure 1 and include: a Rohde & Schwarz FSP-38 spectrum analyzer, a pre-selector/RF frontend with independently selectable bands, three directional antennas (two log-periodic and a microwave horn), a desktop computer and various auxiliary sensors (e.g. a weather station and a GPS receiver).

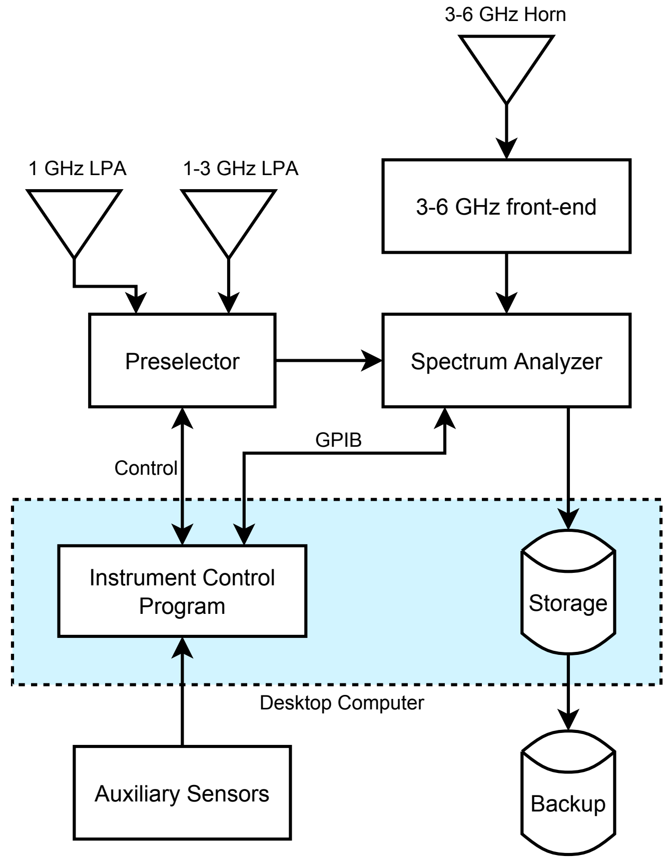

Figure 1. Overview of Spectrum Observatory system

Spectrum occupancy measurement efforts for broad spectral ranges always involve a fundamental trade-off between spectral resolution, time resolution and spectrum coverage. Therefore, the ~6 GHz frequency range of the IIT system is divided into smaller bands of varying spectral widths and frequency resolutions. Some of these band assignments are determined by the preselector ranges, while other band ranges were chosen to match data collection and analysis needs. High frequency resolution requires long sweep times resulting in low time resolution. Depending on the current research focus and related needs, the band assignments of the measurement system have been modified over the 3+ year period, for example, to obtain a high frequency resolution scan of the land mobile radio (LMR) frequencies [BAC10]. A more detailed description of the system can be found in [BAC08] and details on the trade-off between frequency resolution and sweep time duration are discussed in more detail in [BAC10].

The results in this paper are presented only for measurements in the 30 - 3000 MHz range. This range was chosen based on the higher level occupancy and therefore higher interest in signals in this range and because pragmatically, the data in the 3 - 6 GHz range is more difficult to interpret. This is the case because the higher path loss [GOL05] and reduced sensitivity of the observatory at those frequencies often result in misleadingly low occupancy values that are difficult to compare to the lower frequency range results presented here. Measurements in the higher range will, however, be presented in a subsequent publication.

The time resolution of the measurements discussed is approximately 40 - 70 s, which is not granular enough for detailed time-domain characterization of dynamic signals; however, it is ideal for average occupancy estimates. Previous work details specialized measurements taken from several LMR bands with much improved time resolution [BAC10].

III. Data Analysis Methodology

For each sweep of a spectrum region by the analyzer, the spectral occupancy (unoccupied/occupied, or 0/100%) at each measured frequency point was estimated by comparing the measured power density to a threshold. From this, the average occupancy in a given frequency range of a sweep was calculated. Repeating this calculation for every sweep in the three years of data resulted in a time-series representation of the occupancy over this period by frequency band. The time-series is smoothed to undercover underlying trends (e.g. Figure 7).

A major challenge in the undertaking of long-term, wide-band measurements, is handling the large dynamic range that such systems encounter. High sensitivity is obviously an essential requirement, but equally important is the ability to accommodate high-powered signals that may be present in certain bands, particularly those used by broadcast FM radio and television. The use of a preselector with digitally programmable attenuators prevents signals in these trouble-some bands from overloading the frontend of the measurement system, but this also has an effect on the noise floor of the system: the result is that sensitivity varies from band to band.

This issue of varying sensitivity is problematic in occupancy estimation as the noise floor is not flat across bands. The thresholds used to determine occupancy are intended to be set at a fixed offset above the noise floor of the measurement system, but variations in the system's response over frequency and over time necessitated different thresholds for each measurement band and each year. Typically the value chosen was set between 5 and 10 dB above the noise floor, allowing for compensation due to equipment changes (such as an upgraded preselector and the use of a backup spectrum analyzer), and parameter changes (different attenuator values). Care was exercised in choosing the occupancy threshold to avoid system induced inaccuracies in the occupancy calculations.

The spectral occupancy estimates in the 30 - 3000 MHz frequency range were grouped into 21 bands for analysis purposes. These are different from the bands that were used in the measurement system itself, and were roughly based on their FCC designations, such as cellular, FM, LMR, ISM, and so forth. The start- and stop-frequency ranges of these bands are indicated in the bar charts of Section 3 (Figures 2-4).

The occupancy data is presented in several different ways: bar-graphs showing the minimum, average and maximum occupancy by band for each year; smoothed time-series plot that shows occupancy as a function of time in a TV band; and newly devised pseudo-color plots showing occupancy vs. week. A spectrogram is also presented, which shows power levels as a function of both time and frequency.

IV. 2008 - 2010 Occupancy Summary

The bar charts in Figures 2 - 4 show the minimum, average and maximum occupancies in 21 different spectrum bands for the years 2008 - 2010. The results for 2010 (Figure 4) include measurements up to and including the month of October. For each band, these statistical values were obtained from an occupancy time series that was smoothed with a 24 hour moving average filter (Figure 7 plots this time series data for the TV band).

The minimum occupancy (in percent) can be read from the boundaries of the green and yellow bars, the average occupancy is marked by the junction between yellow and red bars, and the maximum occupancy is indicated by the end of the red bar. In these charts, wide yellow bars indicate that the maximum and minimum occupancy values are widely separated; and a wide red bar means that the maximum occupancy observed is significantly higher than the average occupancy: thus a wide range variation in occupancy was in evidence, perhaps due to high-bandwidth signals vacating or coming into existence in that band during the course of the year.

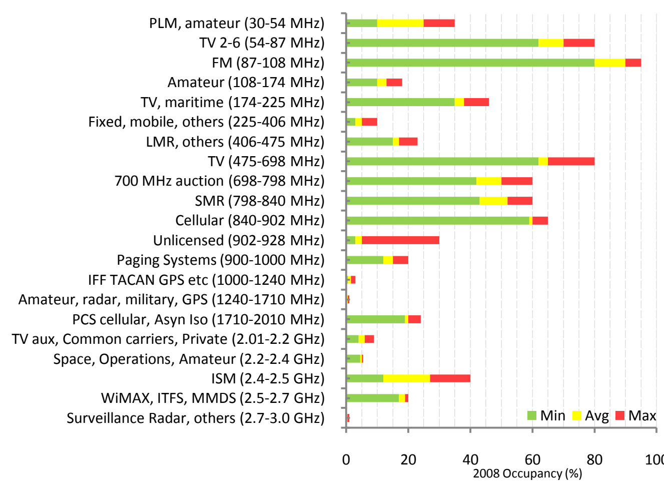

Figure 2. Estimated occupancy by band for 2008. Average overall occupancy is 18% for 30-3000 MHz.

The three charts all show a similar distribution of occupancy levels, namely high occupancy at the lower frequencies (< 1 GHz) used for cellular transmissions and high power, long range applications like broadcast radio and television; and reduced occupancy at the higher frequencies (> 1 GHz) used mostly for satellite and point-to-point communications. The 2.5 - 2.7 GHz band shows an increase in 2008, likely due to the roll-out of CLEAR (TM) (WiMAX) service in the Chicago area. The 2.4 GHz ISM band shows a large range of occupancies: 10 - 40 % in 2008 and 2009 and 15 - 44 % in 2010, while the well-established 800 MHz cellular bands have a fairly constant occupancy within all years.

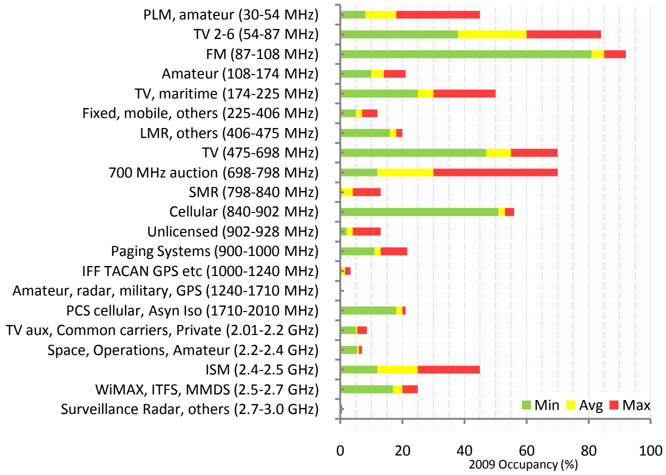

Figure 3. Estimated occupancy by band for 2009. Average overall occupancy is 15% for 30-3000 MHz.

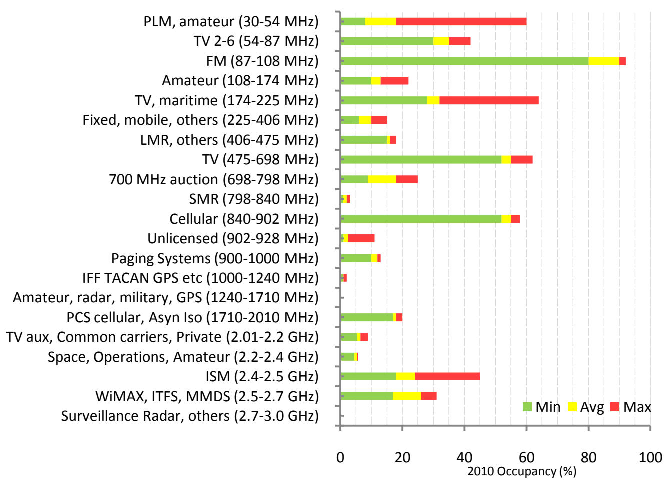

Figure 4. Estimated occupancy by band for 2010 (up to October). Average overall occupancy is 14% for 30-3000 MHz.

The bands between 1000 - 1710 MHz, used by GPS, RADAR, etc., and the 2 - 2.4 GHz bands used for satellite TV and point-to-point communications, show particularly low occupancy. Since our measurement system uses directive antennas on the IIT campus pointed in the direction of downtown Chicago, the measurements most likely do not accurately reflect the true minimum, maximum or average values in these bands. Signals in these bands would require different antenna configurations and perhaps more sensitive equipment to be accurately observed.

As noted earlier, one interesting and noteworthy occurrence in 2009, is the dramatic change that occurred in the TV bands due to the transition from analog to digital transmission, along with the vacating of the 698-806 MHz band. The exact moment of this transition (June 12, 2009 at 11.59pm) was captured by the observatory (a spectrogram of this event can be seen in section V). From Figure 2, the TV (475-698 MHz) band occupancy for 2008 is fairly constant, but the occupancy range is higher in the 2009 year (Figure 3). This happens because a significant amount of TV spectrum was vacated in the middle of 2009 - thus occupancy was high in early 2009, and occupancy was low after mid 2009. This is discussed further in the following two sections.

Computing the average occupancy of the data given in these charts over the 3 GHz span, gives values of 18%, 15% and 14% for the years 2008-2010, respectively. These are of the same order as reported in previous studies [BAC08, MCH05], though not directly comparable due to different thresholds and different measurement equipment, etc. Nonetheless, the opening of spectrum due to the changes in the TV bands, is clearly demonstrated.

V. Occupancy Trends

Daily occupancy trends in different bands, namely those used for cellular and LMR, have been noted in the past [BAC10], but over longer periods of observation, weekly and even yearly trends become evident. Figure 5 illustrates this with data in the 450 - 465 MHz Land Mobile Radio (LMR) band starting from November 9th, 2008 to September 20, 2009. The new method of presenting occupancy data in Figure 5 plots a week's worth of measurements as a horizontal strip, where the occupancy level is indicated by color. A one hour time resolution is used for the plot. Subsequent weeks of measurements are stacked vertically. In this way, long observation intervals can be plotted to allow easy visual analysis of trends. (The white regions in the plot are due to missing data resulting from system downtime due to maintenance.)

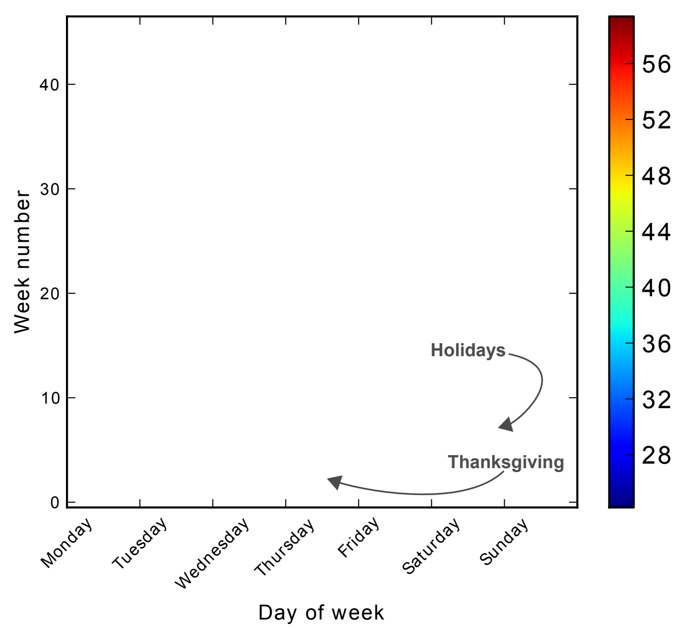

Figure 5. Week by week occupancy in the 450-465 MHz LMR band from November 9, 2008 to September 20, 2009

Daily peaks and troughs in the occupancy levels can be seen, as well as reduced occupancy during weekends. These trends generally continue throughout the year, however significant holidays (Thanksgiving, Christmas and New Years) clearly show reduced levels. Anomalies also occur where there is unusual usage, such as weeks 9 and 30 in the plot.

As another example of the long-term trends that can be observed by this new plotting method, Figure 6 shows the 2009 occupancy in the 1710-2010 MHz frequency range where most of the occupancy comes from radio signals in the PCS cellular band. Daily trends are clearly visible, where the occupancy varies by approximately +/- 4% per day with the lowest usage at night; however significant day of the week variations do not seem to occur. The effect of Daylight savings is noticeable in Figure 6: at week 9 (March) the vertical edges representing the early morning occupancy ramp-ups shift to the left; consequently they shift back to the right around week 44 (November).

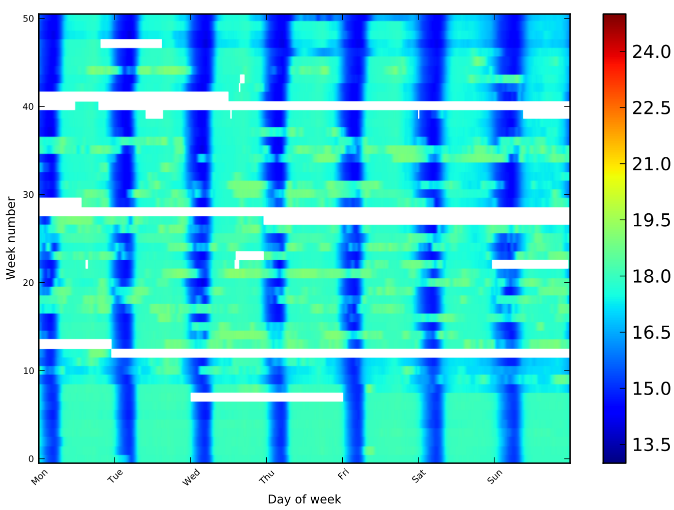

Figure 6. Week by week occupancy in the 1710-2010 MHz range from January 1st to December 31st, 2009

Figure 7 shows a time-series plot of the occupancy in the 475 - 698 MHz UHF television band for 2009. The occupancy levels for January to mid April are fairly constant, at around 55%. From the end of this period until early June, there are fluctuations in the occupancy while television stations conducted tests of their digital transmitters and some began switching completely from analog. On June 12th there is a 10% drop in occupancy as the transition deadline passes (Point A in Figure 7), when all high-power analog transmissions cease. The moment of this transition can be seen at the end of day 2 (June 12th, 2009) in the spectrogram of Figure 8. The distant channels that seem to fade in and out (Figure 8) are also responsible for some of the fluctuations in Figure 7. The sudden jump at the end of October (Point B in Figure 7) is caused by the introduction of another digital channel. The transitional period of 2009 ultimately leads to a slight (~5%) decrease in the overall occupancy of the UHF channels. However, a much greater reduction in occupancy happens in the 698-800 MHz range where all TV channel broadcasts ceased on June 2009 (with the exception of Qualcomm's MediaFLOTM channel [FIT09], as noted in Figure 8).

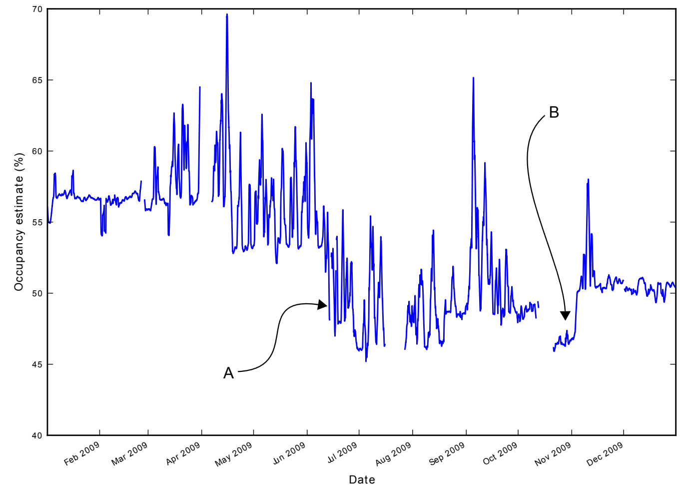

Figure 7. Occupancy vs. time plot in the 475-698 MHz TV band in 2009

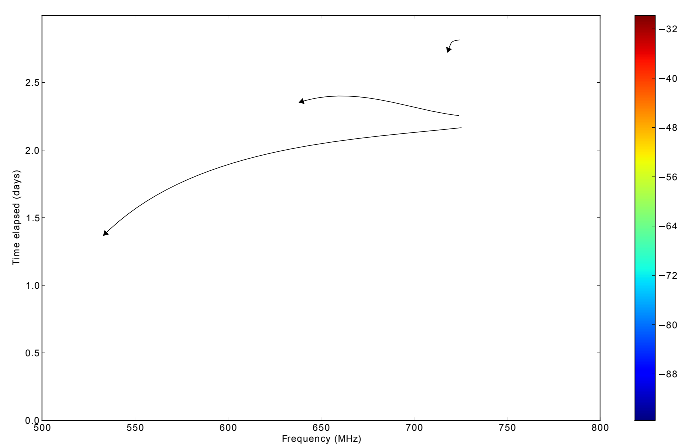

Figure 8. Spectrogram showing the 2009 DTV transition, (Timeline: 00.01 am June 11th to 11.59 pm June 13th, 2009)

VI. Spectral Oppurtunites in TV White Space

The "spectral opportunity" (SO) described in a frequency range [MAR10] can be defined as the complement of the spectrum occupancy OCC (i.e. $SO = 1 - OCC$) when the power measurements are performed with a sensor of bandwidth BW and a detection threshold, T. To calculate the spectral opportunity with the measurements taken by the observatory, the powers levels are combined into bins of the given size bandwidth, BW. The fraction of the bins with power levels below the desired threshold T is then the opportunity. The spectral opportunity calculated in this way is a more practical expression of the prospect of improving spectrum utilization in a band compared to the occupancy measure used in Sections III-V, as it incorporates the bandwidth of the potential application as a parameter, and also gives an indication of its required signal-to-noise ratio (indirectly given by the threshold).

Figures 9 and 10 show the spectral opportunity plots as observed by the spectrum observatory in the frequency range 475-698 MHz for five different signaling bandwidths (0.6, 1, 3, 6 and 12 MHz) as a function of threshold T. Figure 9 shows the spectral opportunity a month before the analog to digital TV transition (April 9th, 2009) and Figure 10 shows it a month after (July 9th, 2009).

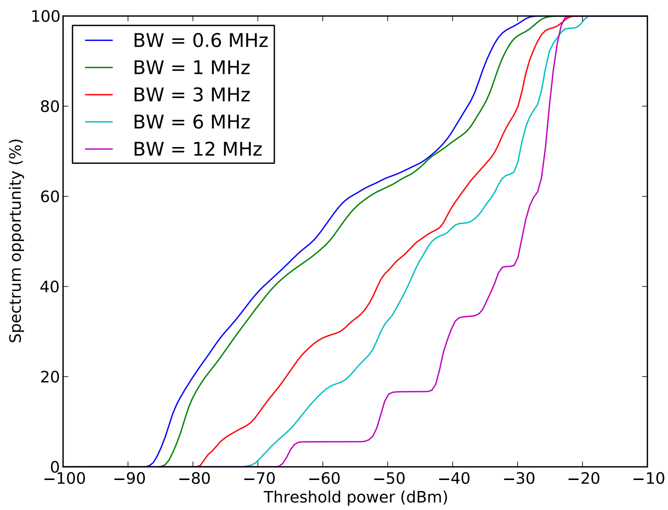

Figure 9. 476 - 698 MHz spectrum opportunity vs. threshold power for several bandwidths (April 9th, 2009, before DTV transition)

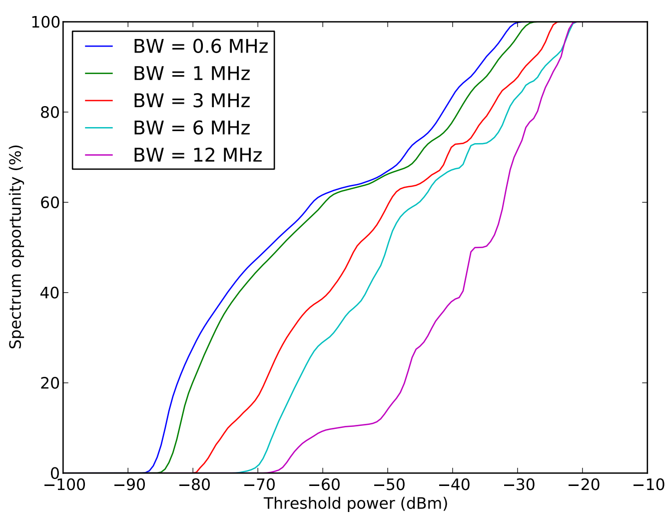

Figure 10. 476 - 698MHz spectrum opportunity vs. threshold power for several bandwidths (July 9th, 2009, after DTV transition)

The shapes of the curves in each figure are similar for low bandwidths cases (0.6 and 1 MHz), as the only difference is due to the linear increase in power caused by the increase in bandwidth. The 6 and 12 MHz cases are different from these, however, indicating reduced SO for signals intending to use such wide bandwidths. The plots show a shift to the left from Figure 9 to Figure 10, indicating increased spectral opportunities in the TV band (476 - 698 MHz) after the

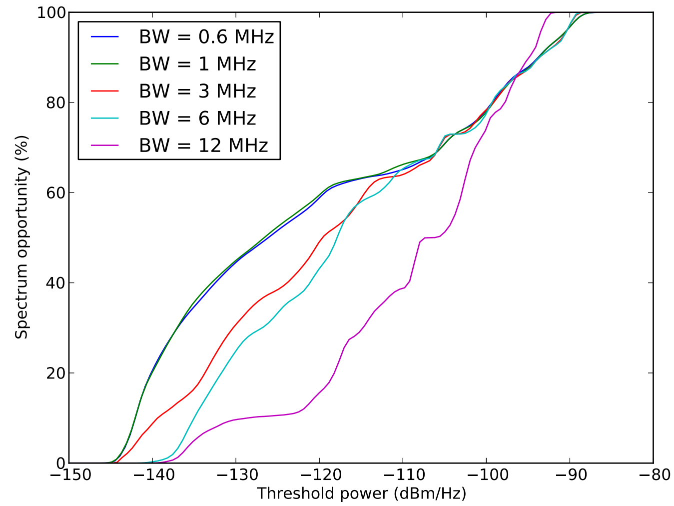

Figure 11. 476 - 698 MHz spectrum opportunity vs. threshold power density (July 9th, 2009, after DTV transition)

transition.

The discrete steps in Figure 9 for the BW = 12 MHz correspond to the power levels of different television channels. The width of the first plateau is proportional to the SNR of the lowest power channels and so on.

The spectrum opportunity plots illustrate how sensitive occupancy calculations can be to the threshold used. The point where the opportunity curve touches the x-axis indicates the lowest power level measured in a given bandwidth, which is typically entirely due to noise. The increase in the opportunity as the threshold is slightly raised beyond this point also corresponds to the presence of noise, until a break-point is reached indicating a signal substantially above the noise floor. This break-point is most noticeable when the measurement bandwidth is large (see Figure 9 and the BW = 12 MHz case). Calculating the occupancy with the threshold corresponding to the break-point will result in an estimate with the highest detection rate, however the false alarm rate may be excessively high as there is likely to be additional noise fluctuations above this point.

In Figure 11, the spectral opportunity data was normalized by dividing the total integrated power in each bin by the bin's bandwidth so that the SO threshold now represents a fixed power density level. The SO is still expected to be a function of the bandwidth; that is, the five curves of Figure 10 will not entirely overlap if the x-axis is normalized to dBm/Hz. Figure 11 shows the normalized SO plot for bandwidths of 0.6, 1, 3, 6 and 12 MHz. As would be expected, high sensor bandwidths will tend to underestimate the opportunity (or, equivalently, overestimate the occupancy) for applications with low power thresholds (the difference becomes negligible when the threshold is high). For example, a 6 MHz bandwidth sensor compared to a 1 MHz one will underestimate the opportunity by almost 30% for a threshold level of -130 dBm/Hz; however, there is very little difference between two sensors with narrow bandwidths (e.g. 600 kHz versus a sensor with 1 MHz bandwidth). In TV white space sensing, this may be useful in selecting a sensor bandwidth for devices which must locate low-power spectrum opportunities as quickly as possible.

VII. CONCLUSIONS

This paper presented and discussed first-order statistical results of occupancy obtained by processing three years worth of spectral measurement data collected at the Illinois Institute of Technology's Spectrum Observatory. In depth analysis of subsets of the measurement data is to be found in [BAC08], [BAC10], and several more upcoming papers. The overall occupancy in the 30 - 3000 MHz region remains low, but there are some bands where high spectrum utilization is evident. Significant changes occurred during 2009, due to the TV band transition as described. Interesting daily, weekly and seasonal trends can also be observed in several bands like the land mobile radio (LMR) and cell bands, and a novel method of displaying long-term trends has been introduced through the pseudo-color plots of Figures 5 and 6. The reduced occupancy in the LMR band during the yearly holidays like Thanksgiving demonstrate the utility of long-term measurements in recording long-term cyclical variations in radio usage.

For future research, the spectral opportunity data should be useful in cognitive radio simulations and ultimately in the development of cognitive radio systems and the regulatory regime that enables these systems. Data showing the weekly and daily trends will be used to generate radio traffic models in several bands of interest like the ISM, public safety and cellular bands. Now that the FCC has approved the unlicensed use of TV white spaces, the empirical data provided about TV band spectral opportunities in Chicago should also be helpful in expediting TV white space utility. As we continue the long-term observations at the IIT Spectrum Observatory, we can observe the changes in occupancy caused by the introduction of these new white space devices.

As with any long term measurement project, valuable lessons were learned regarding the design, operation and maintenance of the Spectrum Observatory. Due to component and cable/connector changes caused by maintenance and aging, the sensitivity of the system has changed with time. A key learning is that regular calibration and recording of the system response is important, so that in the long-term, meaningful comparisons are possible for the power levels measured. The current Spectrum Observatory system is being modified to incorporate an automatic self-calibration capability.

Important lessons were also learned with regards to storing, managing and analyzing the terabytes of data collected. During the course of the last three and a half years, we have executed 3 major revisions to the file structure used to store the measured data. The current format utilizes the HDF5 [HDF5] standard for data storage where the data files are compact and easy to store, copy, and retrieve. Similarly the dissemination of this large volume of data to fellow researchers has been an ongoing challenge.

Over-all, the Spectrum Observatory has provided enormous value to the wireless research community, in documenting spectral usage trends and capturing valuable data covering such a long-period of time in an important urban environment. It is the authors' hope that this value will be multiplied over time as more analysis is pursued using this data and as additional data is captured and refined at this site.

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