Global Spectrum Observatory Network Setup and Initial Findings

Tanim Taher, Ryan Attard, Ali Riaz,
Dennis Roberson, Jesse Taylor, Kenneth Zdunek
Illinois Institute of Technology, Chicago, USA

Juhani Hallio, Reijo Ekman, Jarkko Paavola
Turku University of Applied Sciences, Turku, Finland

Jaakko Suutala, Juha Roning
University of Oulu, Oulu, Finland

Marja Matinmikko, Marko Höyhtyä
VTT, Finland

Allen MacKenzie
Virginia Tech, Blacksburg, USA

***ABSTRACT* – This paper describes the current efforts underway to set up matched long-term continuously running spectrum observatories in the US (in Chicago and Blacksburg) and in Turku, Finland. The measurement equipment setup is described, along with the architecture for the networked database used to aggregate, archive and share the spectrum measurement data collected across the multiple international locations. High performance computer infrastructure to permit analysis and as appropriate fusion specific elements of the terabytes of data is described. The measurement parameters and spectrum measurement band plans are listed. Preliminary analysis results are also provided - particularly, simple occupancy statistics in Chicago and in Turku. To demonstrate the utility of the global spectrum observatory network, an interesting example is provided that compares and contrasts the very different signals that occupy the same spectral band, but in different geographic regions.**

***Keywords*—Spectrum Occupancy measurements; spectrum usage trends; spectrum management; big data; dynamic spectrum sharing**

I. INTRODUCTION

Due to the rapidly expanding adoption of broadband wireless services by consumers, businesses, government, and public safety agencies, an emerging and fundamental RF spectrum shortage is developing on a global basis. In order to apply emerging technologies such as dynamic spectrum sharing to address this problem, there is a critical need to understand the trends in actual RF spectrum usage in various geographic environments and in areas with different population densities. This paper provides an overview of a coordinated multi-national effort currently underway, where a three-pronged approach is being pursued to develop this RF understanding. This includes the: 1) deployment of geographically dispersed, temporally coordinated RF spectrum observatories in multiple locations in the US and Finland. The spectrum observatories are based on a common platform and the goal is to generate a single RF spectrum measurement dataset (database); 2) development of empirically validated, statistical models of spectrum utilization for different wireless application types based on this dataset; 3) use of "big data" analytical techniques to further mine the RF dataset to discover temporal and spectral correlations and relationships not obvious using traditional approaches.

The partners in this multi-national project are based at the Illinois Institute of Technology (IIT), Chicago, USA; Virginia Tech (VT), Blacksburg, USA; Turku University of Applied Sciences (TUAS), Turku, Finland; University of Oulu, Oulu, Finland; and VTT Technical Research Centre, Finland. The funding for the two-year long project is provided by the National Science Foundation in the US and the Finnish Funding Agency for Technological Innovation (TEKES). Specialized spectrum observatories are currently deployed (or being deployed) at three locations (Chicago, Blacksburg and Turku), with the potential to add two more (a second Chicago location and at Helsinki or Turku). A centralized database and analytical processing system is being implemented at the Wireless Networks and Communications (WiNCom) research center at IIT, which is taking the lead role for this project. Data collected at each measurement site is stored locally, as well as being aggregated over the Internet at WiNCom's data center. All the partners in this project have remote access to the central data location for subsequent retrieval and analysis work.

A sufficient management challenge was faced initially in this project due to the large number of participants who are spread across 2 continents and 3 time-zones. Over the course of the past year, this has been mostly overcome. To properly manage the project, teleconferencing meetings are held bi-weekly. Once or twice a year, the Principal Investigators (PIs) meet physically at a conference or at one of the partner institutes. Also, a two-way exchange of graduate students is in the works for 2014 to further share expertise and experience, so as to make best possible use of the knowledge and resources available. Technology sharing (schematics, programs, codes, datasheets, sensor designs, etc.) between the partner groups has greatly accelerated our progress during the year 2013.

This paper describes the spectrum observation equipment used in Section II. The measurement locations are described in Section III. The big data infrastructure for storing and analyzing the spectral measurements is discussed in Section IV, along with the big-data vision for this project. Preliminary occupancy measurements are presented in Section V. Section VI compares the occupancy numbers at Chicago and Turku, and provides an example of a frequency band that is used very

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differently in the two locations, followed by conclusions in Section VII.

II. Spectrum Observatory Overview

Each Spectrum Observatory consists of a CRFS RFeye receiving system, data storage, and data transfer equipment. The antenna is broadband [MP13], omni-directional and multi-polarized and covers the 85 – 6000 MHz frequency range (see Figure 1). The RFeye receiver (shown in Figure 2) is a dedicated FFT-based spectrum monitoring receiver analyzer manufactured by CRFS, UK [RF13] that has the following technical specifications: frequency range 10-6000MHz, fast digital sweep with instantaneous 20 MHz bandwidth, resolution bandwidth (RBW) selectable between .073-1200 kHz, four RF inputs, rugged compact outdoor environment construction, GPS support, and Power over Ethernet (PoE).

Figure 1. Multi-polarized broadband 85 – 6000 MHz antenna

Figure 2. CRFS RFeye receiving spectrum analyzer.

The schematic diagram in Figure 3 shows the specific RF components and cable used in the planned experimental set-ups for the initial 3 locations. The *static* deployment has largely been completed at Turku and is in the process of being installed at Chicago and at Blacksburg. The second directional antenna is optional, and has so far been used at a few measurement locations in Chicago. The measurement parameters consisting of the frequency bands, resolution bandwidths and sweep times are given in Table 1. These parameters have been used at the Turku location during the initial measurement phase. For the Chicago location, a different band plan has been used as part of a related NSF research project; however, the Chicago band-plan overlaps with the Turku measurements in the 100-6000 MHz full band sweep with a 312.5 kHz RBW and a 10 second scan interval. Spectrum data is constantly measured as time looped sweeps based on the band-plan provided. The goal is to collect spectrum data continuously from all locations and store it in the central database at WiNCom. For redundancy, local measurement data is also stored on-site at each observatory.

Band plan parameters are currently under evaluation and may be adjusted if resolutions in time and/or frequency are considered to be either too high or too low. Eventually, when the multi-site deployments have all been completed, identical measurement parameters and band-plans will be used at all the locations, similar to the parameters given in Table 1.

Table 1. Measurement Parameters

Freq. range (MHz)	**Resolution Bandwidth**	**Scan interval**	**Regulatory notes**
85 – 110	39.0625 kHz	3 sec.	FM
380 – 400	39.0625 kHz	3 sec.	TETRA
450 – 470	39.0625 kHz	3 sec.	WRC-07
470 – 694	39.0625 kHz	3 sec.	Broadcasting/mobile
694 – 790	39.0625 kHz	3 sec.	WRC-12/WRC-15
790 – 862	39.0625 kHz	3 sec.	WRC-07
862 – 960	39.0625 kHz	3 sec.	WRC-2000
1710 – 1855	39.0625 kHz	3 sec.	WRC-2000
1855 – 2025	78.125 kHz	3 sec.	WARC-92
2110 – 2200	78.125 kHz	3 sec.	WARC-92
2290 – 2400	78.125 kHz	3 sec.	WRC-07
2400 – 2484	78.125 kHz	3 sec.	RLAN
2500 – 2690	156.25 kHz	3 sec.	WRC-2000
3400 – 3600	156.25 kHz	3 sec.	WRC-07
5150 – 5250	156.25 kHz	3 sec.	RLAN
5250 – 5350	156.25 kHz	3 sec.	RLAN
5470 – 5725	156.25 kHz	3 sec.	RLAN
100 – 6000	312.5 kHz	10 sec.	Full band sweep

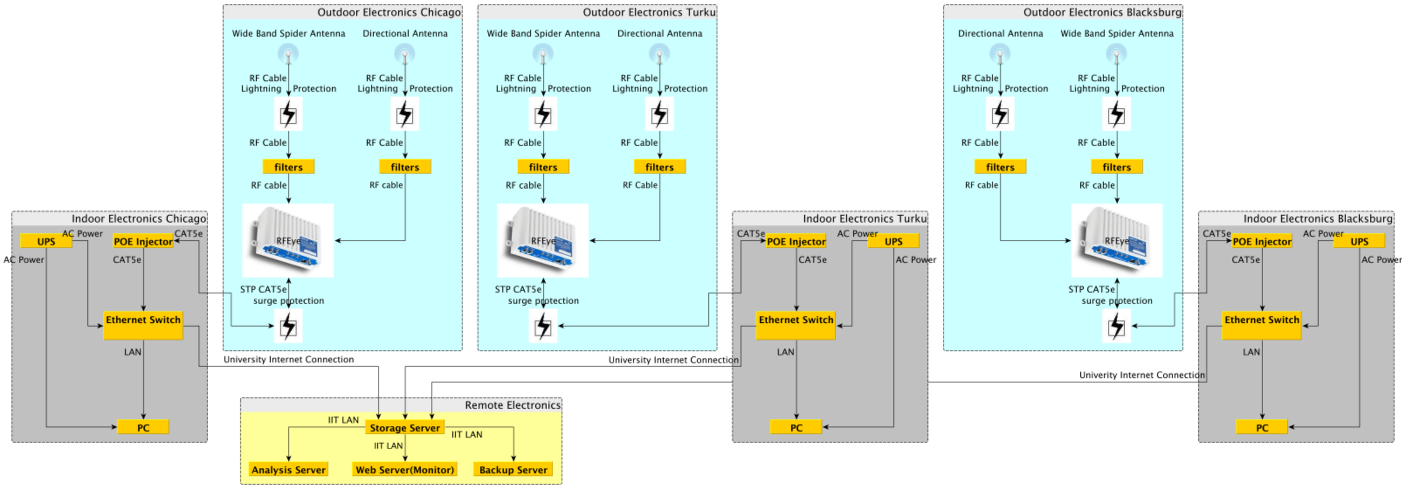

Figure 3. Schematic of multi-site Spectrum Observatory Network

III. MEASUREMENT LOCATIONS

In Finland, the spectrum observatory is located near central Turku, installed on the roof of a four story building at TUAS Sepänkatu-campus. The antenna is mounted on a four meter mast. The power supply and intermediate data storage drives are co-located in the building. The spectrum observatory is designed to operate continuously and independently in case of power outages or network connectivity losses. The observatory system in Turku was procured and deployed during the first half of 2013 and became operational in July 2013. A photograph of the deployment at Turku is given in Figure 4. Another site in Helsinki or Turku, Finland, may be deployed at a later time.

Figure 4. Deployment of RFeye spectrum observatory at Turku, Finland

In Chicago, the selected location of the primary RFeye-based spectrum observatory is on the top of a 22 storey building on the IIT campus that is roughly 5 kilometers south of downtown. The roof of the building provides an unobstructed view of downtown Chicago, and it is also the location of IIT's long-term spectrum-analyzer based observatory that has been operational since 2007 [BAC08] and several other observatory systems of more recent vintage. A second RFeye spectrum observatory has been set up at a height of 168 meters on the roof of the 54 story Harbor Point building located at the eastern edge of downtown Chicago near Lake Michigan. The location for the observatory at Blacksburg, though not finalized, is likely to be at the suburban Virginia Tech campus.

At the time of writing, the RFeye device for the static IIT spectrum observatory has been temporarily reassigned for mobile measurements as part of a related WiNCom project. The RFeye and several antennas have been mounted on the boom of a truck on loan from Motorola Solutions. This lab on wheels, complete with a generator, has an extendable 40 foot boom as shown in Figure 5, and permits mobile short-term measurements at multiple locations. The RFeye sits inside a box attached to the mast of the omni-directional 85-6000 MHz broadband antenna (Figure 1), with a PoE connection from the RFeye extending down to the lab inside the truck. Additional directional antennas are also attached to the mast, and lightning protection has been provisioned. The RFeye is being used to measure several RF bands different from Table 1. As mentioned before, however, it also measures the 100-6000 MHz band every 10 seconds with a 312.5 kHz RBW with input coming from the omni-directional antenna. Therefore this data can be reasonably directly compared with the Turku data.

For the purposes of this paper, the results from analyzing the truck-based spectral measurements in and around Chicago are presented for the wideband 100-6000 MHz scans. This data is supplemented by the data from the Harbor Point RFeye which does use the same band plan as that utilized in Turku affording very direct comparisons of the spectral data. Multiple locations have been scanned using the Motorola Laboratory truck which are listed below:

1. IIT Mies campus (5 km south of downtown)
2. Northerly Island, a manmade island just east of downtown
3. IIT Rice Campus at Wheaton (suburb ~30 km west of Chicago downtown)
4. University of Illinois at Chicago (UIC) campus just west of downtown Chicago
5. Midway airport (airport in Chicago's south-west side)
6. Lincoln Park Zoo (4 km north of downtown)
7. Chicago State University (CSU) campus 16 km south of downtown Chicago

Figure 5. Mobile platform for spectrum observatory

IV. BIG DATA VISION

A. Infrastructure

Operationally, the RFeye spectrum analyzer sweeps the desired bands and saves the gathered data in binary format on the observatory site via a Network Assisted Storage (NAS) drive. The data is then transferred to local storage servers using university intranet. The planned centralized server infrastructure is presented in Figures 3 and 6. The design calls for the data from each site to be automatically uploaded over the Internet to the database at IIT, for organized indexed storage and archival. The researchers from the five partner institutions will have remote access to all the data from IIT over a very fast Internet connection. Specifically, the server has a 10 Gbit/sec link from the server to IIT's connection to the Internet. This is in turn directly connected to one of the major global Internet hubs here in Chicago. This configuration should provide for a very high performance link between the partner sites and over time to the rest of the research community.

IIT is responsible for the role of centralized data storage across the collaborating institutes, due to WiNCom's expertise related to long-term spectrum data collection, as well as IIT's access to vast archival storage (96 TB) in the form of Cleversafe Inc's dsNet object storage platform [CLV13]. Cleversafe's dsNet provides low storage overhead compared to RAID and other redundant storage methods, and also adds the value of an active rebuilder process that guarantees reliability and consistency of data in the long term. Active rebuilding uses Cleversafe's information dispersal algorithms [CLV13] to prevent issues such as bit rot, by recreating data slices when data corruption or loss occurs.

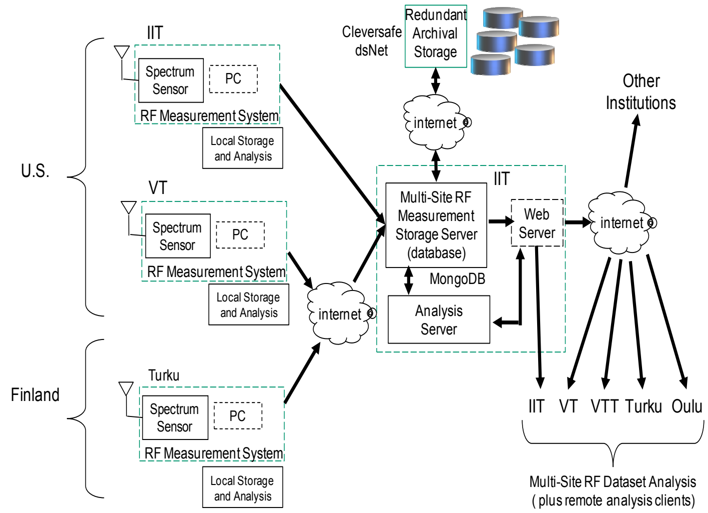

Figure 6. Data paths and aggregation plans for the global network

The databases and multi-site synchronization are currently being implemented to suit research requirements. Since the database is not fully operational yet, a temporary arrangement is currently being deployed, using the SCP file transfer protocol to upload all the RFeye measurements in file format to an alternative storage server at IIT. The researchers at each partner location have access to the file storage server and are able to download the RFeye binary files for post-processing and analysis purposes.

Figure 7. Server Rack with high performance computing equipment (IIT)

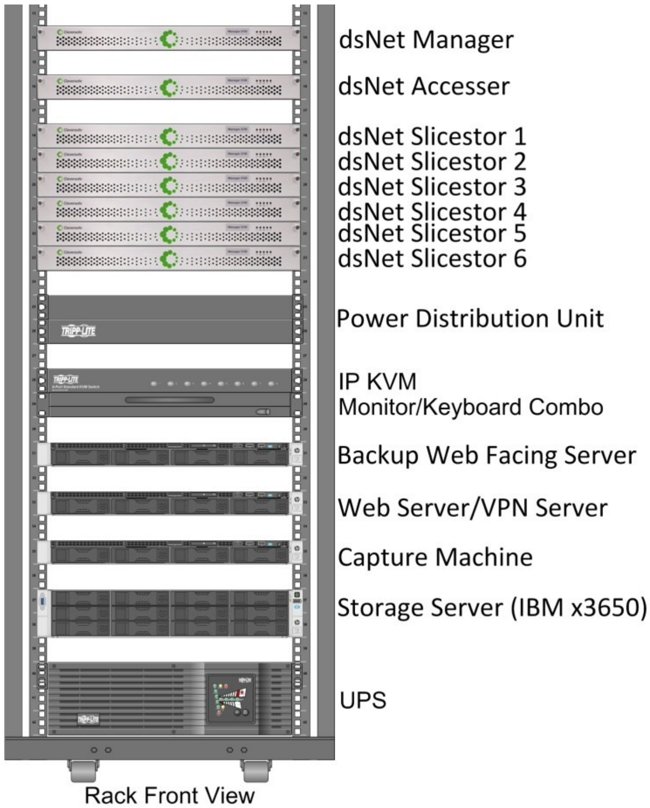

Figure 8. Server Rack schematic (IIT)

In order to leverage the large storage capacity of dsNet and maintain high-speed access, WiNCom has installed a new server cluster on the twenty-first floor of IIT Tower (Figures 7 and 8), whose primary function is to host a database of indexed dsNet storage objects that contain spectrum observatory measurements. To further improve access times and analysis speeds, three other servers have been provisioned. One is purposed to host RF measurement / spectrum observation operations occurring one floor above the cluster location on the roof of the IIT Tower. The others are to be used to host analysis and remote data access – the machine time will be made available to the worldwide partners.

The proposed database architecture is based on the hybrid storage model described in [NOO12]. As noted above, a 10 Gbps fiber-optic link provides a link from the server cluster directly to the Internet via IIT network infrastructure's trunk line. Rather than crossing university intranet switches, switched-local server resources are used to enable greater reliability and dramatically improved access times for local and global database users.

B. Large-scale RF Spectrum & Open Data Analysis, and Prediction

In recent years, there has been increasing interest in statistical analysis and prediction for very large-scale datasets [MAN11]. The concept of big data analytics has evolved in many fields from physics and astronomy to genomics, and from social sciences to business development and marketing, to name a few. The idea is to develop methods that scale with the growing size of high-dimensional data, to be able to perform efficient reasoning in order to discover and integrate knowledge hidden in many distributed and heterogeneous datasets.

Furthermore, the revolution in information technology through the growth of sensor networks, ubiquity of wireless internet connectivity, and advanced data management, has realized the collection, usage, and sharing of many different open datasets [OD13]. The easily accessed and distributed datasets combined with efficient data processing can release scientific and commercial value, as well as providing side information (or metadata) for more specific applications in multiple domains.

In the WiFiUS project, researchers are studying and developing machine learning and statistical analysis methods [MUR12] for long-term radio frequency (RF) spectrum data, collected in recent years as well as data being actively collected. The emphasis is on the use of data-driven techniques with the spectrum observation data being integrated with information from related temporally and spatially oriented open datasets. RF spectrum data is tagged with basic metadata such as time, location, and tags of spectral bands. In conjunction with (supervised) machine learning algorithms, building blocks can be developed for large-scale analysis and prediction tasks such as spectrum occupancy assessment. The data-driven use of time-series, spatial, and spectral information of very large number of long-term frequency bands opens up possibilities for novel findings (e.g., new variables and dependencies between variables) compared to typical short-term experiments [CHE09]. Since measurements are conducted at several locations simultaneously, researchers are able to study spatial correlations [YIN12] in spectrum use as well.

The collected data is not detailed enough to reveal real traffic patterns consisting of very short busy and idle periods in different frequency bands, due to time resolution limitations set by the sweep time. However, the data can still be used to model, classify, and predict the spectrum occupancy patterns with the given resolution and analyse the applicability of the studied channels to secondary use [LOP11], [WEL08], [HOY11], [TAH13].

Besides comparing closely related metadata of RF measurements, the publicly available open datasets can be applied for the RF spectrum analysis in two ways. First, we can further discover novel features or anomalies in the data which are not obvious in the measurements themselves. This could enable the development of more accurate models for spectrum occupancy prediction and the optimization of bands usage.

Second, the RF measurements can be used as input variables (e.g., the raw power spectral densities or the processed occupancy levels) and the metadata extracted from the related open dataset as output response (i.e., the labels or tags for spectrum measurements). The metadata could be used to form novel prediction tasks such as recognition of context information of human behavior, environmental changes, and transportation patterns in urban areas based on distributed or centralized spectrum measurements.

It is hypothesized that using modern machine learning and tools such as non-parametric probabilistic graphical models [KOL09] and kernel learning [RAS06], as well as parallel, distributed Map Reduce implementation of algorithms [DEA04], researchers will be able to discover novel aspects of spectrum occupancy in large-scale as well as to show the predictive ability of the measurements in novel applications for smart city environments. As presented in Section III, large-scale RF datasets are collected simultaneously in Finland and USA using both fixed and mobile sensing platforms. The first stage of the project concentrates on the existing datasets from IIT's long-term spectrum observatory that contains Chicago spectral measurements from 2007 to the present [NOO12] (i.e. over six years worth of data). The initial open datasets of interests are those provided by the City of Chicago through their data portal project [DP13].

V. Preliminary Results

In this section, occupancy statistics at several locations in Chicago and its suburbs are presented, as well as in the corresponding data from Turku, Finland. The measurements in Chicago and vicinity were obtained using RFeye based equipment nearly identical to that deployed in the permanent static observatory in Turku, Finland. The major difference is that it was mounted on a mobile truck platform on loan to WiNCom from Motorola Labs. The results here were obtained from the 100-6000 MHz band measurement with a frequency resolution of 312.5 kHz. Results from IIT's long running spectrum observatory [BAC08] are also presented, but with different measurement parameters compared to the RFeye.

In order to determine the occupancy, it is first necessary to apply a threshold to determine if the measured power exceeds the noise floor and hence constitutes a valid signal that was detected. For such a wide range spanning from 100 to 6000 MHz, the measured noise floor fluctuates by several dB power levels. Hence, a fixed threshold cannot be used for the entire 6 GHz range and different thresholds must be used in each sub-band. Selecting the thresholds individually for such a broad frequency is a non-trivial task, and an automated method to rapidly and accurately select a threshold is desired.

Hence, an algorithm based on [REA97] was developed at IIT and used to automatically estimate the noise floor power at each measurement frequency. The threshold values at each frequency point are then easily calculated as several dBs above the estimated noise floor. The occupancy numbers were calculated from these threshold values.

The algorithm utilizes morphological image processing techniques on 2 dimensional binary images of the power spectrum in order to estimate the noise floor. From the power spectrum, the maximum and minimum power values are found, and the values in between are used as threshold values to create a binary image where the pixels below the power values (Y-axis) at each frequency point (X-axis) are "off" while the pixels above are "on".

The opening operation (a combination of two morphological binary operators – binary erosion and then dilation) is applied to the binary image. The Kernel is defined as the number of adjacent frequency points that are automatically grouped together to form a sub-band. The algorithm begins with a small Kernel size that is incremented in turns. At each iteration, the peaks of the power spectrum binary image are "cut-off" (eroded); and this continues until the noise floor has converged. Convergence is reached when the mean squared difference between the estimated noise floor at the i'th and (i+1)'th iterations falls below a small pre-defined value.

Figure 9 shows an average power spectrum that was obtained by averaging across time all the power measurements for September 8th, 2013 at the Rice campus location. Note the fluctuating noise floor that corresponds to different RF bands' frontends in the RFeye device. The noise floor also changes due to automatic gain control and attenuation settings employed by the RFeye. It is difficult to manually select the noise threshold for each frequency point; however, as Figure 9 demonstrates, the algorithm readily and accurately identifies the noise floor throughout the 100-6000 MHz range. For the threshold, a value of 2 dB higher than the estimated noise floor is used to define occupancy, where the noise floor is estimated from a MaxHold power spectrum obtained from approximately a days' worth of measurements. The high threshold is needed because the RFeye noise shows a high level of variability due to the automatic gain/attenuation function. The noise floor variability is illustrated by the fact that the MaxHold noise power spectrum is 9-11 dB higher than the average spectrum in those frequency locations where signals are absent (Figure 9).

The average occupancy statistics for five measurement locations are shown in Figure 10. Approximately 24 hours' worth of data was used to generate the bar charts. In Figure 10, the first set of bar charts (IIT-SO) is a special case. Data from the long-term spectrum observatory at IIT tower was used for IIT-SO, while RFeye measurements were used for the rest. The IIT-SO system is more sensitive to weaker signals and has a higher dynamic range than the RFeye, but performs a full band sweep at a slower rate of once every 45 seconds compared to 10 seconds for the RFeye. The five locations and the measurement dates corresponding to the data are listed in Table 2 below. In [TAH11a], occupancy bar charts were presented based on IIT-SO data for the years 2008, 09 and 10; the difference in this paper is that the occupancy numbers were calculated over a one day period at *multiple* locations.

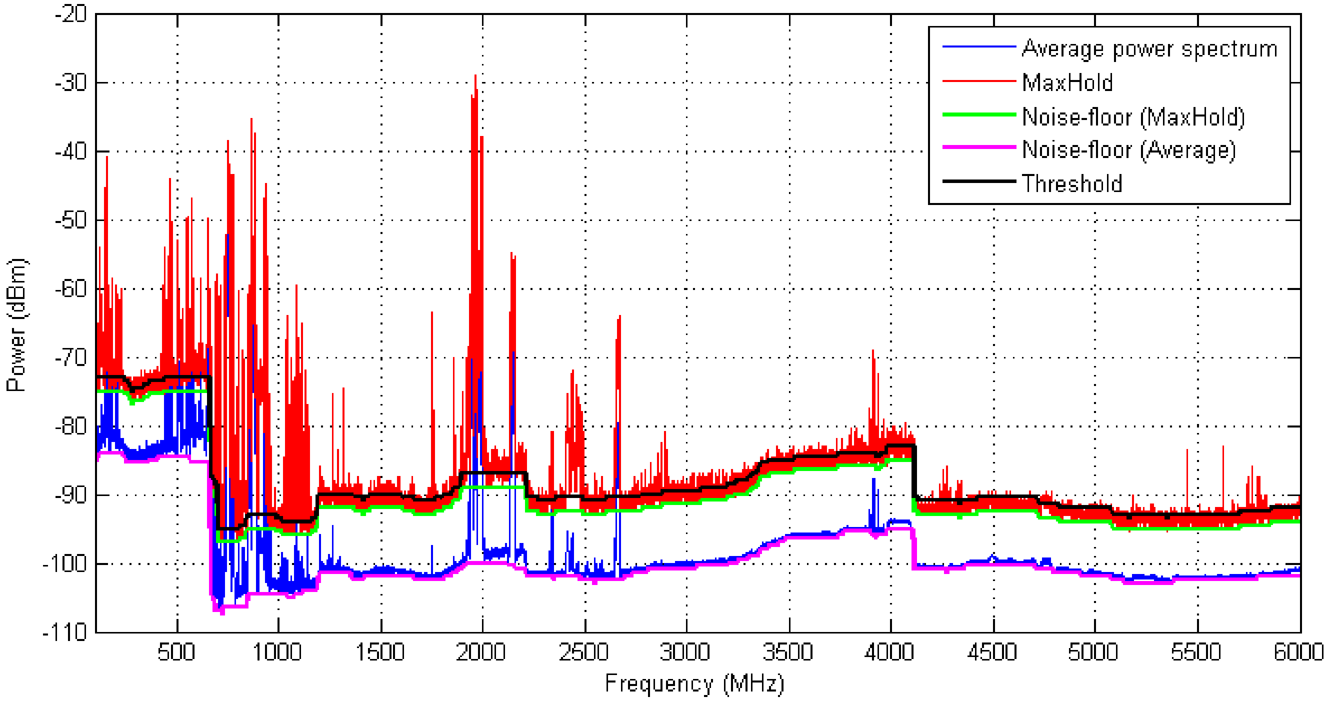

Figure 9. Average power spectrum in Chicago suburb (Wheaton, IL) for Sept 8, 2013 and the estimated noise floor

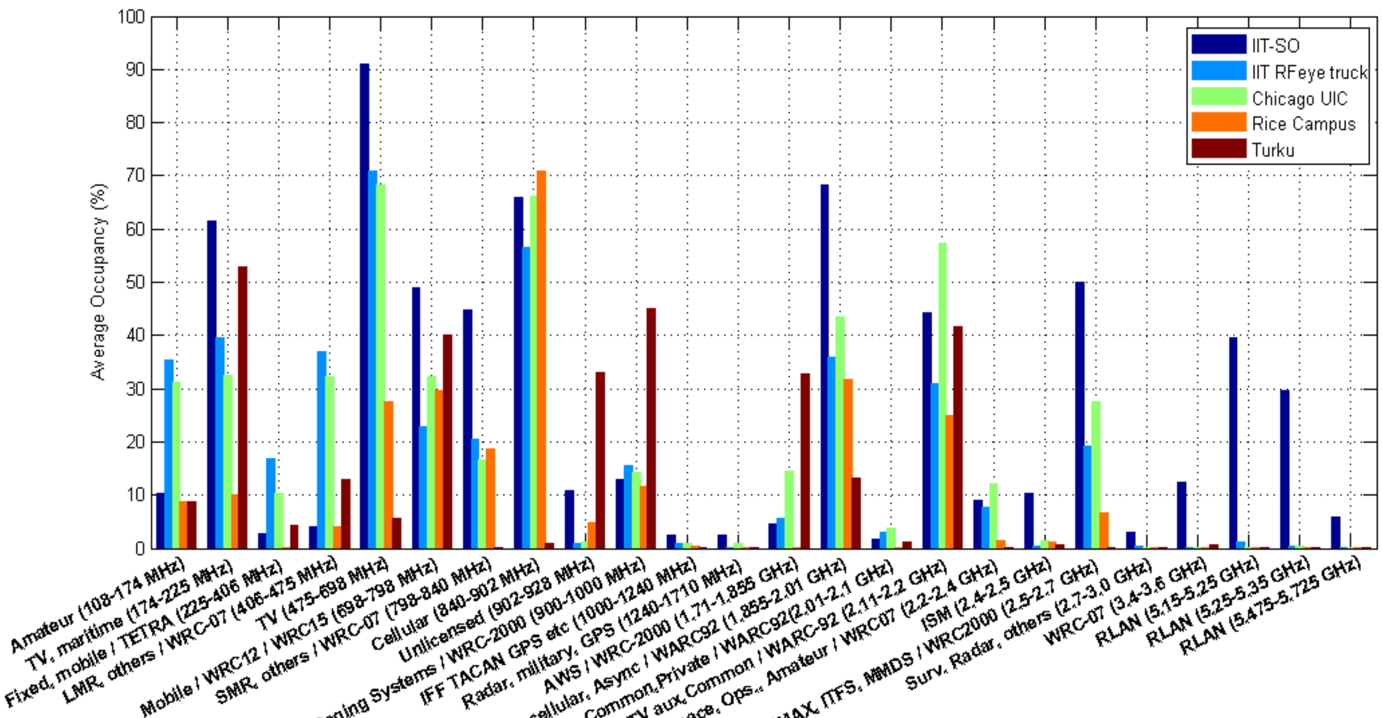

Figure 10. Average occupancies at five locations

In Figure 10, the rotated labels at the bottom of the bars indicate the start and stop frequency of each sub-band. The labels also list some of the wireless services that are deployed in the US at those sub-bands, as well as some ITU-R regulatory notes corresponding to alternate spectrum allocations in the Turku, Finland location.

Table 2. Measurement Locations for Occupancy Bar Charts (Figure 10)

Abbreviation	Location	System Used	Date
IIT-SO	IIT tower, Chicago, IL, USA	Spectrum Analyzer	August 23, 2013
IIT-RFeye truck	IIT campus, Chicago	RFeye on truck	August 23, 2013
Chicago UIC	UIC university, Chicago	RFeye on truck	September 11, 2013

Rice Campus	Wheaton, IL, USA	RFeye on truck	September 8, 2013
Turku	Turku university campus, Turku, Finland	RFeye at fixed location	August 23, 2013

Several factors affect the accuracy of these occupancy estimates:

- Due to the presence of some very high-powered transmitters, the RF front-end uses a high attenuation setting in some of the RFeye's sub-bands. This raises the overall noise floor, which leads to a high noise threshold for those bands. This means that several low-powered signals are missed that are buried below the threshold. An ongoing process to remedy this is through the installation of notch filters tuned to the frequencies where the high-powered transmitters are detected.
- The primary advantage of the energy detection approach used to estimate occupancy is its simplicity; however, its accuracy is poor when the signal-to-noise ratio of the received signals is low, in which case missed detections or false alarms may occur.
- The time resolution of 10 seconds for the measurements may not be high enough to capture shorter duration events such as modern radar signals.
- Directional signals (like satellite communications, point-to-point links, higher frequency directional links) may not be detected by the omni-directional antenna used. For the frequency bands where these signals exist, specialized directional antennas and pre-amplifiers may be necessary to obtain more accurate occupancy numbers.

The occupancy values presented are nevertheless useful for illustrative purposes, and given our multi-site context, for comparative purposes – to compare the usage over time and across different locations. The occupancy numbers are also useful to rapidly identify under-utilized areas of the spectrum, and also to compare the occupancy across different bands of the spectrum.

Comparing the occupancy numbers obtained from the three Chicago locations (IIT-SO, IIT RFeye truck, Chicago UIC), the spectrum usage seems very similar from the IIT-RFeye and UIC data. This is expected as the measurement locations are only about 5 km apart and both are near downtown Chicago. The IIT-SO data for Chicago occupancy, however, shows somewhat higher values in most sub-bands, particularly in the higher frequencies above 2.5 GHz. This is due to the fact that the IIT-SO system is more sensitive than the RFeye, its antennas are located 160 feet higher than the RFeye-truck deployment, and the system has a much lower 3 dB variability in the noise floor that allows a lower signal-power threshold to be used. Also, higher frequency signals are more directional, and so the IIT-SO's higher altitude is more conducive to their observation. In several high utility bands though, like cellular (700, 800 MHz bands), the IIT-SO occupancy numbers are comparable to the IIT-RFeye and UIC measurements.

VI. Measured Differences in Occupancy

Comparing the occupancy bar charts in Figure 10, we notice that the usage in the lower broadcast frequencies (TV bands) is higher in Chicago than in Turku. This is expected since there are more TV channels in Chicago in line with its larger population. The 840-902 MHz band shows high occupancy in Chicago and very low occupancy in Turku. This is because the GSM-850 band is used for cellular services in the US but not in Finland. In contrast, Turku has higher occupancy in the 900-1000 MHz range compared to Chicago due to cellular deployments in the GSM-900 band in Europe. The Chicago location shows significant usage in the 698-798 MHz range, commensurate with the rising popularity of LTE in recent years. In Finland, LTE only recently became operational in the 791-862 MHz region.

In the United States the 1755-1850 MHz band is currently used for military and Federal government services. The US Congress is considering legislation to reallocate the 1755-1780 MHz block for commercial use [HR4817]. The entire 1755-1850 MHz band has also been considered for relocation from military to commercial use, and the Department of Defense (DoD) has estimated that the cost to do so would cost $12.6 billion over 10 years [GAO13]. Commercial wireless service providers have expressed interest in deploying broadband data services in this band, as it is just adjacent to the PCS bands where such services are well established.

In contrast, in Finland, broadband LTE services are already deployed in part of the 1755-1850 MHz region. In particular, the 1805-1880 MHz Digital Cellular System (DCS) band is widely used in parts of Europe including Finland for cellular voice and broadband services.

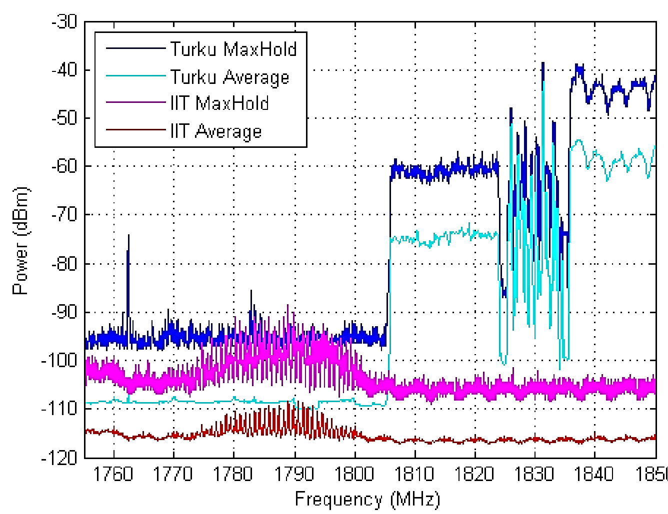

Figure 11. Power spectrum in the 1755-1850 MHz band at Turku and Chicago

Figure 11 is an interesting example that contrasts the different ways in which the 1755-1850 MHz band is utilized in Chicago and Turku. Figure 11 shows the average and MaxHold power spectrum at Chicago (IIT-RFeye truck) and at Turku, as observed on August 23rd, 2013 in the 1755-1850 MHz band. The low-power wideband signal observed in

Chicago is possibly a spread-spectrum radar transmission. The two Turku wideband signals are coming from two cellular base stations operating in the DCS band.

Such comparative spectrum utility and analysis studies are useful to researchers and policy makers who are designing systems or policies intended for worldwide adoption. This example illustrates real differences observed in the empirical data that would aid researchers to mold spectrum solutions that accommodate a range of radio environments across the world.

VII. CONCLUSION

The international effort highlighted in this publication resulted in the deployment of a global spectrum observatory network consisting of identical spectrum observation nodes. This infrastructure enables researchers to access wideband empirical spectrum measurement data from multiple locations and over a long temporal duration. The information is useable for many applications, for example – spectrum audits, comparing radio environments between different geographical regions and over time, generating models of radio usage in bands of interest (example in [TAH12]), employing those models in dynamic spectrum access simulation studies (example in [TAH13]), etc.

Multiple challenges were addressed to set up the whole system – the measurement equipment, the data aggregation and storage components, the networking infrastructure, and technology sharing. The data storage and access infrastructure is by far the most complex part of the project, and work in this area is continuing. Nevertheless, it was a significant technical achievement to bring all the components together in a functioning setup. Important lessons were learned in the process, particularly on how to manage a project with many partners spread across three time zones. Moving forward, technology, resources and expertise sharing among the multiple partners will help the participant groups in a range of research projects.

Simple spectrum occupancy audit results at Chicago, Wheaton (a Chicago suburb) and at Turku were presented, and comparisons were made. Chicago is a major city, Turku is a town, and the suburban locations are Wheaton and Blacksburg. The different measurement locations will allow comparisons between radio environments that are differentiated by geography and population densities. As data collection continues, it will be of interest to examine how the occupancy changes over time and to identify any daily, weekly, monthly trends in the radio environment usage. Much of this information is of interest to radio policy planners, wireless service providers, and to researchers in the area of cognitive radio and dynamic spectrum access (example in [BAC10], [TAH11b]). At present, spectrum sharing approaches are receiving a lot of attention from regulators and researchers alike, and a sister publication [MAT14] discusses recent developments in these areas in detail, both in European and American contexts.

Spectrum observatories like the global spectrum observatory network are generating a lot of interest at present. Spectrum occupancy measurement studies are of increasing importance as international regulatory bodies are interested in the results. The International Telecommunication Union Radio-communication sector (ITU-R) is studying spectrum monitoring in its ITU-R WP1C group. The European Conference of Postal and Telecommunications administrations (CEPT) has also expressed interest in spectrum measurements. In the near future, the global spectrum observatory network is expected to provide these organizations with timely access to relevant measurement information and analysis results. This would enhance the practical impact of the project in the wireless technology world.

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