Measuring and Modeling Spectrum Occupancy: A Massachusetts Perspective

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***Abstract*—In this paper, we provide an overview of three ongoing research activities conducted at the Wireless Innovation Laboratory of Worcester Polytechnic Institute (WPI) in Massachusetts that are related to the measurement and modeling of wireless spectrum. These activities address different yet complementary research topics with respect to wireless spectrum availability, ranging from spectrum occupancy measurement campaigns in four mid-size U.S. cities to feasibility studies of performing dynamic spectrum access in vehicular communication networks operating over television white spaces to the creation of accurate statistical spectrum occupancy models based on parameterized spectrum measurements. The overall goal for all of these activities is to further enhance the research community's understanding of wireless spectrum resources and how they can facilitate development of future wireless communication systems and networking paradigms.**

I. Introduction

With the demand for additional bandwidth increasing due to existing and new services, both spectrum policy makers and communication technologists are seeking solutions for an apparent scarcity of unoccupied wireless spectrum [1, 2]. Meanwhile, measurement studies have shown that much of the licensed spectrum is relatively unused across time and frequency [3–8]. To provide the necessary bandwidth required by current and future wireless services and applications, work has commenced on the concept of unlicensed users "borrowing" spectrum from spectrum licensees. This approach to spectral usage is known as *dynamic spectrum access* (DSA) [9]. Although conventional wireless communication systems from a decade ago did not possess the necessary transmission agility, recent developments in *cognitive radio* [10] technology have now made it possible for wireless communication systems to simultaneously respect the rights of incumbent license holders while providing additional flexibility and access to spectrum.

Although the potential modification to wireless spectrum regulations are based on the assumption that the majority of wireless spectrum is extensively underutilized, which is derived from several independently conducted measurement campaigns, there still exists a need to obtain a deeper understanding of this natural resource. By gaining this insight into wireless spectrum, appropriate technical and legislative actions can be taken in order to support continued growth in the wireless sector.

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Furthermore, one wireless application that could significantly benefit from DSA is vehicular communications. Currently, vehicular communication research is rapidly becoming a major research focus in the wireless communications research community, yielding new results that help ensure safety, comfort and situational awareness of the driver. With the proliferation of vehicular communication applications beyond just safety communications, especially within a dense vehicular traffic environment, there is a growing need for an efficient usage of wireless channels and spectrum resources. Therefore, future vehicular applications require DSA methods to efficiently utilize available spectrum while providing stringent QoS required by vehicular applications. It is envisioned that communication nodes enabled by cognitive radio capabilities such as DSA will support future vehicular communication needs in challenging environments.

Finally, given that the infrastructure and equipment needed to collect wireless spectrum occupancy data can be prohibitively expensive, and may not be accessible by the majority of the wireless research community, there is a need for an accurate time-varying spectrum occupancy model to assess new DSA approaches and algorithms. However, unique variations of spectrum occupancy characteristics specific to frequency bands, geographical locations, and time periods require a method that relates these characteristics as parameters for the model.

In this paper, three ongoing research activities related to the measurement and modeling of wireless spectrum conducted at the Wireless Innovation Laboratory [11] of Worcester Polytechnic Institute (WPI), Worcester, MA, U.S.A. will be presented. These activities involve different yet complementary research topics, ranging from spectrum occupancy measurement studies to feasibility studies of DSA applied to current wireless applications to the creation of accurate statistical spectrum occupancy models.

The rest of this paper will provide an overview of the following three projects: In Section II, a quantitative assessment of wireless spectrum occupancy across the spatial, temporal,

TABLE I

LIST OF MEASUREMENT LOCATIONS DURING THE SUMMER 2008 SPECTRUM OCCUPANCY MEASUREMENT CAMPAIGN (FROM [3]).

Location	**City**			
	ROCHESTER, NY 19^{th} & 20^{th} June 2008	BUFFALO, NY 21^{st} & 22^{nd} June 2008	PITTSBURGH, PA 23^{rd} & 24^{th} June 2008	WORCESTER, MA 17^{th}, 26^{th}, & 27^{th} July 2008
SITE 1	S. Plymouth & Exchange Blvd	E. Huron St. & Washington St.	16th St Bridge & N of 1711 Penn. Av.	SE of Boynton Hall WPI
SITE 2	Jay St. & Verona St.	Swan St. & E. Michigan Av.	Sheraton St. & Fort Pitt Bridge	Vernon St. & Dorchester St.
SITE 3	Prince St. & Univ. Av.	Pearl St. & Church St.	Riverfront Park next to Birmingham bridge	Bell Hill Park (off Belmont St.)
SITE 4	Mortimer St. & N. Clinton St.	W. Genesee St. & Seventh St.	Craig St. & N. 5th Av.	Major Taylor Blvd. & Thomas St.
SITE 5	Pearl St. & Averill Av.	Oak St. & Clinton St.	Grandview St. & Ulysses St.	Gateway Park (Parking lot) WPI

and frequency domains of four mid-size U.S. cities that includes Worcester, MA [3]. Section III presents a feasibility study of applying DSA to highway-based vehicular communication networks using digital television spectral whitespace measurements along the entire length of Interstate 90 in Massachusetts [12]. Finally, we describe in Section IV the creation of a statistical wireless spectrum occupancy model that accurately depicts its spatial, temporal, and frequency characteristics and is based on parameters obtained from actual spectrum measurements [13].

II. QUANTIFICATION OF METROPOLITAN SPECTRUM OCCUPANCY[1]

Although the allocation of spectrum for a specific wireless application is uniform across the nation, its usage varies from region to region. Thus, the location and size of spectrum holes also varies randomly with respect to time and geography. Although short-term spectrum measurements have provided snapshots of these spectrum holes, their long-term behavior has yet to be characterized. Moreover, these measurement campaigns have focused mostly on the "worst cases" in terms of spectrum occupancy, such as very large cities and/or special events that result in increased communication traffic. Finally, these measurement studies have mostly assessed the spectrum occupancy across a small geographical region. As a result, we do not fully understand the broader spectrum usage picture with respect to the *electrospace* [14] properties of a large geographical area. In this work, we attempt to accurately characterize the availability of prime spectrum in several mid-size American cities, i.e., the "average case" that most commonly occurs, for secondary access via theoretical and experimental techniques. Using these measurements, the long-term behavior and trends of spectrum occupancy can be studied, as well as quantitatively compute the rate at which spectrum scarcity is occurring. Finally, the electrospace characteristics over a large metropolitan area using the spectrum measurements can be studied.

[1]The work was presented in parts at the *2009 International Conference on Cognitive Radio Oriented Wireless Networks and Communications* [3].

Fig. 1. A photograph of the employed mobile wireless spectrum measurement testbed, which include a mini-discone/ridged-horn antenna, a spectrum analyzer and a laptop with SQUIRREL installed (from [3]).

During our measurement campaign, two antennas were used for scanning different frequency ranges that were broadly classified to two groups, namely, low frequency and high frequency. For the low frequency range *i.e.*, from 88 MHz to 1240 MHz, we used a Diamond D-220 mini-discone antenna with an operating frequency range of $100-1600$ MHz. For the high frequency range *i.e.*, from 1850 MHz to 2686 MHz, we used an Advanced Technical Materials (ATM) 07-18-440-NF horn antenna with an operating frequency range of $0.7-18$ GHz and an aperture of 60^o. This helped us in observing the variation in spectrum usage across different angles of arrival. During our operation, one of these antennas is wired to an Agilent CSA series $N1996A$ spectrum analyzer with frequency range ranging from 100 kHz - 3 GHz and consisting of a low noise amplifier (LNA). We use an in-house software tool called SQUIRREL (Spectrum Query Utility Interface for Real-time Radio Electromagnetics) to communicate remotely with the spectrum analyzer via commands issued through a simple graphical user interface on a laptop. The GUI accepts details, such as the center frequency, the span around the center frequency, and the resolution bandwidth. SQUIRREL communicates with the spectrum analyzer using TCL (Tool Command Language) over TCP/IP. After the sweep action is performed by the spectrum analyzer, the data points are returned to the GUI in a comma spaced value format. In its current format, the GUI and the server are written in JAVA and can be deployed on a variety of operating systems and computers. A photograph of the mobile wireless spectrum

TABLE II
BANDWIDTH OCCUPANCY RESULTS FOR SELECTED BANDS MEASURED DURING THE SUMMER 2008 SPECTRUM OCCUPANCY MEASUREMENT CAMPAIGN (FROM [3]).

Location	**City**															
	ROCHESTER, NY				BUFFALO, NY				PITTSBURGH, PA				WORCESTER, MA			
	TV7-13	Paging	PCS	WCS	TV7-13	Paging	PCS	WCS	TV7-13	Paging	PCS	WCS	TV7-13	Paging	PCS	WCS
SITE 1	28.45	3.85	7.59	8.37	93.69	72.24	15.05	6.69	11.63	10.85	12.28	9.91	13.73	5.58	8.14	17.74
SITE 2	19.08	2.96	8.64	10.97	42.26	7.64	9.58	12.83	35.34	8.75	14.8	10.89	32.19	6.68	8.42	22.62
SITE 3	29.71	3.04	5.66	1.45	19.09	4.92	10.64	6.62	22.30	5.73	8.23	0.53	35.31	4.48	3.04	11.99
SITE 4	15.70	8.86	16.77	13.11	6.05	5.71	8.09	2.65	9.14	2.72	9.10	0.30	24.98	3.77	7.96	12.15
SITE 5	20.38	4.67	4.35	6.08	8.01	7.21	4.94	12.43	26.82	9.33	8.89	13.55	48.42	3.23	7.61	7.02
Average	22.66	4.68	8.60	7.99	18.85	6.37	9.66	8.24	21.05	7.48	10.66	7.04	30.93	4.75	7.03	14.3

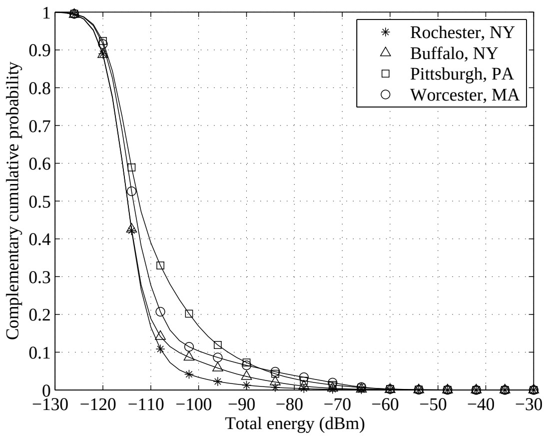

Fig. 2. Cumulative distribution functions showing spectrum occupancy for the four cities surveyed (from [3]).

measurement testbed is shown in Fig. 1.

The details about the locations and the dates of our spectrum measurement campaign is given in Table I. Five locations were chosen that were at least a mile apart from each other such that we would be able to capture the spatial variation as we go higher in the radio frequency (RF) spectrum. We measured usage activity across approximately 70% of the wireless spectrum from 88 MHz to 2686 MHz. Furthermore, we omitted those bands in which the average usage has been previously reported to be extremely low. Thus, we focused on the remaining bands of interest. Also, in our measurement procedure, we sweep a particular frequency band, for example, Personal Communications Service (PCS) from 1850 MHz to 1990 MHz, completely for a specific number of times and then proceed to the next band instead of scanning a wide frequency range. By performing the sweeps in this manner, our goal was to capture temporal variations over small periods of time. We chose a constant resolution bandwidth of 20 kHz and the number of sweeps recorded per band per site is 25. Fig. 2 provides a first step summary of all the data points collected across all the frequencies in bins of 20 kHz. This plot is a complementary cumulative distribution function showing the spectrum occupancy in each of the four cities as a function of energy.

Table II provides the complete picture of the spectrum usage across the four cities for the following bands: TV 7-13 (174-214 MHz), Paging band (928-948 MHz), PCS (1850-1990 MHz) and WCS/DARS (2300-2360 MHz). The results from Table II clearly illustrate that there are significant variations in the spectrum usage across different sites in the same city. The difference in the occupancy percentages for broadcast type signals (*i.e.*, TV 7-13) and signals of bursty nature is also apparent. Furthermore, the occupancy values highlighted in red for the city of Buffalo in site 1 for TV 7-13 and paging is extremely high. When we checked with the energy spectral density plots for these frequency ranges, we noticed that broadband noise has corrupted the data points. Therefore, these two values of spectrum occupancy are incorrect. We have also omitted these points in calculating the average bandwidth occupancy.

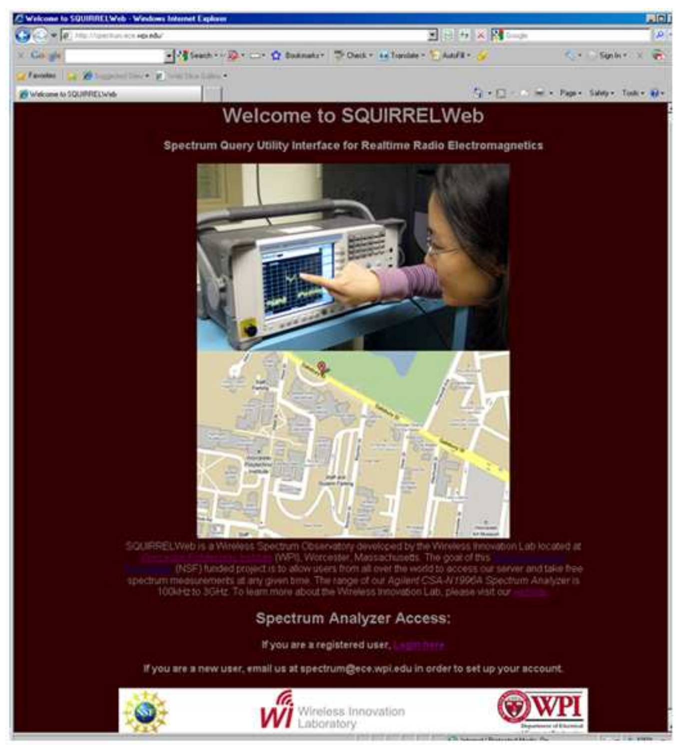

Fig. 3. Screen capture of the SQUIRRELWeb spectrum observatory web site [15], which is located and hosted at WPI.

Although conducting wireless spectrum measurement campaigns in the field possess important information regarding the issue of spectrum scarcity, additional value can be obtained from the same measurement setup when configured as a *wireless spectrum observatory*, especially when attempting to collect spectrum measurements over long periods of time in order to quantify the rate at which spectrum scarcity is occurring. Leveraging existing spectrum measurement resources at the Wireless Innovation Laboratory, a permanent wireless spectrum observatory was constructed at the Atwater Kent Laboratories building, which is located on the main campus of WPI. This spectrum observatory is used to measure wireless spectrum close to the downtown Worcester area, which is available 24 hours per day and with the results being accessible via the Internet using a web interface [15]. Referred to as "SQUIRRELWeb", this spectrum observatory can help researchers by providing them with actual spectrum measurements across any portion of the frequency band ranging from 88 MHz to 3 GHz. A screen capture of the web interface to the SQUIRRELWeb spectrum observatory is shown in Fig. 3.

III. Television Spectral White Space for Vehicular Communications[2]

The application of dynamic spectrum access (DSA) to vehicular communication networks in order to enable secondary utilization of licensed wireless channels for both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications is a growing area of research activity [16–18]. However, in order for the DSA concept to be successfully applied to vehicular communication networks, slowly time-varying spectral occupancy characteristics are required. Consequently, one frequency band that possesses this key characteristic is the television spectrum, where unlicensed vehicular wireless networks can readily communicate amongst each other within a licensed frequency band.

The requirement for a slowly time-varying spectral occupancy characteristic is due to the high level of mobility of the wireless devices within a vehicular DSA (VDSA) network. Consequently, TV spectral occupancy characteristics that were once observed as being static at a fixed geographical location now appear to be changing based on the direction and speed of mobile vehicular wireless device. As opposed to other frequency bands, where spectral occupancy changes may occur relatively quickly over time and geography, TV spectrum still possesses the advantage of having relatively slow spectral occupancy variations over large distances and periods of time. Thus, this research activity focuses on the feasibility of performing VDSA communications over television frequency bands. In particular, one of the main objectives of this activity is to create a geo-location database of actual television spectrum measurements collected along the portion of Interstate 90 located in Massachusetts. Using this database, we can assess the total number of channels available, the number of non-contiguous blocks, and the implications on the design of the transceiver that utilizes channels in such a non-contiguous scenario as a function of distance.

The first phase of the spectrum measurement campaign was conducted on June 7, 2009 and June 11, 2009 across 48 locations between Boston, MA and West Stockbridge, MA. The second phase which consisted of collecting spectrum measurements in a vehicle traveling at approximately 60 miles per hour between the same locations was done on June 30, 2009. We selected a frequency resolution of 20 kHz and collected 10 sweeps per site. Since the goal of the project is to characterize DTV spectrum over several locations on I-90 in the state of Massachusetts, most sites were chosen to be within half mile from I-90 for the purpose of avoiding interference to the ongoing traffic. The locations were also selected such that they were spaced approximately 2 miles apart. The map of the measurement sites is shown in Fig. 4.

The measurement setup used to collect spectrum measurements in the television band is shown in Fig. 5. An Agilent N1996A Spectrum Analyzer (SA) with an operating frequency of 100kHz - 3GHz was used in this research activity. It is connected to a laptop installed with SQUIRREL via an Ethernet cable. SQUIRREL (Spectrum Query Utility Interface for Real-time Radio Electromagnetics) is an in-house software tool which communicates with the spectrum analyzer using TCL (Tool Command Language) over TCP/IP. The GUI accepts details, such as the center frequency, the span around the center frequency, and the resolution bandwidth. After the sweep action is performed by the spectrum analyzer, the data points are returned to the GUI in a comma spaced value format. In its current format, the GUI and the server are written in JAVA and can be deployed on a variety of operating systems and computers. The mini-discone antenna is a Diamond D-220 antenna with an operating frequency range of 100MHz - 1600MHz and is connected to the SA by a coaxial cable. The antenna is fixed to a bike-rack mounted on the trunk of a car in order to make the entire setup portable.

In Fig. 6, the data points collected on June 30, 2009 are presented, where the measurement setup was mounted on a moving vehicle traveling along I-90 at an average velocity of 60 miles per hour. Essentially, Fig. 6 shows the energy spectral density plot for the TV bands in the higher frequency range which is the region primarily identified as the suitable for dynamic spectrum access. In this figure, the x-axis represents the frequencies swept during our study and the y-axis represents the sweep index. We reduced the frequency range swept in order to obtain finer time resolution. That is instead of the entire UHF TV range, we selected 600 - 750 MHz and captured four sweeps per minute on average along the length of I-90 [3] . The sweep index increases from 1 on the top left corner of each figure and indicates our drive as we travel along I-90 in the state of MA from west to east. The western most point in our study was West Stockbridge, MA

[2]The work was presented in parts at the *2009 IEEE Vehicular Networking Conference* [12].

[3]The measurement results pertaining to the complete UHF range *i.e.*, 470-806 MHz will be presented in our future work.

Fig. 4. A map of the forty eight locations close to I-90 between Boston, MA and West Stockbridge, MA over which spectrum measurements were collected on June 7, 11, and 12 in 2009 (from [12]).

Fig. 5. A photograph of the employed mobile wireless spectrum measurement testbed, which includes a mini-discone/ridged-horn antenna, a spectrum analyzer and a laptop with SQUIRREL installed (from [12]).

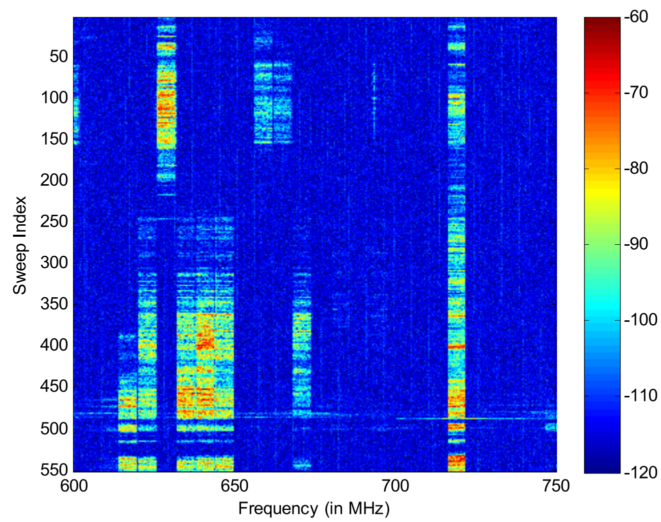

Fig. 6. Spectrogram plot for the TV frequencies in the frequency range, 600 - 750 MHz over 550 time sweeps on I-90 between Boston, MA and West Stockbridge, MA. The measurement setup was located in a vehicle moving at an average velocity of 60 miles/hr (from [12]).

and the eastern most point was Boston, MA. The intensity of each pixel indicates the energy level observed during the study. From this figure, a clear indication of the variation in the energy levels across any particular channel is evident. The total absence of any signal towards the end of our drive (around sweep index 520-530) occurred during the time when measurement vehicle was driving under Boston Harbor through the Ted Williams Tunnel. An interesting thing to note is that as we move farther away from Boston towards Palmer (which corresponds to a sweep index of around 220), the energy values decrease in general. However, going from Palmer towards West Stockbridge (which corresponds to a sweep index of around 120), the energy values show an increasing trend indicating that we were approaching a nearby TV transmitter. Another observation from this figure is that there are several locations close to Boston, MA where we observed strong signals of the order of -60 dBm indicating that our measurement sites were close to TV transmitters.

Figs. 7 and 8 provide further insight into the non-contiguous nature of the channel availability in the UHF TV band. For example, in Framingham, MA, even though the total bandwidth available for secondary usage is around 100 MHz, there are 11 non-contiguous blocks of vacant spectrum of

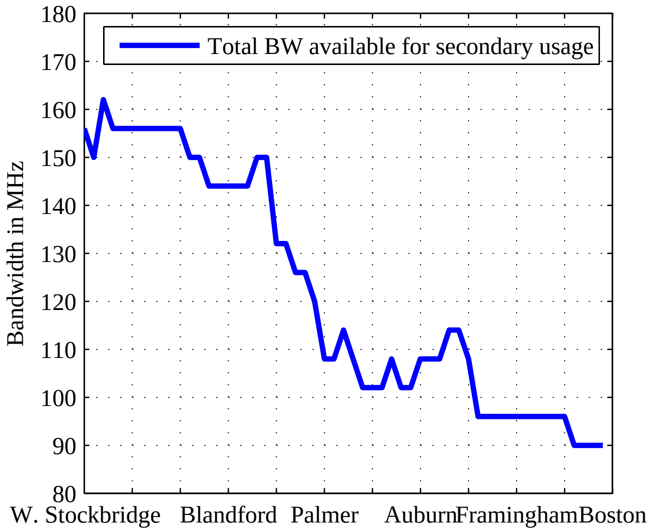

Fig. 7. The total available bandwidth for secondary usage at different locations along I-90 in the state of Massachusetts, USA (from [12]).

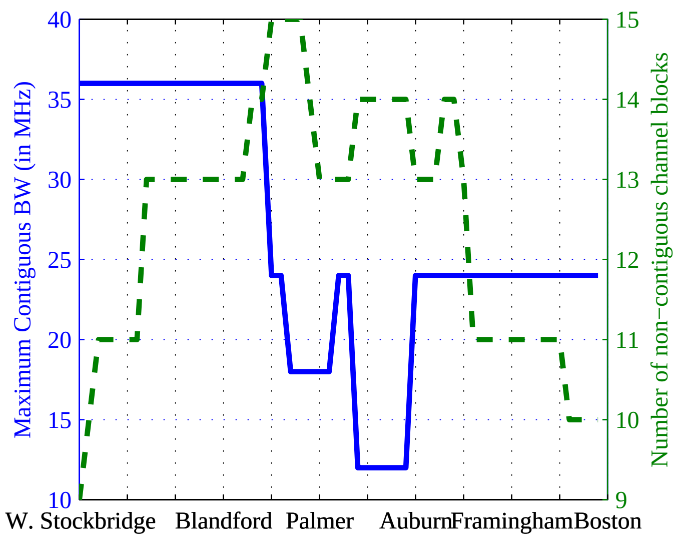

Fig. 8. Maximum contiguous bandwidth and the number of non-contiguous channel blocks at different locations along I-90 in the state of Massachusetts, USA (from [12]).

which a maximum of 24 MHz is available as one contiguous block.

IV. Statistical Modeling of Spectral Occupancy[4]

To conduct research into DSA networks, it is important to validate new designs and concepts via computer simulation. However, the validity of the simulation results is dependent on the spatial, temporal, and frequency wireless spectrum occupancy characteristics. Although estimates about the spectrum utilization by the primary users can be obtained via spectrum occupancy measurement campaigns, the infrastructure and equipment needed to collect this data can be prohibitively expensive and may not accessible by the majority of the wireless research community. Thus, we have devised a time-varying statistical model for spectrum occupancy that uses actual wireless frequency measurements in determining key model parameters. The fundamental difference between our proposed model relative to other existing research work is the realistic emulation of primary user occupancy for different sub-bands.

Let SB denote the set of N sub-bands and is represented as $\mathrm{SB} = 1, 2, \cdots, N$. At this point, we assume that each sub-band is licensed to one and only one licensed user, hereafter referred to as a PU, i.e., primary user. The utilization of the i^{th} licensed sub-band SB_i by the i^{th} PU is modeled as a Poisson process with arrival rate, λ_i, where $i = 1, 2, \cdots, N$. The entity λ_i, $i = 1, 2, \cdots, N$ is extracted from actual wireless spectrum measurements. A single duration of utilization of the i^{th} sub-band by a PU is denoted by $t_{\mathrm{ON}}(i)$. Similarly, a single duration of the i^{th} sub-band being idle is denoted by $t_{\mathrm{OFF}}(i)$. If the number of utilization times for an SB_i is k with arrival rate, λ_i, then the probability of having k utilization periods during the experiment conducted can be expressed as [19]:

$$f(k, \lambda_i) = \frac{\lambda_i^k e^{-\lambda_i}}{k!}, \; i = 1, 2, \cdots, N. \tag{1}$$

Hence, the duration between two utilization periods, *i.e.*, the inter-arrival rate of the i^{th} PU, $i = 1, 2, \cdots, N$, follows an exponential distribution. The probability density function of $t_{\mathrm{OFF}}(i)$ for the i^{th} sub-band can be expressed as [13]:

$$f(t_{\mathrm{OFF}}(i); \lambda_i) = \begin{cases} \lambda_i e^{-\lambda_i t_{\mathrm{OFF}}(i)}, & t_{\mathrm{OFF}}(i) \geq 0 \\ 0, & t_{\mathrm{OFF}}(i) < 0. \end{cases} \tag{2}$$

Similarly, the probability density function of $t_{ON}(i)$ for the i^{th} sub-band is expressed as [13]:

$$f(t_{\mathrm{ON}}(i); \lambda_i) = \begin{cases} \lambda_i e^{-\lambda_i t_{\mathrm{ON}}(i)}, & t_{\mathrm{ON}}(i) \geq 0 \\ 0, & t_{\mathrm{ON}}(i) < 0. \end{cases} \tag{3}$$

The central idea of exploiting the Poisson and exponential distributions is to track the arrival rate of PUs and as well as their departure for each sub-band over the duration of the simulation. This can further assist the SUs to perform spectrum sensing only on the detected ON times of the sub-bands and judiciously use the sub-bands during the OFF times. It is intuitive that higher values of OFF times are prospective for SUs using those sub-bands for longer duration of time. An additional feature has been incorporated in our simulation. Each time a PU arrives (ON time), it can select an operating frequency different from the frequency in its previous ON time.

Assuming that the power distribution of a PU in its sub-band follows a Gaussian distribution, the peak at which a transmission is detected, gives us its operating frequency. Ideally, the operating frequency of a transmission in a sub-band is at the center of the band, *i.e.*, the mean operating frequency, with variance implying the extent of the distribution. The

[4]The work was published in parts in the *IEEE Transactions on Wireless Communications* [13].

probability density function of the operating frequency f_i is expressed as [19]:

$$f(f_i) = \frac{1}{\sqrt{2\pi\sigma_i^2}} e^{-\frac{(f-\mu_i)^2}{2\sigma_i^2}}. \quad (4)$$

In real time, it has been observed that the operating frequency f_i of an i^{th} PU transmission often deviates from its ideal frequency, though it ranges between its mean operating frequency μ_i and its variance σ_i^2 of its Gaussian distribution. Hence, in our model, the entity f_i for an i^{th} PU transmission is chosen from a uniform distribution governed by the values of μ_i and σ_i^2. Theoretically a PU can assume a frequency that is equally allowable within a band. Wireless spectrum measurements in the paging band indicate that PU frequency allocations are usually discretized on the number of frequencies allocated. Hence, the spectrum occupancy can be governed by an uniform distribution. The probability density function for the i^{th} operating frequency f_i can be expressed as [19]:

$$f(f_i) = \begin{cases} \frac{1}{2\sqrt{\sigma_i^2}}, & \text{for } \mu_i - \sqrt{\sigma_i^2} \leq f_i \leq \mu_i + \sqrt{\sigma_i^2} \\ 0, & \text{otherwise.} \end{cases} \quad (5)$$

V. Concluding Remarks

Modern society depends on communications networks in order to function properly. Furthermore, the demand for both existing and new wireless services and applications shows no sign of slowing down. However, the current command-and-control regulatory structure for licensing spectrum has been unable to cope with the drastic growth demands of the wireless industry, thus giving rise to an “artificial scarcity” of usable spectrum. Consequently, this may result in spectrum license price levels that are prohibitively expensive, preventing many small to medium size businesses from entering the wireless market. Thus, conducting research activities such as those described in this paper in the area of spectrum measurement and modeling is an important endeavor. Knowledge of how much spectrum is actually available and where those opportunities are located in frequency, time, and space is of vital importance to the wireless industry, which has experienced rapid growth over the past several years and continues to accelerate. Using this information to guide the future development of wireless communication systems and networks will help ensure that this natural resource remains accessible in sufficient supply for use by modern society.

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