Characterizing Spectrum Goodness for Dynamic Spectrum Access

Aakanksha Chowdhery[1], Ranveer Chandra[2], Paul Garnett[2], and Paul Mitchell[2]

Abstract— **The combination of exclusive use spectrum licensing and growing demand for voice, data, and video applications is leading to artificial spectrum scarcity. A recent approach to alleviate this artificial spectrum scarcity innovatively uses unused TV spectrum, also called the TV white spaces, through dynamic spectrum access (DSA) techniques. Wireless devices can use DSA techniques such as sensing and geo-location databases to learn about available TV channels for wireless communication. One obvious question to ask is whether the technology enabler for white space networking, i.e. dynamic spectrum access, is viable in other portions of the spectrum?**

This paper extends our research on networking devices in TV white spaces over the last seven years to other licensed spectrum bands between 30 MHz and 6 GHz. Typically, the goodness of licensed spectrum bands is measured using spectrum occupancy as a goodness metric, but the DSA opportunities in different bands can depend on several factors. We propose a novel DSA goodness metric to compare the opportunity of capitalizing on available spectrum using DSA techniques in various licensed bands. Further, we use these metrics to evaluate the data from the ongoing spectrum measurement campaign at Microsoft Research over one year.

I. Introduction

The existing licensing model of spectrum bands has limited the amount of usable spectrum for wireless data communications. A small portion of spectrum is allocated for data communications, even though the demand for data, voice, and video traffic continues to explode on Internet-enabled mobile devices. To obtain more spectrum for these applications, regulators around the world are considering proposals to assign more spectrum for exclusive use licensing.

However, nearly all the RF spectrum is allocated for specific applications, making reallocation of exclusive use licenses extremely challenging and time consuming. In reality, large portions of the allocated spectrum are not actively used in space and time. To alleviate this disparity in spectrum use, researchers and policy makers have proposed the concept of Dynamic Spectrum Access (DSA), allowing devices to use unoccupied portions of spectrum without interfering with the licensee's transmissions [1], [2], [3], [4]. This technology was recently approved by the FCC for data communication in the unused TV channels, (also referred to as the TV white spaces) [5]–[10].

In this paper we investigate the use of DSA in other portions of spectrum beyond the TV bands. Using DSA to open more spectrum has been identified by the FCC in its Notice of Inquiry (NoI) [11] and the recent report by the President's Council of Advisors on Science and Technology (PCAST) [12], which recommends that the President direct government agencies to identify 1000 MHz to "create the first shared use spectrum super highways". This report also makes recommendations on various portions of federally-owned spectrum that can be dynamically shared with other devices.

However, despite the enthusiasm and excitement surrounding DSA, its usefulness in different portions of the spectrum, beyond TV, is largely unknown. This is because of two main reasons. First, the spectrum occupancy at different points in space and time is not available. Second, there is no good way to translate the occupancy in space, time, and frequency into the goodness of DSA techniques. For example, a 50% available spectrum might not be great for DSA if it is occupied for 500 ms every second, or uses 100 KHz in every 200 KHz of spectrum.

In this paper we take a two-pronged approach to identify the goodness of spectrum for DSA. First, through a unique measurement setup we scan different locations for spectrum availability in time, space and frequency. Second, we propose a framework to analyze the goodness of various spectrum bands for DSA by applying simple machine learning techniques, communication theory, and DSA principles. This framework proposes a DSA goodness metric to account for the time overhead of detecting the primary user (using sensing, geo-location database, etc.) and the frequency overhead for protecting primary users on adjacent frequencies. The proposed DSA goodness metric uses various tunable parameters, thus, allowing us to quantify and compare spectrum bands for a variety of DSA transmission and detection techniques.

The proposed DSA goodness metric is useful for spectrum regulators, existing licensees, and white-space devices. Spectrum regulators can use it to identify, compare and rank different bands in which DSA can be applied. Existing licensed spectrum holders can use this metric to determine the opportunity to send additional data on their spectrum. Finally, white-space devices can use this metric to identify and operate on spectrum bands that provide maximum available throughput.

In this rest of this paper we first discuss related work in Section II and then propose the DSA goodness metric in Section III. We present our measurement methodology in Section IV, some results based on our spectrum measurements in Section V, before concluding in Section VI.

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II. Related work

The utilization of licensed spectrum bands has been studied in several spectrum measurement campaigns to analyze the opportunity of dynamic spectrum access. Examples of some limited "snap-shot" spectrum occupancy studies in USA include [13] in Chicago, [14] in San Francisco, [15] in Denver, and [16]–[22] in other locations. Similar examples of international spectrum measurement campaigns include [23] in New Zealand, [24] in Singapore, [16] in Ireland, [25], [26] in Germany, and [27] in China. These spectrum measurement campaigns clearly indicate that the static spectrum allocated to licensed users is heavily underutilized.

Typically, the goodness of various spectrum bands in these studies is characterized by spectrum occupancy, i.e., statistical percentage of time the channels are occupied by licensed users. While spectrum occupancy is a good first-order indicator of the amount of spectrum available, DSA techniques often are not able to capitalize each available spectrum chunk because of several limitations. To account for this, the statistics of duty cycle, i.e., the time duration for which primary user turns on, have also been studied in [13], [24], [26]. Further, the temporal, spatial, and spectral correlation of some of the licensed spectrum bands has been studied in [27].

Clearly, DSA opportunity in any spectrum band will not only depend on the amount of unused spectrum, but other factors such as duty cycle, correlations in time, frequency or spatial dimensions, etc. as discussed in above-mentioned references. However, it is unclear how these metrics combine to give us a single goodness metric to compare the DSA opportunity in various spectrum bands. Reference [28] tries to address this question by studying the amount of usable 200 KHz chunks for sensing based DSA techniques based on four different spectrum measurement datasets. Although it presents useful aggregate information, [28] falls short of our goal in this paper – to come up with a general methodology that compares the goodness of spectrum bands for dynamic spectrum access.

III. Defining a DSA Goodness Metric

Dynamic spectrum access allows a secondary user, which we also refer to as a white-space device in this paper (since it uses unoccupied spectrum), to use the unused portions of the spectrum in licensed bands. The white-space devices periodically detect primary licensed users, using either sensing or geo-location services, and operate in the spectrum band if it is unoccupied in that slot.

While spectrum occupancy by licensed users provides a good first-order metric to identify the amount of unused spectrum, effective use of available spectrum chunks requires each white-space device transceiver to establish spectrum availability and transmit in the available spectrum chunk with minimal overhead. Thus, the usefulness of any available spectrum chunk to a white-space device depends on the choice of DSA transmission and detection technique, and even the useful spectrum chunks incur additional overheads in lieu of protecting the primary users from harmful interference.

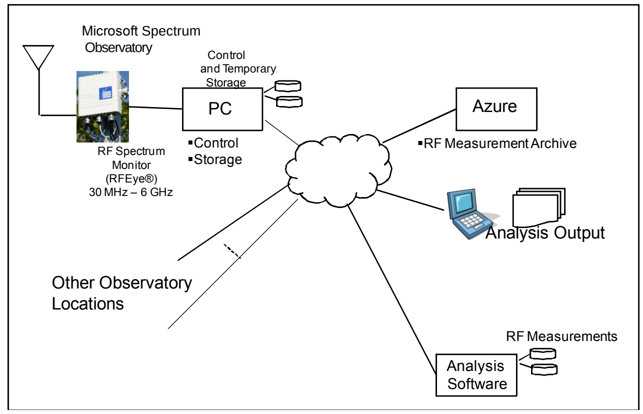

Fig. 1. Setup of the Microsoft Spectrum Observatory. Power spectral density measurements are collected in 30 MHz–6 GHz by a wideband antenna and RFeye receiver device. The data is stored in the cloud and selectively retrieved by analysis software to obtain DSA goodness metric etc.

In this paper, we propose a novel *DSA goodness metric* to quantify the usefulness of DSA in different portions of the spectrum. We propose two different metrics to account for transmission overheads and for the overheads in detecting an unused spectrum chunk: *DSA bandwidth metric* and *DSA detectability metric*. We combine the two metrics in a single DSA goodness metric, which also uses a DSA spatial variability metric to account for the spatial variation in unused spectrum chunks at the white-space device transmitter and receiver. To evaluate the goodness of different spectrum chunks, we require spectrum occupancy measurements of these spectrum chunks at different points in space, time, and frequency. For this purpose, we use power spectral density (PSD) measurement data collected at a spectrum observatory in spectrum bands between 30 MHz and 6 GHz. Figure 1 illustrates the setup of the spectrum observatory where the collected PSD measurement data is downloaded from the cloud and analyzed to evaluate the DSA goodness metric in different spectrum bands. Further details on the setup in Figure 1 are discussed in Section IV.

In the following subsections, we first review the spectrum availability metric and then propose our new DSA goodness metric.

A. DSA Spectrum Availability Metric

We first answer the following question: which portions of spectrum from our measurement are unoccupied?

A white-space device may use a variety of techniques to detect unused portions of the spectrum, such as, energy detection, cyclostationary detection, and beacon detection [3], [29]. However, to establish the goodness of various spectrum bands, a spectrum observatory is more likely to use the simplest technique, i.e. energy detection over a wide bandwidth, that captures the received energy values in dBm/Hz in different portions of the spectrum. The challenge in analyzing the collected power spectral density (PSD)

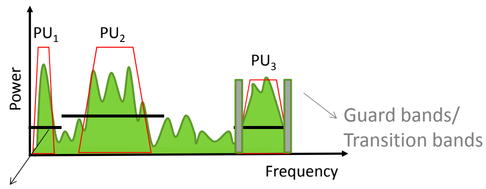

Fig. 2. Plot of collected PSD values with frequency (x-axis). The collected PSD values correspond to primary user's transmission or noise. A guard band can be used to determine the licensed user's noise floor. PSD Threshold is chosen such the PSD values below the threshold indicate unused spectrum available to a white-space device.

values is translating them to the goodness of different spectrum bands for DSA. A thresholding technique is the simplest way to separate the PSD values that correspond to a primary user's signal from the noise and interference. In the thresholding technique, as shown in Figure 2, a PSD threshold is chosen such that any PSD value above the threshold means the spectrum chunk is occupied by the primary user, while a PSD value below the threshold means we are detecting noise and a white-space device may use the spectrum chunk.

Techniques to set PSD thresholds for TV white-space devices have been studied widely in the literature, for example, binary hypothesis testing [29]. Typically, a PSD threshold set at the noise floor of the primary user devices means the white-space device is unlikely to interfere with the primary user. Setting the PSD threshold lower than the noise floor would result in missed opportunities of available white-spaces. The threshold can be set higher if we have knowledge of the primary transceiver's noise figure etc., but it may increase the number of missed detections of primary transmissions.

The problem of detecting a primary user from a spectrum observatory is more complicated. First, in our measurement setup we want to detect occupancy beyond a single measurement point. So, the threshold should be set to the lowest possible level. Second, the noise floor and primary user's transceiver knowledge may not always be available when we attempt to compare the goodness of a diverse set of spectrum chunks occupied by primary users such as radars, satellites, TV stations, GPS etc.

Many spectrum measurement campaigns in the literature [13], [24], [26], [27] use a fixed PSD threshold across various spectrum bands that is set conservatively based on a randomly picked value because of inadequate knowledge in various spectrum bands. In this paper, we propose a thresholding technique based on the empirical data collected from the spectrum observatory.

In our proposed method, the PSD threshold is set based on the probability distribution of the primary user's signal, PSD values in a guard band, and the measurement noise floor. We first obtain the measurement equipment noise floor by collecting the PSD statistics when the spectrum observatory is not collecting any data. Thereafter, we determine the primary user's noise floor by collecting PSD statistics in a guard band because the guard band is likely to be empty or only contain noise. In the case of TV channels, an empty TV channel can also be used to determine the TV channel's noise floor. Thereafter, we compute the empirical probability distribution of PSD values in the primary user's spectrum chunk. The PSD statistics of the primary user's signal are compared to the PSD statistics of the primary user's noise floor in the guard band and measurement equipment noise floor. We set the PSD threshold at the maximum noise floor in the primary user's band. This method is particularly useful in setting the appropriate noise floor in different spectrum bands from empirical data when the primary user's signal can be clearly separated from the noise signal. Further, we can combine it with primary receiver sensitivity and noise figures where such information is available.

Consider a spectrum band i of bandwidth B_i where N PSD measurements have been collected at a sampling frequency of B_i/N at sampling times $\{s = 1, \ldots, S\}$ for a long duration. Let $\{b_1, \ldots, b_N\}$ denote the bandwidth of N sampled frequency points in the spectrum band and $PSD(b_k, s)$ denote the PSD measurement at sampled time s in the k-th sampled frequency point. Then, the above-mentioned technique gives us the PSD threshold $PSD\text{-}Thresh(B_i)$ for the spectrum band at each sampling time s. All PSD measurements below the PSD threshold $PSD\text{-}Thresh(B_i)$ indicate the spectrum band is available for DSA use. Therefore, the spectrum availability metric that quantifies the percentage of unused bandwidth can be mathematically defined as follows

$$\text{DSA-SA}(B_i, S, N) = \frac{\sum_{s=1}^{S} \sum_{k=1}^{N} b_k 1_{\{PSD(b_k,s) \leq PSD\text{-}Thresh(B_i)\}}}{B_i S}, \tag{1}$$

where $1_{\{\text{condition “c”}\}}$ is an indicator function that takes the value 1 when condition “c” is evaluated true and takes value 0 otherwise. While spectrum availability serves as a good first-order metric to quantify the unused spectrum and the potential of DSA use, it fails to account for transmission overheads or overheads in detecting the unused spectrum chunks.

B. DSA Goodness Metric

In this subsection, we propose a novel DSA goodness metric to quantify the usefulness of DSA techniques in different spectrum chunks. The usefulness of a DSA technique depends on how much of the unused spectrum can be used for actual data communication by a white-space device. For example, a 50% available spectrum might not be great for DSA if it is occupied for 500 ms every second, or uses 100 KHz in every 200 KHz of spectrum. Each unused or available spectrum chunk incurs overheads based on the choice of transmission technique and detection method for determining available spectrum chunks. These overheads will be different based on the properties of the licensed user in different spectrum bands. We first discuss a DSA bandwidth metric to account for the transmission overheads and then a DSA detectability metric to account for the detection overheads. Finally, we combine the two metrics to a DSA goodness metric that can translate the occupancy in space, time and frequency into the goodness of DSA techniques.

1) DSA Bandwidth Metric: The unused spectrum chunks in any spectrum band may vary in their widths based on the licensed user's behavior. For example, TV bands use channelization and each empty TV channel makes available a 6 MHz unused spectrum chunk. On the other hand, licensed bands occupied by multiple licensed users or frequency-hopping radars do not have a clear channelization pattern and the unused spectrum chunks might vary in width.

A white-space transmitter-receiver pair may choose between single-carrier, multi-carrier, or frequency hopping transmission schemes based on the licensed user's behavior and the channel characteristics. However, the white-space device must capitalize on contiguous spectrum chunks because non-contiguous chunks of spectrum incur additional overhead in terms of guard bands to protect the primary user's transmission. Figure 3 illustrates an example of two different spectrum bands with two unused spectrum chunks where these chunks are contiguous in band 1 thus resulting in a single guard band, while these chunks are non-contiguous in band 2 thus resulting in four guard bands. DSA bandwidth metric measures the spectrum availability in contiguous spectrum chunks and accounts for transmission overheads as a result of these guard bands. Therefore, DSA bandwidth metric is higher for band 1 in this example.

Consider a white-space transmitter-receiver pair would like to use a set of K_i contiguous spectrum chunks $\mathscr{C}_i = \{C_1, \ldots, C_{K_i}\}$ in the i-th spectrum band with bandwidth B_i. Let $\{b_1(i,C_j), \ldots, b_{N_j}(i,C_j)\}$ denote the bandwidth of N_j sampled frequency points and let $PSD(b_k(i,C_j),s)$ denote the PSD measurement collected at k-th sampled frequency point at sampled time s in spectrum chunk C_j of the i-th band. Then, the spectrum chunk C_j is unused if the PSD measurements are below the PSD threshold $PSD\text{-}Thresh(B_i)$ at all the sampled frequency points, i.e., C_j is available if $PSD(b_k(i,C_j),s) < PSD\text{-}Thresh(B_i) \quad \forall\{k = 1, \ldots, N_j\}$. DSA bandwidth metric quantifies the spectrum available only in contiguous spectrum chunks and incurs a penalty for guard bands. It can be mathematically defined as follows

$$\text{DSA-BW}(B_i, \mathscr{C}_i, S, G_i) = \frac{\sum_{j=1}^{N_j} \sum_{s=1}^{S} (BW(C_j) - 2G_i) 1_{\{C_j \text{ available at time } s\}}}{B_i S}, \quad (2)$$

where $BW(C_j) = \sum_{k=1}^{N_j} b_k$ is the total unused bandwidth in spectrum chunk C_j, and G_i is the penalty incurred for non-contiguity in terms of a guard band used on both edges of a contiguous spectrum chunk.

DSA bandwidth metric serves as a useful parameter for measuring the useful bandwidth after accounting for transmission overheads in protecting the primary users, but abstracts out the actual transmission technique used based on the channel fading and SINR conditions. The contiguous spectrum chunks may correspond to the channels used by the white-space device such as 6 MHz channels for TV bands if the white-space device uses single-carrier transmission. The contiguous spectrum chunk may be further sub-divided into sub-carriers if the channel is frequency-selective and requires multi-carrier transmission. DSA bandwidth metric accounts for available spectrum in contiguous spectrum chunks, but fails to account for the time duration for which these contiguous spectrum chunks are available.

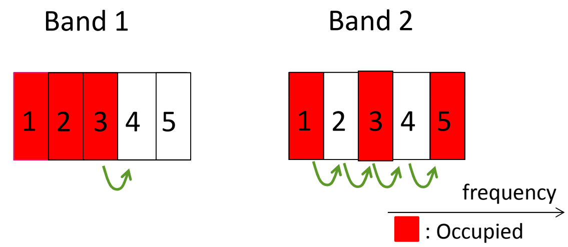

Fig. 3. DSA bandwidth metric for Band 1 is higher than Band 2 because a contiguous spectrum chunk is available to white-space device in Band 1. Each transition from or to an unused spectrum chunk (green arrows) is penalized by guard bands.

2) DSA Detectability Metric: When the availability of contiguous spectrum chunks changes, a white-space device must detect this change of availability and handshake with its receiver to re-establish communication with its receiver, thus incurring additional overhead. A white-space device may therefore choose a transmission time duration such that a fraction of this duration is used for detecting unused time slots and handshake protocol with the receiver, while the remaining is used for data communication. Clearly, the transmission time duration must be chosen such that most of this time is used for data communication. Therefore, some available spectrum chunks available for very short durations may not be useful for DSA because most of the time is used up in detection and handshake overhead, for example, when a spectrum chunk is occupied for 500ms in every second.

DSA detectability metric quantifies the useful transmission time for various DSA techniques by accounting for the detection overheads. Figure 4(a) illustrates an example where DSA detectability metric for band 2 is higher than band 1 because availability of spectrum chunks changes in every time slot in band 1 even though larger contiguous spectrum chunks are available at first time slot while the second, third, and fifth spectrum chunks are available contiguously for three time slots in band 2. The overhead of detection and handshake protocols varies for different DSA techniques and we discuss the overheads of some known DSA techniques below:

1) Oracle-based DSA technique: This technique assumes the presence of an oracle that informs the white-space device when the licensed user turns on or off. Thus, the overhead is merely in handshake protocol between white-space device transmitter to begin or terminate the communication. We can quantify this overhead in terms of guard slots in time for each state transition of the licensed user from 'on' state to 'off' state and vice-versa as shown in Figure 4(a).
2) Sensing-based DSA technique: This technique assumes that the white-space device uses energy detection or

sensing to establish the presence of licensed user [29]. Therefore, it incurs an overhead of sensing time it takes to establish the licensed user's presence because the white-space device requires a sufficient number of PSD measurements to establish the presence of a licensed user [30]. The number of samples required by an energy detector can depend on the signal-to-noise ratio of the primary user, probability of false alarm and missed detections, and the noise uncertainty model as discussed in [30]. The exact sensing time may be computed based on the number of samples required, but we can account for the sensing time overhead by treating it like a guard slots in time for each state transition of the licensed user from 'on' state to 'off' state and vice-versa similar to Oracle-based DSA technique.

3) Geo-location based DSA technique: This technique assumes that the white-space device uses a geo-location database to ascertain the presence of licensed users. Typically, a geo-location database [4] uses a polling time interval that defines the time intervals at which the geo-location database is updated. Thus, one can't use spectrum slices that are available for less than the polling time interval as shown in Figure 4(b). Further, the white-space device establishes communication with its receiver by either querying the geo-location database or listening to a primary user's beacons. Therefore, the overhead for this technique is the beacon duration or the duration for enquiring the database.

Let us define the transmission time duration as ΔT. As discussed for DSA bandwidth metric, consider a white-space transmitter-receiver pair that decides to use a set of K_i contiguous spectrum chunks $\mathscr{C}_i = \{C_1, \ldots, C_{K_i}\}$ in the i-th spectrum band with bandwidth B_i. At sample time s, the spectrum chunk C_j is unused if the PSD measurements are below the PSD threshold $PSD\text{-}Thresh(B_i)$ at all the sampled frequency points, i.e., C_j is available if $PSD(b_k(i,C_j),s) < PSD\text{-}Thresh(B_i) \quad \forall\{k = 1,\ldots,N_j\}$. Let $\{\Delta t_1,\ldots,\Delta t_M\}$ be M contiguous time durations for which the spectrum chunk C_j becomes available. Then, the DSA detectability metric for each spectrum chunk C_j in the i-th spectrum band accounts for the useful transmission time in time durations where the chunk is available for a contiguous time duration larger than transmission time duration ΔT and incurs a penalty for the detection overhead. It can be mathematically defined as follows

$$\text{DSA-DET}(C_j, S, \Delta T, \Delta t_{det\text{-}overhead}) = \frac{\sum_{m=1}^{M} (\Delta t_m - \Delta t_{det\text{-}overhead}) 1_{\{\Delta t_m > \Delta T, C_j \text{ available for duration } \Delta t_m\}}}{S}, \tag{3}$$

where $\Delta t_{det\text{-}overhead}$ is the overhead in time incurred for detection and handshake protocol in each transmission time duration ΔT.

3) DSA Goodness Metric – Combining DSA Bandwidth and DSA Detectability Metric: A white-space device transmitter and receiver can establish a link successfully if they can detect the unused spectrum chunks and transmit

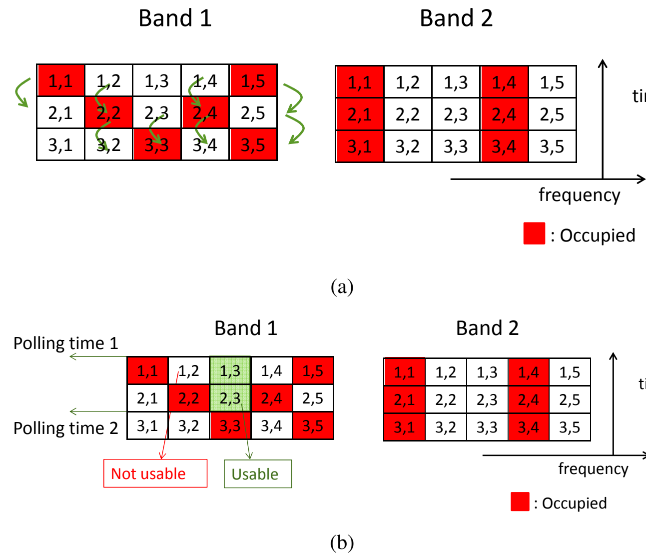

Fig. 4. DSA detectability metric is higher for Band 2 because the contiguous spectrum chunks have fewer transitions and thus lower overhead in detection and handshake as shown for (a) Oracle based or sensing based DSA techniques and (b) Geo-location based DSA techniques.

on them with minimal overheads. In the previous subsections, we discussed DSA bandwidth metric that accounts for transmission overheads and DSA detectability metric that accounts for the detection overheads. However, both these metrics only considered the PSD measurement values from a single spectrum observatory location that can correspond to a white-space transmitter. We would like to consider the spectrum availability at both white-space transmitter and receiver. Therefore, we define a DSA spatial variability metric that captures the conditional probability the spectrum C_j is available at a white-space receiver assuming it is available at the white-space transmitter, i.e., $\text{DSA-SV}(C_j) = Pr(C_j \text{ available at white-space RX} | C_j \text{ available at white-space TX})$. Then, we can define DSA goodness metric as follows

$$\begin{aligned} &\text{DSA-Goodness}(B_i, \mathscr{C}_i, S, \Delta T, G_i, \Delta t_{det\text{-}overhead}) = \\ &\sum_{j=1}^{N_j} Pr(C_j \text{ available at both white-space TX and RX}) = \\ &\sum_{j=1}^{N_j} Pr(C_j \text{ available at white-space TX}) \times \text{DSA-SV}(C_j), \end{aligned} \tag{4}$$

where the availability of spectrum chunks is assumed to be independent if they are different. Now, we can compute the $Pr(C_j \text{ available at white-space TX})$ using the DSA bandwidth and detectability metrics by $\frac{(BW(C_j) - 2G_i)}{B_i} \times \text{DSA-DET}(C_j, S, \Delta T, \Delta t_{det\text{-}overhead})$, where the first fraction derives from the DSA bandwidth metric and accounts for the transmission overheads in spectrum chunk C_j. Therefore, DSA goodness metric quantifies the usefulness of spectrum bands at the white-space transmitter by combining both the DSA bandwidth metric and DSA detectability metric, while the DSA spatial variability metric accounts for the spatial variation in spectrum availability at the white-space receiver relative to the transmitter. After substituting the expression for $Pr(C_j \text{ available at white-space TX})$ in equation (4), the

DSA goodness metric can be mathematically defined as follows

$$\text{DSA-Goodness}(B_i, \mathscr{C}_i, S, \Delta T, G_i, \Delta t_{\textit{det-overhead}}) = \sum_{j=1}^{N_j} \frac{(BW(C_j) - 2G_i)}{B_i} \times \text{DSA-DET}(C_j, S, \Delta T, \Delta t_{\textit{det-overhead}}) \times \text{DSA-SV}(C_j). \tag{5}$$

For this paper, we will assume DSA spatial variability metric to be 1, i.e., spectrum chunk C_j is assumed to be available at a receiver if it is available at transmitter. We will investigate the spatial variability further in future studies with additional PSD measurements around the spectrum observatory locations.

IV. Measurement Methodology

This section discusses the measurement setup for spectrum observatory as shown in Figure 1. The spectrum observatory has been set up initially in three different locations: Redmond, Seattle, and Washington DC. A wideband MP Ultra Base Antenna and a CRFS RFeye receiver collects PSD measurements at a sampling interval of 1–2 seconds from 30 MHz–6 GHz. The sampling frequency at which measurements are collected in different bands varies with the spectrum bands and only the sampling frequencies for spectrum bands considered in Section V are discussed here. The sampling frequency is set to 163.2 KHz in the TV bands (512–700 MHz), 54.69 KHz in ISM band (902–928 MHz), 312.5 kHz in the cellular bands (1850–2000 MHz), satellite digital audio radio service (SDARS) (2320–2345 MHz), educational/broadband radio band (2500–2655 MHz), and wifi bands (2400–2483.5 MHz and 5470–5725 MHz).

Each spectrum observatory collects the PSD measurement data from the RFEye receiver in temporary storage and subsequently pushes it via internet to a storage archive in Azure. The analysis software retrieves the relevant datasets from Azure and processes them in .NET framework to collect relevant statistics such as goodness metrics, part of which are published on the Microsoft spectrum observatory website [31].

V. Evaluation Methodology & Numerical Results

This section discusses the evaluation methodology to obtain the DSA goodness metric based on the PSD measurement data collected using the measurement setup (Figure 1). For the sake of simplicity, the results in this section are based on the measurements for a single day (18 July, 2012) and a single location Redmond.

As a first step, the PSD threshold is chosen in each spectrum band based on the collected PSD measurement data using the approach discussed in Section IIIA. We choose a guard band set of 200 kHz on the edge of the spectrum band and compare the cumulative distribution function (CDF) of the PSD values collected for the measurement equipment noise floor, guard band, and the spectrum band without the guard band. The PSD threshold is chosen such that signal values in the spectrum band are clearly separated from the noise floor or interference in the guard band.

The results in this section use a conservative PSD threshold set to the maximum of 100-th percentile value of measurement noise floor PSD values and the primary user noise floor PSD values in the empty guard band. Figure 5 illustrates an example of PSD CDF plots for the 584–590 MHz TV channel and 1850–2000 MHz cellular band. The CDF for PSD values of the spectrum (red) is clearly separated from the guard band and measurement noise floor and we use the above procedure to set the PSD Threshold at -101 dBm/Hz for the 584–590 MHz TV channel and -100 dBm/Hz in the cellular band (1850–2000 MHz). Also, note that one of the guard band for TV channel (black) in Figure 5(a) is heavily corrupted by adjacent channel interference and is not considered. Similar procedure results in PSD threshold set to -101 dBm/Hz in the other TV channels (524–530 MHz and 566–572 MHz), -107 dBm/Hz in the ISM band (902–928 MHz), -99 dBm/Hz in satellite digital audio radio service (SDARS) (2.32–2.345 GHz), -99 dBm/Hz in 2.4–2.4835 GHz wifi band, -96 dBm/Hz in 5.47–5.725 GHz wifi band, and -90 dBm/Hz in 2.5–2.655 GHz educational/broadband radio band. Note that these PSD thresholds are compared against the PSD value at each sampled frequency point and a fair comparison of PSD thresholds in different bands must account for the sampling frequency in those bands.

The spectrum availability and DSA goodness metric can be analyzed once a PSD threshold is chosen for any given spectrum band. The DSA bandwidth metric is computed using equation (2) where we choose the size of the contiguous spectrum slice $BW(C_j) = BW(C_k) \forall j \neq k \quad j,k \in \{1,\ldots,K_i\}$ for the i-th spectrum band and the white-space device transmits on this contiguous spectrum slice. If the size of contiguous spectrum slice equals the sampling frequency, then, the DSA bandwidth metric would only incur the penalty of guard bands over spectrum availability metric. However, as we set the contiguous spectrum slice to higher values of 1 MHz, 10 MHz and so on, DSA bandwidth metric will lose the non-contiguous spectrum slices and thus, decrease compare to the spectrum availability metric. Figure 6 illustrates the decrease in DSA bandwidth metric as the size of contiguous spectrum slice, also known an channel width here, increases from 1 MHz to 20 MHz for different bands.

The DSA detectability metric for each contiguous spectrum slice is computed using equation (3) where we choose the transmission time duration ΔT or the polling duration ΔT for geo-location database. For a given size of the contiguous spectrum slice $BW(C_j)$, the DSA detectability metric will decrease as ΔT increases from sampling time interval to higher values of 20 seconds or 1 minute. Figure 7 illustrates the decrease in the DSA detectability metric for different contiguous spectrum chunks (denoted by different colors) as transmission time interval ΔT increases in 902–928 MHz ISM band and 1850–2000 MHz cellular bands. The size of contiguous spectrum chunk or channel width is set to 2 MHz

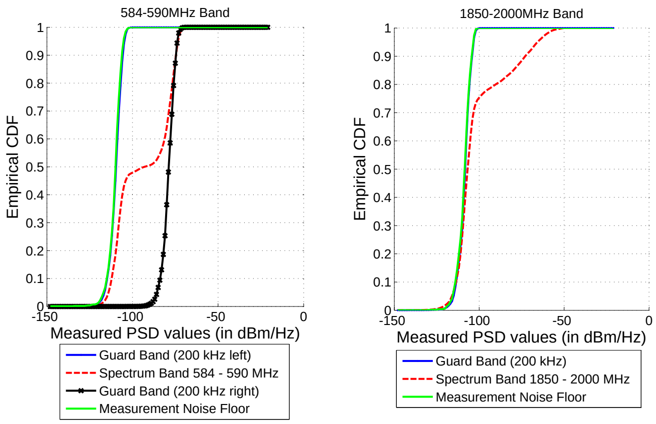

Fig. 5. Cumulative distribution function of measured PSD values in (a) (left) TV channel 584–590 MHz (b) (right) Advanced wireless services 2 (AWS2) band 1850–2000 MHz. Note that the measurement noise floor (green) and guard band (blue) curves overlap.

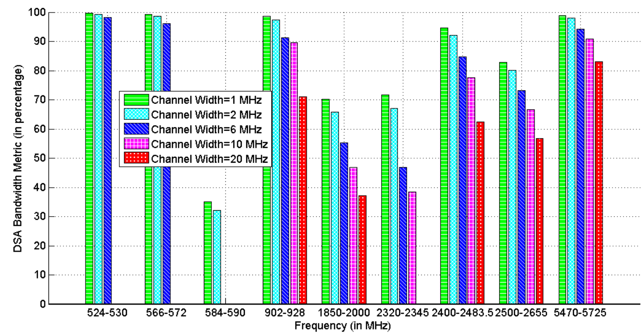

Fig. 6. DSA Bandwidth Metric (in percentage) remains same or decreases for different spectrum bands as channel width increases. Note that DSA Bandwidth Metric (y-axis) is plotted as a percentage of the absolute bandwidth available in the band, i.e. 50% availability in 150 MHz provides more bandwidth than 100% availability in a 6 MHz band.

for 902–928 MHz ISM band and 5 MHz for 1850–2000 MHz cellular band. Note that different channels (denoted by different colors) can exhibit a large variation in DSA detectability metric in a band for the same transmission time interval ΔT. This emphasizes the importance of DSA detectability metric and why spectrum availability metric and DSA bandwidth metric alone do not characterize the goodness of a spectrum band.

The DSA goodness metric is computed using equation (5) where we can tune the size of the contiguous spectrum slice $BW(C_j)$, the transmission time duration ΔT or the polling duration ΔT, the penalties for guard band and detection overhead: G_i and $\Delta t_{det\text{-}overhead}$. Figure 8 illustrates a comparison of spectrum availability metric and DSA goodness metric with different values of $BW(C_j)$ and ΔT for 902–928 MHz ISM band and 1850–2000 MHz cellular band. Here, the spectrum availability metric quantifies the unoccupied spectrum in the spectrum band by using equation (1) to quantify the PSD measurement values below the chosen PSD threshold. These examples clearly indicate that the DSA goodness metric can be much lower than the spectrum availability and spectrum availability alone does not capture how much of the spectrum is usable in different spectrum bands.

The DSA goodness metric results assumed zero penalty for guard band and detection overhead, but any non-zero penalties decrease the DSA goodness metric further. However, appropriate choice of guard band and detection overhead requires us to bound the white-space device transmit powers and the potential interference from white-space device users to licensed users. The calculation of white-space device transmit powers is not considered in this paper, but will be investigated further in our future studies.

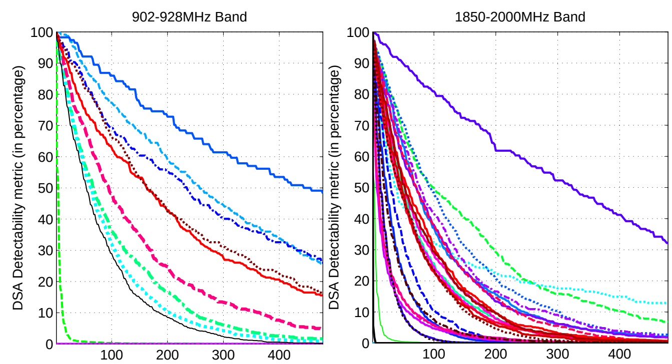

Fig. 7. DSA Detectability Metric (in percentage) for different contiguous chunks decreases as transmission time duration ΔT increases for (a) (left) ISM band 902-928 MHz with channel width = 2 Mhz, (b) (right) Advanced wireless services 2 (AWS2) band 1850–2000 MHz with channel width = 5 MHz. Note that the rate of decrease can vary widely for different contiguous chunks in the same band.

VI. Conclusions & Future Work

DSA is considered to be one of the key alleviators of the current spectrum crunch. It allows devices to send and receive data in unused portions of spectrum in such a way that these devices do not interfere with a primary user's transmissions. Therefore, an important question confronting the spectrum regulators and policy makers is which bands to open up for DSA networks.

In this paper we have presented a framework and a new metric to evaluate different portions of spectrum for DSA. We have shown that more available bandwidth does not always translate to better DSA networks, and have presented a metric that captures the different variables that affect the goodness of DSA.

However, we are not done yet. Moving forward we want to analyze the data over longer durations, and over many more locations. In particular, we are actively working on adding mobile measurements in our setup to capture the spatial

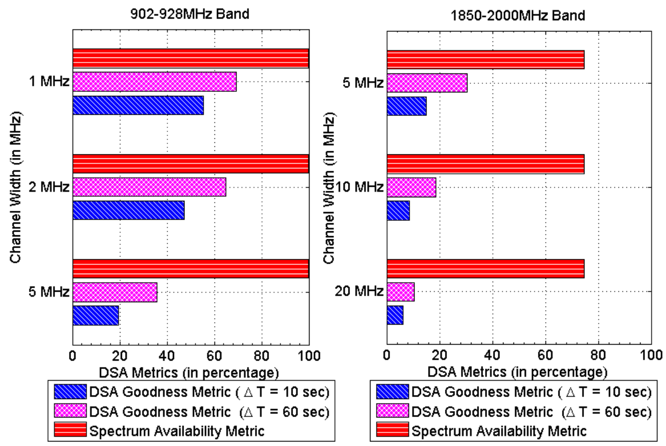

Fig. 8. Comparison of Spectrum Availability Metric and DSA Goodness Metric (in percentage) for different channel widths and transmission time interval ΔT in, (a) (left) ISM band 902–928 MHz and (b)(right) Advanced wireless services 2 (AWS2) band 1850–2000 MHz. DSA goodness metric decreases as both channel width and ΔT increases. Note that DSA metrics (x-axis) are plotted as a percentage of the absolute bandwidth available in the band.

variation in spectrum use. Together, we hope to achieve the vision of more efficient spectrum use through DSA in all the spectrum bands.

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