Multi-Tier Exclusion Zones for Dynamic Spectrum Sharing

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Abstract—Reducing the size of exclusion zones (EZs) in spectrum sharing is vital for efficient utilization of fallow spectrum as well as for the economic viability of spectrum sharing itself. In this paper, we explore two approaches for reducing the size of EZs. We show that multi-tiered EZs can be used to improve spectrum utilization efficiency by implementing the concept of differential spectrum access hierarchy. Also, we provide quantitative results that show the impact of using a point-to-point mode terrain profile in calculating an EZ’s contour. Such a terrain profile captures the effects of propagation losses due to area-specific topography, which are not considered by the F-curves, a common method of calculating an EZ’s boundary. Our results indicate that the use of such a terrain profile results in a noticeable decrease in the size of an EZ.

I. INTRODUCTION

The Federal Communications Commission (FCC), in its Notice of Proposed Rule Making (NPRM) [1] for the 3.5 GHz band, proposed the use of small cells and spectrum sharing in the newly created Citizens Broadband Service (CBS) band. The FCC’s plans for the CBS band include the use of Spectrum Access System (SAS) for managing spectrum sharing. SAS is a dynamic database system that is capable of adding a number of unique capabilities such as real-time assessment of spectrum availability, adjustment of the Exclusion Zones (EZs) of the Primary Users (PUs), interference protection, operational privacy [2], enforcement of regulatory policies, and other interference mitigation and coexistence techniques [3]. It will ensure that the CBS users operate only in areas where they would not cause harmful interference to the PUs, and could also help manage interference protection among different tiers of CBS users. The three tiers of service, as proposed in the FCC’s NPRM are: Incumbent Access (IA), Priority Access (PA) and General Authorized Access (GAA). IA users have exclusive rights to the spectrum while GAA users are the lowest priority users in accessing the shared band.

EZs are static spatial separation regions around the PU where secondary users (SUs) are not allowed to operate [4]. EZ boundaries are based on interference threshold at which the receiver’s performance starts to degrade, for both primary and secondary receivers [1]. Existing techniques for computing PU EZ either use statistical pathloss models or models that have very limited usage of the terrain [4], [5]. This leads to conservatively large EZ boundaries as the model has to account for possible deep fades, the 802.22 working group specifications require detectors to have a sensitivity of -116 dBm which corresponds to a safety margin of roughly 20 dB (equivalent to an increased radius of the EZ by 110 km) [6]. In most situations, detectors do not face such severe fading, and hence the SUs are unnecessarily prohibited from using the band even though they do not cause interference to the PUs.

Shrinking the size of EZs can greatly increase the economic benefits of spectrum sharing, as the following example shows. Based on NTIA’s EZ calculations for shipborne radar systems in 3.5 GHz band, it is estimated that approximately 60% of the United States population fall within the EZs [7]. This implies that a reduction in EZ size by x in percent) enables x × (60% of 308.745 million) = 185.247x million of potential users to use the CBS band, assuming a uniform population density. Here, the US population of 308.745 million is taken from the US census 2010 [8]. Since the spectrum price is inversely proportional to the square of the frequency [9], and the 700 MHz band is currently priced at $1.50 per MHz/POP ($1.28 from 2008 auction adjusted for inflation) [10], sharing the CBS bandwidth of 150 MHz results in an increased revenue of 1.67x billion dollars, assuming that a licensed-like scheme will be implemented. Note that this increased revenue is in addition to the revenue collected by sharing the band outside the current EZs.

To overcome the underutilization of the precious spectrum, terrain details can be incorporated to capture the actual propagation environment between the PUs and SUs. For contour estimation over irregular terrain, the terrain profile of a particular area needs to be taken into account for estimating the pathloss [11]. The terrain profiles between two points in any geographical area can be extracted from the publicly available terrain databases such as Global Land One-km Base Elevation (GLOBE) [12], Shuttle Radar Topographic Mission (SRTM) [13], National Elevation Dataset (NED) [14], etc. It may vary from a simple curved earth profile to a highly irregular mountainous profile. The presence of scattering due to trees, buildings, and other obstacles must also be taken into account. These realistic propagation effects make the EZ irregular shaped and significantly smaller in size.

Propagation models like the Irregular Terrain Model (ITM) in point-to-point (P2P) mode includes the terrain details in the pathloss computation [15]. It is often argued that sophisticated propagation models like the ITM are computationally expensive, and they cannot be implemented in real-time. However, since the EZs are static in nature (for stationary PUs), advanced geolocation databases like the SAS can pre-compute the pathloss over the entire service area. The pathloss computations can be coarse in less populated areas while it can

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be done with fine resolution in highly populated areas for maximizing the spectrum utilization. These pre-computed pathloss values can then be used to compute spectrum availability in real-time, and provided to the requesting SUs.

There are several types of PUs in the CBS band, but in this paper, we limit our discussions to the analysis of EZs of large-scale PUs that have high transmit powers and their EZ spans over a substantial geographic area. On the other hand, SUs (PA/GAA users) are small cell technologies and they transmit with relatively low power [1]. In this scenario, the minimum distance between a PU and SUs is large enough and the transmission power discrepancy between the two is sufficiently large such that interference from SUs to a PU is negligible. In order to increase spectrum utilization, we propose to divide a EZ into multi-tiered EZs, where the boundary between two tiers is defined based on the interference tolerance threshold, \(I_{th}\), of SUs. SUs with larger \(I_{th}\) (GAA users) will be able to operate closer to PUs as compared to SUs with smaller \(I_{th}\) (PA users). This approach is in line with NPRM’s proposed-idea of differential spectrum access hierarchy for distinct tiers of SUs that are in the vicinity of PU. Our proposed interference based multi-tier EZs are smaller than conventional EZs, and offer improved SU spectrum utilization by allowing more area for SU usage around the PU location.

The core contributions of this paper are summarized below:

- We propose the concept of differential spectrum access hierarchy, and define it in the context of a multi-tiered EZs that are based on quantiles of tolerable interference levels for different tiers of SUs. We also quantify and show the gain in SU capacity (or throughput) obtained by using multi-tiered EZs for different tiers of SUs.
- Using simulation results, we show that the size of EZs can be significantly reduced with the use of a terrain-based propagation model that considers terrain profile for signal attenuation between PUs and SUs in the P2P link.

Most of the existing work on techniques for reducing the size of EZs focus on the TV band. Unfortunately, the propagation characteristics and the spectrum sharing paradigm of the CBS band are quite different from that of the TV band (e.g., multi-tier EZs in CBS as opposed to single EZ in TV band). Hence, the existing techniques cannot be directly applied to the CBS band. This paper, to the best of our knowledge, is the first to present quantitative results on the impact of reducing the size of the EZs on the spectrum utilization efficiency of the SUs operating in the CBS band.

II. RELATED WORK

In spectrum sharing studies, the F-curves [16], [17] are well accepted and widely used for propagation analysis. However, these models have a drawback that they are only statistical indicators of the expected field strengths and received signal power, given an antenna model [18]. Actual PU received interference fluctuate based on terrain variations, environmental conditions, achieved antenna gain patterns, etc. Since a database-driven spectrum sharing uses propagation models to define the EZs, their accuracy in practice is of utmost importance. The most common cause of propagation modeling error is due to non-average terrain variations. In practice, actual terrain variations often induce more pathloss, and hence, often reduce the size of EZ than that generated by the statistically modeled values. These effects typically become even more pronounced for low antenna height systems, such as would be typical in small cell CBS systems. The ITM in P2P mode provides terrain-specific propagation losses along with the statistical reliability parameters as predicted by the F-curves. These capabilities makes it a preferred propagation model for use in the SAS.

The major drawback of using terrain enabled propagation models is their added computational complexity and memory requirement when compared with the models without terrain. Despite these drawbacks, recent studies have shown encouraging results towards using terrain enabled models in database-driven spectrum sharing for identifying TV whitespaces. In [19], Gurney et. al. argued that the actual propagation calculations do not have to store detailed terrain databases, but can still incorporate terrain effects into the service contour calculations. In [20], Murty et. al. showed that FCC’s PU database update is relatively less frequent, once in two days on average. Based on this observation, they demonstrated the viability of pathloss (and whitespace) pre-computations to reduce the computational burden of the database. These pre-computed results can be cached and reused for replying to future spectrum queries. They also showed that maintaining a per-region terrain server for each region further reduces the computation latency. These studies show that using terrain information in the pathloss computations leads to a substantially large gain in the available white spaces for secondary usage, which justifies their use in the development of spectrum sharing systems despite their added complexity. Furthermore, a similar terrain-based frequency coordinator (which is similar in concept to the SAS) was proposed in the medical body area networks (MBANS) FCC ruling for the 2360–2390 MHz band [21].

III. TECHNICAL BACKGROUND

A. Exclusion Zones

The FCC proposes to create the CBS in the 3.5 GHz band [1]. A three-tiered spectrum access and authorization framework [22] with IA, PA and GAA users is proposed with the use of EZs for coexistence between federal systems and commercial broadband systems. The NPRM acknowledges that the current interference analysis technique used in the fast track report [4] needs significant improvement, so that the size of the EZs can be reduced. This will allow more commercial uses of the band in highly populated areas. Furthermore, a SAS [3] will be managing the operations of multiple tiers of users in this band.

We define EZs for PUs with high transmit power and a substantial signal coverage area [4]. In this case, the SU interference is negligible due to: (1) low transmit power of SUs, and (2) the large distance between a PU and the SUs. The size of an EZ depends on interference from a PU to SUs and is calculated based on the \(I_{th}\) of the SUs. In this case, a minimum propagation loss is required to preclude potential interference from a PU to SUs. The required propagation loss is then used to determine the minimum separation distance.
between the PU transmitter and the SU, such that the SU can achieve a certain desired quality of service (QoS). This minimum separation distance establishes the radius of the EZ around a PU.

In the case of a multi-tier shared access model, a SU’s \( L \) depends on the user’s access priority. For example, PA users like public safety systems and mission critical users have low \( L \), and hence need to operate further away from the PU. On the other hand, GAA users, such as commercial broadband systems, have higher \( L \), and can operate closer to the PU. This multi-tier shared access model requires varying levels of interference protection from PUs, that can be provided with multiple EZs [7] defined for different types of SUs.

B. Terrain based Propagation Models

Terrain is used in two ways for propagation analysis: (1) one is the P2P mode, where the actual obstruction between the two users is taken into account, and (2) the other one is area based mode, where the terrain irregularity parameter (\( \Delta h \)) specifies the interdecile range of terrain elevations that separates the two users. Existing techniques for EZ computation use pathloss models that do not consider the terrain profile in the P2P link. This does not capture the actual propagation environment between a PU and SUs. For an accurate contour estimation over irregular terrain, the terrain profile of a particular area needs to be taken into account for estimating the pathloss.

A terrain enabled propagation model such as the Institute for Telecommunication Sciences (ITS) ITM operates in P2P mode, and uses details of the environmental parameters of the region where PU and SUs operate [23]. These parameters include \( \Delta h \), electrical and ground constants, surface refractivity \( N_s \), climate, etc. which contribute to signal attenuation due to scattering, diffraction and absorption. In this paper, we synonymously use the term terrain profile based propagation model to refer to the ITM propagation model in P2P mode.

IV. EXCLUSION ZONES WITH TERRAIN PROFILES

The contour of an EZ is defined by the surrounding area around a PU’s location. EZs depend on the interference from PU to SU and are calculated based on the \( L \) of the SUs [4] to maintain a desired QoS level. The QoS is defined as the required signal to interference and noise ratio (SINR), \( \rho_s \), to achieve the desired throughput between the secondary base station/access point and user equipment. The SINR depends on secondary transmit power \( P_t \) and interference power \( I_r \) from the PU. \( I_r \) at the secondary receiver is calculated as \( I_r = P_tG_{tp}G_{rs}/L_r \), where \( P_t \) is the PU transmit power, \( G_{tp} \) is the primary transmitter antenna gain, \( G_{rs} \) is the SU receiver antenna gain and \( L_r \) is the required propagation loss between the PU and SU. If SU \( I_r \) is known for a certain SINR level, then the minimum propagation loss required to prevent non-negligible interference from a PU to the SU is given by \( L_r = P_tG_{tp}G_{rs}/I_r \). The required propagation loss \( L_r \) is then used to determine the minimum separation distance between the PU and the SU.

A terrain enabled propagation model like ITS-ITM [15] is used in the P2P mode for propagation calculations over different types of terrain. The model classifies the topography of the desired service area into terrain categories based on ground profile information. It creates a propagation map of the desired service area around the PU location. The characteristics of the propagation environment significantly affects the pathloss map of the desired area [11]. The distance at which the SUs can reuse the PUs’ bands depends on a required propagation loss for the desired SU \( I_r \). It varies significantly based on the ground profile between the transmitter and the receiver. For instance, when there is a clear line-of-sight (LOS) between the transmitter and the receiver, a larger distance is required in order for the propagation loss to be sufficiently large to enable coexistence of a PU and SUs.

As mentioned earlier, \( L_r \) is the required propagation loss used to determine the minimum separation distance between the PU transmitter and the SU. It is calculated using the ITS-ITM model [15], as shown below

\[
L_r = 32.44 + 20\log(f) + 20\log(r) + A_{ref} (1)
\]

\[
20\log(r) = P_{tp} + G_{tp} + G_{rs} - I_r = 20\log(f) - 32.44 - A_{ref} (2)
\]

where \( f \) is the channel frequency, \( G_{tp} + G_{rs} \) depends on the antenna coupling between the transmitter and receiver. The antenna coupling is calculated from the main beam gains and azimuth orientation of the two antennas, their location dependent relative orientation and statistical antenna gain model. From these parameters the antenna gain is calculated as a function of the off-axis angle for the given main beam angle. The minimum separation distance \( r \) establishes the radius of the EZs around the PUs. The EZ radius is calculated for the whole \( 2\pi \) radians around the PU location. Due to variability in the attenuation factor, \( A_{ref} \), for each measurement degree, the EZ contour may have different radius in each different direction. Hence the propagation loss can be defined as,

\[
L_r = \begin{cases} \frac{L_{r_1}}{r_1}, & r_1 \\ \frac{L_{r_2}}{r_2}, & r_2 \\ \vdots \\ \frac{L_{r_n}}{r_n}, & r_n \end{cases}
\]

where \( L_{r_i} \) is the required propagation loss with exclusion radius \( r_i \) for \( i = 1, 2, 3, ..., n \). The EZ contour is formed by connecting the points of location with the required propagation loss, calculated from the PU transmitter. Due to variation in the radii \( r_1, r_2, ..., r_n \), the contour formed is irregular in shape.

Furthermore, the EZ contour is calculated by segmenting the area around the PU location. The segmentation of the area can be done by using the transmitted antenna gain pattern, which divides the area into a number of segments, each with its own angular sector \( \theta \). The contour estimation algorithm takes the transmitter antenna gain pattern and calculates the edge of the EZ in each sector. The total area of the EZ is the summation of the area of each segment, which can be calculated through the following equation:

\[
A_{EZ} = \sum_{i=1}^{n} \frac{\pi r_i^2 \theta_i}{360} (4)
\]

where \( \theta_i \) is the angular resolution factor and \( n \) is the number of segments in the EZ contour. The angular resolution, \( \theta_i \),
determines the granularity in estimating the EZ’s area, $A_{EZ}$. Angular resolution of the contour estimation has a dominant impact on SU area sum capacity (ASC). ASC is the sum of the channel capacities of all the SUs that are operating outside the PU EZ within a considered geographical area (The precise definition is given in Equation (13)). If the angular resolution, $\theta_i$, is reduced, then an EZ’s area increase and vice versa.

A polygonal approximation algorithm is used for estimating the EZ contour around the PU with different radii in each direction [24]. It takes an array of points $r_n : (x_1, y_1), ..., (x_n, y_n)$ and generates a small number of vertices on the contour formed around these points. The number of points in the contour radii depends on the PU antenna gain pattern, granularity of the contour estimation and dynamics of the terrain.

V. MULTI-TIERED SECONDARY USERS

Unlike other databases that only protect PUs from potential interference [20], the SAS provides interference protection to the SUs operating in the same frequency band. For this purpose, the SAS defines differential spectrum access hierarchy [22] through multiple EZs for different tiers of SUs operating around the PU location [7] [22].

A SU’s $I_{th}$ is defined according to its desired QoS. We consider $k$ threshold values $I_{th}^{(1)}, ..., I_{th}^{(k)}$ to identify $k$ different tiers of SUs. The PU’s EZs for these SUs are calculated based on the terrain profile between the PU and SUs in the P2P link. The area for secondary spectrum reuse depends on the performance of the propagation model in predicting the interference region of the PU. The authors in [25] introduced the concept of quantiles of received PU power on radials around the PU location. We build on that concept for defining spatial interference quantiles for different tiers of SUs. The quantile model is used for classification of area around the PU into distinct EZs. A hypothesis test is performed at every grid location with multiple thresholds $I_{th}^{(i)}$ for $i = 1, 2, 3, ..., k$ of PU received interference calculated through the terrain enabled propagation model in P2P mode. The channel at the location is considered available if the propagation model predicts the received interference from PU to be below the threshold limit $I_{th}^{(i)}$ defined for that EZ. We denote the output of the hypothesis test by $D_i$ for each grid location. The symbol $D_i$ represents if the grid location $loc_i$ is inside the PU’s $i^{th}$ EZ denoted by $\mathbb{R}_i^2$. The indicator function is used to denote spectrum opportunity at each grid point $x = loc_i$ [25].

$$1_{D_i(x)} = \begin{cases} 1 & \text{if } x \in D_i \subset \mathbb{R}_i^2 \\ 0 & \text{if } x \in D_i \not\subset \mathbb{R}_i^2 \end{cases}$$  (5)

We compute quantiles of received signal interference in the geographic area around the PU location [23]. The quantile is a set consisting of the interference distributions defined by the influence function $\psi$, and is a function of grid point location $loc_i$; denoted by $Q(loc_i, \psi)$. The influence function $\psi$ depends on the application of the quantile model. In [25], it is estimated based on uncertainty and desired performance, while in [26] it is defined by the Huber’s $\psi$ function. We define the influence function as the Gaussian $\text{erf}$ function. Let $F$ be the set of all the distributions that the PU interference can take over a given geographical area. The interference distribution at the grid point $loc_i$ is denoted by $F_{loc_i} \in F$ and is calculated as,

$$P_{f_{loc_i}}(I_{rs} < Q(loc_i, \psi)) = \chi,$$  (6)

where $I_{rs}$ is the average power of the PU interference at the SU receiver and $0 \leq \chi \leq 1$. For a set of $k$ threshold values for different tiers of SUs, a $k$-quantile model with a set of distributions $F$ of interference is defined by a set of numbers $(\chi_1 < \chi_2 < ... < \chi_k)$ with a corresponding list of functions $Q_i(loc_i, \psi_1), ..., Q_k(loc_k, \psi_k)$. A distribution $F_{loc_i} \in F$ iff \forall $i \leq k$.

$$P_{f_{loc_i}}(I_{rs} < Q_i(loc_i, \psi_i)) = \chi_i$$  (7)

In this paper, the quantiles are chosen based on the $i^{th}$ limits of different tiers of SUs. A hypothesis test is used to classify the area around the PU into multiple EZs based on SU interference threshold levels. For the test, the test statistic $T(I)$ is the received interference as predicted by the propagation model over the geographical area for an interference threshold limit of $I_{th}^{(i)}$. From [15], the test statistic is distributed normally with different mean values, and a multiple hypothesis testing problem is formulated for the area classification, as shown below.

$$T(I) \sim \begin{cases} \mathbb{N}(I_{th}^{(0)}, \sigma_0^2) & \text{when } H_0 \\ \mathbb{N}(I_{th}^{(1)}, \sigma_1^2) & \text{when } H_1 \\ ... & \text{when } H_k \end{cases}$$  (8)

where $I_{th}^{(k)} < ... < I_{th}^{(1)} < I_{th}^{(0)}$. The PU interference is classified based on mean value of the Gaussian statistic, which changes value in different regions around the PU location. In this case $I_{th}^{(0)}$ is the mean value of PU interference inside the forbidden area, while $I_{th}^{(1)}, I_{th}^{(2)}, ..., I_{th}^{(k)}$ are the mean interference values for different EZs around the PU.

The hypothesis testing is used to find the decision function $\delta(I) \in \{1, 2, ..., k\}$ such that $\delta(I) = EZ$ if the test decides that hypothesis $H_i$ holds when $I = I_{th}^{(i)}$ where $I$ is the PU interference predicted by the propagation model at the test grid. The decision function $\delta(I)$ specifies a $k$-fold partition $I = \cup_{i=1}^k I_{th}^{(i)}$ with $I_{th}^{(i)} \cap I_{th}^{(j)} = \emptyset$ for $i \neq j$. As the PU interference is distributed normally, the maximum likelihood decision function $\delta(I)$ is given by the following equation.

$$\delta(I) = \arg \min (I - I_{th}^{(i)})^T K^{-1} (I - I_{th}^{(i)})$$  (9)

where $K$ is the covariance matrix of the gaussian interference functions. The decision function $\delta(I)$ partitions the area around the PU into multiple EZs based on the SU interference thresholds $I_{th}^{(i)}$. It is used to generate a set of all the points $loc_i = (x_i, y_i)$ that are within the boundry of each EZ defined by its corresponding $I_{th}$. 

VI. SPECTRUM UTILIZATION EFFICIENCY

We consider a deterministic model for SU distribution outside the PU EZs. The model distributes SUs along a grid with a distance of $d$ between their centers. The goal of the analysis is to estimate the spatial spectrum utilization of the
multi-tier EZs. We define spectrum utilization in terms of ASC, which is the summation of channel capacity values of each coexisting SU in its tier within the considered SAS service area. The SU’s ASC depends on its spectral efficiency (bps/Hz), the channel bandwidth ($W_s$) and the number of SU cells in the geographical area.

As the size of EZ is substantial due to the huge discrepancy between the PU and SU transmit power levels, the interference from SUs to PU is negligible. In this case, the SUs can use the maximum power level of $P_{max}$ as recommended by the FCC CBS NPRM [1]. So, the maximum transmit power (MTP) function is given by,

$$P_{tx} = P_{max} \text{ mWatt}$$

(10)

From the MTP function, the SU’s SINR $\rho_s$ is calculated using Equation (11) [5], which determines the secondary achievable data rates.

$$\rho_s = \frac{P_{tx}}{L_\text{S}(r_{\text{cell}}) + I_{P2S} + I_{S2S}}$$

(11)

where, $L_\text{S}(r_{\text{cell}})$ is the path loss between the SU transmitter and receiver in the cell with radius $r_{\text{cell}}$, $n_s$ is the background noise power spectral density at the secondary receiver, $W_s$ is the bandwidth per SU, $I_{P2S}$ is the primary to secondary interference, and $I_{S2S}$ is the secondary to secondary interference.

From the SINR ($\rho_s$), the achieved capacity by each SU is calculated through the Shannon capacity formula.

$$C_{SU} = W_s \log_2(1 + \rho_s)$$

(12)

The EZs are defined for PA-SU and GAA-SU with parameters given in the Table I. For a given analysis area, $N_k$ represents the total number of SU cells that are within the area defined for the tier-k SUs. Assuming that each cell has a single user, the SU ASC for $k^{th}$ tier, $C_k$, is given by equation (13).

$$C_k = W_s \sum_{i=1}^{N_k} \log_2(1 + \rho_s(\text{loc}_i)),$$

(13)

where, $\rho_s(\text{loc}_i)$ is the SINR at SU location $\text{loc}_i$. The Equation (13), takes into account the impact of location dependent interference from PU to SU ($I_{P2S}$) through the SU SINR ($\rho_s(\text{loc}_i)$), as well as the number of SU cells ($N_k$) operating in the $k^{th}$ tier. The total SU ASC in a given area can be obtained by summing $C_k$ for all $k$ tiers.

VII. SIMULATION RESULTS

In this section, we present the simulation results for EZ computation using ITM area based mode and P2P mode, and compare the SU ASC achieved by them. We also show the resulting gain in total SU ASC when multi-tier EZs are used.

Let us consider a database coverage area with a single PU transmitter at the center. To study the effect of SU $I_{th}$ on the size of EZs, we consider a two-tier SU model. The detailed operating parameters of the PU as well as the two tier SUs are listed in Table I. The database coverage area is divided into $m \times n$ grids/cells depending on the granularity of the terrain database. The interference from PU is calculated using the ITM model for each grid in the area. The ITM is used in P2P mode with terrain profile of the area between the two systems from the SRTM-3 terrain database. For the area based mode, a terrain irregularity factor, $\Delta h$, of 90 m is used. The area around the PU is divided into two EZs based on the $I_{th}$ of the two tiers of SUs. In [27], it is shown that secondary LTE networks can tolerate a vast range of interference from PUs. Based on their analysis, we choose two $I_{th}$ values for the SUs (see Table I). The inner EZ is referred to as tier-3 EZ and outer EZ is referred to as the tier-2 EZ. Tier-3 EZ is based on higher $I_{th}$ of GAA users.

Figure 1(a) shows a significant gain in SUs’ ASC when ITM in P2P mode is used as compared to the area based mode. This gain is a direct consequence of the accurate pathloss computations by the ITM in P2P mode. The P2P mode takes into account terrain obstructions, which causes diffraction and scattering of signals resulting in higher propagation losses compared to the area-based mode which only considers the terrain irregularity factor $\Delta h$ of the area. Note that the normalized plot is generated by using the SU ASC over the analysis area as a normalizing constant assuming there is no PU and all the area is used by the SUs.

Figure 1(b) shows the gain in SU ASC when the SAS uses multi-tier EZs as compared to a single monolithic EZ. For these simulations, we fix tier-3 EZ boundary at $I_{th}^{(3)} = -70$ dBm and vary the tier-2 EZ threshold from $I_{th}^{(2)}$ to $I_{th}^{(3)} = -30$ dBm. We use ITM in P2P mode for this analysis. The gain in SU ASC is recorded for each threshold value. The result is that the total SU ASC starts to saturate as the SU $I_{th}$ is increased. This saturation comes from two major effects. First is that the capacity in the area gained by increasing $I_{th}$ beyond $-40$ dBm is negligible due to interference from PU to SU, $I_{P2S}$, which reduces the SINR in Equation (13), second is that the gain in the area made at higher $I_{th}$ is smaller compared to the gain made at lower $I_{th}$.

Figure 1(c) shows the effect of SU cell size on the SU ASC for the ITM P2P and the area based modes. For these set of simulations, we consider a single tier EZ defined by $I_{th} = -62$ dBm. It is evident from the figure that SU ASC is increased when small cells are used in combination with a terrain enabled ITM P2P model. Figure 1(c) shows another important result: the SU ASC gain from P2P mode is higher for small SU cell size, and it decreases as the SU cell size increases. This is because ASC is directly proportional to the number of cells where each cell reuses the same bandwidth. As the SU cell size decreases, the number of cells that can be packed into a given area increases; hence the result.

Terrain features affect the size of EZs, which tends to be greater for flat areas while hilly and mountainous terrains have smaller EZs due to greater propagation losses due to the terrain. Hence, the difference in the SU ASC values calculated from P2P and area-based modes of the propagation model will vary based on the type of terrain being considered in the analysis.

VIII. CONCLUSION

This paper explored the concept of multi-tiered EZs. We have shown that the concept of differential spectrum access hierarchy can be implemented for different tiers of SUs by assigning SUs with different interference thresholds to
different EZ tiers. In addition, we have provided quantitative results that show the gain in SU’s ASC due to employment of P2P terrain profiles in computing EZ boundaries.

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REFERENCES


