Capacity Considerations for Secondary Networks in TV White Space

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Abstract

The so-called 'TV white spaces' (TVWS) - representing unused TV channels in any given location as the result of the transition to digital broadcasting - designated by U.S. Federal Communications Commission (FCC) for unlicensed use [1]–[3] presents significant new opportunities within the context of emerging 4G networks for developing new wireless access technologies that meet the goals of the US National Broadband Plan [4] (notably true broadband access for an increasing fraction of the population). There are multiple challenges in realizing this goal; the most fundamental being the fact that the available WS capacity is currently not accurately known, since it depends on a multiplicity of factors - including system parameters of existing incumbents (broadcasters), propagation characteristics of local terrain as well as FCC rules. In this paper, we explore the capacity of white space networks by developing a detailed model that includes all the major variables, and is cognizant of FCC regulations that provide constraints on incumbent protection. Real terrain information and propagation models for the primary broadcaster and adjacent channel interference from TV transmitters are included to estimate their impact on achievable WS capacity. The model is later used to explore various trade-offs between network capacity and system parameters and suggests possible amendments to FCC's incumbent protection rules in the favor of furthering white space capacity.

Index Terms

Whitespaces, Dynamic Spectrum Access, TV White Space, Cognitive Radio, Cellular Network, Unlicensed Spectrum

I. Introduction

Next generation of cellular data networks will face an exponential growth of wireless data traffic resulting from the boom in multimedia applications running on smart phones, tablets, and other wireless devices [5]. Available 4G (licensed) spectrum will clearly be insufficient to meet this demand, leading to cellular operators searching for novel mechanisms to achieving operational efficiencies that enhance network capacity. Obviously, an essential response to this increasing demand is the opening of new spectrum - both licensed, and recently, *unlicensed*. Resulting from the transition to digital TV broadcasting[1] and the consequent freeing up of VHF/UHF spectrum (between

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[1]In the U.S. this was completed by June 2009.

50-700 MHz), FCC took the unprecedented step of allocating significant portions for unlicensed use, intended for providing enhanced wireless broadband access [2], [3]. These bands - collectively denoted as TV White Spaces (TVWS) - are interspersed with the 4G 700 MHz *licensed* bands[2] and will allow secondary (unlicensed) users to opportunistically access them provided *interference protection guarantees* to the neighboring primary (licensed) networks are ensured. A strategy for *coordinated use of both licensed and unlicensed 700 MHz spectrum* is the likely answer for 4G cellular operators, just as offloading to 802.11 WLAN hotspot networks has proved to be a boon for 3G network providers. TVWS (sometimes subbed as 'super Wi-Fi') may potentially provide even more significant offload/spectrum aggregation opportunities, considering other proximal government held spectrum are also being explored for de-regulation [6]–[10].

Clearly, the most critical task for a Dynamic Spectrum Access (DSA)-based cognitive users is finding spectrum 'holes' efficiently [11], i.e., spectrum resources in *time-frequency-spatial* dimensions at any location that are currently available, which can be then used for unlicensed operation. Current FCC rules of operation for unlicensed users in TVWS require them to register with and obtain recommendations from a list of approved Database Administrators (DBA) - such as a list of available TVWS channels - for their operation, so as to ensure interference protection to the incumbents. The DBA is responsible for complying with FCC regulations [3] in modeling all primary users status, as a basis of providing the necessary recommendations to the secondary users requesting access.

In this work, we explore a fundamental issue pertaining to WS usage by secondary networks, which may be succinctly captured by the question *How much WS network capacity actually exists per FCC rules*?. Clearly, the answer to this question is of paramount importance to 4G network operators as they consider new infrastructure for unlicensed WS access as part of their operations. We show that it depends on multiple factors:

◇ Primary Network Parameters (transmit power and signal masks, modulation/coding)

◇ FCC rules for protection of primary users/networks by limiting secondary operation (protection regions, adjacent TV channels, primary receiver design and sensitivity)

◇ Propagation Characteristics (location dependent terrain models, heights etc.)

◇ Secondary network parameters (transmit power and signal masks, modulation/coding, multiple access schemes)

Prior works on this topic, notably [12]–[15] do not provide a sufficiently nuanced exploration of this question (available secondary network capacity) as a function of *all* the parameters above. Notably, the *structure of the spatial variations* in secondary capacity has not been adequately captured, in our opinion. Further, FCC regulations have evolved significantly since the first release of TVWS [1], [3] which in turn impact TVWS capacity analysis. Mutual effects of secondary and primary networks, such as co-channel and adjacent-channel interference, are not considered. Furthermore, realistic and empirical path loss models that are based on actual terrain information together with sensitivity to path loss variation have not been previously used.

We develop a *spatial description of WS capacity* via a model that captures both primary and secondary network aspects as well as channel and environmental characteristics. An important side benefit of our analysis is the

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[2]For example, portions of 698-806 MHz were auctioned off by 2008 in the U.S. to provision for 4G mobile broadband services.

spotlight it shines on *whether the current incumbent protection rules proposed by the FCC may need amending in the interests of promoting more WS availability*. Our analysis thus provides fundamental insights into aspects of coexistence between secondary users and primary transmitters as a function of FCC regulations [2], [3]. The rest of the paper is organized as follows. Section II defines the network structure for coexistence of secondary and primary users. Section III formulates capacity of each secondary cell. The problem of channel availability determination is discussed in section IV which includes current FCC rules, primary protection region definition as well as selection of propagation (path loss) model along with underlying physical environmental parameters. Section V introduces interference models. Numerical calculations in section VI provides high level results on available secondary capacity whereas section VII explores multiple trade-offs that arise. Finally, section VIII concludes the paper and some supplementary details are related to Appendices A and B.

II. SECONDARY NETWORK ARCHITECTURE

In practice, secondary networks can be deployed arbitrarily as an ad-hoc network. However, the outcome of such ad-hoc networks will be increased mutual interference and degradation of throughput (this is what has already been observed in chaotic WiFi deployments in 2.4 GHz). Therefore, cellular planning is a smarter choice; a very good use case are Small Cells that are deployed outdoors (stadiums, halls etc. for events) under control of the network operator. In this section, we consider secondary cellular networks that coexist with primary network.

Cellular communication systems are based on the notion of *frequency reuse* which allows a channel to be spatially re-used by different users, as long as the co-channel interference is within acceptable bounds. However, for TVWS applications, the cellular layout of the secondary cells (SC) is further restricted by the primary protection regions, as shown in Fig. 1. This figure presents TV towers as an *irregular* primary network, where each primary cell corresponds to the coverage area of the associated tower. Here, r_i is the maximum distance at which the received TV signal is above the detection threshold [3], [16], [17]. The regions outside the primary transmitter coverage area constitute the white/gray space [18] that can be utilized by secondary networks; secondary cells are naturally much smaller than primary cells, due to power and antenna height limitations.

Characterizing the white spaces and the primary-to-secondary interference requires knowledge of deployment of TV towers (primary transmitters) and their parameters, which is available from the FCC database [19]. Comparing the examples of TV channels 13 (see Fig. 6) and 5 (see Fig. 7) indicates that the patterns of spatial reuse for primary (TV channels) are irregular (across channels). As a result, the availability of WS shows significant spatial variations, which we explore in more details later.

Define the set of available channels in a secondary cell A (according to FCC rules for protection of *primary users*) as

$$\Upsilon(A, \Gamma_A) = \{c_i : \quad \text{Channel } c_i \text{ is available at cell A with parameter } \Gamma_A\}$$

where Γ_A represents all relevant network parameters. Note that $\Upsilon(B, \Gamma_B)$ represents a different list of available channels. In order to protect secondary users from secondary interference, only a subset of available channels are assigned to each secondary cell which is considered in section V.
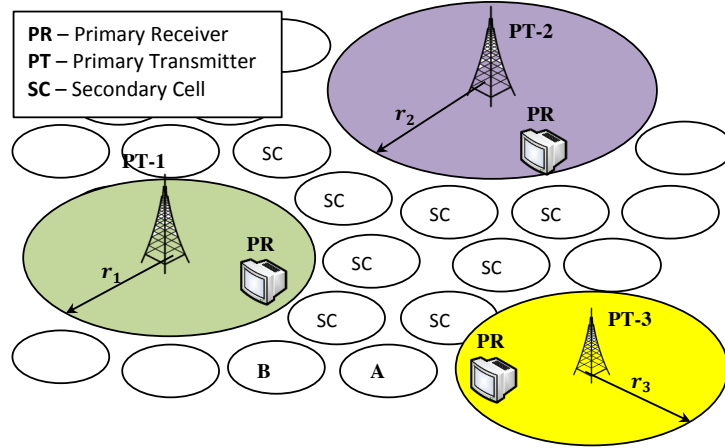
Fig. 1. Coexistence of primary and secondary cellular networks

III. SECONDARY LINK CAPACITY

We begin developments by computing the Shannon capacity of a (hypothetical) secondary transmitter-receiver pair located at a point, i.e. the capacity of an infinitesimal cell with one active link where the separation between the source and receiver is negligible. At this point, we assume that the secondary users are allocated one of the available channels $c_i \in \Upsilon(A, \Gamma_A)$ at any secondary cell A (this assumption will later be generalized by summing over all possible channels), the capacity is a function of the usual parameters - *signal to noise + interference ratio* and *available bandwidth*

$$C_{cell} = W_0 \log_2(1 + \text{SINR}) \tag{1}$$

where $W_0 = 6$ MHz represents the bandwidth of an NTSC TV channel. Since the allocated channel c_i is not available at every location, a more appropriate measure of available capacity is an *area average*. To do this, we introduce a Bernoulli random process for the availability of any secondary WS channel, as follows:

$$W(Q_T, \Gamma) = \begin{cases} W_0 & Q_T \notin \Omega \text{ and } \Gamma \vdash \text{FCC rules} \\ 0 & Q_T \in \Omega \text{ or } \Gamma \nvdash \text{FCC rules} \end{cases} \tag{2}$$

where Q_T is the transmitter location, Ω is the set of all protection regions for the channel currently under exploration. Γ, as defined before, is the set of network parameters that can affect channel availability, including transmission power, antenna height above average terrain, out of band emission, etc., which must comply with FCC requirements ($\vdash$) for incumbent protection. Using this, let's define the *channel availability* $p(\Gamma) = Pr[Q_T \notin \Omega]$ as the normalized average of $W(Q_T, \Gamma)$ over an area $\mathcal{A}$

$$p(\Gamma) = \frac{1}{\mathcal{A}} \int_{\mathcal{A}} \frac{W(Q_T, \Gamma)}{W_0} dQ_T \tag{3}$$

The capacity averaged over transmitter and receiver locations is thus

$$\overline{C_{cell}}(\Gamma) = p(\Gamma)W_0 \int_{\mathcal{A}} \frac{\log_2(1 + \mathrm{SINR}(Q_R))}{\mathcal{A}} dQ_R \tag{4}$$

where the SINR depends on (secondary) receiver's location Q_R. Eq. (4) can be calculated for every channel separately and the overall capacity of a cell that is exploiting all available channels is obtained by summing over all channels

$$\overline{C_{cell,total}}(\Gamma) = \sum_{c_i \in \Upsilon(cell, \Gamma_{cell})} p(\Gamma, c_i)W_0 \int_{\mathcal{A}} \frac{\log_2(1 + \mathrm{SINR}(Q_R, c_i))}{\mathcal{A}} dQ_R \tag{5}$$

IV. CHANNEL AVAILABILITY DETERMINATION

Availability of every permissible TV channel $c_i \in \{2 : 51\}$ is mainly a function of location and secondary user transmission characteristics. FCC defines various rules for secondary TV band devices (or TVBDs, subsequently) to protect primary receivers [2], [3] that affect the probability of channel availability. A brief summary of the relevant FCC regulations follows:

◇ **Permissible Channels**: A fixed TVBD may operate on any channel in $\{2 : 51\}\backslash\{3, 4, 37\}$ subject to conditions below [2], [3]. Further, personal/portable devices may only transmit on available channels above channel 20, $\{21 : 51\} \backslash \{37\}$ subject to following requirements.

◇ **Power limit**: For fixed TVBD, the maximum power delivered to antenna may not exceed 1 watt in 6 MHz with a maximum of 6-dBi gain for antenna (maximum 36-dBm of EIRP[3]). For personal/portable TVBD, the maximum EIRP shall not exceed 20dBm per 6 MHz. If portable TVBD is transmitting in an adjacent channel to a primary transmitter, then maximum EIRP is limited to 16-dBm.

◇ **Antenna height**: The transmit antenna for fixed devices may not be more than 30 meters above the ground. In addition, fixed devices may not be located at sites where the antenna height above average terrain is more than 250 meters. Portable device antenna is assumed to be less than 3 meters above the ground.

◇ **Interference protection**: TVBD must protect digital and analog TV services within the contours defined in Table VI for various types of TV services. Fixed and portable TVBD are not allowed to transmit within a minimum separation distance from the border of protected contour that is defined in [3] based on secondary transmitter class and height above average terrain (HAAT). Fixed devices must be outside protection regions of co-channel and adjacent channel stations. Portable devices are allowed to transmit within adjacent channel contours with a maximum power of 40 mW.

◇ **PLMRS/CMRS**: In 13 major metropolitan areas that are specified by FCC, some of the channels between 14 to 21 are reserved for PLMRS/CMRS. Therefore, TVBD may not operate at distances less than 134-km for co-channel operation and 131-km for adjacent channel operation from those designated areas and channels.

◇ **Radio Astronomy Sites**: TVBDs are not allowed to operate at any TV channel within 2.4 km from registered radio astronomy sites in FCC database.

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[3]Effective Isotropic Radiated Power

⋄ **Microphone Reserved**: The first available TV channel above and below channel 37 are reserved for wireless microphones. If no channel is available above(below) channel 37 then the two channels below(above) are reserved. TVBDs are not permitted to operate on these reserved channels.

The aggregate effect of FCC rules is modeled through defining protection regions for primary users, as discussed below, where no secondary is allowed to transmit. Note that protection region includes protection contour as well as minimum separation distance. Therefore, channel availability probability represents the ratio of the area where channel is considered free (according to regulations above) to the total area of discussion.

A. Primary Protection Region

Considering a permissible WS channel c_i at any location and an area $\mathcal{A}$ with N co-channel secondary and M adjacent-channel (either channels $c_i - 1$ or $c_i + 1$) primary users. For every licensed device, a protected contour [2], defined by FCC for different types of stations, is considered that represents the coverage area of that transmitter. This grade B contour for TV broadcasters, is a function of following parameters:

⋄ P_t: Primary transmitter effective power (EIRP)

⋄ Δ: Minimum required signal for primary receiver, defined in Table VI

⋄ f: Frequency

⋄ h_t/h_r: Tx/Rx Antenna height above average terrain (HAAT)

⋄ ΔH: Terrain irregularity parameter which distinguishes plains versus mountains.

⋄ Service type: FCC regulates different rules for various services in TV band, such as PLMRS/CMRS[4] versus low power auxiliary services including wireless microphones.

⋄ Environmental effects that changes propagation path loss, such as radio climate, conductivity of ground, surface refractivity, etc.

The overall protection region is an area of radius $r_p = r_{PC} + d_{MS}$ where r_{PC} is the protected contour radius and d_{MS} is an additional minimum separation distance as shown in Fig. 2. Detailed description of protection region calculation is provided in Appendix A. We define this area as the primary network cell shown in Fig. 1. The secondary cells can exist in any region beyond these primary protected cells. Therefore, the channel availability probability is defined, using an area average, as

$$p(\Gamma) = 1 - \frac{\sum_{j=1}^{N} \mathcal{A}_{p,co}(j) + \sum_{k=1}^{M} \mathcal{A}_{p,adj}(k) - \sum_i \sum_j \mathcal{A}_p(i,j)}{\mathcal{A}} \tag{6}$$

where $\mathcal{A}_{p,co}(j)$ is the co-channel protection area for transmitter $j \in \{1 : N\}$ and $\mathcal{A}_{p,adj}(k)$ is adjacent-channel protection area for transmitter $k \in \{1 : M\}$. In most cases, as our simulation reveals, there are significant overlaps between co-channel and adjacent channel areas which is considered in $\mathcal{A}_p(i,j)$. Dependency of $\mathcal{A}_{p,co}$, $\mathcal{A}_{p,adj}$ on Γ is removed for notational simplicity.
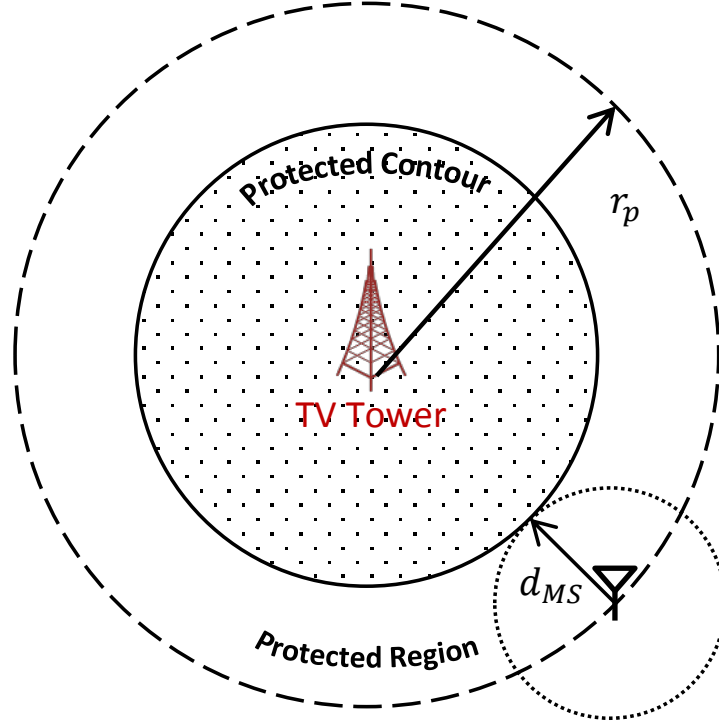
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[4]Personal Land/Commercial Mobile Radio Services

Fig. 2. Protected contour v.s. protection region defined by FCC

We remark that the protection region in reality is generally an irregular area that is non-circular, due largely to varying terrain heights as a function of azimuth angles as seen at a primary transmitter location. The FCC simplifies this by averaging the HAAT over all azimuth into a single quantity and representing the area by a circle of radius r_p. This approach is acceptable for a 1st-order model for primary coverage, but not for accuracy in estimating WS network capacity. In our simulation, we will thus consider non-circular protection regions that preserves the variation of coverage distance as a function of angle.

B. Path Loss Model

Choosing an appropriate path loss model is very important in TVWS capacity analysis because it directly affects all subsequent results and choice of secondary parameters. There are various path loss models in the literature that has been adopted for different applications, frequency range and environments [17], [20]–[24]. Except for free space model that is derived from pure theory, most useful path loss models are based on experimental measurements; this includes the well-known *HATA* model family for different terrain categories such as urban, suburban and rural areas [21] that has been widely used in cellular network planning. However, such path loss models are significantly limited in terms of accuracy in their range of parameters such as transmitter/receiver antenna height, coverage distance and frequency. Therefore, for TV tower specifications including very high altitude (as high as 700 meters) and broad coverage area (upto 100 km), more general models are required that incorporate real terrain information.

We thus settle on the Longley-Rice (ITM) model that is measurement-driven and covers a wide range of input parameters, appropriate for TV coverage estimation [16]. A computer implementation of this model is provided by NTIA [23] called ITM, and is described here.

Irregular Terrain Methodology (ITM) estimates radio propagation losses for frequencies between 20-MHz and 20-GHz as a function of distance and the variability of the signal in time and space. It is an improved version of the Longley-Rice Model [25], which gives an algorithm developed for computer applications. The model is based on electromagnetic theory and signal loss variability expressions derived from extensive sets of measurements [22], [26]. It is applicable to point-to-area calculations with *point* being the location of a broadcast station or a base station for mobile service and *area* refers to locations of broadcast receivers or mobile stations. The area is described by the terrain roughness factor (irregularity parameter) Δh, which is defined as the interdecile value computed from the range of all terrain elevations for the area, calculated separately in every direction.

Based on Longley-Rice methodology, calculation of coverage is as follows. For analog TV, computation are made inside the conventional Grade B contour defined in Section 73.683 of the FCC rules, with the exception that the defining field for UHF channels is modified by subtracting a dipole factor. The same adjustment is needed for digital TV calculations. Modified signal strength tables for analog and digital TV are shown in Table VII.

1) ITM - Input Parameters: The following input parameters are required for a proper description of the communication link. The main parameters affecting this model are:

⋄ f: frequency, 20 MHz to 20 GHz.

⋄ d: Distance between the two terminals, 1 km to 2000 km.

⋄ h_{g1}, h_{g2}: Antenna structural heights, 0.5 m to 3000 m.

⋄ pol: Horizontal or Vertical polarization.

⋄ Δh: Terrain irregularity parameter. This is the main parameter that captures the effect of terrain elevation on path loss calculation.

Note that antenna heights are calculated relative to average terrain height surrounding TV transmitter. This in fact changes in different angles and results in non-circular path loss patterns just as terrain roughness parameter Δh creates angle dependency.

V. INTERFERENCE MODEL

SINR is by definition the ratio of received power at receiver location to noise and interference:

$$\text{SINR}(Q_R) = \frac{P_{sec,RX}(Q_R)}{N_0 W_0 + I(Q_R)} \tag{7}$$

There are two sources of interference in TV white space networks:

A. *Primary-to-Secondary*

Although primary users are protected from undesired interferences from unlicensed devices, they introduce a significant source of interference to secondary users working in the same or adjacent bands. The level of interference

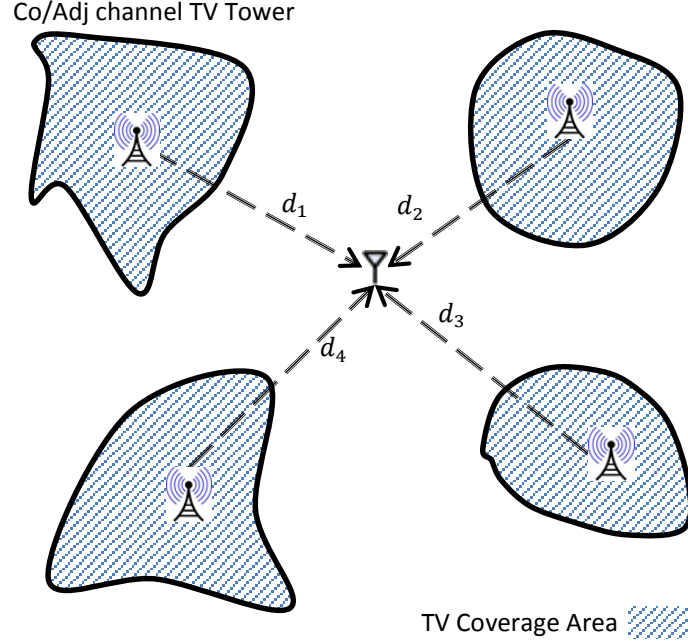Co/Adj channel TV Tower

TV Coverage Area

Fig. 3. Primary-to-Secondary interference

at every location depends on the distance from the secondary receiver to nearby TV broadcasters, as shown in Fig. 3, as well as other physical parameters such as antenna height.

TV transmitters introduce both co-channel and adj-channel interference to secondary users, due to signal leakage from each channel to lower/upper bands. The aggregate interference for the receiver location Q_R is:

$$I_{P2S}(Q_R) = \sum_{i=1}^{N} (1-\eta) \frac{P_i G_i}{L_{TV}(d_i)} G_r + \sum_{j=1}^{M} \eta \frac{P_j G_j}{L_{TV}(d_j)} G_r \qquad (8)$$

where P_i/G_i is the transmitter power and antenna gain, $L_{TV}(.)$ is path loss function from TV broadcaster, G_r is the receiver antenna gain and N/M is number of co-channel/adj-channel surrounding TV towers (we consider TV transmitters up to a distance of 300 km in numerical calculation section). η is the leakage factor for TV transmitters defined as the ratio of power transmitted in upper/lower band to total power and d_i is distance to primary transmitter i. Note that, location dependency, $I_{P2S}(Q_R)$ is hidden inside distance factor d_i.

In order to consider adjacent channel interference in simulation, we consider a practical transmission mask, introduced for 8-VSB standard [27], shown in Fig. 4 for full service digital TV transmitters. It defines maximum power leakage to upper and lower channels for a maximum of two channel distance. Similar masks are defined for TV translators and low power TV broadcasters [27]. Full service transmitter mask is defined as below:
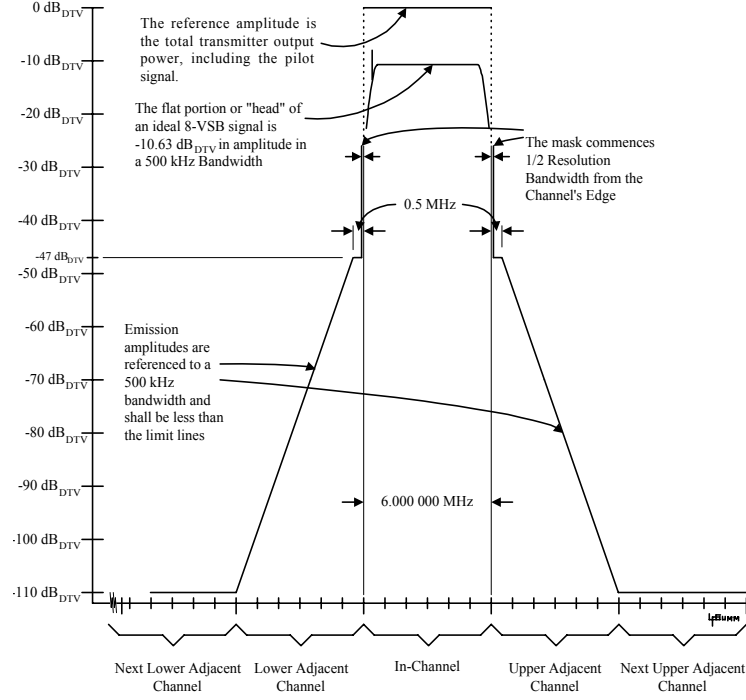
Fig. 4. 8-VSB Full Service Transmitter Emission Limits [28]

◇ In the range between Channel Edge and 500 kHz from the Channel Edge: $Emission \leq -47 dB_{DTV}$[5]

◇ More than 6 MHz from Channel Edge: $Emission \leq -110 dB_{DTV}$

◇ At any frequency between 500kHz and 6 MHz from the Channel Edge: $Emission \leq -(11.5(|\Delta f| - 0.5) + 47) dB_{DTV}$, with Δf being the frequency difference in MHz from the Channel Edge.

By defining the emission mask function $E(f)$ as above for full service DTV, the overall leakage to adjacent channels with respect to total power is:

$$\eta_{\pm 1}(DTV) = \int_0^6 10^{E(f)/10} df = 1.75 * 10^{-5}$$

$$\eta_{\pm 2}(DTV) = \int_0^6 10^{-110/10} df \approx 0$$

Following the same procedure for LPTV DTV or translator services results in:

$$\eta_{\pm 1}(LPTV) = \int_{0.5}^3 10^{-(1.15(f-0.5)+4.7)} df$$

$$+ 5 * 10^{-5.7} + 3 * 10^{-7.6} = 1.76 * 10^{-5}$$

$$\eta_{\pm 2}(LPTV) = \int_0^6 10^{-76/10} df = 1.51 * 10^{-7}$$

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[5]dB_{DTV} is the relative power with respect to *total power in the transmitter's 6 MHz Channel including the pilot*

B. Secondary-to-Secondary

The interference that is experienced by a white space receiver from *other* TVBD users has severe impacts on its performance. As discussed before, the area $\mathcal{A}$ is divided to multiple cells and each channel is used several times in non-adjacent cells. The minimum distance that allows the same frequency to be reused will depend on many factors, such as the number of co-channel cells in the vicinity of the center cell, the type of geographic terrain contour, the antenna height, and the transmitted power at each cell site, [29].

The frequency reuse distance D can be determined from

$$D = \sqrt{3K} r_{cell} \tag{9}$$

Where K is the frequency reuse pattern, defined by shift parameters $K = i^2 + ij + j^2$. In theory, increasing D will reduce the chance of co-channel interference and is desired. On the other hand, spectrum inefficiency will also increase as the ratio of $q = \frac{D}{r_{cell}}$ increases. The goal is to obtain the smallest K that maximizes efficiency and still meets the protection requirements on incumbents. This involves estimating co-channel interference and selecting the minimum frequency reuse distance D feasible.

Here, we assume that secondary cell size is fixed and is determined by the coverage area corresponding to the secondary transmit power [29]. For a homogeneous secondary network with fixed cell size, the co-channel interference is *independent* of the transmitted power of each cell, i.e. the receiver threshold at a mobile secondary receiver is adjusted to the size of the cell. The received carrier-to-interference ratio at the desired mobile receiver is [29]

$$\frac{C}{I} = \frac{C}{K_I \sum_{i,j \in [0,1,...]} I_{i,j}} \tag{10}$$

where K_I is the number of interferer at each tier and $I_{i,j}$ is the interference of the co-channel cell shifted by i,j. In a fully equipped hexagonal-shaped cellular system, $K_I = 6$ and $I_{i,j} = P_{sec,TX} G_{sec}^2 L_{sec}(D_{i,j})$ where $D_{i,j}$ is the distance from (i,j)'s interfering cell and $D_{i,j} = \sqrt{i^2 + ij + j^2} D$. The overall experienced secondary-to-secondary interference is

$$I_{S2S} = P_{sec,TX} G_{sec}^2 K_I \sum_{i=0}^{\infty} \sum_{j=i,j\neq 0}^{\infty} L_{sec}(D_{i,j}) \tag{11}$$

In practice, the closest cells are the prominent interferers and the sum above is practically limited to $i,j = 2$ instead of infinity. Note that in theory, I_{S2S} depends on precise location of the receiver inside the cell but we calculate the interference for the center of the cell site. Therefore, this will relax dependency of I_{S2S} on Q_R. The resulting SINR is

$$\text{SINR}(Q_R) = \frac{P_{sec}/L_{sec}(r_{cell})}{N_0 W_0 + I_{P2S}(Q_R) + I_{S2S}} \tag{12}$$

Using (4), (6) and (7), the average capacity per cell for each individual TVWS channel is

$$\overline{C_{cell}}(\Gamma) = \frac{p(\Gamma)}{K} W_0 \int_{Q_R} \log_2 \left(1 + \frac{P_{sec}/L_{sec}}{N_0 W_0 + I_{P2S}(Q_R) + I_{S2S}} \right) dQ_R \tag{13}$$

VI. NUMERICAL CALCULATIONS

In this section, numerical results are provided by evaluation of the analysis in previous sections. The main focus is to explore dependency of network capacity on various parameters and subsequent optimization of parameter choices. All simulations are performed on a TVWS simulation platform developed at University of Washington, a snapshot of which is shown in Fig. 5. This platform models protection regions for all primary transmitters registered in the FCC database [19], and applies all FCC regulations to determine available channels to secondary devices. It also estimates interference level and capacity at any location inside the United States. Significantly, actual terrain information[6] was used for accurate computation of path loss function.

We use particular path loss models for different parts of the analysis. Specifically, we use Longley-Rice in area mode to calculate protected regions of TV broadcasters. For primary to secondary interference, Longley-Rice in point to point mode is used that highly depends on the terrain profile between transmitter and receiver. This is a non-monotonic (with respect to distance) path loss model well designed for calculation of path loss between two specific points and small changes in the location of transmitter or receiver can significantly change the results. Finally, Hata model is used for secondary to secondary interference because it is especially designed for mobile services in urban, suburban and rural areas.

Fig. 6 and 7 shows the protection regions for TV transmitters on channel 13 and 5 across the continental US, using Longley-Rice methodology in area mode for path loss prediction. The spatial distribution of transmitters as well as non-circularity of protections regions, as a result of terrain variations, are well highlighted in the figures. Note the general lack of structure in the distribution of TV transmitters for channels 5, 13, indicating the lack of any prior planning (as in cellular layout) for TV broadcast.

A. Channel Availability Statistics

FCC regulation restricts TVBD in many aspects from maximum power and antenna height to not using adjacent channel to active TV stations. In this section, we provide some *statistical information* about how these rules affects the total number of available WS channels for *fixed* and *portable* devices.

Table I shows the average number of available channels for *fixed* and *portable* TVBD in various frequency bands. In addition, the number of channels that are used by TV transmitters (Busy channels) as well as the total number of channels that are not released for unlicensed operation (because they are adjacent to busy channels or reserved for wireless microphone or other services) are provided. At the bottom of the table is the final utilization factor that is achieved by permitting unlicensed operation and it is defined as $CUF = 1 - \dfrac{\text{Unused Channels}}{\text{Total TV Channels}}$. As the table suggests, an average of 9.05 channels are still left unused even with operation of TVWS devices, which is $\approx 19\%$ of all channels. By repeating this simulation for non-uniformly distributed locations, selected separately from urban

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[6]Terrain data, obtained from Globe [30], used in calculation of two parameters, first, transmitter HAAT, second, terrain irregularity ΔH, both versus angular direction with 1-degree resolution.

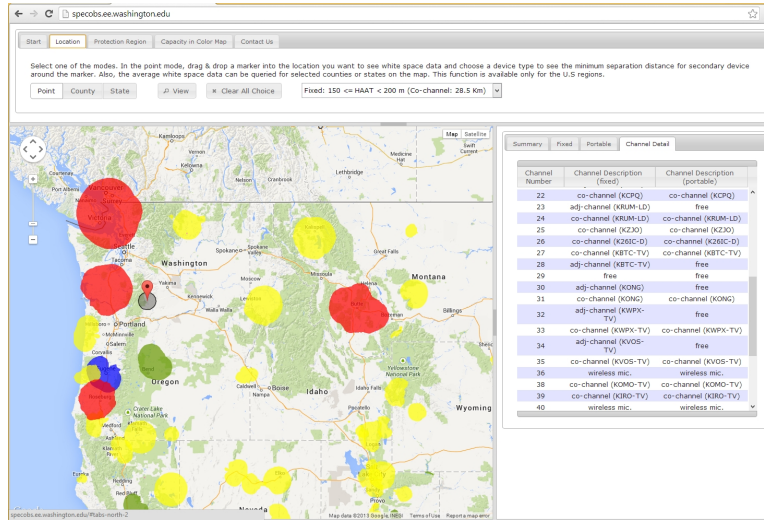[8]This simulator considers all FCC regulations as specified in [32] and is publicly available at http://specobs.ee.washington.edu/

Fig. 5. TVWS simulation engine, developed at University of Washington[8], a cloud based simulator for TVWS. Protection regions are shown for channel 19 across Washington state; List of available channels for fixed and mobile devices, as well as estimated interference level and capacity are shown for available channels [31]
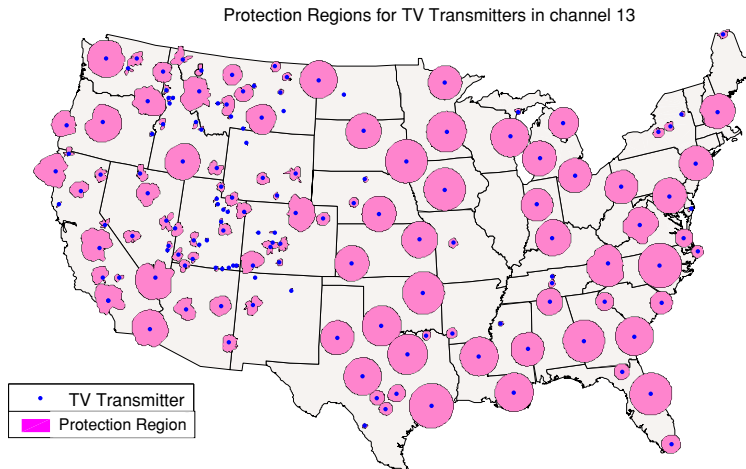

Fig. 6. Protection region for TV transmitters broadcasting on channel 13; Using Longley Rice model in area mode

and rural areas, interesting results are observed. As shown in Table II and Table III, the number of available WS channels is highly dependent on population density. The total number of channels in rural areas are twice as many as in the urban areas, mainly because of significant reduction in the number of active TV transmitters; however, the number of unused channels is approximately the same in both.

The variation of the average number of channels versus population density is also of interest. Fig. 8 shows the total number of available channels, sub-divided into those for fixed and portables devices. There is a noticeable big reduction in TVWS channels as population density approaches 1000 per sq. mile (representing transition from

TABLE I

AVERAGE NUMBER OF AVAILABLE CHANNELS FOR DIFFERENT TVBD CLASSES. AVERAGE NUMBERS ARE PROVIDED FOR THE
CONTIGUOUS UNITED STATES FOR 10000 UNIFORMLY DISTRIBUTED LOCATIONS.

Device Type	LVHF (2:6)	HVHF (7:13)	LUHF (14:51\37)	Total
Total Available	2.36	2.59	21.77	26.73
Fixed Devices	2.36	2.59	15.2	20.17
Portable/Personal	0	0	18.79	18.79
Reserved (Microphone)	2	0	2	4
Busy Channels by TV	0.45	2.22	10.43	13.11
Unused Channels	2.18	2.19	4.67	9.05
Channel Utilization Factor	56%	68.7%	87.4%	81.5%

TABLE II

AVERAGE NUMBER OF AVAILABLE CHANNELS FOR URBAN AREAS; A MINIMUM POPULATION DENSITY OF 1000 PERSON PER SQ. MILES IS
CONSIDERED AS URBAN AREA.

Device Type	LVHF (2:6)	HVHF (7:13)	LUHF (14:51\37)	Total
Total Available	1.69	0.76	7.85	10.3
Fixed Devices	1.69	0.76	1.95	4.4
Portable/Personal	0	0	7.3	7.3
Reserved (Microphone)	1.81	0	1.88	3.69
Busy Channels by TV	0.91	3.92	23.2	28
Unused Channels	2.4	2.32	4.67	9.4
Channel Utilization Factor	52%	67%	87%	81%

TABLE III

AVERAGE NUMBER OF AVAILABLE CHANNELS FOR RURAL AREAS; WITH POPULATION DENSITY LESS THAN 1000 PERSON PER SQ. MILES

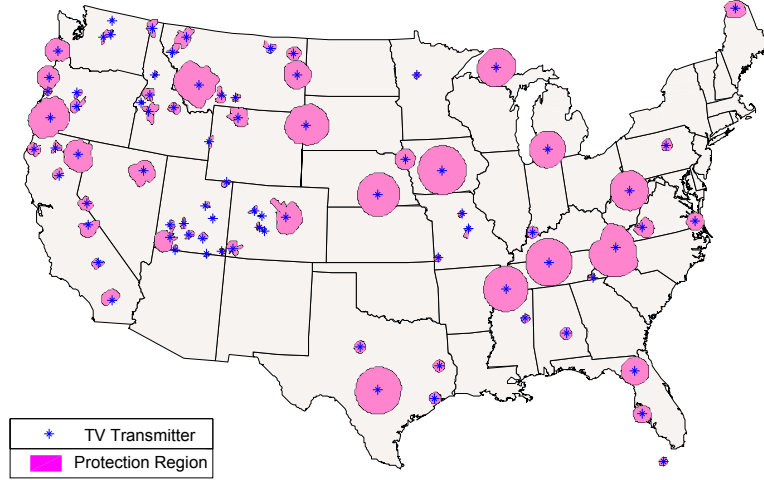| Device Type	LVHF (2:6)	HVHF (7:13)	LUHF (14:51\37)	Total
Total Available	2.20	1.60	17.4	21.2
Fixed Devices	2.2	1.60	8.82	12.63
Portable/Personal	0	0	15.56	15.56
Reserved (Microphone)	1.87	0	1.98	3.85
Busy Channels by TV	0.5	2.75	14.05	17.3
Unused Channels	2.3	2.64	5.23	10.17
Channel Utilization Factor	54%	62%	86%	79%

Fig. 7. Protection region for TV transmitters broadcasting on channel 5; Using Longley Rice model in area mode

TABLE IV

AVERAGE NUMBER OF AVAILABLE, BUSY, AND UNUSED CHANNELS FOR SELECTED CITIES IN UNITED STATES

Location	New York	Houston	Chicago	Seattle	Miami	Denver
Total Available	.05	5.16	5.57	12.81	1.65	3.176
Fixed Devices	0	2.13	1.06	4.67	0	1.058
Portable/Personal	.05	3.04	4.50	9.8	1.65	2.176
Reserved (Microphone)	3.93	3.93	3	4	3	4
Busy Channels by TV	37.1	31.25	31.51	25.5	38.23	37.5
Unused Channels	8.10	11.58	9.92	10.7	8.11	8.29
Channel Utilization Factor	81%	76%	80%	78%	83%	83%

rural to semi-urban areas) and thereafter, the changes are slower. The number of unused channels does not change much with population density, as noted in Tables II and III. Fig. 9 illustrates cumulative density function (CDF) for total number of available channels as well as number of available channels for fixed and portable devices, in urban and rural areas, defined as:

$$CDF(x) = Pr[\text{Number of channels } \leq x] \tag{14}$$

The rural CDF is shifted by approximately 10 channels, relative to urban CDF which again highlights further availability of TVWS in rural places.
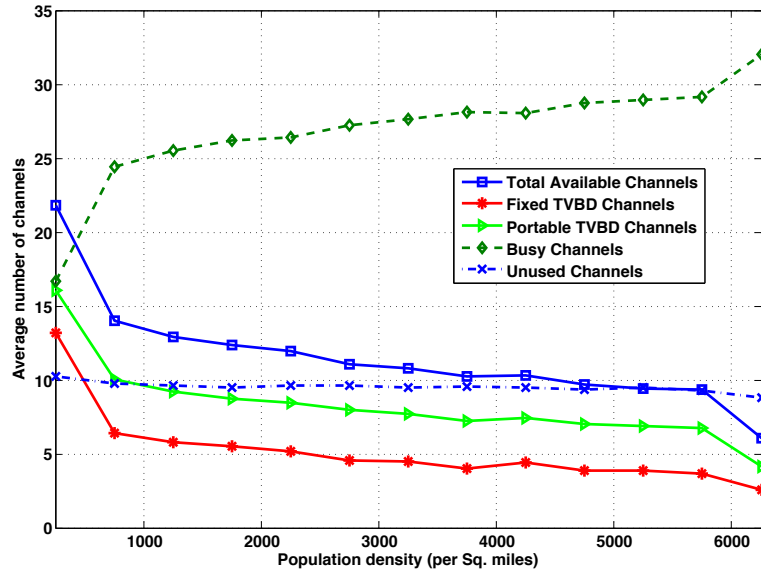
Fig. 8. Average number of available channels vs. population density, calculated over the contiguous United States [33].
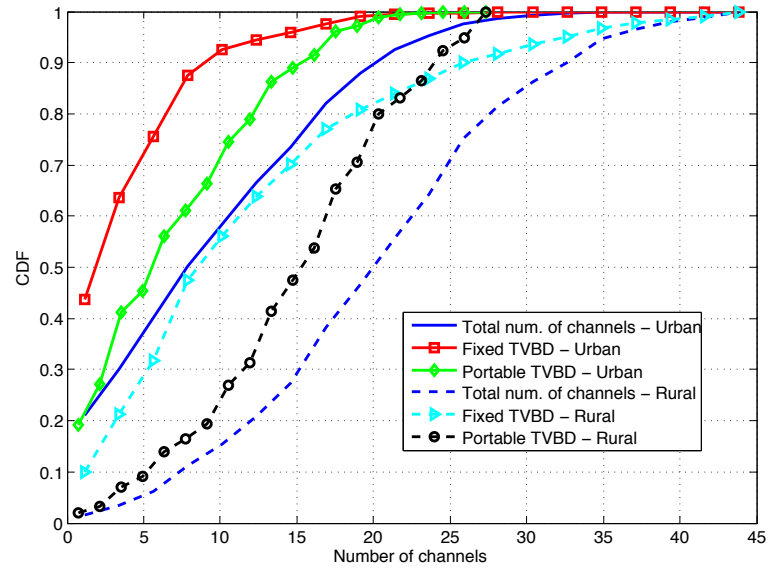

Fig. 9. Cumulative density function of number of available channels for different TVBD classes. Statistics are provided for the contiguous United States.
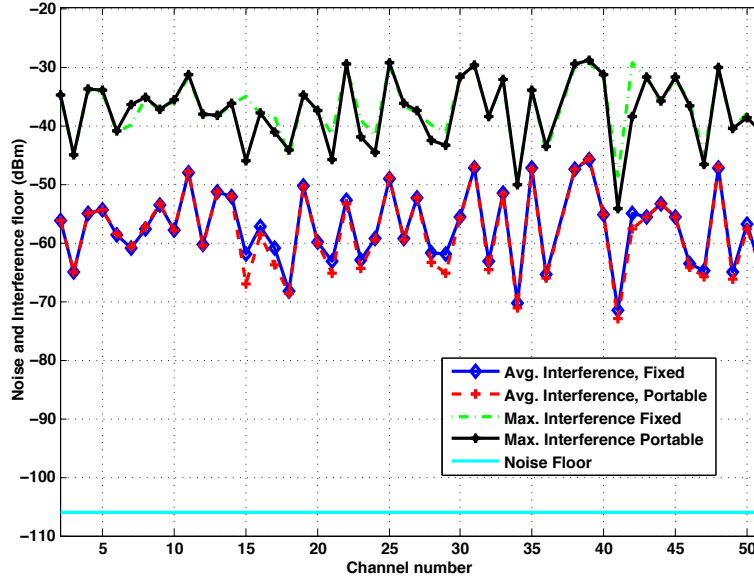
Fig. 10. Noise and interference floor for *fixed* and portable TVBD, (8).

B. *Primary to Secondary Interference*

Primary transmitters are usually of very high power with a poor transmission mask, as shown in Fig. 4. Therefore, they have considerable out-of-band emissions up to two adjacent channels, which significantly reduces secondary user's SINR. As a result, TV *white space* is in fact *gray space* with different levels of pollution in different channels. Fig. 10 illustrates noise and interference levels in all free channels (outside protection contour for primary transmitter) for *fixed* and *portable* devices. The figure also shows maximum and minimum interference level for both device types. The minimum interference is practically the same as thermal noise floor -106 dBm. On the other hand, the maximum noise level can be as large as -30 dBm which is significantly high and can severely affect the performance of secondary network.

The level of interference to *fixed* devices is generally larger than *portables*. This is due to higher antennas that are used for *fixed* transmitters (up to 30 meters is allowed according to FCC regulation [3]) while *portable* transmitter antenna is supposed to be less than 3 meters high. The extend of this difference depends on specific location of the receiver and can be as large 15~20 dB.

While it is expected to receive higher noise level at lower frequencies, the Fig. 10 does not reveal any specific pattern for noise level. This is mainly because the number of TV transmitters in each channel and their corresponding transmission power and antenna height is different. Here, we have considered TV transmitters in a range of 300-km from the receiver's location.
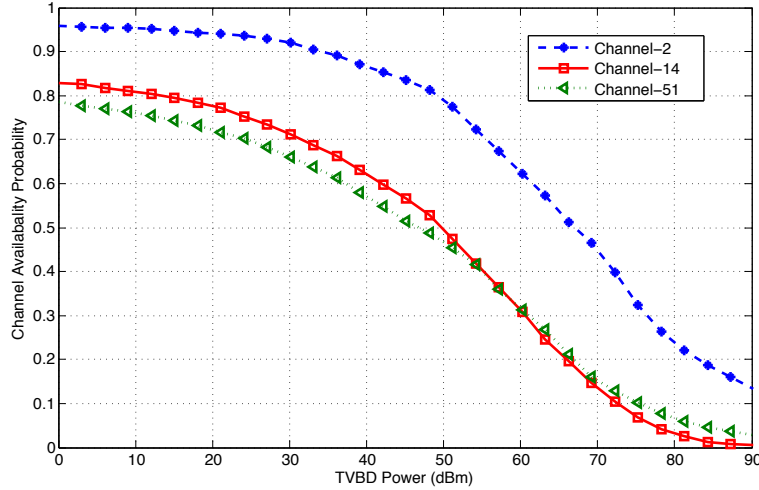
Fig. 11. Channel availability probability vs. TVBD power. Longley-Rice model is used for TV broadcasters and HATA model for 1-km distanced TVBDs. TVBD height is set to 30-m according to FCC regulations. Results are averaged over the contiguous United States.

VII. PRACTICAL TRADE-OFFS IN SECONDARY NETWORK DESIGN

A. Link Capacity vs. TVBD Power

Suggested by (13), link capacity is a function of available bandwidth $p(\Gamma)W$ and SINR = $\frac{P_{sec}/L_{sec}}{N_0 W_0 + I}$. Given that the bandwidth is fixed, in order to increase link capacity in a channel, secondary power P_{sec} should be increased. In contrast to regular communication systems, higher power in TVWS has a negative effect on link capacity since it expands protection region of TV transmitters. As a result, channel availability probability $p(\Gamma)$ defined in (6) decreases and average link capacity will diminish. The natural question is of course *what is the optimum secondary power?* In order to see the relative effects of secondary power, Fig. 11 shows channel availability probability $p(\Gamma)$ as a function of secondary power for three different channels. Obviously, increasing power will decrease probability of finding channel available. Channel 2 is generally more available than channel 14 and 51 since there are fewer active TV transmitters on this band. Fig. 12 shows average network capacity versus TVBD transmitter power. Increasing power initially increases capacity by improving SINR. However, as power is further increased, the reduction in the number of locations where the channel is available (outside the protected region in Fig. 2) leads to capacity decreasing. The interesting point is that all channels are optimized around the same secondary power even though the frequency band is considerably different (57-MHz for channel 2 and 695-MHz for channel 51) which results in smaller protection regions at higher frequency (excessive path-loss). This is mainly because there are less number of active transmitters at lower frequencies than at the higher ones which compensate for bigger protected regions.

B. Link Capacity vs. TVBD Antenna Height

The height of the secondary user's antenna is also affecting network capacity by changing path loss for TVBD transmitter. Increasing antenna height has following effects on network capacity:
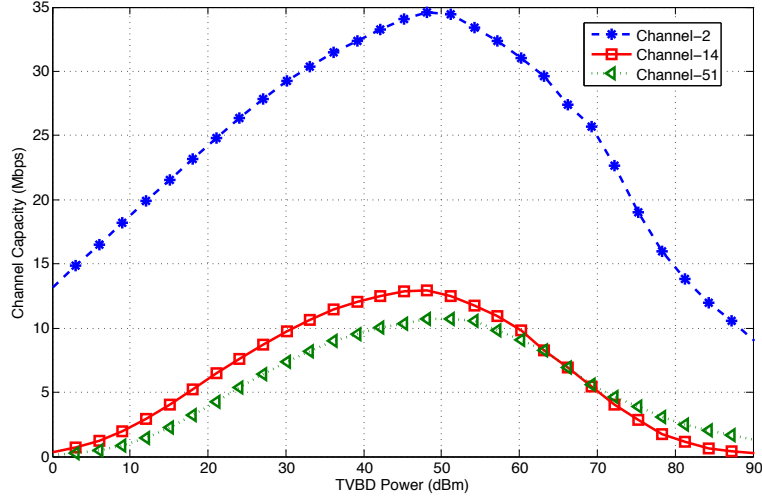
Fig. 12. Secondary network capacity vs. TVBD power. Longley-Rice model is used for TV broadcasters and HATA model for 1-km distanced TVBDs. TVBD height is set to 30-m according to FCC regulations. Eq. (13) is used for a pair of hypothetical secondary users exploiting the entire WS capacity in each channel. Results are averaged over the contiguous United States.

- ⋄ Secondary to secondary path loss decreases, higher capacity.
- ⋄ Minimum distance increases, hence $p(\Gamma)$ reduces and results in lower capacity.
- ⋄ Primary to secondary interference increases, lower capacity.

The overall effect of increasing antenna height depends on transmitter power, link distance and other fundamental parameters in (4). But the trade-off is obvious that increasing height will not continuously enhance capacity and there should be a cutting point. This optimization rises from the counter effects of higher received power at the receiver against less channel availability and more interference. Fig. 13 shows dependency of channel availability probability on TVBD antenna height for various transmission powers. Increasing antenna height monotonically reduces channel accessibility due to extended protection regions for TV transmitters.

Fig. 14 displays secondary network capacity as a function of TVBD antenna height. For lower power scenarios (EIRP≤2W), increasing height will improve capacity through a certain point where extended interference becomes dominant and capacity degrades. As can be seen from this figure, the higher the transmission power, the lower this optimum antenna which is reasonable because higher transmission power translates to amplified interference from secondary users in adjacent cells. For higher power scenarios (EIRP≥4W) interference is so dominant that increasing height will always decrease capacity.

C. Link capacity vs. Terrain Irregularity

The characteristics of propagation environment is modeled through ΔH parameter in ITM model. It ranges from $\Delta H = 0$ for extremely flat to $\Delta H = 500$ for rugged mountainous-type area. Our previous simulations were based on calculating a ΔH in every direction around TV transmitters (resulted in non-circular contour models) for
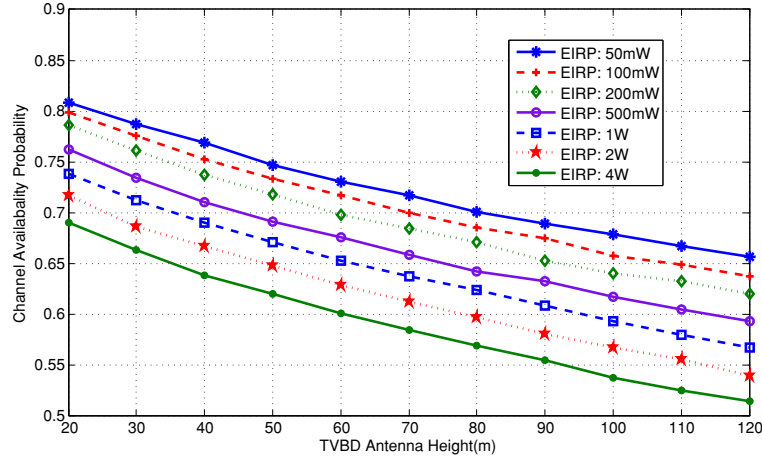
Fig. 13. Channel availability probability vs. TVBD antenna height. Longley-Rice model in area mode is used for TV transmitters and HATA model for 1-km distanced TVBDs. Results are provided for various transmission powers over channel 14. Calculation is provided for the entire United States.
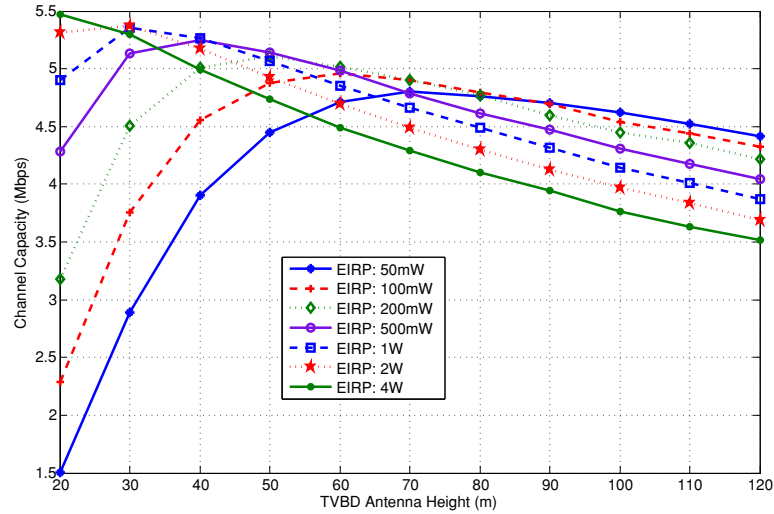

Fig. 14. Secondary network capacity vs. TVBD antenna height. HATA model is used for 1-km distanced TVBDs. Cell size is assumed to be 2-km wide. Results are provided for various transmission powers in channel 14. Average results are provided over the entire United States.

computation of protection contour. The effect of this parameter on network capacity is through $p(\Gamma)$ in (6) which directly modifies the overall capacity (13). Precise evaluation of ΔH is very critical since it significantly affects ITM path loss model (and any other empirical model). Calculating the exact value of ΔH is very challenging mainly because available terrain information is sparse, for example Globe [30] provides terrain height for every 30 arc-seconds (or approximately every 1 *km* in latitude and longitude) which may easily miss localized tall buildings or skyscrapers. Therefore, it is necessary to understand how the value of ΔH affects $p(\Gamma)$.

Fig. 15 plots $p(\Gamma)$ versus ΔH for channel 14 and for different values of EIRP. Increasing ΔH translates to
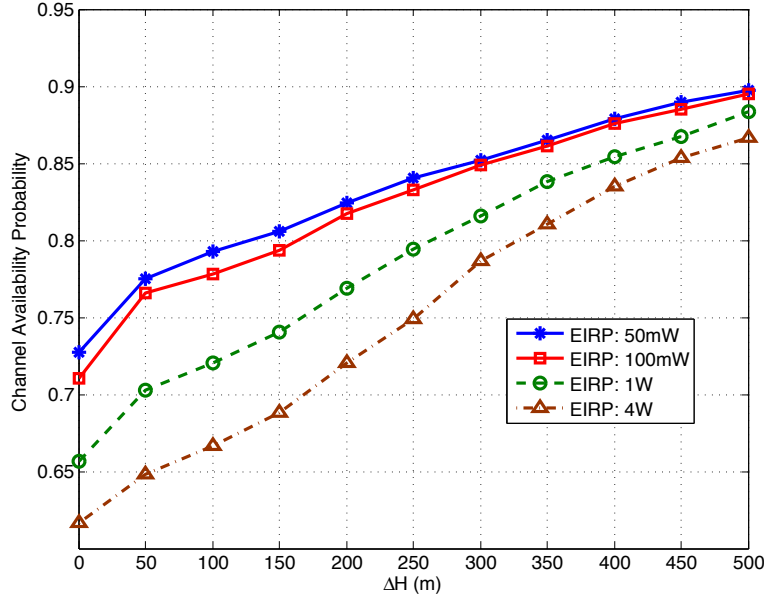
Fig. 15. Channel 14 availability probability vs. terrain irregularity parameter ΔH. Results are averaged over the contiguous United States.

further irregularity of the area, larger values of path loss and eventually smaller protection regions. This will leave wider areas for unlicensed operation by TVBDs and therefore $p(\Gamma)$ increases. FCC has overlooked the use of this variable in calculating protection regions in [2], [3], [32]. This figures shows how significantly the value of $p(\Gamma)$ varies (from 60% to 90%) depending on the value of ΔH.

D. Cell Size

The throughput of each user in the secondary cellular network depends on the available capacity in that cell as well as the number of users U_R requesting service in the cell. By assuming a MAC layer with efficiency of η_{MAC}, capacity per user can be formulated as

$$C_{User} = \frac{\eta_{MAC}\overline{C_{cell}}}{U_R} \tag{15}$$

The number of service requests in a cell depends on population density and cell size, $U_R \propto \rho_{Pop}A_{cell}$. Thus $U_R = \alpha\rho_{Pop}\pi r_{cell}^2$ where α is proportionality constant. Therefore, capacity per user can be rewritten as

$$C_{User} = \frac{\eta_{MAC}}{\alpha\rho_{Pop}\pi}\frac{\overline{C_{cell}}}{r_{cell}^2} \tag{16}$$

where the first factor is a constant and does not depend on network planning parameters. The second factor however is the normalized total capacity per area (bit/sec/m^2) and must be optimized to achieve the best throughput per user. The capacity per area (CPA) depends on the various parameters that we studied before as well as cell size. In the following, we will explore the behavior of CPA versus r_{cell} for which we employ (13) and evaluate it for various values of r_{cell}.
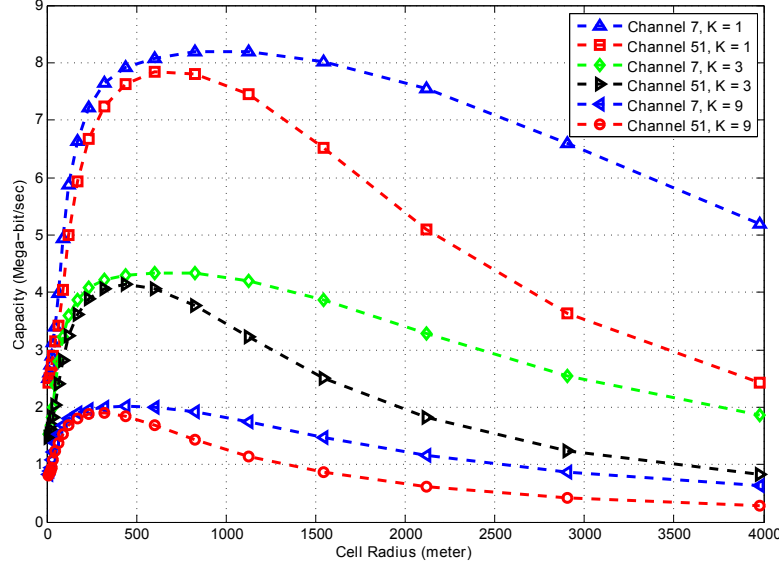
Fig. 16. Cell capacity versus cell radius for static (non-mobile) user, for various values of K and channel number
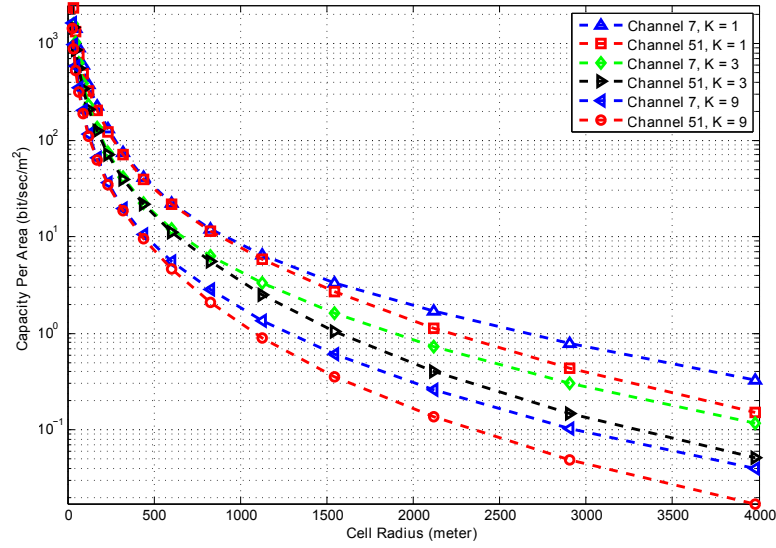

Fig. 17. Average area capacity versus cell radius for static (non-mobile) user, for various values of K and channel number

Fig. 16 shows capacity of a cell on different channels (channel 7 and 51) as a function of cell radius. The trade-off between the cell size and total capacity on each channel is clear for different frequency reuse patterns, $K = 1, 3, 9$ which is due to counter effect of higher received power and higher inter-cell interference. These results are averaged over different distances within the cell. The capacity per user, however, shows a different behavior versus cell size as shows in Fig. 17. Here, the capacity per area is presented which is proportional to capacity per user as in (16). The results predicts a uniform increase in capacity per user as cell radius decreases which is
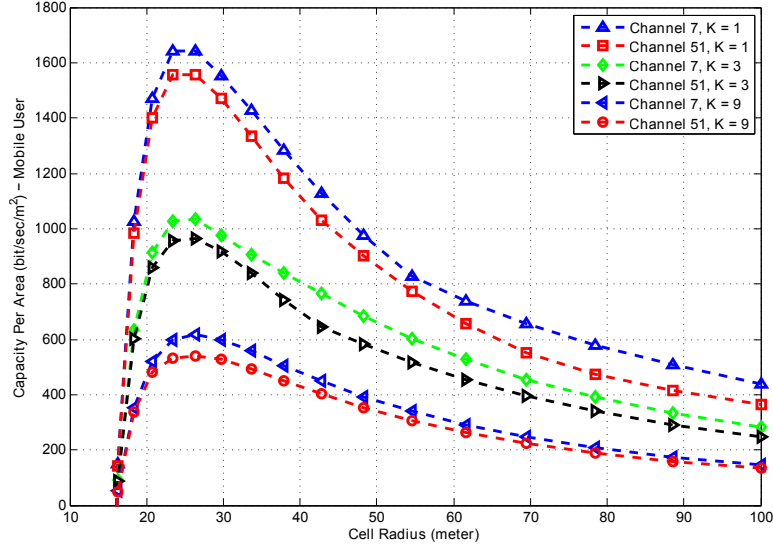
Fig. 18. Average area capacity versus cell radius for mobile user with speed of 50 Km/h, for various values of K

because the number of users in the cell decreases proportional to $\frac{1}{r_{cell}^2}$. This is an interesting effect because we can improve the capacity of each user by deploying more and more base stations with reduced coverage range. This conclusion however is valid only for stationary users that are not moving from cell to cell and therefore they do not incur additional overhead of being handed off from one cell to another.

For a mobile user that is moving from one cell to another cell, if the cell size is very small then the user has to be handed off very often. The hand-over process usually takes a certain delay overhead τ_{HO}, during which user data is not transmitted to base stations. Let's assume user is moving in a straight line with speed V m/s. During a duration of t, the number of times that the user must be handed off is proportional to $\frac{Vt}{r_{cell}}$. Therefore, the effective capacity that is experience by the mobile user is

$$C_{Mobile} = (1 - \frac{\alpha \tau_{HO} V}{r_{cell}})C_{User} \tag{17}$$

with α being a proportionality constant. Fig. 18 shows the result for a mobile user of speed V=50 km/h and hand-over delay $\tau_{HO} = 1s$. As this figure suggests, the cell size cannot be less than 25 meters because the effective capacity drops fast.

VIII. CONCLUSION

In this paper, we introduced a framework for analysis of secondary networks operating in the TV white space spectrum. There are two important factors which determine the overall performance of any secondary device in this band, *number of available channels* and *capacity of each available channel.* Both factors are spatially variable because of the irregular structure of the primary network (TV transmitters and other certified devices in TV band).

The number of available channels is defined through FCC regulations (which describes how primary services must be protected) and TVBD system parameters such as *power, antenna height, device type*. We studied white

space availability for both fixed and portable devices over the contiguous United States by considering all FCC rules. Our simulation results revealed that there is a significant difference in total number of available channels between rural (avg. of 21.2) and urban (avg. of 10.3) areas and the average number of available channels monotonically decreases as population density increases. Even in urban areas, there are significant variations between different markets; while no white space is available in New York, there are 12.81 channels available in Seattle.

The white space availability of a TV channel at any location is expected to be based on presence of active TV transmitters. However, our results showed that an average of 10 channels are left unused[9] (neither by TV transmitters nor by TVBD) and this average number does not change with population density. This is because current FCC rules are over protective, mainly due to poor design of TV receivers which cannot coexist with adjacent channel transmitters and a number of reserved channels for devices that may not necessarily use the channel at a given time/location.

We introduced a detailed model for secondary network capacity that includes the key parameters in both primary and secondary networks. The model includes two sources of interference for the secondary network, *primary transmitters* and *other secondary devices.* The information from current FCC database for TV broadcasters together with real terrain data and Longley Rice model were utilized to estimate co/adjacent channel noise floor at different channels (a standard transmission mask for TV broadcasters were considered that extends beyond the 6-MHz channel up to two adjacent channels). The results shows that primary to secondary interference can be as large -30 dBm in certain locations. This is particularly important for network operators that are interested in using TV band as an off-loading mechanism for their services; high base stations can receive significant interference from TV broadcasters.

The proposed secondary network was arranged in a cellular layout inside the allowed regions for sharing WS channels between TVBDs. The cross interference between secondary devices were defined in the context of this cellular layout. We used this model to evaluate various trade-offs that exists between available capacity versus power, antenna height, cell size and path loss parameters to illustrate possible optimizations in future TVWS network designs. We also explored the available capacity per user for both stationary and mobile user. The results showed a trade-off between average area capacity and cell radius for the case of mobile user.

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APPENDIX A

PROTECTION RADIUS CALCULATION

A. Protected Contour r_{PC}

For a given TV transmitter, protection contour r_{PC} is found by finding the maximum distance where signal strength (in dBu) or equivalently signal power (in dBm) drops to minimum threshold Δ, defined in Table V. The received power P_r is defined in terms of transmitted power P_t as:

$$P_r = P_t + G_t - L_{TV}(r_{PC}) + G_r = \Delta \tag{18}$$

where G_t (G_r) is transmitter (receiver) antenna gain and $L_{TV}(.)$ is the path loss model for TV signals as a function of distance to transmitter. The range of protection contour highly depends on this path loss model:

$$r_{PC} = L_{TV}^{-1}(P_t + G_t + G_r - \Delta) \tag{19}$$

Note that protection contour is only a feature of TV transmitter and does not depend on secondary user parameters.

B. Protection Region r_p

Protection region is defined for every application of secondary users. For example for fixed TVBD, power limit is higher and it forces secondary users to be further away from TV transmitter than portable devices with much lower power limits. Let's assume γ is the desired interference ratio $\gamma = \frac{\text{Desired Signal Power}}{\text{Undesired Signal Power}}$, P_{sec} is the power of secondary user, and G_{sec} is the antenna gain of secondary transmitter. The minimum separation distance d_{MS} as shown in Fig. 2 should be such that resulting γ is at least equal to threshold γ_0 given by Table V for various TV channels and services.

$$P_{sec} + G_{sec} - L_{sec}(d_{MS}) + G_r \leq \Delta - \gamma_0 \tag{20}$$

where $L_{sec}(.)$ is the path loss model for secondary transmitter. Using this, r_p is found to be:

$$r_p = d_{MS} + L_{sec}^{-1}(P_{sec} + G_{sec} + G_r - \Delta + \gamma_0) \tag{21}$$

This equation shows how P_{sec} plays an important role in calculation of channel availability.

APPENDIX B

ITM PATH-LOSS MODEL

The ITM models path loss in area mode in terms of a reference attenuation A_{ref}. This is the *median* attenuation relative to a free space signal that should be observed on the set of all similar paths during times when the atmospheric conditions correspond to a standard, well-mixed, atmosphere.

The reference attenuation is determined as a function of the distance d from the piecewise formula:

$$A_{ref} = \begin{cases} \max[0, A_{el} + K_1 d + K_2 \ln(d/d_{Ls})], & d \leq d_{Ls} \\ A_{ed} + m_d d, & d_{Ls} \leq d \leq d_x \\ A_{es} + m_s d, & d_x \leq d \end{cases} \tag{22}$$

TABLE V

DESIRED TO UNDESIRED SIGNAL RATIO DEFINED BY FCC FOR MAXIMUM TOLERABLE INTERFERENCE IN VARIOUS TV APPLICATIONS

Type of Station	Protection ratios	
	Channel Separation	D/U ratio (dB)
Analog TV, Class A, LPTV, translator and booster	Co-channel	34
	Upper adjacent	-17
	Lower adjacent	-14
Digital TV and Class A	Co-channel	23
	Upper adjacent	-26
	Lower adjacent	-28

TABLE VI

TV STATION PROTECTED CONTOURS; NOTE THAT THRESHOLD VALUES ARE IN dBu AND REPRESENTS SIGNAL STRENGTH (NOT POWER)

Type of Station	Protection contour		
	Channel	Contour (dBu)	Propagation curve
Analog: Class A, LPTV, translator and booster	Low VHF (2-6)	47	F(50,50)
	High VHF (7-13)	56	F(50,50)
	UHF (14-51)	64	F(50,50)
Digital: Full service TV, Class A TV, LPTV, translator and booster	Low VHF (2-6)	28	F(50,90)
	High VHF (7-13)	36	F(50,90)
	UHF (14-51)	41	F(50,90)

TABLE VII

MODIFIED FIELD STRENGTHS DEFINING THE AREA SUBJECT TO CALCULATION FOR ANALOG STATIONS

Channels	Defining Field Strengths, dBu, to be predicted using F(50, 50)
2 - 6	47
7 - 13	56
14 - 69	$64 - 20 \log_{10} \left(\frac{615}{\text{channel mid frequency in MHz}} \right)$

where the coefficients A_{el}, K_1, K_2, A_{ed}, m_d, A_{es}, m_s, and the distance d_x are calculated using the ITM algorithms. The three intervals defined here are called the line-of-sight, diffraction, and scatter regions. The dependency of path loss on frequency is not apparent in (22) but all the parameters are function of frequency[10]. The total path loss is the sum of A_{ref} and free space path loss which also depends of frequency:

$$L(d) = A_{ref} + 20 \log_{10}\left(\frac{4\pi df}{C}\right) \tag{23}$$

where C is the speed of light in vacuum. The irregularity parameter for an average terrain is $\Delta H = 90$; Using this, the reference attenuation for lowest/highest available frequency in TV band (channel 2 = 57 MHz, channel 51 = 695 MHz) are found as: Channel 2:

$$A_{ref} = \begin{cases} \max[0, -7.1 + d \times 4.03e - 4], & d \leq 94.1 \text{ km} \\ 5.87 + d \times 2.65e - 4, & 94.1\text{km} \leq d \leq 159 \text{ km} \\ 38.58 + d \times 5.95e - 5, & 159 \text{ km} \leq d \end{cases}$$

Channel 51:

$$A_{ref} = \begin{cases} \max[0, -17.94 + d \times 5.08e - 4], & d \leq 94 \text{ km} \\ -17.2 + d \times 5.0e - 4, & 94\text{km} \leq d \leq 136 \text{ km} \\ 42 + d \times 6.56e - 5, & 136 \text{ km} \leq d \end{cases} \tag{24}$$

According to analysis in sec. II to sec. V, determination of free channels as well as capacity calculations in TVWS highly depends on path loss model behavior. The more precise the model the less spectrum resources are wasted and the better protection is provided to TV receivers. In order to achieve some intuition about how coefficients in ITM model, (22)-(23), depends on fundamental parameters such as *frequency*, *antenna height* and *irregularity parameter*, a simplified version of ITM model that is more specific to TVWS system parameters is provided here. The original detailed ITM model can be found in [23].

$$A_{ref} = \begin{cases} \max[0, A_{el} + K_1 d + K_2 \ln(d/d_{Ls})], & d \leq d_{Ls} \\ A_{ed} + m_d d, & d_{Ls} \leq d \leq d_x \\ A_{es} + m_s d, & d_x \leq d \end{cases} \tag{25}$$

where line-of-sight distance d_{Ls} is defined as:

$$d_{Ls} = d_{Ls1} + d_{Ls2} = \sqrt{\frac{2h_{g,TX}}{\gamma_e}} + \sqrt{\frac{2h_{g,RX}}{\gamma_e}} \tag{26}$$

where $h_{g,TX}/h_{g,RX}$ are transmitter/receiver structural height and γ_e is the Earth's curvature constant. The diffraction range parameters are defined as:

$$m_d = \frac{A_{\text{diff}}(d_L + 4.3161X_{ae}) - A_{\text{diff}}(d_L + 1.3787X_{ae})}{2.7574X_{ae}} \tag{27}$$

$$A_{ed} = A_{\text{diff}}(d_L + 1.3787X_{ae}) - m_d * (d_L + 1.3787X_{ae}) \tag{28}$$

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[10]This dependency is not straightforward. They also depend on terrain irregularity parameter, Tx/Rx height, radio climate, polarization, etc.

with

$$d_L = \sqrt{\frac{2h_{g,TX}}{\gamma_e}}e^{-0.07\sqrt{\Delta h/h_{g,TX}}} + \sqrt{\frac{2h_{g,RX}}{\gamma_e}}e^{-0.07\sqrt{\Delta h/h_{g,RX}}} \tag{29}$$

$$X_{ae} = \left(\frac{2\pi}{\lambda}\gamma_e^2\right)^{-1/3} \tag{30}$$

illustrates dependency on antenna heights and terrain irregularity ΔH. The diffraction function $A_{\text{diff}}(s)$ is a complex function in terms of Fresnel integral [23]. The line-of-sight coefficients in (25) are simplified to $K_2 = 0$,

$$K_1 = \begin{cases} \frac{A_{ed}+m_d d_{Ls}-A_{\text{los}}(d_0)}{d_{Ls}-d_0} & , A_{ed} > 0 \\ \frac{A_{ed}+m_d d_{Ls}-A_{\text{los}}(d_1)}{d_{Ls}-d_1} & , A_{ed} < 0 \end{cases} \tag{31}$$

where

$$d_0 = \min(\frac{d_L}{2}, 1.908 k h_{g,RX} h_{g,TX}) \tag{32}$$

$$d_1 = \max(A_{ed}/m_d, d_L/4) \tag{33}$$

A_{los} is also defined in [23] in terms of the 'extended diffraction attenuation', A_d and the 'two-ray attenuation', A_t:

$$A_{\text{los}} = (1-\omega)A_d + \omega A_t \tag{34}$$