Practical Implementation of Geo-location TVWS Database for Ethiopia

Habib M. Hussien[1](✉), Konstantinos Katzis[2], Luzango P. Mfupe[3],
and Ephrem T. Bekele[1]

[1] School of Electrical and Computer Engineering, Addis Ababa Institute of Technology (AAiT),
AAU, Addis Ababa, Ethiopia
`{habib.mohammed,ephrem.teshale}@aait.edu.et`
[2] Department of Computer Science and Engineering, School of Sciences, 6 Diogenes Street
Engomi 1516, Nicosia, Cyprus
`K.Katzis@euc.ac.cy`
[3] CSIR Meraka Institute, Scientia Campus, Brummeria, Pretoria 0001, South Africa
`Lmfupe@csir.co.za`

Abstract. The beginning of TV white space (TVWS) for cognitive system is amongst the perceptible move towards solving the spectrum scarcity as well as rural connectivity problems. For the reason that this section of the spectrum band has higher bandwidth, good transmission characteristics and wide coverage. In this paper, we proposed a realistic implementation of the TVWS assignment simulation method focused on geo-location that solves the issue of spectrum under-utilization. The model is aided by the Calculation Engine of CSIR which is used in the radio frequency band of interest in Ethiopia to Intelligently quantify white spaces. More broadly, we aimed at the necessary input parameters, like radio propagation models suitable for the Ethiopian terrain environment, and calculation procedures to determine underutilized TVWSs. The models used by the Engine will approximate the contour coverage span of the incumbent TV station, separation distances for neighboring and co-channel locations, co-channel lists, as well as adjacent channels. In addition, using the planned implementation for the Ethiopia usage case; substantial amounts (87.9–98.23%) of geographically unoccupied broadcast TV channels are identified, such channels can be used for secondary provisioning of inexpensive broadband wireless networks.

Keywords: Calculation engine · Cognitive radio · Geolocation database · HAAT · Propagation model · Secondary user · TV white space

1 Introduction

These days, it has become difficult to allocate new spectrum for additional services. The spectrum has already been allocated for various wireless systems; thus, spectrum scarcity is nowadays one restrictive factor in incorporating more wireless services due to the fact that these systems have authorized users, users with exclusive access to the

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spectrum. However, studies indicate that white spaces, wide idle spectrum, exist amongst these exclusive bands [1]. Currently, White Spaces in the broadcast television band are the prime focus of studies. Digital Switch Over (DSO), migration from analog to digital broadcasting, is expected to increase the available White Space in the TV band. To realize secondary use for TVWS a technology called Cognitive Radio (CR) has been proposed [2]. CR allows secondary communication devices to access the spectrum, which is idle or underused by the authorized users. When countries like Japan [19], US [3, 35], South Africa [6, 7, 38], Ghana [39], UK [17, 32], Tanzania [37] switched to digital broadcast spectrum was left in the TV band that permitted use of CR.

The United States Federal Communications Commission (FCC) sanctioned the operation of unlicensed transmitters in broadcast TV spectrum according to set rules [3]. The European Conference of Postal and Telecommunications Administrations (CEPT) issued European Electronic Communications Committee (ECC) report 186 [4], which specifies the requirements for geo-location approach based operation of White Space Devices. The DSO is scheduled to be completed in Ethiopia by 2020 [5], after which some of the networks will be declared as digital dividends. Harmful interference is to be avoided in TVWS channels by using low power WSDs. The WSDs require techniques for authorized users services protection and TVWS sensing even though there is a large amount of TVWS available. Two strategies for the operation of TVWS networks have been proposed by many regulatory bodies worldwide, such as in the US, Europe and several African countries (South Africa, Malawi, Botswana, Mozambique, Ghana and so on).

These are (1) Geo-location White Spectrum Databases (GLSDs) (2) Spectrum sensing. From the two, GLSDs [6, 7] is better suited for the following reasons.

- It interprets the regulations of protective WS spectrum use issued by the national regulatory authorities for the spectrum.
- Primary user networks are protected from harmful interference when locally available spectrum is assigned.
- Techniques to access available local spectrum that are available for the WSDs.

It is expected that the database prioritizes incumbent users. Parameters such as location, antenna height, maximum effective radiated power (max ERP), site name, channel, frequency and other related information need to be sent to the system seeking WSD. Using the incumbent user information, the calculation engine defines the accessible channels and power levels at a particular location. The result is then forwarded to the device containing the available channels and powers, after which the device can start to transmit [8].

The remainder of the paper is arranged as follows: Related work is gggiven in Sect. 2; Sect. 3 includes Calculation Engine Specifications for White Space Calculation; Sect. 4 presents how the white space engine operates; Finally, the experimental findings and conclusion are discussed respectively in Sects. 5 and 6.

2 Related Work

The The FCC pioneered GLSD dynamic WS access [9]. Murty et al. [10] mobile users' convenience and stability may be increased by using GLSD assisted white spaces networking. Gao et al. [11, 13] designed GLSD based opportunistic spectrum use for vehicle-to-vehicle communication. Madhavan et al. [13, 14] applied in low range cellular network the utilization approach. Ameigeiras et al. [15] studied TV white space use in dynamically deploying small cells. In USA, the average UHF band can only accommodate 5 channels per person and 18% per person is available in Europe. In the United Kingdom [18], Japan [19], South Africa [6, 7, 38], Tanzania [37] and Ghana [39] similar studies have been conducted. In countries with poor spectrum utilization, such as Ethiopia where there is a single broadcaster transmitting two channels all over the country with each channel occupying a mere 8 MHz much of the spectrum is yet to be used. The digital switch over [5] is expected to avail a large number of unused bands, which may be used for rural communication [20].

3 White Space Calculation Engine Parameters

3.1 Terrestrial Television Planning Models

First, the planning strategy of Ethiopia must be understood to use the terrestrial television for TVWS. The desired parameters that can be included in the TV planning are allocation of frequencies, transmitters' status and their power limits [6, 7). The signal field strength or the appropriate calculations based on collected data can be expended to assure the received signal quality [21, 22]. The construction of the database is influenced by national terrestrial television planning. These are influenced by the recommendations of the ITU, by international and national conventions, and by multilateral ITU arrangements [23–25]. Transmitter-receiver pairs are configured in different modes. A fixed outdoor receiver antenna of 10 m and indoor/outdoor portable receiver antenna of 1.5 m are used. Transmitter-receiver pairs can be digital or analog. Digital technology can be used with transmitter-receiver pairs, which are outdoor or indoor. However, analog can only be used for fixed outdoor receivers. Reference values for receiver field strength, probability of location and level of interference are usually set forth in configurations of reference planning [6, 7].

3.2 Terrestrial TV Network Frequency

Secondary use of a network is only possible by knowing the frequencies used by a channel. A large power transmitter is surrounded by low-power repeaters in some situations. These repeaters may be property of TV planning authority or a village seeking better connectivity. Terrestrial TV networks may be single frequency transmitter or multiple frequency transmitters [6, 7].

Single Frequency Transmitters: Such transmitters broadcast over a single channel. This scheme might extend to a national level in which all TV information is transmitted over a single channel. To alleviate interference, enough gap must exist in transmission. To have multiple transmitters channel reuse is required [6, 7].

Multiple Frequency Transmitters: A single transmitter uses several frequencies to broadcast. Interference control scheme to limit co-channel and adjacent interference is essential for the transmitters. It is possible to reuse the channels which results in better channel utilization compared to single frequency transmission.

3.3 Terrestrian Television Coverage Determination Approaches

The power and/or field strength are used to determine the area of coverage of a TV transmitter. The further you go from the transmitter the signal quality degrades and at some point becomes undetectable. This field strength value is considered the minimum median field strength, the value of which is determined by the planning body. The region between the transmitter and points having a signal strength equal to the minimum median field strength is known as coverage area [6, 7]. There are two approaches.

Noise Limited Contour: The area for which the difference of minimum receivable signal power and noise floor are greater than the carrier to noise ratio threshold is taken as the coverage area.

Interference Limited Contour: The coverage is measured here as the noise-limited contour with the noise floor substituted by the interfering signal strength. It is assumed/considered that multiple frequency transmitters operate in the system. The CNR is about 8.05 dB higher for analogue TV than the SNR [22].

3.4 Protection for Terrestrial TV

The transmission by authorized users must be protected from interferers. Hence, the approved received signal protection ratio (PR) is defined to protect incumbent receivers from interferers. In the protection ratio equation [6, 7, 26, 27], CNR, CIR, NIR, and SNR may be used.

3.5 Path Loss Models for Terrestrial TV

There are propagation models for terrestrial TV broadcasting frequencies. The models may be categorized as deterministic, empirical and hybrid [6, 7].

Empirical Models: The data collected from location in the signal path is used to model the propagation. There will be less reliance on terrain modeling and other signal loss factors in this modeling, as the data is taken from the location of the signal path.

Deterministic Models: Here equations are formulated that predict the behavior of a signal on a path. These equations predict field strength and power at a particular distance. There are versions, too that use both strategies. These are known as combined versions (Table 1).

Significant parameters which affect the WSD and transmission by incumbent users must be considered in the database design.

Table 1. Selected propagation models [6, 7, 28]

Model	Frequency range (GHz)	Distance (km)	Category	Typical application
Extended Hata	0.03–3	Up to 40	Empirical	Point-to-point short-to-medium spectrum preparation of short-to-medium height antennas for terrestrial television stations. Measured terrain information is utilized in the form of curves
Longley-Rice [29]	0.02–40	1–2000	Mixed: Empirical/deterministic	Point-to-averaged-radial and point-to-multipoint planning and generic coordination- planning of terrestrial broadcast stations. Uses terrain profile elevation and measured data
ITU-R P.1546-5 [34]	0.03–3	1–1000	Mixed: Empirical/deterministic	Point-to-multipoint generic coordination-Terrestrial radio station preparation. Using determined terrain details in the form of curves and elevation of the terrain profile 3–15 km from the transmitter
TM-91-1 [30]	0.04–1	<16	Empirical	Point-to-point planning for short distances
ITWOM [31]	0.02–20	1–2000	Mixed: Empirical/deterministic	Point-to-point and point-to-multipoint planning of terrestrial broadcast stations. Elevation of the surface profile and measured data were used

Protection Ratio: For the protection of incumbents from harmful interference there must a minimum signal threshold. Different regulators working at the national level have recommended safety ratios for co-channels and neighboring channels. Protection ratios have differing values depending on the ITU region of interest. For Ethiopia, which is in the ITU region 2 the values are given in Table 2 below.

Table 2. Protection Ratios (PR) [32]

Regulatory body: Ofcom, UK (Class 1 WSD)	
Bandwidth of Channel (MHz)	8
The sort of channel which should be protected	PR (dB)
Co-channel ($\Delta F = 0$)	17
Adjacent channel ($\Delta F = \pm 1$)	−36

WSD Emission Mask: This is a limit for out of band emission for the operating WSDs. The emission mask is determined using emission power and frequency of operation [6, 7].

4 How White Space Calculation Engine Works

The figure below shows the Ethiopian GLSD front end which uses the CSIR calculation engine JSON RPC 2 [6, 7, 36]. The front end obtains unoccupied bandwidth, accessible channels and intermediate values via the API, such as distance of contour coverage, adjacent and co-channel separation distance, adjacent occupied and co-channel separation distance (Fig. 1).

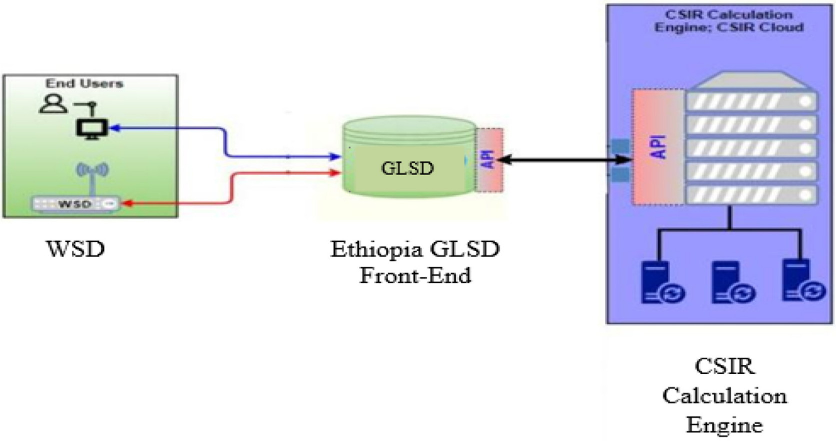

Fig. 1. Ethiopia GLSD front-end and CSIR engine collaboration architecture [6, 7, 36]

Implementation starts by identifying TV stations. The datasets/technical information for transmitters, which includes the location coordinates are obtained from the Ethiopian Broadcasting Authority (EBA). After preprocessing the data from EBA and converting to appropriate format, computation can take place. For each WSD the area in its vicinity is scrutinized. The calculation engine requires authentication, where the presence of the WSD in the allowed list is checked. If authenticated, the WSD forwards it GPS coordinates to the calculation engine. In addition, the WSD device sends the height of its antenna measured from the ground. The calculation engine then checks if the antenna height is above or below 30 m. In deciding the free channels, the following steps can take place.

- Following authentication, Height Above Average Terrain is computed
- Model of propagation TM-91-1 used for heights below 10 m [6, 7, 35]; use [6, 7, 30] to measure the distance of separation between the covered contour and the WSD.
- The ITU-R 1546-5 propagation model [34] for HAAT above 10 m is used for a given $\mathrm{E_{WSD}}$ value using interpolation. The determined D_{sep} is then used to compute the available channels.

4.1 Determination of HAAT/Effective Antenna Height

The calculation/computation requires the location coordinates of the antenna as an input. Then, starting from true north radials are taken with the desired resolution (typically 10 degree) to compute the average terrain. By measuring the terrain, height from 3.2 km to 16 km in equal step sizes the HAAT is determined. Similarly, by taking measurements from 3 km to 15 km at equivalent phase sizes, the effective antenna height is determined/calculated. The terrain closer than 3 km to the antenna does not affect coverage; hence, is neglected. The mean for the means of the radials is then taken as the HAAT. HAAT is not permitted to exceed 250 m.

4.2 Maximum Allowable WSD field strength (EWSD) Calculation

The protection ratio, protected contour median field strength and front-to-back ratio can be used to compute the maximum allowable field strength as follows.

$$E_{WSD} = E_{med} - R_p + R_{FP} \tag{1}$$

Where: E_{WSD} is maximum allowable WSD field strength, E_{med} is minimum median field strength R_p is protection ratio of incumbent receiver, R_{FB} is receiver's front to back ratio.

The TM-91-1 model [30], implies:

$$E_{WSD} = 1.414 + 20\log(h_1 h_2) - 40\log D_{sep} + 10\log P_{WSD} \tag{2}$$

Where: h_1 and h_2 are heights of antenna above average sea level, D_{sep} is distance between WSD and incumbent contour and, P_{WSD} is ERP of a WSD.

The separation distance may then be computed as:

$$\mathrm{D_{sep}} = \frac{1.085 * \sqrt{h_1 h_2} \ * \sqrt[4]{P_{WSD}}}{10\exp\left(\frac{E_{WSD}}{40}\right)} \tag{3}$$

A minimum distance of D_{sep} from the incumbent transmitter's protected contour is required if channels are to be available. For heights exceeding 10 m, the ITU-R 1546-5 propagation model is used at 50% location and 1% time in computing the D_{sep}. The field strength of the WSD may then be computed by taking into account the protection ratio, HAAT and path loss as follows:

$$E_{WSD} = 106.9 - 20\log D \tag{4}$$

Where: E_{WSD} is free space field strength for 1kW ERP, D is the distance in km [17].

It is now possible for each operating frequency to determine the distance value; however, interpolation and/or extrapolation may be required to do so.

4.3 Contour Distance for Incumbent Transmitter

The field strength can be computed/calculated by taking the normalized field strength at Half Power Beam Width or using depression angle to calculate the normalized field strength first. The square of normalized field strength is then multiplied by the maximum ERP of the incumbent transmitter. This value is known as the radial ERP. The radial power is then computed by converting the last value into dB using 1 kW as a reference. The difference between minimum median field strength and radial power yields radial field strength. By using this radial field strength at 95% location and 50% time the contour coverage can be computed using ITU-R 1546-5 propagation model. Interpolation according to the following formula may be necessary in case the values are not in the tables provided.

$$D_c = D_{\inf}\left(\frac{D_{\sup}}{D_{\inf}}\right)^{\left(\frac{E_r - E_{\inf}}{E_{\sup} - E_{\inf}}\right)} \tag{5}$$

where, D_c is contour coverage distance, D_{sup} is the distance for E_{sup}, D_{inf} is the distance for E_{inf}, E_r is radial field strength, E_{sup} is the nearest field strength above E_r, E_{inf} is the nearest field strength below E_r.

The incumbent transmitter's contour coverage and location should be saved in the database. Whenever a WSD requests for free spectrum, the database repackages the request and forwards it to the CSIR calculation engine. Upon receipt of the results from the calculation engine the database sends the results to the WSD. The detailed process is described as follows. The WSD begins by sending its HAGL, ERP, location along with its channel request. The GLSD authenticates the device. For a certified device, the GLSD computes HAAT by using HAGL and WSD location. The minimum median field strength, front to back ratio and protection ration are then used to compute the maximum allowed field strength for the WSD. The separation distance for the WSD is then computed from this information. The transmitters within 150 km of the transmitter are in the region where WSD causes interference. The separation distance is added to the contour coverage after which it will be deducted from the incumbent transmitter-WSD separation. If x, the last result, is greater than zero then the channels are available if not the channels shall not be used as it will cause interference.

4.4 Haversine Function Formula

With the following calculations, we have used the Haversine theorem to describe the locations that would be impacted by the WSD. The formula Haversine is also used to measure the WSD distance. The formula takes latitude and longitude inputs from the two positions for which the degree of separation between them is calculated [6, 7].

$$D = 2Rarcsin\sqrt{haversine(\varphi 2 - \varphi 1) + \cos(\varphi 1)\cos(\varphi 2)haversine(\lambda 2 - \lambda 1)} \qquad (6)$$

$$Haversine\ (\theta)\ =\ sin2\ (\theta/2) \qquad (7)$$

Where, R is the radius of Earth, φ1 and φ2 are latitude of point 1 and 2, λ1 and λ2 are longitude of point 1 and 2 respectively.

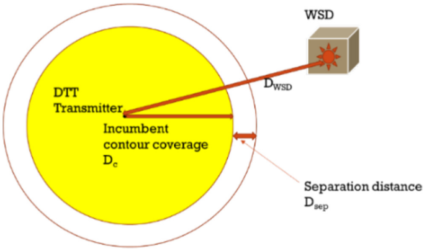

Fig. 2. Illustration of WSD and DTT transmitter location

For the illustration of parameters as seen in Fig. 2 above, the database will be built to operate as shown in Fig. 3 of the flowchart.

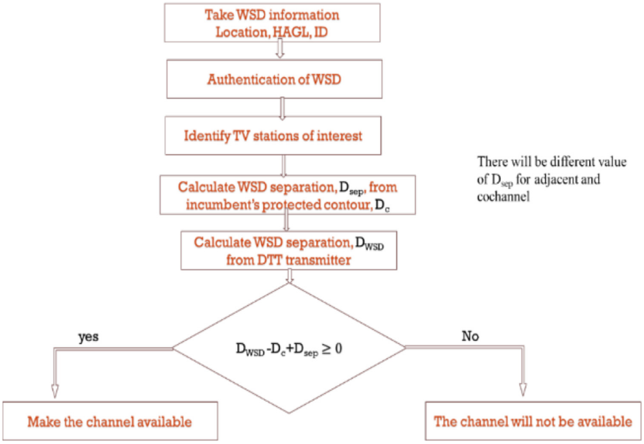

Fig. 3. Flow chart for the calculation engine

5 Experimental Results

We have taken the WSD to be located at a plateau near Tulu Dimtu (Addis Ababa) condominium site with transmitter HAGL to be 30 m. For DTT transmitters, we have also assumed to be 30 m HAGL. However, when we identified the transmitters which could be affected by the WSD, there was only Furi site (Addis Ababa) identified as depicted in Fig. 4. As it can be seen from Table 3 Using GLSD Calculation Engine, we have able to determine the coverage contour distance of the given free channels and the separation distance of the adjacent and the co-channel transmitters from the contour for protecting the incumbents from harmful interference. For instance for Furi Transmitter site, the adjacent and co-channel separation distance between the WSD and the incumbent coverage contour is 1.027 km and 58.48 km respectively. To be specific, the WSD must be 1.027 km away from the protected contour of adjacent incumbent transmitter and 58.48 km away from the protected contour of co-channel incumbent transmitter for TVWS free channels to be available. From the Table 4 we can see that, by using the Geo-location White Spectrum Calculation Engine, we can have a minimum of 51 free channels and maximum of 57 free channels among the total number of 58 TV transmitters' channels in Ethiopia. For example, When Calculation Engine has made a calculation for Furi transmitter site coordinates; there are about 3 occupied TV Transmitter channels and 55 free TVWS channels. In other words, the TVWS availability around Furi Area (Test Place) is around 94.8%. In general, the range of TVWS availability in Ethiopia is from 87.9%–98.23%.

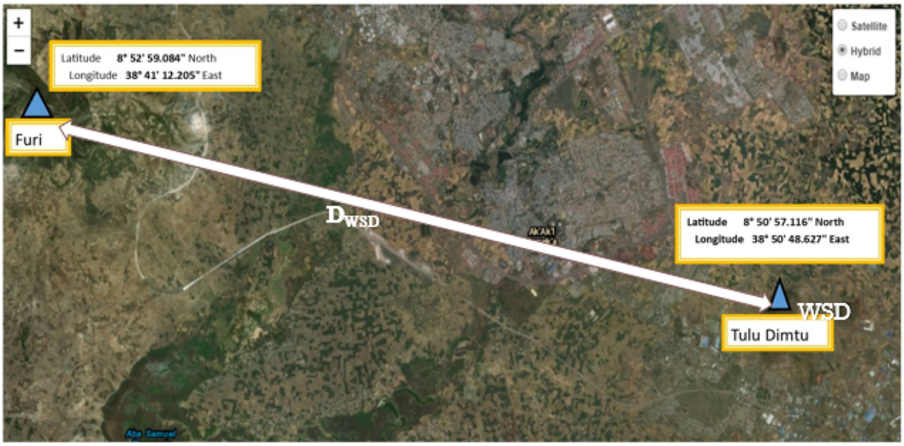

Fig. 4. Testing the calculation engine at Addis Ababa

Table 3. Coverage contour distance, adjacent and co-channel contour distances using the proposed calculation engine.

Site name	Channel	Coverage contour distances (km)	Adjacent separation distance (km)	Co-channel separation distance (km)
Furi	5	88.267	1.0207	58.48
Furi	7	88.267	1.0207	58.48
Harar	7	83.382	1.0207	58.48
Dire Dawa	5	84.495	1.0872	60.418
Jijiga	11	82.404	1.0207	58.48
Nazireth	11	85.423	1.0872	60.418
Dessie	9	79.91	0.9094	55.157
Jimma	5	79.302	0.9094	55.157
Nekemte	9	80.96	0.9625	56.737
Shashemene	5	81.552	0.9625	56.737
Dila	11	84.811	1.0872	60.418
Gondar	7	84.811	1.0872	60.418
Bahirdar	5	82.648	1.0207	58.48
Mekele	7	84.382	1.0528	59.423
Axum	9	81.552	0.9625	56.737
Assosa	11	79.91	0.9094	55.157
Gode	9	81.552	0.9625	56.737
Adi Remest	35	60.891	0.3885	35.087
Ankober	34	61.146	0.3932	35.325
Assosa	60	55.51	0.2977	30.793
Debark	57	56.061	0.3063	31.207
Dessie	48	57.864	0.3355	32.587
Dila	29	62.51	0.4191	36.59
Kebridahar	24	57.651	0.3316	32.422
Fiche	50	57.442	0.3285	32.261
Furi	42	59.216	0.3578	33.642
Gore	50	57.442	0.3285	32.261
Jijiga	43	58.981	0.3531	33.457
Jimma	45	58.524	0.3469	33.099
Jinka	46	58.3	0.3427	32.925

(*continued*)

Table 3. (*continued*)

Site name	Channel	Coverage contour distances (km)	Adjacent separation distance (km)	Co-channel separation distance (km)
Kuni	35	62.224	0.4138	36.326
Maichew	54	56.635	0.3158	31.643
NefasMewca	21	65.061	0.4684	38.927
Shebel	28	62.802	0.4246	36.86
Tendaho	43	58.981	0.3531	33.457
Weldia	25	63.723	0.4424	37.705
Nekemte	38	60.174	0.3744	34.418
Gode	28	62.802	0.4246	36.86
Mekele	54	56.635	0.3158	31.643
Axum	51	57.236	0.3241	32.102
Dire Dawa	42	59.216	0.3578	33.642
Mega	53	56.832	0.3182	31.794
ChokeTeraa	32	61.673	0.4033	35.815
Abiy Adi	24	64.046	0.4486	38
Amentila	40	59.698	0.3667	34.022
Derba	34	61.146	0.3932	35.325
Warder	47	57.014	0.3382	32.754
Filtu	41	56.759	0.3618	33.83
Adigrat	51	57.236	0.3241	32.102
Ginir	45	58.524	0.3469	33.099
Dellomena	40	58.6	0.3667	34.022
Fik	51	56.186	0.3241	32.102
Maji	36	59.605	0.3838	34.85
Guba	23	64.377	0.4555	38.302
Yabello	50	55.353	0.3285	32.261
Samre	47	58.081	0.3382	32.754
Bella/Ghimi	24	57.651	0.3316	32.422

Table 4. Identification of occupied adjacent and co-channels TV spectrums for each TV transmitter sites in Ethiopia for interference protection.

Site name	Channel	Occupied adjacent	Occupied co-channel
Furi	5	11, 38 and 42	11, 38 and 42
Furi	7	11, 38 and 42	11, 38 and 42
Harar	7	5, 11 and 42	5, 11, 42 and 43
Dire Dawa	5	5 and 42	5, 11 and 42
Jijiga	11	11 and 43	5, 11 and 43
Nazireth	11	11	11, 38 and 42
Dessie	9	9 and 48	9, 48 and 25
Jimma	5	5 and 45	5 and 45
Nekemte	9	9	9
Shashemene	5	5 and 11	5, 11 and 29
Dila	11	5, 11 and 29	5, 11, 29 and 34
Gondar	7	7	5, 7 and 57
Bahirdar	5	5	5 and 7
Mekele	7	7, 54, 24, 40 and 47	7, 9, 54, 24, 40, 51 and 47
Axum	9	9, 51 and 24	7, 9, 51, 24 and 51
Assosa	11	11 and 60	11 and 60
Gode	9	9 and 28	9 and 28
Adi Remest	35	35	7 and 35
Ankober	34	34	11 and 34
Assosa	60	11 and 60	11 and 60
Debark	57	7 and 57	7, 9, 35 and 57
Dessie	48	9 and 48	9, 48 and 25
Dila	29	5,11 and 29	5, 11, 29 and 34
Kebridahar	24	24	24
Fiche	50	50	50 and 38
Furi	42	11, 42 and 38	11, 42 and 38
Gore	50	50	50
Jijiga	43	11 and 43	5, 11 and 43
Jimma	45	5 and 45	5 and 45
Jinka	46	46	46
Kuni	35	35	5 and 35
Maichew	54	7, 54 and 47	7, 54, 40 and 47

(*continued*)

Table 4. (*continued*)

Site name	Channel	Occupied adjacent	Occupied co-channel
Nefas Mewcha	21	21	7, 5 and 21
Shebel	28	28	28
Tendaho	43	43	43
Weldia	25	25	9, 48 and 25
Nekemte	38	38 and 42	11, 38, 42 and 50
Gode	28	9 and 28	9 and 28
Mekele	54	7, 54, 24, 40 and 47	7, 9, 54, 24, 40, 51 and 47
Axum	51	9, 51 and 24	7, 9, 51, 24 and 51
Dire Dawa	42	5 and 42	5, 11 and 42
Mega	53	53	53
Choke Terara	32	32	5 and 32
Abiy Adi	24	7, 9, 24 and 47	7, 9, 24, 40, 47, 51 and 54
Amentila	40	7, 40, 47 and 54	7, 9, 24, 40, 47 and 54
Derba	34	34	11, 29 and 34
Warder	47	47	47
Filtu	41	41	41
Adigrat	51	7, 9 and 51	7, 9, 24, 51 and 54
Ginir	45	45	45
Dellomena	40	40	40
Fik	51	51	51
Maji	36	36	36
Guba	23	23	23
Yabello	50	50	50
Samre	47	7, 24, 40, 47 and 54	7, 9, 24, 40, 47 and 54
Bella/Ghimbi	24	24	24

6 Conclusion

This paper focused on the realistic application of GLSD modeling approaches to forecast the quantity of TVWS in the Ethiopian use case based on the CSIR engine. The experimental findings have shown that much of the spectrum of Ethiopian TV is underutilized or unused. From the performance of the results, we will note that the model applied is good at estimating the number of white spaces as well as the coexistence of primary and secondary devices. Rural areas in Ethiopia therefore have a promising future, given the usage of these free networks for rural broadband as well as for the resolution of spectrum shortages in urban areas.

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