SYSTEMATIC ANALYSIS OF GEO-LOCATION AND SPECTRUM SENSING AS ACCESS METHODS TO TV WHITE SPACE

ABSTRACT

Access to the television white space by white space devices comes with a major technical challenge: white space devices can potentially interfere with existing television signals. Two methods have been suggested in the literature to help white space devices identify unused channels in the TV frequency band so that they can avoid causing harmful interference to primary services legally protected to run on the bands. These methods are a geo-location spectrum database and spectrum sensing. Discussions in the literature have placed much emphasis on the limitations of the spectrum sensing approach and mainly based on the developed world environment ignoring the performance requirements of the geo-location approach and how the absence of these requirements in a developing region could affect its performance. This paper considers a broader analysis of the approaches by looking at factors that can affect the performance of each approach and how the presence or absence of these factors in a developed region or developing region can affect their performance. In so doing, the paper highlights the need to conduct more research on the performance of spectrum sensing in developing regions where there are plenty of white spaces to ascertain its use in these regions.

Index Terms— Geo-location database, spectrum sensing, performance factors, best approach

Introduction

In the current static spectrum-allocation policies followed by governmental agencies, licensed holders are assigned wireless spectra on a long-term basis. The static spectrum-allocation policies have shown to be inefficient [1]. The inefficiency is more apparent in the TV broadcasting frequency band as several studies have shown that a huge portion of the assigned spectra is unused [1][2][3][4] most of the time. The unused TV channels (so called TV white spaces) have been hyped as the solution to meet the growing demand for the wireless data transmission. At the moment, governments are seeking better and innovative techniques that will offer new ways of exploiting the existing spectrum [5]. An efficient long-term solution that has been proposed is dynamic spectrum access (DSA) [6].

Detection of vacant channels by secondary devices called white space devices (WSDs) is difficult as the vacant channels vary according to location and time, and as such, utilizing these channels comes with a major challenge since any secondary access service can potentially cause harmful interference to the primary TV services already running in the band if the channel is mistakenly assessed as vacant. This places a mandatory requirement on any white space device (WSD) to check if a primary user signal is present or absent in a channel before it goes ahead using it. Two techniques have been suggested to help WSDs do this: geo-location spectrum database and spectrum sensing.

Discussions in the literature have placed much emphasis on the limitations of the spectrum-sensing approach, which are based mainly on the developed world environment. This may have been the case because the idea to use TV white space (TVWS) originated from the developed world and the initial experiments were conducted there. Critical performance requirements that each of the technique requires to perform well have not been discussed in the literature clearly. The presence or absence of these requirements in a region could potentially affect their performance. Therefore, this paper considers a broader analysis of each approach by looking at factors that can affect their performance and also by looking at the impact of these factors in a developed region and/or developing region.

The paper is structured as follows; Section 2 gives a general discussion of the two approaches. This is followed by a discussion of the relevant performance factors of the approaches, provided in Section 3, and a discussion of what is considered to be the best approach, in Section 4. Section 5 provides ground truth evaluation of the approaches by comparing paths losses derived from measurement data versus predicted path-loss values of some propagation models being suggested for used in geo-location databases. Section 6 concludes the paper.

1. WHITE SPACE SPECTRUM DETECTION TECHNIQUES

Two approaches have been proposed to help WSDs measure the available TVWS in the TV frequency band. The first approach is to use a database processing information about known primary transmitters (geo-location spectrum database approach). An alternative is to use one device or a network of devices to physically scan the radio waves to detect the presence of TV signals (spectrum sensing approach).

1.1. Geo-location spectrum database

This approach consists of a WSD accessing a database of known transmitters and their primary operational characteristics such as location, antenna parameters (radiation pattern, height above the ground), transmit power, times of operation, protection requirements, allowed WSD transmitter power, and other related parameters [6][7]. The database information is used to predict which frequencies are available at different locations using the primary transmitters details and radio propagation models. These models can be statistical, based only in distance and frequency, or they can based in ray tracing techniques that require detailed information about the terrain elevation in the area of interest. Therefore, correct identification of the presence of a TV signal at a given location depends on the fidelity of the database information and quality of the propagation model used to predict signal coverage [6]. A simple implementation example of this approach is shown in Figure 1a.

1.2. Spectrum sensing

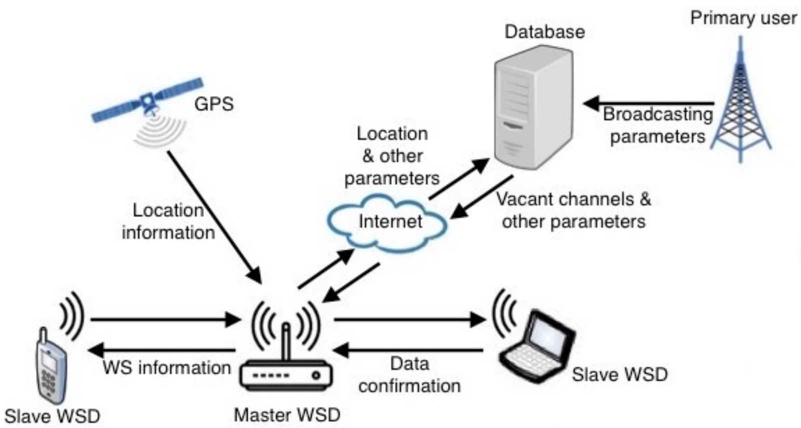
In the spectrum sensing approach, the spectrum is analyzed by a secondary user to decide whether the spectrum is occupied or not by a primary user. This analysis is based in two general categories: energy detection or feature extraction. The energy detection can be performed with a spectrum analyzer like the Radio Frequency (RF) Explorer (*see Figure 1b*), while feature extraction is based on specific characteristics of the type of signal to be detected and is therefore more sensitive but also more complex [6]. Energy detection is the commonly proposed method due to its simplicity. It works by measuring the energy contained in a spectrum band and then comparing that with a set threshold value. If the energy level is above the threshold value, then the primary user signal is considered present otherwise the spectrum band is considered vacant.

2. RELEVANT PERFORMANCE FACTORS

Figure 2a and Figure 2b provide a general overview of the geo-location database approach and the spectrum sensing approach respectively. Some factors contribute to the optimal performance of each approach. For example, geo-location database approach requires the following factors to perform optimally in a region: propagation models whose predictions in the area of interest is close to the measured data done in the area; an Internet backbone infrastructure to facilitate efficient and frequent communication between a master WSD and a slave WSD and a master WSD and a geo-location database; existence of detailed centralised TV database information in the area of interest. For the spectrum sensing approach to perform optimally, the following factors must exist: detection threshold value that is optimal such that there is no harmful interference to the primary users or any missed opportunities by secondary users; minimal to no mult-path fading and shadowing to avoid hidden user problem; large blocks of TVWSs in the area of interest. Note that the list of factors mentioned here may not be exhausitive.

3. WHAT IS THE BEST APPROACH?

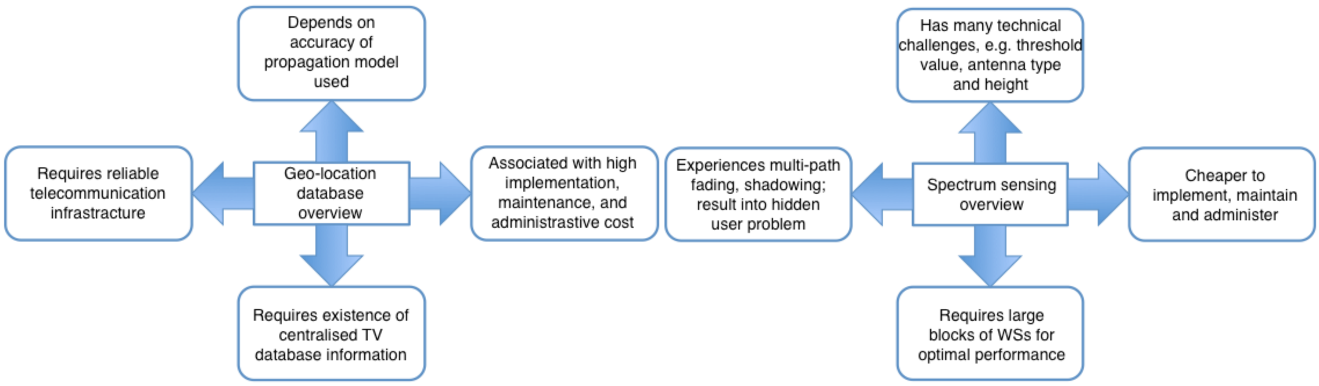
Since optimal performances of both approaches are dependent on some factors that may not be present or exist in some regions, none can produce superior performance in all possible regions. For example, in regions or countries where propagation models have been tried and tested extensively such that their prediction results are close to ground truth data, there is reliable Internet backbone infrastructure and a centralized detailed TV database information is also available, the geo-location database approach is expected to perform better than spectrum sensing. That could be the case with developed regions such as the US and Europe where all the three factors are present. It is therefore not surprising that the geo-location approach is being given preference as the main technique of finding TV white spaces [8] in those regions at the moment. However, conditions in developing regions are



(a) Geo-location database implementation

(b) RF Explorer

Fig. 1: A simple geo-location database implementation and a Spectrum analyzer



(a) Overview of geo-location database approach

(b) Overview of spectrum sensing

Fig. 2: Overview of the TVWS identification approaches

quite different from developed regions. Internet backbone infrastructure is poor and unreliable, more especially in the rural areas; propagation models have rarely been tested here such that their behaviour is unclear at the moment; spectrum usage information is scattered and stored in many formats, electronic and paper, and the regulators have not collected it into a useful centralized database that is publicly available. Therefore, at these prevailing conditions, the use of a geo-location spectrum database based approach may not produce optimal results.

Fading, shadowing and the *hidden user problem*, relevant to spectrum sensing, can be severe in the developed world because of many tall buildings, which are also close together. Consequently, primary TV signals in the band are difficult to detect accurately by spectrum sensing alone and could result in harmful interference. Therefore, performance of spectrum sensing in urban areas may be low. On the contrary, rural areas, especially those of developing world countries, where white space could be used to provide broadband connectivity, are sparsely populated with small isolated traditional building structures, which are unlikely to cause considerable fading, shadowing or bring about the *hidden user problem*. In terms of the Fresnel zone concept, these small isolated building structures could block the Fresnel zone to a maximum obstruction allowable level of not more than 40%, which produces little to no interference.

Most rural areas of developing regions, for example sub-Saharan Africa, have vast tracts of unused spectrum in the ultra-high frequency (UHF) band [9], which do not require stringent restrictions like the developed regions. This makes the use of the spectrum sensing approach a suitable alternative because problems limiting its use in developed regions may be considered to be much more forgiving than the circumstances associated with dense urban areas. Furthermore, cooperative spectrum sensing reduces errors in spectrum sensing caused by multi-path fading and is a possible solution to the *hidden user problem*. Therefore, even these problems may exist in the rural regions, the use of cooperative spectrum sensing can improve its performance.

There are some additional factors that can come into play when deciding which technique to use, apart from the above-mentioned performance factors. One such metric is the cost to implement, maintain, and administer the approaches. Geo-location approach requires a complex centralized structure and even more complex logistics, and as such, its implementation cost, maintenance cost and administrative cost is higher than spectrum sensing approach [8]. This too is likely to make spectrum sensing a more favourable approach to the developing world as most countries in this region may not have the necessary infrastructures present and must be built especially for the DSA, which is more expensive.

4. GROUND TRUTH EVALUATION

As argued in the paper that there are no propagation models clearly known to perform better in regions of the developing world that can be used in geo-location databases, the first step that countries in these regions should take is to perform extensive spectral measurements and compare values of the path losses obtained from the measurements against those estimated by propagation models suggested for use in geo-location databases. Therefore, the authors did a limited physical evaluation of the approaches by conducting spectral measurements and comparing values of the path losses obtained from the measurements against those estimated by some common propagation models. The experiments were conducted in the city of Cape Town in South Africa. This section gives a detailed discussion of how the whole process was carried out.

4.1. Propagation models examined

Five propagation models were examined and compared with values from measurement data; Longley-Rice (Irregular Terrain Model), Hata for urban areas, Egli, Ericsson 9999 and Free Space Path Loss (FSPL).

4.2. TV transmitter used

An analog terrestrial television (ATT) transmitter of one of the public TV broadcasters in South Africa called South Africa Broadcasting Corporation 2 (SABC2), located on latitude 33°52′31″S and longitude 18°35′44″E, was used as a base station (BS) transmitter. Its transmission parameters obtained from the Terrestrial Broadcasting Frequency Plan 2013 document by the Independent Communications of South Africa (ICASA) [10] are: UHF channel = 22, frequency = 479.25 MHz, Effective Radiated Power (ERP) = 2 KW = 63.01 dBm, antenna polarisation = vertical.

4.3. Measurements points

Twelve locations located at different distances from the BS transmitter site were identified where measurements were done. Tables 1 shows the geographical positioning system (GPS) coordinates of the sites and their distances away from the BS transmitter. The table also shows values of the height above avarage terrain (HAAT) of the sites calculated using GLOBE 1 km Base Elevation database [11] with the number of evenly spaced radials equal to 360° in each case. Figure 3 shows the measurement points relative to the BS transmitter generated using google maps.

4.4. Spectrum measurements setup

Outdoor spectrum measurements in the UHF ATT frequency band were done at the locations using a hand-held RF Explorer model WSUB1G, which has a measurement frequency range of 240 MHz to 960 MHz. The model was fitted with a Nagoya NA-773 wide band telescopic antenna with vertical polarization, which has wide band measurement capability. The RF Explorer was connected to an Android phone installed with an android code that starts to measure spectrum immediately after the RF Explorer is connected using an On-The-Go (OTG) cable. At each site, spectrum monitoring was done for 3 hours during the day.

4.5. Results

The 3-hour measurements at each measurement location in channel 22 from which the BS transmitter was broadcasting were averaged and the mean value was taken as the received signal power R_x. As a starting point of our analysis, we decided to confirm the square law dependence of power loss with distance first. We used the average value of the measured power at the closest point to the BS transmitter (SITE 1) and estimate from there the power received at longer distances along the same approximate radial by using the Friis transmission equation [12] (equation 1).

$$Pr(d) = Pr(d_o) + 20 * log(d_o/d) \tag{1}$$

where $Pr(d)$ is the received power at distance d in the same radial where d_o is calculated, $Pr(d_o)$ is the received power at a close-in-reference-distance d_o.

In that way, we were able to compare the measurements with those values obtained using equation 1. As Table 2 shows, there is reasonable agreement between the measured and calculated values. This confirm that the square law dependence of power loss with distance is adequate.

The accuracy of an Effective Isotropic Radiated Power (EIRP) of a transmitter, the gain and return loss of a receiving antenna determines the real path loss. In this experiment,

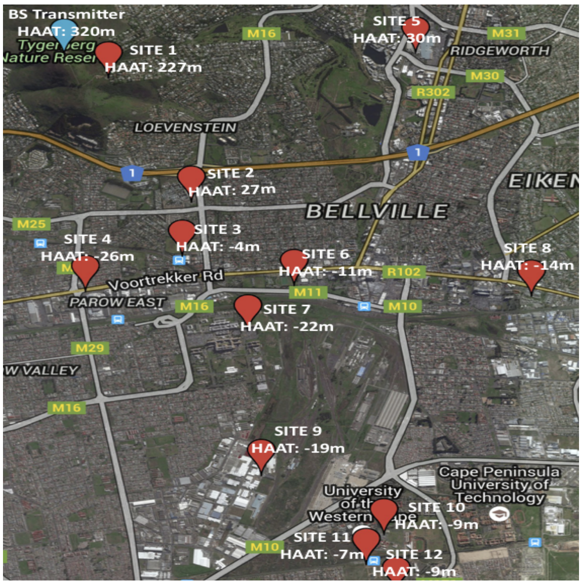


Fig. 3: Measurement sites relative to BS transmitter

Table 1: GPS coordinates of measurement sites and their distances away from BS transmitter

Site name	Latitude Longitude	HAAT (m)	d_{km}	Site name	Latitude Longitude	HAAT (m)	d_{km}
Tygerberg Natural Reserve (**SITE 1**)	-33°52′41″ 18°36′1″	227	0.54	Tygerberg Hospital (**SITE 7**)	-33°54′32″ 18°36′56″	-22	4.18
Harl Bremer Hospital (**SITE 2**)	-33°53′36″ 18°36′34″	27	2.37	Bellefleur Flats, Bellville (**SITE 8**)	-33°54′17″ 18°38′47″	-14	5.71
Bellville Business Park (**SITE 3**)	-33°53′59″ 18°36′30″	-4	2.98	Parow Industrial Area (**SITE 9**)	-33°55′36″ 18°37′1″	-19	6.04
Parow Centre (**SITE 4**)	-33°54′15″ 18°35′52″	-26	3.21	University of the Western Cape (**SITE 10**)	-33°56′2″ 18°37′49″	-9	7.26
Tyger Valley Shopping Centre (**SITE 5**)	-33°52′30″ 18°38′1″	30	3.51	Unibell Train Station (**SITE 11**)	-33°56′15″ 18°37′42″	-7	7.55
Bellville Market (**SITE 6**)	-33°54′12″ 18°37′14″	-11	3.89	Henry Peterson Residence (**SITE 12**)	-33°56′28″ 18°37′54″	-9	8.04

the BS transmitter antenna parameters such as pointing direction, pattern and gain were unknown, which brings in a degree of uncertainty about the real EIRP dissipated by the transmitter in the direction where the measurements were made. Therefore, we had to make the following assumptions in order to be able to analyse the results further:

1. The published ERP of the TV transmitter (63.01 dBm) minus 2.15 dB is the EIRP dissipated in the direction where the measurements were taken and attribute the difference between the received power at the antenna input of the spectrum analyzer and the actual power measured by the spectrum analyser at Site 1 as a resultant effect of the return loss and the antenna gain of the Nagoya NA-773 wide band telescopic antenna at the broadcasting frequency of 479.25 MHz of the TV transmitter.
2. The path loss at 0.54 Km distance from the transmitter is equal to the free-space path loss.

Assumption 1 is based on the fact that the square law dependence of power loss with distance is adequate and also that the measurements at similar distances from the TV transmitter are similar as shown in Table 2. The 2.15 dB subtracted from the ERP is the gain of the half-wavelength dipole antenna, assumed to be the antenna used by the TV transmitter. A dipole antenna, which is electrically one half wavelength long, in free space, exhibits a gain in its direction of maximum radiation of 2.15 dB over a theoretical isotropic radiator because it concentrates the energy in a certain direction so that the radiation in that direction is greater than the radiation from an isotropic source with the same input power.

The assumed resultant effect of the return loss and the antenna gain of the Nagoya NA-773 wide band telescopic antenna was regarded as a correction factor (CF) to every measurement. Using the FSPL equation 2, the FSPL at 0.54 Km distance and at the broadcasting frequency of 479.15 MHz was calculated as 80.71 dB, and the CF as 60.54 dB (Assumed EIRP - measurement at Site 1 + assumed FSPL at Site 1).

$$P_L = 32.45 + 20 * log(f) + 20 * log(d) \quad (2)$$

where P_L is the free space path loss in dB, f is the frequency in MHz and d is the distance in kilometers.

The calculated CF was added to every measurement power at each location to get the corresponding antenna input power. Table 3 shows the measured power by the spectrum analyser at each measurement location and the corresponding spectrum analyser's input power.

The path loss is calculated by subtracting the received signal at the antenna input at each measurement location from the EIRP (60.86 dBm). For each propagation model, the path loss from the BS transmitter is estimated for distances corresponding to those at which measurements were taken using their formulas. The path losses from the measurements and those estimated by the propagation models are shown in Table 4. To get a clearer picture of the pattern of the losses, they were plotted in graphs as shown in Figure 4. Path loss errors (average error, average absolute error, standard deviation) between measurements and the propagation models are shown in Table 5. The RMSE between the measured received signal power and that estimated using each of the propagation models is shown in Table 6.

4.6. Discussion of the results

From the plots of the path losses in Figure 4 and the path loss errors in Table 5, the FSPL is the closest model to the measurements. The accurancy of the FSPL can be attributed the possiblity of clear line of site between the transmitter and the measurement locations since the measurement locations were just few kilometers away from the transmitter site. The L-R (ITM), using Radio Mobile [13], was also accurate as it uses terrain elevation data of an area to compute the path

Table 3: Measured power and antenna input power

No.	Name	d_{Km}	Measured (dBm)	Antenna input (dBm)
1	Tygerberg Natural Reserve	0.54	-80.39	-19.85
2	Harl Bremmer Hospital	2.37	-97.30	-36.76
3	Bellville Business Park	2.98	-86.45	-25.91
4	Parow Centre	3.21	-93.34	-32.80
5	Tyger Valley Shopping Centre	3.51	-94.52	-33.98
6	Bellville Market	3.89	-92.58	-32.04
7	Tygerberg Hospital	4.18	-96.43	-35.89
8	Bellefleur Flats	5.71	-97.75	-37.21
9	Parow Industrial Area	6.04	-91.77	-31.23
10	UWC	7.26	-97.33	-36.79
11	Unibell	7.55	-94.25	-33.71
12	HPR	8.04	-94.23	-33.69

Table 2: Comparison of calculated vs measured power

No.	Name	d_{Km}	Measured (dBm)	Calculate ($Pr(d)$) (dBm)	Measured - Calculated (dBm)
1	Tygerberg Natural Reserve	d_0= 0.54	$Pr(d_o)$= -80.39	Ref. power	-
2	Harl Bremmer Hospital	2.37	-97.30	-93.24	-4.06
3	Bellville Business Park	2.98	-86.45	-95.23	8.78
4	Parow Centre	3.21	-93.34	-95.87	2.53
5	Tyger Valley Shopping Centre	3.51	-94.52	-96.65	2.13
6	Bellville Market	3.89	-92.58	-97.54	4.96
7	Tygerberg Hospital	4.18	-96.43	-98.17	1.74
8	Bellefleur Flats	5.71	-97.75	-100.01	2.26
9	Parow Industrial Area	6.04	-91.77	-101.36	9.59
10	UWC	7.26	-97.33	-102,96	5.63
11	Unibell	7.55	-94.25	-103,30	9.05
12	HPR	8.04	-94.23	-103,85	9.62

Table 4: Path losses

No.	Name	d_{km}	Path Losses (dB)					
			Measured	**FSPL**	**L-R**	**Ericsson 9999**	**Egli**	**Hata**
1	Tygerberg Natural Reserve	0.54	80.71	80.71	99.70	90.68	86.32	108.88
2	Harl Bremmer Hospital	2.37	97.62	93.56	97.10	110.18	112.01	131.17
3	Bellville Business Park	2.98	86.77	95.55	99.50	110.18	115.99	134.62
4	Parow Centre	3.21	93.66	96.19	95.40	114.18	117.28	135.75
5	Tyger Valley Shopping Centre	3.51	94.84	96.97	99.70	115.36	118.84	137.09
6	Bellville Market	3.89	92.90	97.86	98.80	116.72	120.62	138.64
7	Tygerberg Hospital	4.18	96.75	98.48	99.60	117.66	121.87	139.73
8	Bellefleur Flats	5.71	98.07	101.19	109.70	121.78	127.29	144.43
9	Parow Industrial Area	6.04	92.09	101.68	102.30	122.52	128.27	145.27
10	UWC	7.26	97.65	103.28	105.50	124.94	131.46	148.05
11	Unibell	7.55	94.57	103.62	104.70	125.46	132.14	148.64
12	HPR	8.04	94.55	104.17	105.40	126.29	133.23	149.58

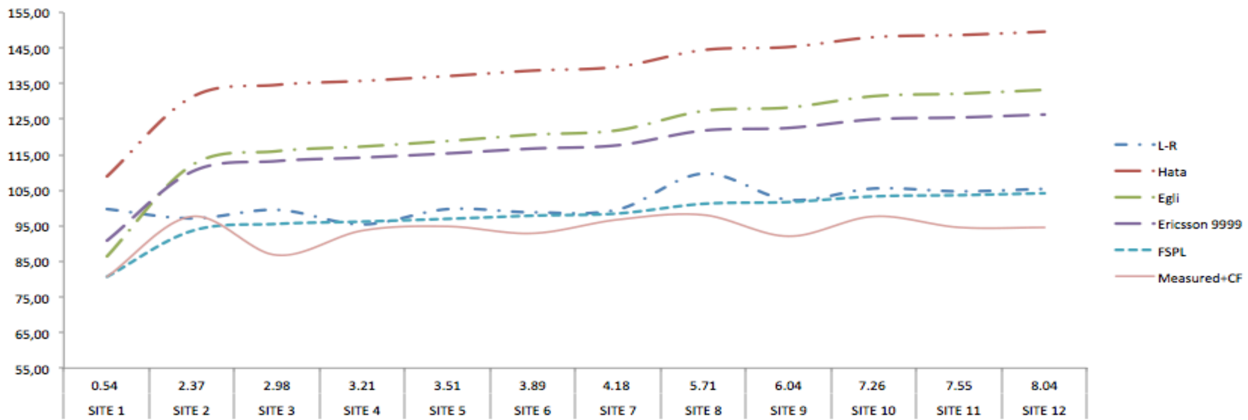


Fig. 4: Plots of path losses

Table 5: Mean error, mean absolute error and standard deviation

No.	Name	Path loss Errors (dB)				
		Measured & FSPL	Measured & L-R	Measured & Ericsson 9999	Measured & Egli	Measured & Hata
1	Tygerberg Natural Reserve	0.00	18.99	9.98	5.61	28.17
2	Harl Bremmer Hospital	-4.06	-0.52	12.56	14.40	33.55
3	Bellville Business Park	8.78	12.73	26.43	29.22	47.86
4	Parow Centre	2.53	1.74	20.52	23.63	42.09
5	Tyger Valley Shopping Centre	2.13	4.86	20.52	24.00	42.25
6	Bellville Market	4.96	5.90	23.82	27.72	45.74
7	Tygerberg Hospital	1.74	2.85	20.91	25.12	42.98
8	Bellefleur Flats	3.12	11.63	23.71	29.22	46.36
9	Parow Industrial Area	9.59	10.21	30.43	36.18	53.18
10	UWC	5.63	7.85	27.29	33.81	50.40
11	Unibell	9.05	10.13	30.89	37.57	54.07
12	HPR	9.62	10.85	31.74	38.69	55.04
	Mean	4.42	8.10	23.23	27.10	45.14
	Mean absolute	5.10	8.19	23.23	27.10	45.14
	Standard deviation	4.32	5.45	6.87	9.67	8.11

loss. The Ericsson 9999, Egli and Hata underestimated the received signal power such that their estimated path losses are greater than the derived path losses from the measurements at each location.

Although the FSPL model is closest to the measurement data as its RMSE (6.06 dB) from Table 6 falls within the acceptable range of 6-7 dB for urban areas [14], we cannot conclusively say that is the best-fit model for the area within the distances where the measurements were taken. Extensive long-hours spectral measurements are needed and also more measurement sites need to be included to confirm the validity of a model for the area, which may be costly and time consuming.

Table 6: RMSE between measured and models' estimation power

Propagation Model	RMSE (dB)
FSPL	6.06
L-R	9.64
Ericsson 9999	24.15
Egli	28.64
Hata	45.80

5. CONCLUSION AND FUTURE WORK

Discussions in the literature have placed much emphasis on the limitations of the spectrum-sensing approach and mainly based on the developed world environment ignoring the limitations of the geo-location approach and its impact on the developing world. This paper considered a broader analysis of the approaches by looking at factors that can affect the performance of each approach and how the presence or absence of these factors in a developed region and/or in a developing region can affect their performance. In so doing, the paper has highlighted the need to conduct more research on the performance of spectrum sensing in regions where there are plenty of white spaces such as rural areas of developing world countries.

Our analysis shows that information that is needed by the geo-location approach to perform optimally may not exist in most developing world countries especially in the rural areas where telecommunication infrastructure is lacking and white spaces are abundant. Further analysis was done by comparing predicted path loss values of some common propagation models with path losses derived from outdoor spectrum measurements. Based on the absence of factors that are needed by the geo-location approach to perform optimally in developing world regions, presence of abundant white spaces in rural areas of developing world regions and also considering the implementation, maintenance and administrative cost of geo-location approach, we have concluded that spectrum sensing is more favourable to use in rural areas of developing world countries than geo-location database approach.

Since cooperative spectrum sensing eliminates the limitation of local spectrum sensing, the authors would like to investigate a white space network detection framework based on cooperative spectrum sensing using hand-held spectrum analyzers as part of their future work, and also extend the analysis to find the available white spaces at UWC measurement site, which could be used for campus networking.

6. REFERENCES

[1] I.F. Akyildiz, W. Lee, M.C. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey," *Computer networks*, vol. 50, no. 13, pp. 2127–2159, 2006.

[2] R. Kaniezhil, C. Chandrasekar, and S. NithyaRekha, "Performance evaluation of qos parameters in dynamic spectrum sharing for heterogeneous wireless communication networks," 2012.

[3] Y. Yuan, P. Bahl, R. Chandra, T. Moscibroda, and Y. Wu, "Allocating dynamic time-spectrum blocks in cognitive radio networks," in *Proceedings of the 8th ACM international symposium on Mobile ad hoc networking and computing*. ACM, 2007, pp. 130–139.

[4] J. Carlson, N. Ntlatlapa, J. King, F. Mgwili-Sibanda, H. Hart, C. Geerdts, and S. Song, "Studies on the use of television white spaces in south africa: Recommendations and learnings from the cape town television white space trial," electronic, https://www.tenet.ac.za/tvws/recommendation-and-learnings-from-the-cape- town-tv-white-spaces-trial, 2013.

[5] T. Yücek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *Communications Surveys & Tutorials, IEEE*, vol. 11, no. 1, pp. 116–130, 2009.

[6] T. Brown, E. Pietrosemoli, M. Zennaro, A. Bagula, H. Mauwa, and S. Nleya, "A survey of TV white space measurements," in *e-Infrastructure and e-Services for Developing Countries*. 2014, pp. 164–172, Springer International Publishing.

[7] L. Doyle, *Essentials of cognitive radio*, Cambridge University Press, 2009.

[8] V. Gonçalves and S. Pollin, "The value of sensing for TV white spaces," in *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on*. IEEE, 2011, pp. 231–241.

[9] E. Pietrosemoli and M. Zennaro, *TV White Spaces. A pragmatic approach*, vol. 1, chapter 4, pp. 35–40, ISTB, December 2013.

[10] ICASA, "Terestrial broadcasting frequency plan 2013," Tech. Rep., Independent Communications Authority of South Africa, 2013.

[11] Federal Communications Commission et al., "Antenna height above average terrain (haat) calculator," *Online, Retrieved*, vol. 4, no. 7, pp. 16.

[12] S. Rao, "Estimating the zigbee transmission-range ism band-designers of short-range wireless devices in the 900-mhz and 2.4-ghz band need to understand what and how parameters affect the transmission range," *EDN*, vol. 52, no. 11, pp. 67–74, 2007.

[13] R. Coudé, *Radio Mobile - RF propagation simulation software*, http://radiomobile.pe1mew.nl/, 1998.

[14] N. Blaunstein, D. Censor, D. Katz, A. Freedman, and I Matityahu, "Radio propagation in rural residential areas with vegetation," *Progress In Electromagnetics Research*, vol. 40, pp. 131–153, 2003.