

## A Review of Spectrum Utilization and TV White Space Detection

H. O. Lasisi<sup>a</sup>, B. F. Aderinkola<sup>b\*</sup> and F. M. Adeagbo<sup>a</sup>

<sup>a</sup>Department of Electrical and Electronic Engineering, Osun State University, Osogbo, Nigeria

<sup>b</sup>Department of Electrical and Electronic Engineering, The Federal Polytechnic, Ede, Nigeria

*Corresponding Author: fattyade2307@gmail.com*

### ARTICLE INFO

*Received: January, 2021*

*Accepted: April, 2021*

*Published: April, 2021*

#### **Keywords:**

Spectrum analyser

TV white space

Threshold

Spectrum measurement

Database.

### ABSTRACT

*Due to limited availability of frequency bandwidth and request for continuous increase in its use due to technological inventions of smart phones, tablets, online gaming and many newly invented smart systems, many research efforts by academia, scientists and telecommunication engineers on the improvement of the bandwidth and effective use of the available ones have been documented. More so, much attention is being paid to the television band due to the possibility of exploiting the existing white space, if any, to increase the opportunistic spectrum utilization. The part of the spectrum in the ultrahigh frequency/very high frequency bands that is unutilized based on time and location is referred as TV white space. In this paper, the authors carried out holistic review on the spectrum utilization and television white space detection techniques in the TV band by the previous authors and present a concluding remarks on how to maximize the use of available bandwidth.*

### 1. INTRODUCTION

The increase in the request for bandwidth has compelled numerous scholars around the universe to measure and study the utilization of spectrum in various nations. These measurements proposed that apart from the bands assigned to services like cellular technologies, and the industrial, scientific and medical (ISM) bands, greatest part of the assigned bands is greatly underused (Naik *et al.*, 2014). The underutilization of the spectrum occurs when primary users (PU) are not completely utilizing the spectrum at all the time and in all locations. In recent times, a great consideration has been given to TV band owing to the possibility of exploiting the unoccupied white space, if any, to enhance the opportunistic spectrum usage.

Television white space (TVWS) is a portion of the spectrum in the Very High Frequency/Ultra High Frequency (VHF/UHF) bands that is unused based on time and location. TVWS are vacant frequencies situated amid broadcast TV channels in the VHF/UHF range and can be detected between 54 and 806 MHz (Andersson, 2014). The VHF range falls between 30 and 300 MHz on the electromagnetic spectrum, and comprises of channels two to thirteen (2 – 13) whereas the UHF range, which falls on 300 MHz and above on the electromagnetic spectrum, consists of channels fourteen to fifty one (14 – 51) (Andersson, 2014). The operational systems in the TV bands are analogue TV, digital TV and wireless microphone each having sensitivity value of -94 dBm, -116dBm and -107 dBm respectively (Faruk *et al.*, 2013). With respect to this, Federal Communications Commission (FCC) in the United States declared a threshold of -114 dBm as the standards for TVWS (FCC, 2008). This is to enable exploitation of the vacant band of the licensed user for

unlicensed access to facilitate low powered white space devices (WSD) utilization of this spectrum deprived of interference to the licensed user. The unexploited broadcast TV channels differ barely from one locality to another.

TVWS covers between 470 MHz – 698 MHz in the United Kingdom. The authorized structures are Digital TV Transmission, Digital Terrestrial Television (DTT) and Program Making and Special Events (PMSE) like wireless microphones and in-ear monitors. DTT information is sustained by Ofcom. The protection method is 100 m by 100 m pixel map based restriction regions that describe the utmost permissible broadcast powers for several white space device parameter sets (Kokkinen, 2020).

In Nigeria, the present television broadcasting services generally run on analogue broadcast in the VHF range spanning from 174 – 230 MHz and UHF range spanning from 470 – 860 MHz band excluding the television stations that changed to digital propagation platform (Adediran *et al.*, 2014). It is visualized that migrating from analogue services to DTT will generate extra band opening that can be accessed by TVWS, and the monitoring organizations of various nations had started delving into this chance of addressing band insufficiency (Van de Beek *et al.*, 2011). Consequently, it is obvious that at the end of the digital switchover process, certain percentage of the analogue TV channels would turn out to be completely free as a result of transition to advanced band efficiency digital television (DTV). Though, a number of these free spectrum especially the International Mobile Telecommunication spectrum allotted to mobile usage could be reassigned by the regulatory agencies to different facilities, many TV channels might be idle in every geographical region. Even though, the extent of spectrum exploitation and TVWS accessibility have not been exclusively carried out in Nigeria, outcomes of various nations show the obtainability of TVWS (Elshafie *et al.*, 2014).

## 2. TV WHITE SPACE ESTIMATION/MEASUREMENT TECHNIQUES

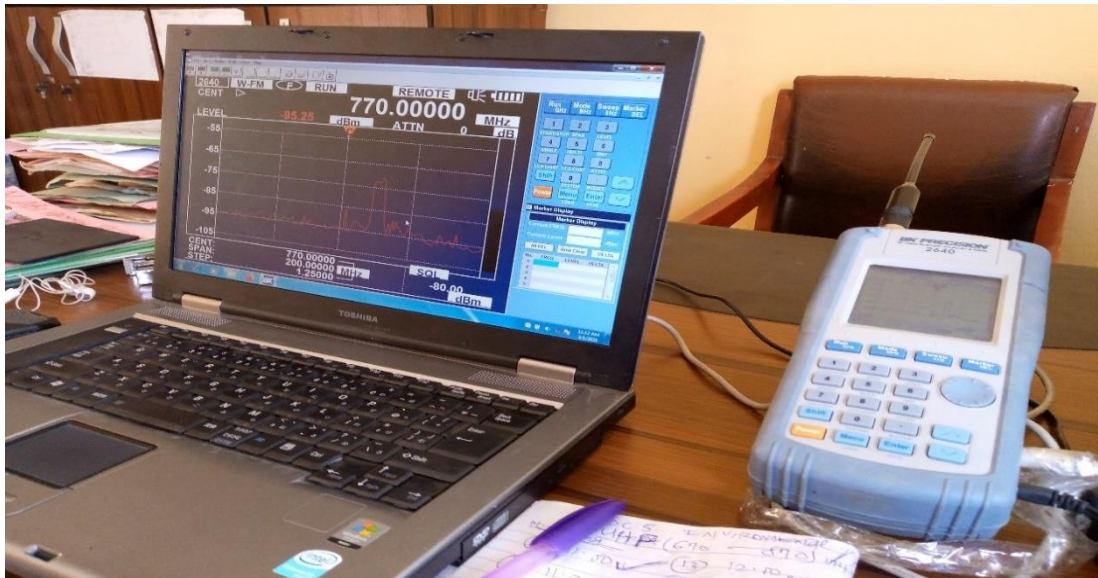
Several researchers have conducted and published work on TV white space detection or assessment in different geographical locations around the globe. There are many techniques available to quantify or estimate TV white space, but the two basic techniques are the real spectrum measurement technique (or energy detection) and the propagation model (or database) techniques. In either method, the data collected must be construed to delineate the "available" white space spectrum.

### 2.1 Energy Detection or Direct Measurement Technique

This is an experimental measurement set up employed to objectively institute the kind and degree of spectrum utilization and the consequential TVWS accessibility. This technique employs the use of measurement device alongside a measurement plan. There is discrepancy in the measurement set up from one researcher to another based on what is delineated as occupied or unoccupied. So also, there exist variations in the measurement plan i.e. whether the measurement is made indoor or outdoor, in rural area as in Ufoaroh and Abu, 2019 or in urban area; and the kind of occupancy metrics employed. This techniques is also known as the energy detection techniques. It involves setting up test measurement in any geographical region of interest with the use of spectrum analyzer, an antenna, a laptop or personal computer with an installed spectrum analyzer software (optional, depending on the type of analyzer employed), a storage device and other peripheral for connectivity purpose. Figure 1 depicts a typical measurement setup for the energy detection method of quantifying TVWS.

A spectrum analyzer possesses the capability of detecting a signal depending on its features. However, its sensitivity ascertains how weakened the signal could be and yet, be detected. There are essential restrictions to the manner a weakened signal is measurable in conformity with the noise floor, which is influenced by the bandwidth, existing intruding signal and the spectrum analyzer's noise figure (Brown *et al.*, 2014). The configuration of the antenna also influences the measurement. Antennas with higher gain improve sensitivity

even though they focused more in a narrower directions. This reliance on the antenna configuration can be eliminated by setting decision thresholds based on the field strength.



**Figure 1:** A typical measurement setup for quantifying TVWS.

The consideration of the measurement location, measurement frequency and measurement time is what is termed as the measurement plan. For example, the measurement can be done by moving the device through an area in search of a particular TV signal or placing the device in a fixed location in quest of existing TV signals around the spectrum. The presence of a specific TV signal might also be tracked over time. However, atmospheric situations can allow TV signals to be discovered hundreds of kilometers outside their usual coverage region. The quantity of channels received in a certain topographical region can then be employed to evaluate the existing gray space. With this perspective, white space can be defined as the difference between the total quantity of channels and the quantity of channels detected in a particular locality. White space could as well be established as the region beyond the TV covering region. In this approach, white space is considered as the amount of channels that are not effectively detected in a specific locality (Adediran *et al.*, 2014). This technique has been employed by many researchers and organizations alike. The challenge associated with this method is the probability of the existence of detection errors which may occur when the analyzer is unable to sense the existence of a television signal or provides wrong receptions while television station is non-existing due to the presence of noise and other signals. Nevertheless, these measurement campaigns evidently help to determine spectrum utilization and quantitatively understand the existing pattern of use, hence, the possibility of ascertaining the extent of the vacant white space band. As spectrum application differs in time and space, spectrum measurements offer considerable chances of authenticating TVWS spectrum (Brown *et al.*, 2014).

Using fixed site monitoring, Ufoaroh and Abu (2019) employs an RF explorer 3G combo model equipped with other devices to assess the TV white space availability in Ugbowo, Benin City, a Southern Nigeria. Kumar *et al.*, (2013) used an RF Explorer model WSUB1G to take 24-hour long spectrum measurements from 240 MHz to 960 MHz at three different places in India. “Power level cumulative distribution” and “maximum contiguous bandwidth available” were two metrics used to liken the results at different geographical locations. NARDA SRM-3006 spectrum analyzer was used by Bedogni *et al.* (2014) to carry out indoor spectrum measurement in the 470MHz – 798MHz band for the reception of TV white space in Turin, Italy. An outdoor measurement campaign was carried out in ten dissimilar locations in Samsun City,

Turkey by Kurnaz *et al.* (2016) using RTL2832U R820T software defined radio and ANRITSU S332E spectrum analyzer.

In Jayavalan *et al.* (2014), an antenna was positioned outside using tripod stand while the spectrum analyzer and the personal computer were placed indoor in order to avert any impairment from rain. The antenna was connected to the Advantest U3741 spectrum analyzer employed with the aid of a coaxial cable. Babalola *et al.*, (2015) employed Agilent N9342C Handheld Spectrum Analyzer (HSA) and a data storage to carry out spectrum occupancy measurement in rural, urban and sub urban locations in Kwara State.

## 2.2 The Database and Propagation Model Technique

This technique involves retrieving a database of familiar transmitters and their functional features like the transmitter site, the antenna's radiation pattern and height above the ground, the transmission power, working periods of the transmitter etc. These data obtained are then used to foretell the frequencies present at different regions and times. In this approach, accurate identity of television stations existence at a particular place is influenced by authenticity of the data and that of propagation model employed in predicting the signal coverage (Brown *et al.*, 2014).

In wireless communication, especially at radio frequency level, several models are available to use for one thing or the other. In TV white space, several published research have used different models among which are the statistical propagation model (ITU – R model) which uses the distance to a TV transmitter as its parameter and a deterministic propagation model as employed by Van de Beek *et al.* (2011). Many different deterministic propagation models have been employed, among which are, the path loss and spectrum sharing model, Hata model, Longley-Rice irregular terrain model etc. One of the new innovative technique of reclaiming the TVWS is the *pollution viewpoint*, which uses the secondary user transmission and noise floor's point of view. In this method, as employed by Naik *et al.* (2014), transmitter database gotten from the Federal Communication Commission (FCC) was used to figure out the present TVWS. Effective radiated power, latitude, longitude and transmitter's height were the parameters of the licensed transmitter supplied by the database. These parameters were used alongside ITU-R 1546-3 propagation model in estimating the pollution radius, then the TVWS. Here, any point outside the pollution radius is regarded as white space.

Another approach is the protection viewpoint as in Faruk *et al.* (2015) where an idea of *keep-out distance*, that is the least parting separation of secondary users from the secured outline of a licensed digital television, would be found. Adopting the same method, Kang *et al.* (2012) presented the outcome of experiment and simulation for exploiting TVWS by secondary networks. In Japan, availability of TVWS was assessed on the ground of separation distance with the use of Desired-to-Undesired ratio (D/U) and Interference-to-Noise (I/N) coverage criteria basis by Oyama *et al.* (2012). A geo-location based approach was used by Makris *et al.* (2012) in quantifying TV white space in Europe while Adediran *et al.* (2014) employed geo-spatial technique to obtain spatially, the existing UHF channels in Nigeria. Here, protection contour alongside no-talk radius was employed to define TVWS with respect to the region covered by television broadcasting system.

The major limitation to database method is getting the correct data, even though information relating to spectrum use can be stored electronically or in black and white, in some countries, most regulators have not accumulated the information into a beneficial unified database which is openly accessible. Even if accessible, the technique is mathematically exhaustive when evaluating a big place. In addition, the type of propagation model used always has effect on the spatial configuration of the assessed white spaces. Some of the result obtained through the use of both direct measurement (detection) and databases techniques are as presented in Table 1.



**Table 1:** Amount of TV white spaces estimated by various researches in MHz

Technique	Location	Urban (Outdoor)	Rural (Outdoor)	Urban (Indoor)	Year Published
Detection	Selangor, Malaysia	≈284			2014 (Jayavalan <i>et al.</i> , 2014)
Detection	Samsun, Turkey	120			2016 (Kurnaz <i>et al.</i> , 2016)
Detection	Anambra, Nigeria		312		2019 (Abu and Ufoaroh, 2019)
Detection	Benin, Nigeria	232			2019 (Ufoaroh and Abu, 2019)
Detection	Turin, Italy	48			2014 (Bedogni <i>et al.</i> , 2014)
Detection	New Delhi, India	≈194	≈217		2013 (Kumar <i>et al.</i> , 2013)
Database	India	112			2014 (Naik <i>et al.</i> , 2014)
Database	Europe	≈125		30	2012 (Makris <i>et al.</i> , 2012)
Database	Europe	≈179			2011 (Van de Beek <i>et al.</i> , 2011)
Database	Kwara, Nigeria	368			2014 (Adediran <i>et al.</i> , 2014)

### 3. RELATED STUDIES

This section reviews related studies on the spectrum utilization and television white spaces detection in the UHF bands within 470 and 870M Hz. Some of the reviewed paper studied a subdivision of this frequency range in proportion to spectrum allotment for the UHF and VHF TV bands in the respective region of the researchers. Van de Beek *et al.* (2011) studied the detail quantitative evaluation of the vacant TVWS within 470 – 790MHz UHF band in Europe. Two propagation models were employed, a statistical propagation model (ITU – R model) which uses the distance to a TV transmitter as its parameter and a deterministic propagation model where Longley-Rice irregular terrain model was adopted. The results reveals that, on an average locality in a typical region in Europe, about 56% of the band is unexploited by TV systems. On using white space spectrum, Webb (2012) worked on the exploration, usage and regulation of white space using database approach. The available white space spectrum was explored using a modified Hata model. Result showed that 50% white space was available. However, real spectrum measurement was not carried out.

In the work of Kumar *et al.* (2013), the detection and outlining of TVWS in the National Capital Region (NCR) of India was presented. The study also characterizes and compare the spectrum utilization in rural and urban expanses of NCR. An RF explorer model WSUB1G was used to take 24-hour long spectrum measurements from 240 to 960 MHz at different localities. “Power level cumulative distribution” and “maximum contiguous bandwidth availability” were the metrics used to liken the results obtained at various locales. Result revealed that most TV bandwidth in the NCR province in India is unused, even without digitization. Arcia-Moret *et al.* (2013) focused on the white space monitoring in the 470 – 960 MHz range. Measurement campaign was carried out to assess the UHF TV spectrum use in urban and rural Venezuela. An RF explorer and Raspberry Pi was employed in the mobile measurement campaign. Result showed that there is abundance of prospective white spaces even in the central metropolis. An assessment study on white spaces in Malawi using affordable tools was done by Zennaro *et al.* (2013). Here, an RF explorer spectrum analyser was employed in carrying out the mobile measurement campaign in six spatially distributed locations for TVWS accessibility within 400 – 899MHz bands. Results revealed that abundant spectrum for TVWS application exists in Malawi. However, the available white spaces were not quantified.

Spectrum occupancy measurements and analysis was carried out by Xue *et al.* (2013) in Beijing. In this work, spectrum measurement drive was done in the frequency band of 450 – 2700 MHz so as to observe the state of radio spectrum allocation in Beijing. Agilent N9030A spectrum analyser was employed for the measurement and data collection. The result revealed that, in the frequency bands of 470 to 806 MHz which is the band assigned to both the analogue and digital Chinese broadcasting services, the average band use is about 0.42. Though most of the TV stations do not operates 24 hours a day. However, averagely, only

13.5% of the entire 450-2700 MHz spectrum in Beijing was occupied. This implies that virtually 86.5% of the allotted band was idle for this period. In DTV coverage and protection contour estimation for spatial white space by Faruk *et al.* (2013), spatial TVWS for digital television coverage within the frequency range of 470 to 790 MHz was exploited using protection viewpoint approach. A decision algorithm was developed for predicting service and protection contour and subsequently established the white space accessibility. HATA, COST231, CCIR and OPT path loss model were considered. Result analysis showed that spectrum hole were present in the frequency band and that more of it were obtained when grade B contour was employed as a reference threshold. Though, the available white spaces was not quantified. Jayavalan *et al.* (2014) analyses the presence of white spaces in UHF TV bands 470 – 798 MHz in Malaysia. The analysis was centred on the spectrum use at cellular and UHF TV broadcasting bands, and the measurement was carried out at College of Information Technology (COIT), Universiti Tenaga Nasional (UNITEN), Selangor, Malaysia, using Advantest U3741 spectrum analyser. Result showed that virtually all the assigned TV bands recorded less than 15% occupancy.

Naik *et al.* (2014) focused on the quantitative assessment of TVWS availability within UHF TV band in India. Two methods were employed in quantifying the existing TVWS; the protection and pollution viewpoints and practical requirement by the FCC. Result revealed that over 100 MHz spectrum was, on the average, present as TV white space within the band, even though real spectrum measurement was not carried out. Adediran *et al.* (2014) presented the evaluation of the amount of TVWS within UHF band in Nigeria. Here, the existing TVWS was quantified using geo-spatial approach. In this approach, a protection viewpoint was used from which the spectrum sharing model was established. The results showed that about 368MHz of spectrum available can be assessed by secondary users. Nevertheless, the model employed decreases the opportunity of extracting all the white space. Real spectrum measurements and analytical modelling was employed by Bedogni *et al.* (2014) for indoor reception of TVWS in Turin, Italy. The spectrum measurement was conducted using a NARDA SRM-3006 spectrum analyser, to measure the spectrum and deduce how indoor communication may possibly influence the DTV receiver. Result showed that, out of the three scenario used, there exists lesser vacant gray spaces in one while there is higher availability of gray spaces in others, though the available white spaces were not quantified. Spectrum occupancy measurements in the TV and CDMA bands by Babalola *et al.* (2015) employed Agilent N9342C Handheld spectrum analyser to carry out measurement in the 48.5 – 880MHz band. The measurement was conducted outdoor, in rural and urban localities in Kwara State, Nigeria. Result obtained from measurement indicated that, averagely, TV bands utilization in the urban areas is quite lesser at 12.02%.

Spectrum occupancy measurements and lessons learned in the context of cognitive radio was presented by Mehdawi *et al.* (2015). The measurements was carried out on the rooftop of the Applied Science building at the University of Hull, UK, using Agilent E4407B Spectrum analyser. Result obtained from the measurement confirmed the presence of a substantial amount of spectrum which is possibly existing for impending use by cognitive radio networks. Ding *et al.* (2016) worked on the exploitation of unlicensed TVWS for device to device infrastructures in cellular networks. Here, mobile crowd sensing (MCS) technique was used to perform spectrum measurements using massive mobile smartphones, tablets, and in-vehicle sensors. Result of simulation revealed that the proposed method can effectively support D2D communications in TVWS without interfering with the licensed digital TV services. Kurnaz *et al.* (2016) worked on the determination of TVWS spectrum availability in Samsun city centre, Turkey. The measurements were implemented in the 470 – 790 MHz band, at ten sites. A software based RTL2832U-R820T frequency analyser was used in carrying out the measurement spatially in six of the locations and temporally in the remaining four locations, with all locations separated from TV transmitter stations. Results revealed that the existing TVWS is 37.5% in Samsun city centre. Seflek and Yaldiz (2017) carried out outdoor measurements of spectrum occupancy at a single location which is Selçuk University, Faculty of Engineering building in Konya, Turkey. The measurements cover 30 – 3000 MHz frequency range using Rigol DSA 1030 spectrum analyser. Measurement controls, data acquisition and analysis was realized with

MATLAB program. Result indicated that the occupancy rate for TV band 470 MHz – 790 MHz is 8.49% while the total occupancy rate for the full studied band (30 – 3000 MHz) is 7.63%.

Paulson *et al.* (2017) investigated the spectrum utilization within 700 – 2200 MHz frequency band in Ikeja, Lagos State, Nigeria. Aaronia AG HF–6065 V4 Spectrum analyser was used for the measurement and was conducted indoor. The measured frequency span was divided into several continuous sub-bands. Result from the measurement showed that the analogue TV band has a utilized spectrum value of 148.5 MHz, while 151.5 MHz corresponding to 50.5% of the spectrum is unused. Hence, a substantial quantity of spectrum is existing for futuristic use cognitive radio systems. Oki *et al.* (2019) developed a testbed in measuring the utilization of spectrum in KwaDlangezwa town in South Africa. The testbed was situated inside the Centre of Excellence, University of Zululand. The spectrum analyser, BladeRF X40, was employed for the measurement in the 470 – 890 MHz TV bands assignment of South Africa. Result revealed that there exists vacant spectrum in the TV bands in KwaDlangezwa which may be re-allocated to secondary users by the spectrum regulatory body.

Ufoaroh and Abu (2019) concentrated on the assessment of TVWS existence in Ugbowo, Benin City, Southern Nigeria. An RF explorer 3G combo model was used to collect some feasibility-oriented parameters of TV Stations situated in Ovia North, Ugbowo, Edo State. UHF TV band 470 – 870 MHz was considered and the spectral analysis for frequency span 470 – 570 MHz, 570 – 670 MHz, 670 – 770 MHz and 770 – 870 MHz was plotted. Results showed that the available TVWS was 58% corresponding to 232 MHz in the dense area of Benin City which indicate that reasonable percentage of the TV band is unused, even without digitization. Estimation and application of TVWS for rural broadband connectivity (internet access) was carried out in Mgbakwu, a rural area in Anambra State by Abu and Ufoaroh (2019). Spectrum analyser RF explorer 3G combo model was employed for the measurement in the 470 – 870 MHz UHF TV band. Results showed that the total free spectrum was 312 MHz which corresponds to 78% TVWS availability in the area.

#### 4. POSSIBLE BENEFITS OF TVWS

The possible use of TVWs is basically unlimited, as it could be employed for quite an extensive range of services and technologies. TVWS has some essential features that makes it extremely suitable for use in wireless infrastructures services such as campus broadband networks, wide area wireless internet, household and venture wireless networking and smart city systems (Adediran *et al.*, 2014). Moreover, telecommunication service providers can employ it as a bearer support substitute in order to lessen network congestion in peak periods. Furthermore, it is an exceptional candidate that fits well into several heterogeneous wireless platform as a result of expanded and novel wireless communication services (Gbenga-Ilori and Sanusi, 2014).

TVWS expertise could be an efficiently cherished supporter to the wireless bionetworks that supports broadband services to both urban and rustic environments which are yet to be served or are underserved in the African continent. Presently, large numbers of consumer electronics companies as well as various Internet/software companies with Microsoft and Google not left out are now leveraging these potentials. When compared with other technologies that use higher frequencies, TVWS offers outstanding radio propagation features and this is due to the fact that it works on the lower frequency bands and consequently unaffected by mist, snowfall, downpour and further inherent disasters. It is a model know-how that possesses the prospect of bridging the digital divide and substantially enhance the finances of setting up wireless broadband in an under-served environments (Roberts *et al.*, 2015).

## 5. CHALLENGES

The review shows that there are various techniques available for detecting television white space in the UHF band. Each of these techniques has its associated challenges. The fidelity of information obtained in the database approach may not be guaranteed and the amount of television white space to be detected, in the spectrum measurement attempt, depends on such factors as whether the measurement was conducted indoor or outdoor, in rural or urban locale, and whether or not guard bands are taking into consideration, hence, the need to specify these factors in order to portray the exact TVWS availability and its possible usage.

## 6. CONCLUSIONS

From the papers reviewed, it can be concluded that a substantial quantity of TVWS spectrum may be obtained within UHF band for deployment by an unlicensed consumers. Among the techniques, direct spectrum measurement has been widely employed as it provides a more accurate assessment of spectrum utilization. It is however noted that, as at the time of this review, extensive research has not been done in the south-western part of Nigeria. Quantifying the vacant white spaces, which is the major gap here, is very important so as to provide useful information for the regulator for necessary deployment devoid of interference to the primary user. However, setting up of decision threshold to deduce band use is highly essential while advance research is necessary to improve its selection.

## References

- Abu, K. and Ufoaroh, S. U. (2019). Estimation and Application of TV Whitespaces for Rural Broad Band Connectivity (Internet Access). *American Journal of Engineering Research*, 8(8): 19 - 28. Retrieved from [www.ajer.org](http://www.ajer.org)
- Adediran, Y. A., Faruk, N., Ayeni, A. A., Kolade, O., Surajudeen-Bakinde, N. T. and Bello, O. W. (2014). TV White Space in Nigeria in UHF Band: Geo-spatial approach. *IEEE 6th International Conference on Adaptive Science & Technology (ICAST), 2014* (pp. 1-6). Ota, Nigeria: IEEE. doi:10.1109/ICASTECH.2014.7068105
- Andersson, K. (2014). *Using TV White Space for Rural Broadband*. Retrieved from Carlson wireless Technonogies, white paper: <http://www.carlsonwireless.com/products/ruralconnect-ip.htm>
- Arcia-Moret, A., Pietrosevoli, E. and Zennaro, M. (2013). WhispPi: White Space Monitoring with Raspberry Pi. *Global Information Infrastructure Symposium (GIIS 2013)*. Trento, Italy: IEEE. doi:10.1109/GIIS.2013.6684374
- Babalola, O., Garba, E., Oladimeji, I., Bamiduro, A., Faruk, N., Sowande, O. and Muhammad, M. (2015). Spectrum Occupancy Measurements in the TV and CDMA Bands. *2015 International Conference on Cyberspace (CYBER)*. Abuja, Nigeria: IEEE. doi:10.1109/CYBER-Abuja.2015.7360504
- Bedogni, L., Felice, M. D., Malabocchiay, F. and Bononi, L. (2014). Indoor Communication over TV Gray Spaces based on Spectrum Measurements. *IEEE Wireless Communication and Networking Conferences, WCNC*, (pp. 1 - 6). Istanbul, Turkey. doi:10.1109/WCNC.2014.6953057
- Brown, T. X., Pietrosevoli, E., Zennaro, M., Bagula, A., Mauwa, H. and Nleya, S. M. (2014). A Survey of TV White Space Measurements. *Africomm2014*, 1 - 9. Retrieved from [wireless.ictp.it](http://wireless.ictp.it)
- Ding, G., Wang, J., Wu, Q., Yao, Y. D., Song, F. and Tsiftsis, T. A. (2016). Cellular-Base-Station Assisted Device-to-Device Communications in TV White Space. *IEEE Journal on Selected Areas in Communication*, 34(1): 107-121.
- Elshafie, H., Fisal, N., Abbas, M., A., H. W., Mohamad, H., Ramli, N. and Zubair, S. (2014). A survey of cognitive radio and TV white spaces in Malaysia. *Transcations on Emerging Telecommunications Technologies*, 26(6): 975 – 991.
- Faruk, N., Adediran, Y. A. and Ayeni, A. A. (2013). Onthe Study of Empirical Path Loss Models for Accurateprediction of TV Signal for Secondary Users. *Progress in Electromagnetic Research (PIER) B, USA*, 49: 155 - 176.



- Faruk, N., Adediran, Y., Ayeni, A., Surajudeen-Bakinde, N., Bello, O., and Kolade, O. (2015). Geospatial Approach to Quantifying TV White Space in Nigeria in the UHF Band. *Journal of Next Generation Information Technology (JNIT)*, 6(4): 1 - 13.
- Faruk, N., Ayeni, A. A. and Adediran, Y. A. (2013). DTV Coverage and Protection Contour Estimation for Spatial White Space. *2103 IEEE International Conference on Emerging and Sustainable Technologies for Power and ICT in a Developing Society (NIGERCON)* (pp. 96 - 100). Owerri, Nigeria: IEEE. doi:10.1109/NIGERCON.2013.6715643
- FCC (Federal Communications Commission). (2008). Second Report and Order and Memorandum Opinion and Order, ET Docket Nos. 08-260. *Technical Report*, November 2008. FCC, US.
- Gbenga-Ilori, A. O. and Sanusi, O. I. (2014). Maximizing TV White Space in Nigeria using an Optimized SFN and k-SFN Network Design. *International Journal of Science, Environment and Technology*, 3(4): 1489-1501.
- Jayavalan, S., Mohamad, H., Aripin, N. M., Ismail, A., Ramli, N., Yaacob, A. and Ng, M. A. (2014). Measurements and Analysis of Spectrum Occupancy in the Cellular and TV Bands. *Lecture Notes on Software Engineering*, 2(2), 133 - 138. doi:10.7763/LNSE.2014.V2.110
- Kang, K. M., Park, J. C., Chio, S. I. and Jeong, B. J. (2012). Deployment and Coverage of Cognitive Radio Networks in TV White Space. *IEEE Communication magazine*, 50(12): pp. 88 - 94.
- Kokkinen, H. (2020). TV White Space Spectrum Sharing Using Geolocation Databases. In *TV White Space Communications and Networks* (pp. 29-43). Finland: Fairspectrum, H2020 Coherent, Espoo.
- Kumar, P., Rakheja, N., Sarswat, A., Varshney, H., Bhatia, P., Goli, S. R. and Sharma, M. (2013). White Space Detection and Spectrum Characterization in Urban and Rural India. *2013 IEEE 14th International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)*. Madrid, Spain: IEEE. doi:10.1109/WoWMoM.2013.6583462
- Kurnaz, C., Engiz, B. K., and Albayrak, Z. E. (2016). Determination of TV White Space Spectrum Availability in Samsun Turkey. *24th Telecommunications Forum TELFOR 2016*. Belgrade, Serbia. doi:10.1109/TELFOR.2016.7818747
- Makris, D., Gardikis, G., and Kourtis, A. (2012). Quantifying TV white Space Capacity: A Geolocation-Based Approach. *IEEE Communication Magazine*, 50(9): 145 – 152.
- Mehdawi, M., Riley, N. G., Ammar, M., Fanan, A. and Zolfaghari, M. (2015). Spectrum Occupancy Measurements and Lessons Learned in the Context of Cognitive Radio. *2015 23rd Telecommunications forum (TELFOR)*. Belgrade, Serbia: IEEE. doi:10.1109/TELFOR.2015.7377446
- Naik, G., Singhal, S., Kumar, A., and Karandikar, A. (2014). Quantitative Assessment of TV White Space in India. *2014 Twentieth National Conference on Communications (NCC)*. Kanpur, India: IEEE. doi:10.1109/NCC.2014.6811306
- Oki, O. A., Zulu, A. S. and Adigun, M. O. (2019). Analysis of TV Spectrum Occupancy in KwaDlangezwa Township South Africa. *2019 IEEE AFRICON Conference*. Accra, Ghana: IEEE. doi:10.1109/AFRICON46755.2019.9133908
- Opawoye, I., Faruk, N., Bello, O. W. and Ayeni, A. A. (2015). Recent Trend on TV White Space DEployments in Africa. *Nigerian Journal of Technology*, 34(3): 556-563. doi:http://dx.doi.org/10.4314/njt.v34i3.19
- Oyama, T., Shimomura, T. and Seki, H. (2012). TV White Space Availability in Japan Estimated Using D/U-based and I/N-based Protection Rules. *2012 IEEE Global Communications Conference (GLOBECOM)*, (pp. 1320 - 1325). Anaheim, CA, USA: IEEE. doi:10.1109/GLOCOM.2012.6503293
- Paulson, E. N., Adedeji, K. B., Kamaludin, M. Y., Popoola, J. J., Jafri, B. D. and SharifahKamilah, S. Y. (2017). Spectrum Occupancy Measurement: A Case for Cognitive Radio Network in Lagos, Nigeria. *ARNP Journal of engineering and Applied Sciences*, 951-955.

- Roberts, S., Garnett, P. and Chandra, R. (2015). Connecting Africa using the TV White Spaces: From Research to Real World Deployments. Local and Metropolitan Area Networks (LANMAN). *IEEE International Workshop on Local and Metropolitan Area Networks* (pp. 1-6). IEEE, 2015.
- Seflek, I. and Yaldiz, E. (2017). Spectrum Occupancy Measurement at University Campus in Turkey. *International Journal of Electronics and Electrical Engineering*, 5(1): 1-6. doi:10.18178/ijeee.5.1.1-6
- Ufoaroh, S. U. and Abu, K. (2019). Assessment of TV White Spaces Availability in Southern Nigeria (A Case Study of Ugbowo, Benin City). *International Journal of Electrical and Telecommunication System Research*, 10(10): 22 - 31.
- Van de Beek, J., Riihijarvi, J., Achtzehn, A. and Mahonen, P. (2011). UHF White Space in Europe - A Quantitative Study into the Potential of the 470 - 790 MHz Band. *IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)* (pp. 1 - 9). Aachen, Germany: IEEE.
- Webb, W. (2012). On Using White Space Spectrum. *IEEE Communications Magazine*, pp. 145 - 151.
- Xue, J., Feng, Z. and Zhang, P. (2013). Spectrum Occupancy Measurements and Analysis in Beijing. *2013 International Conference on Electronic Engineering and Computer Science (IERI Procedia 4)* (pp. 295 - 302). Elsevier B. V. doi:10.1016/j.ieri.2013.11.042
- Zennaro, M., Pietrosemoli, E., Mlatho, J., Thodi, M. and Mikeka, C. (2013). An Assessment Study on White Spaces in Malawi using Affordable Tools. *2013 IEEE Global Humanitarian Technology Conference (GHTC)*. San Jose, CA, USA: IEEE. doi:10.1109/GHTC.2013.6713693