Research article

Propagation curves and coverage areas of digital terrestrial television base stations in the tropical zone

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ABSTRACT

This study investigated the propagation curves and coverage areas of some Digital Terrestrial Television Broadcast Stations (DTTBS) over four climatic zones of coastal (Lagos), tropical rain forest (Akure), Sudan Savannah (Kaduna) and Sahel Savannah (Katsina) cities of Nigeria. Measurement of the Received Signal Strength (RSS) was carried out along different routes with each of the DTTBS as reference points. Measurements of RSS were carried out using two specified antenna receiver heights of 1.5 and 3.0 m for each data point. The GPS receiver was used to measure the geographic coordinates, elevation and Line of Sight (LOS) of data points along the routes in a drive test. Measurement was done during dry and wet season months at 1 km interval up to about 20 km in each of the selected routes covering a period of three years (2016–2018). Mean data were obtained and used to generate the propagation curves and the coverage areas over the study locations. Generally, results revealed that RSS undulates with LOS separation distance from DTTBS in all routes irrespective of seasons and routes. Particularly, RSS reduces to about half of its base station's value at about 8 and 12 km LOS from the DTTBS in Akure and Katsina respectively while, it reduces to about half of its base station's value at about 6 km from the DTTBS in Lagos and Kaduna. The implication of this is that higher coverage areas were obtained in suburban compared to urban cities. In addition, radial maps showing coverage areas and their grades useful for networking purposes were generated. Television White Spaces (TVWS) for secondary users were also proposed. For networking purposes and spatial arrangements of DTTBS that will ensure optimum coverage over the study locations, DTTBS can be sited at 8.0 and 13.5 km (LOS) interval from each other in urban and suburban cities respectively. The overall results will enable system engineers to know the appropriate distance(s) and locations to site additional DTTBS for networking purposes and prepare power budget for optimum coverage area and good quality of services for terrestrial digital channels.

1. Introduction

Digital Terrestrial Transmission of signal on the Ultra High Frequency (UHF) broadcast band is by space wave which propagates on Line of Sight (LOS) from source (transmitter) to destination (receiver) through the troposphere. Since the inception of television broadcasting, terrestrial television broadcasting has been on the analogue transmission and reception technology until a couple of years ago that Digital Terrestrial Television (DTTV) Technology was proposed in a bid to maximize frequency spectrum by releasing the upper UHF bands for broadband services. Consequently, the International Telecommunications Union (ITU) demanded the world wide release by the year 2015 of the upper UHF band, for the implementation of mobile broadband. DTTV utilizes conventional antennas instead of satellite dishes or cable connections to deliver video and audio services to subscribers. The major difference between DTTV and ATT is that digital signals are transmitted by multiplex transmitters and are radiated from the transmitting antenna whereas in ATT, analogue signals are transmitted through a single channel by an analogue transmitter. Multiplex transmitters enable the transmission of multiple channels in a single frequency range. DTTV network comprises of several terrestrial transmitters with a specific coverage areas. The coverage area of terrestrial television can be influenced by many factors; the output power of the transmitter, the height of transmitting and receiving antennae (Akinbolati et al., 2016), terrain between the transmitter and receiver (Kennedy and Bernard, 1992), effect of

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meteorological parameters Ajewole et al. (2014) and foliage (Ayekomi-logbon et al., 2013) amongst others.

Many developed Countries of the World have switched from ATT to DTTV. In Africa, only few Countries have achieved full digitization with majority still on the ATT. There are other Countries that have partially switched over from ATT to DTTV including Nigeria. Nigeria had missed two deadlines (June 17, 2015 and June 17, 2017) from Analogue Switch Off (ASO) to Digital Switch Over (DSO). As the government is working on policy and logistics to achieve full DSO so also radio scientists and engineers should be engaged with scientific study that will ensure QoS and networking for DTTV in Nigeria. Analogue TV signal generally experiences loss of signal strength from source to destination (Akinbolati et al., 2016, 2017), so also a correctly formatted DTTV signal is exposed to various attenuation factors that can degrade it before it reaches the intended users (Armoogum et al., 2010). It has therefore become expedient to investigate the propagation pattern and coverage areas of DTTV over the various climatic zones which are aimed at improving its QoS over Nigeria. No comprehensive work had been done in this regard on DTTV channel. This may be tolerated in ATT in which the transmitted signal can be received with the aid of a receiving antenna (Ajayi and Owolabi, 1979; Ajewole et al., 2014; Akinbolati et al., 2015). All stations have their expected coverage areas and their signals should not constitute interference to others. Determination of coverage areas of broadcast channel is useful in the assessment of QoS rendered by broadcasting stations so as to minimize coverage failures and enhance optimum coverage of the areas the station was originally designed to service. Coverage areas for terrestrial broadcast channels are classified into three, namely:

i. Primary coverage area (1): This is defined as a region about the transmitting station in which the signal strength is strong enough to override ordinary interference at all times. The signal strength is dependable and could be received clearly at all times. According to ITU-R recommendation, ITU-R BT. 2035 (2003), the signal level equivalent to DTTV primary coverage area is: Received Signal Strength (RSS) \( \geq -53\, \text{dBm} \)

ii. Secondary coverage area (2): In this region about the transmitting station, the signal strength is often sufficient to be useful but not strong enough to override ordinary interference at all times. The use of an active receiving antenna may be needed for a clear reception. According to ITU-R recommendation, ITU-R BT. 2035 (2003), the signal level equivalent to DTTV secondary coverage area can be classified as: \(-54 \leq \text{RSS} \leq -68\, \text{dBm}\)

1.1. Propagation curve and coverage area for broadcast channels

Propagation curve is an essential parameter in radio wave propagation especially television and radio. It is the variation of the electric field strength of a radio signal with distance and terrain. It depends on transmitter power, the nature of signal path (rural or urban) and the terrain of the locations involved (Akinbolati et al., 2016). It is useful in the prediction of coverage areas and path losses and accurate prediction of path loss is a key factor in the good design of mobile systems (Nisirat et al., 2011). Propagation curves reveal the propagation pattern of any radio signal as it interacts with terrestrial features along the path of propagation. The ITU-R, has encouraged study on propagation curves by scientist and engineers in their respective regions of the world (ITU-R, 1995).

Coverage area for broadcast channels is the radial LOS distance away from the transmitter in which the transmitted signal can be received with the aid of a receiving antenna (Ajayi and Owolabi, 1979; Ajewole et al., 2014; Akinbolati et al., 2015). All stations have their expected coverage areas and their signals should not constitute interference to others. Determination of coverage areas of broadcast channel is useful in the assessment of QoS rendered by broadcasting stations so as to minimize coverage failures and enhance optimum coverage of the areas the station was originally designed to service. Coverage areas for terrestrial broadcast channels are classified into three, namely:

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![Figure 1. The study area.](image)

| S/N | Parameter | DTTBS |
|-----|-----------|-------|
| 1   | Base station’s location and geographic coordinates | Ikorodu - Lagos (Lat. 6° 37’ 43" N, Long. 3° 31’ 42" E) | Akure (Lat. 7° 15’ 08" N, Long. 5° 07’ 53" E) | Kaduna (Lat.10°32’16N", Long. 7°28’18” E) | Katsina (Lat.13°01’50" N, Long. 7°32’51" E) |
| 2   | Base station transmitted power (kW) | 2.20 | 2.20 | 2.30 | 2.20 |
| 3   | Base station’s frequency (MHz)/Channel | 658/44 | 722/52 | 714/51 | 530/28 |
| 4   | Height of transmitting antenna (m) | 182.5 | 182.5 | 182.5 | 182.5 |
| 5   | Height of mobile antenna AGL (m) | 1.5 and 3.0 | 1.5 and 3.0 | 1.5 and 3.0 | 1.5 and 3.0 |
### Table 2. Typical Route Definition for each of the Transmitting Digital Terrestrial Television Base Stations (DTTBS) used as the Source of Signals during the Field Strength Measurement.

| Route | Route Definition | Features | Path Loss (LOS) |
|-------|------------------|----------|-----------------|
| A     | From base of the transmitter in Unguwai - Rimi | Features urban, with congested high rising structures and 75% dual and 25% single carriage way. | 16 km |
|       | From base of the transmitter in Magodo, Ikorodu - Lagos | Features urban, with congested building structures and 60% dual and 40% single carriage way. | 19 km |
| B     | From base of the transmitter along Jibia Road, Katsina towards Batsari Town (0–12 km LOS) | Features urban, with fairly congested building with trees. It also has about 20% dual carriage way and 80% single carriage way. | 12 km |
| C     | From base of the transmitter along Jibia Road, Katsina towards Daura Town (0–14 km LOS) | Features Sub urban, with fairly congested building with trees. It also has about 20% dual carriage way and 80% single carriage way. | Not applicable |
|       | From base of the transmitter along Jibia Road, Katsina towards Dutsin-Ma Town (0–19 km LOS) | Features Sub urban, with fairly congested building with trees. It also has about 20% dual carriage way and 80% single carriage way. | Not applicable |
|       | From base of the transmitter along Jibia Road, Katsina towards Mando Town (0–16 km LOS) | Features Sub urban, with fairly congested building structures and 75% dual and 25% single carriage way. | Not applicable |

iii. Fringe (tertiary) coverage area (3): In this region about the transmitting station, the signal strength is often weak and not dependable; its service can neither be guaranteed nor be protected against interference. The use of an active receiving antenna may not bring about a clean reception at all times (Ajayi and Owolabi, 1979; Ajewole et al., 2014; Akinbolati et al., 2015). According to ITU-R recommendation, ITU-R BT. 2035 (2003), the signal level equivalent to DTTV fringe coverage area is: $-68 < \text{RSS} < -116 \text{dBm}$.

In addition, study on propagation curves and coverage area is useful in path loss estimation and prediction of TV White Spaces (TVWS) for secondary users. According to ITU-R and the IEEE 802.22 draft (Faruk et al., 2013) spatial TVWS for DTTV can be defined as the distances from the base station in which the signal cannot be received from the station due to attenuation of the signal. Technically this is the signal’s sensitivity value which is -116 dBm for DTTV. When the signal strength is less than this value the signal cannot be successfully received. TVWS can be temporal or spatial; temporal has to do with the use of the channel at the time the original DTTV channel is off air. However, this has been difficult to achieve since DTTV is designed to operate 24 h services. The spatial white space is the supposed coverage area of the channel in which the signal is below the minimum threshold and therefore cannot be received.

In this area, the frequency can be used (frequency re-use) by secondary users for low power and low range wireless devices in a strictly localized manner. At the white spaces, the secondary users can utilize the white spaces without interfering with the TV transmission.

2. Related study

Okumura et al. (1968) carried out an intensive field strength measurement in Tokyo, Japan. The work was successful and he predicted power loss in urban areas as an empirical formula and the work was widely accepted. The disadvantage of the model is that, it is not suitable for use in irregular terrain and its limitation to frequency range of 150–1500 MHz. Hata (1980), reformulated Okumura model in the form of empirical relations for use in urban and rural areas. He also applied correction factors. The model is known as Okumura–Hata (Okumura-a-Hata, 1980). This was widely accepted globally and adopted by the ITU-R as a global model to benchmark new approaches Armoogum et al. (2010). This model depends on antenna height, frequency, types of environment amongst others. It was based on extensive series of field strength measurement carried out in and around Tokyo city within the frequency range of 200 MHz and 2 GHz. The models are categorized into urban, sub urban and rural. The model for urban areas has been standardized in 1997 for international use as ITU recommendation (Rec. ITU-R P.529; ITU report, 1995). Furthermore, Perez-Vega and Zamaniilo (2002) carried out similar study in Spain. The result proposed a propagation model for use on the VHF and UHF bands. The work was based on the data provided by Federal Communication Commission (FCC), F (50, 50) propagation curves. Its drawback is that it is not frequency dependent in the band of interest. Prasad (1997) carried out an intensive field strength measurement over Indian subcontinent and the calculated path loss was compared with Perez-Vega and Zamaniilo (2002) and others. The shortcoming of this work is that no model was proposed from the observations and results. Armoogum et al. (2010) carried out a comprehensive study on propagation models and their applications in digital television broadcast network design and implementation using the Island of Mauritius as a case study. The team of researchers carried out field strength measurement on digital terrestrial television broadcast signal for the purpose of network design implementation. Analysis and comparisons of field strength and height gain in North and South Mauritius were conducted to find out the types of terrain and the reasons why television signals suffer attenuation. Two techniques were proposed for the development of new propagation models. Akingbade and Olunjnib (2013) carried out the field strength measurement of the analogue UHF channel 23 signal in Akure Metropolis, Ondo State, Nigeria along
two routes from the base station. The data obtained were used to propose new path loss model based on Hata model. The limitation of this work is that the model was based on analogue UHF signal and one season for the study. In addition, Ajewole et al. (2014) and Akinbolati et al. (2015) carried out the electric field strength measurements for the UHF channels 23, 25 and 27 for both wet and dry seasons in Ondo State, Nigeria. The data obtained were used to determine the effect of precipitation on UHF signal strength and as well classify the coverage areas and grades of coverage across the state. The limitations of the study are its restriction to analogue UHF channels and one climatic zone (Tropical rainforest) in Nigeria. Obiyemi and Ojo (2014) carried out a study on the technical preparedness for digital switch over in Nigeria and a review of the performance of the analogue TV-transmitters in Oshogbo Osun State. It was based on extensive field measurement over, Oshogbo. He classified the grades of coverage of the transmitting ATT and made recommendation for DTT. Akinbolati et al. (2016) studied the signal strength variations and propagation profile for an analogue UHF channel in Akure, Ondo State. It was based on field strength measurement of the channel. The work revealed the effect of elevation pattern on the signal and that UHF signal experienced the highest losses towards the southern parts of the State compared to other parts due to the low elevation profile of the zone. Adediji et al. (2017) studied the variability of microwave radio refractivity and field strength across seven cities in Nigeria. The work made use of two years’ data from Tropospheric Data Acquisition Network (TRODAN) in Ayingba, Nigeria. Results showed that surface radio refractivity were higher during the rainy compared to dry season and in the coastal areas than the other locations. The uniqueness of this work over previous literature is to come out with findings on DTTV propagation curves and coverage areas that will be useful at improving the QoS of existing DTTBS and networking purposes over study locations.

Figure 2. Google Map of different Routes in the City of Akure.

Figure 3. Google Map of different Routes in the City of Kaduna.
3. Methodology

This study was carried out in four major cities over Nigeria, namely: Ikorodu-Lagos, Akure, Kaduna and Katsina representing the coastal, tropical rain forest, Sudan Savannah and Sahel Savannah climatic zones of Nigeria. It was carried out for a period of three years (2016–2018) covering wet and dry season months using the four Digital Terrestrial Television Base Stations (DTTBS) in each of the cities under study. Figure 1 presents the digital map of study area whereas Table 1 presents the characteristics of the transmission parameters of the DTTBS. Table 2 presents the route description for field strength measurement and data collection while Figures 2 and 3 present typical Google Maps showing measurement routes in Akure and Kaduna respectively.

3.1. Equipment used and experimental arrangement

A digital field strength meter was used to measure the signal strength by connecting the UHF receiver (antenna attached to a variable antenna stand) to the meter. A Global Positioning System Receiver (GPS Map 78s personal navigator) was used to monitor the values of elevation, geographic coordinates and the line of sight of the various data locations from the base station during the drive test. The drive test method of field strength measurement had been deployed locally and internationally leading to the formulations of empirical models whose findings have been approved and standardized by the ITU-R. Prominent amongst such are the works of Okumura et al. (1968), Okumura-Hata, 1980, Armoogum et al. (2010), Nisirat et al., 2011. Figure 4 presents some of the equipment used for data collection during field work.

3.2. Data collection, computation and analysis

Measurement of the Received Signal Strength (RSS) for the four DTTBS under study was carried out along different routes with each of the DTTBS as reference points. Two sets of RSS data were obtained for two specified receiver antenna heights of 1.5 and 3.0 m for each location. The geographic coordinates of each DTTBS were logged and used as the reference point by the GPS receiver for all the routes around the station. During the field work, the Line of Sight (LOS) separation distance of data

| Location       | Descriptive Statistics | Mean     | Standard Deviation | n  |
|----------------|------------------------|----------|--------------------|----|
| Ikorodu dry    | LOS distance from DTTBS (km) | 4.589    | 3.428              | 12 |
|                | RSS (dBm) at 1.5 m Receiver Height (RxHt) | -46.833  | 13.265             | 12 |
|                | RSS (dBm) at 3.0 m RxHt | -41.010  | 12.121             | 12 |
|                | Elevation (ELV) of data points (m) | 33.250   | 6.283              | 12 |
| Akure dry      | LOS distance from DTTBS (km) | 7.978    | 5.363              | 12 |
|                | RSS (dBm) at 1.5 m Receiver Height (RxHt) | -62.667  | 17.191             | 12 |
|                | RSS (dBm) at 3.0 m RxHt | -59.083  | 16.692             | 12 |
|                | Elevation (ELV) of data points (m) | 360.833  | 24.617             | 12 |

| Location       | Descriptive Statistics | Mean     | Standard Deviation | n  |
|----------------|------------------------|----------|--------------------|----|
| Ikorodu wet    | LOS distance from DTTBS (km) | 4.605    | 3.443              | 12 |
|                | RSS (dBm) at 1.5 m Receiver Height (RxHt) | -49.917  | 14.279             | 12 |
|                | RSS (dBm) at 3.0 m RxHt | -42.833  | 10.735             | 12 |
|                | Elevation (ELV) of data points (m) | 32.750   | 6.353              | 12 |
| Akure wet      | LOS distance from DTTBS (km) | 8.497    | 5.341              | 15 |
|                | RSS (dBm) at 1.5 m Receiver Height (RxHt) | -65.067  | 16.158             | 15 |
|                | RSS (dBm) at 3.0 m RxHt | -61.400  | 16.208             | 15 |
|                | Elevation (ELV) of data points (m) | 364.410  | 19.588             | 15 |
Table 5. Descriptive statistics of parameters in Kaduna and Katsina DTTBS during the dry season months.

| Location  | Descriptive Statistics  | Mean    | Standard Deviation | n  |
|-----------|-------------------------|---------|--------------------|----|
| Kaduna dry| LOS distance from DTTBS (km) | 6.607   | 4.636              | 16 |
|           | RSS (dBm) at 1.5 m Receiver Antenna Height (RxHt) | -55.438 | 17.025             | 16 |
|           | RSS (dBm) at 3.0 m RxHt | -52.875 | 15.019             | 16 |
|           | Elevation (ELV) of data points (m) | 607.875 | 29.118             | 16 |
| Katsina dry| LOS distance from DTTBS (km) | 7.021   | 4.333              | 14 |
|           | RSS (dBm) at 1.5 m Receiver Antenna Height (RxHt) | -46.214 | 8.954              | 14 |
|           | RSS (dBm) at 3.0 m RxHt | -42.786 | 9.141              | 14 |
|           | Elevation (ELV) of data points (m) | 517.429 | 4.501              | 14 |

Table 6. Descriptive statistics of parameters in Kaduna and Katsina DTTBS during the wet season months.

| Location  | Descriptive Statistics  | Mean    | Standard Deviation | n  |
|-----------|-------------------------|---------|--------------------|----|
| Kaduna wet| LOS distance from DTTBS (km) | 6.626   | 4.634              | 16 |
|           | RSS (dBm) at 1.5 m Receiver Antenna Height (RxHt) | -57.813 | 14.044             | 16 |
|           | RSS (dBm) at 3.0 m RxHt | -54.250 | 13.188             | 16 |
|           | Elevation (ELV) of data points (m) | 607.813 | 28.992             | 16 |
| Katsina wet| LOS distance from DTTBS (km) | 8.375   | 5.835              | 14 |
|           | RSS (dBm) at 1.5 m Receiver Antenna Height (RxHt) | -54.286 | 11.269             | 14 |
|           | RSS (dBm) at 3.0 m RxHt | -50.571 | 11.824             | 14 |
|           | Elevation (ELV) of data points (m) | 524.286 | 10.702             | 14 |

Figure 5. Influence of LOS distance from DTTBS on RSS for the two specified receiver antenna heights for Ikorodu- Lagos during dry season months' for year (a) 2017; (b) 2018.
points from each base station was monitored using the GPS, which equally measures the geographic coordinates and the elevation above sea level during the drive test.

The research crew usually stops at an interval of 1 km LOS for measurement to be taken. At each point of data collection, all the equipment would be set up and operated. The field strength at receiver height of 1.5 m would be measured and recorded followed by the field strength at receiver height of 3.0 m. The choice of the specified receiver antenna's height was based on this premise; 1.5 m was chosen to represent the average television placement height in most homes that make use of the internal receiver antennas over the study area. Most subscribers simply put their receiver antenna (indoor) on the television or hanging it on the wall. This reference height is to measure the value of the signal strength at this height. As a matter of fact, when DTT was launched in Nigeria the
antenna type used was monopole of small size usually placed on the television by subscribers. It was equally chosen to be in compliant with the minimum antenna height required for portable outdoor reception (ITU-R BT. 2383-1, 2006). The 3.0 m height was chosen as the average height where subscribers mount their receiver antenna heights (outdoor) over the study area. The exercise usually takes about 20 min for each point before moving to another point and the distance considered for each route was up to about 20 km.

Figure 8. Influence of LOS distance from DTTBS on RSS for the two specified receiver antenna heights during dry season months in Akure for year (a) 2017 (b) 2018.

Figure 9. Influence of LOS distance from DTTBS on RSS for the two specified receiver antenna heights during wet season months in Akure for year (a) 2017 (b) 2018.
Measurements were carried out for consecutive days, (each day for a route) in six phases for each station; three phases each during dry and wet seasons’ months peculiar to each of the DTTBS covering the period of three years (2016–2018). In summary, the RSS values, geographic coordinates, elevation above sea level as well as the LOS of the various data points were recorded in about 150 data points for each phase totaling about 1000 data points for the study period. In order to ensure the accuracy of the obtained data, mean values were computed and used for the analysis presented in this study. Tables 3 and 4 present typical descriptive statistics of data for dry and wet season months over the study locations.

4. Results and discussion

4.1. Descriptive statistics of parameters

Mean and Standard Deviation were carried out on the data for each season in all the study locations. Tables 3 and 4 present the descriptive statistics in Ikorodu – Lagos and Akure for dry and wet season respectively while Tables 5 and 6 present these parameters and their values for dry and wet season months in Kaduna and Katsina respectively. From the Tables, it was generally observed that higher receiver antenna provided better signal quality compared to lower antenna in all the study locations irrespective of seasons. This is obvious because higher antenna minimizes the attenuation effect of multi paths on the UHF band. Mean elevation values of 33.00, 362.62, 607.84 and 520.86 m were obtained in Ikorodu – Lagos, Akure, Kaduna and Katsina cities respectively.

4.2. Propagation curves over study areas

This sub section presents results on the influence of LOS separation distance on RSS over each of the study locations. The variations were observed at the two specified receiver antenna heights of 1.5 and 3.0 m. Figures 5 and 6 present typical influence of LOS separation distance on RSS for Lagos during dry and wet season months respectively covering the years 2017 and 2018. Generally speaking over the two seasons, RSS undulates with distance; it did not vary inversely as expected theoretically by the inverse square law. This can be attributed to the influence of elevation and tropospheric components peculiar to each location. There were farther trans-receiver distances along the LOS that recorded higher signal values compared to nearer distances from the base stations. These are represented by typical points a, b, c, d and are referred to as Enhanced Signal Points (ESP). Similar trend was observed for all the routes during
the period of investigation. General observation on the influence of LOS distance on RSS in Ikorodu-Lagos shows that on the average, RSS drops to about half (-54 dBm) of its average initial base station's value (-27 dBm) at about 6 km LOS from the base station in Lagos as presented in Figure 7.

This distance is termed the Average Half Decay denoted by AHD in this work which is the approximate distance from the DTTBS (trans-receiver distance) in which the signal strength reduces to about half of its initial value.

Figure 12. Influence of LOS distance from DTTBS on RSS for the two specified receiver antenna heights during wet season months in Kaduna for year (a) 2017; (b) 2018.

Figure 13. Propagation curves depicting the half decay of the signal strength with distance in Kaduna.

Figure 14. Propagation curves depicting AHD of the signal strength with distance in Katsina.
Figures 8 and 9 present influence of LOS separation distance on RSS for Akure during dry and wet season months covering the year 2017 and 2018. The influence of LOS distance from base station on RSS in the tropical rain forest zone (Akure) for all routes and seasons considered show similar trend with that of Lagos with typical ESP $i, j, k$ and $l$. This can be attributed to the influence of terrain particularly elevation above sea level of the study areas and tropospheric components. RSS was generally higher at receiver antenna height of 3.0 m irrespective of the routes and seasons. This is due to the fact that higher receiver antenna height minimizes losses due to multi paths effect. It was equally observed that the use of 3.0 m receiver antenna does not show any significant improvement over the 1.5 m at the micro cell (0–1.0 km). Another finding from the propagation curves is that RSS averagely drops to about half (-70 dBm) of its initial base station’s value (-35 dBm) at about 8 km LOS distance from the base station in Akure. Figure 10 presents the AHD which is the LOS distance at which the signal reduces to half of its initial base station value.

This trend continues in the remaining study locations (Kaduna and Katsina) though with little deviation in Kaduna (Figures 11 and 12) where minimal difference in the signal strength values for the 1.5 and 3.0 m antenna height was observed (with ESP $p, q, r$ and $s$). This might be due to the fact that Kaduna is an urban centre with high rising buildings ranging from 3.0 to about 18.0 m alongside tall trees particularly in some areas like: Ungwai Rimi, Ahmadu Bello way, State secretariat, government house area, Nigerian Defence Academy (NDA) area, Airport road amongst others. High rising buildings with congested terrestrial features might have prevented the reception of the direct transmitted signal from the base station by both antennae leading to multipath fading. Multipath fading occurs as a result of signal encountering an obstacle leading to different paths before getting to the receiver (Ojo et al., 2019). The signal

| Study location   | (R) for dry season months | (R) for wet season months | Average (R) |
|------------------|---------------------------|---------------------------|-------------|
| Ikorodu-Lagos    | -0.763                    | -0.935                    | -0.849      |
| Akure            | -0.863                    | -0.903                    | -0.883      |
| Kaduna           | -0.848                    | -0.703                    | -0.776      |
| Katsina          | -0.883                    | -0.907                    | -0.895      |

Table 7. Correlation coefficient between LOS separation distance and RSS over the study areas.

Figure 15. Radial Map of Coverage Areas and their Grades for Lagos-Ikorodu DTTBS.
received by both antennae might primarily be the reflected or scattered signal as line of sight could not be established between transmitting and receiving antennae. Therefore, for subscribers of DTTV in Kaduna city, especially along route A, to access optimum signal level high receiving antenna is recommended. On the average, RSS reduces to about half (-60 dBm) of its average initial base station’s value (-30 dBm) at about 6 km LOS separation distance from the base station in Kaduna as presented in Figure 13. Similarly, RSS reduces to about half (-62 dBm) of its average initial base station’s value (-31 dBm) at about 12 km LOS separation distance from the base station in Katsina as presented in Figure 14.

4.3. Correlation coefficient between LOS (separation distances from DTTBS) and RSS

Statistical analyzes of data revealed that RSS is inversely proportional to LOS separation distances from the DTTBS in all the study locations irrespective of the seasons as presented in Table 7. The Table shows higher negative correlation coefficients in the wet months compared to the dry season months over the study locations. The implication of this is that the signal experiences higher losses during wet compared to the dry season. The highest mean correlation coefficient (R) of -0.90 was obtained between LOS separation distance and RSS in Katsina while the least (R) of -0.78 was obtained in Kaduna. These findings will be useful to radio scientist and engineers to design terrestrial digital television links with high reliability.

4.4. Classification of coverage area

Coverage area can also be classified in terms of AHD. This could be achieved based on the observation from this work. For example, beyond 6 km LOS (irrespective of the season) RSS reduces to about 50% especially in Lagos and Kaduna (Figures 7 and 13). Similarly, beyond 8 and 12 km, it reduces to about 50% in Akure and Katsina (Figures 10 and 14) respectively. In addition, the IEEE (IEEE 802.22 draft, 2011) recommended sensitivity values of DTTV signal of -116 dBm (Faruk et al., 2013) and the standard definition of coverage areas (Ajayi and Owolabi, 1979; Ajewole et al., 2014; Akinbolati et al., 2015, 2016) as well as the ITU-R (BT. 2035) report are equally employed in the classification of coverage areas in this study. Figures 15, 16, 17, and 18, present the radial maps for the coverage areas in Lagos, Akure, Kaduna and Katsina respectively. The percentage of coverage areas as a function of the radial distance covered by each of the DTTBS was estimated based on the radial concentric. Tables 8 and 9 present the characteristics of the estimated coverage areas and the percentage of coverage area as a function of the radial distance covered by the DTTBS respectively. DTTBS located in Katsina (Sahel Savannah) has the highest percentage of primary coverage.
areas followed by Akure and Ikorodu-Lagos while Kaduna recorded the least. On the other hand, the highest percentage of fringe coverage was recorded in Kaduna followed by Akure and Lagos while Katsina recorded the least. This implies that DTTV signal experiences the least attenuation in the Sahel Savannah compared to other climatic zones as earlier discussed.

From the Table, the fringe coverage areas have the highest coverage in all the study locations, meaning that a good number of the citizens do not have access to quality of service. The service providers with relevant stakeholders should take necessary steps by establishing repeater stations at the fringe or increase transmitter power to enhance QoS.

4.5. Proposed TV white spaces (TVWS) over the study areas

According to ITU-R and IEEE (Faruk et al., 2013) the IEEE 802.22 draft defines spatial TV white space for DTTV as the distances from the base station in which the signal cannot be received from the station due to attenuation of the signal. Technically this is the signal’s sensitivity value which is -116 dBm. When the signal strength is less than this value DTTV signal cannot be successfully received. In this area, the frequency can be used (frequency re-use) by secondary users for low power and low range wireless devices in a strictly localized manner. At the white spaces, the secondary users can utilize the white spaces without interfering with the TV transmission. Based on this and the classification of coverage areas in this work, the following spatial white spaces are proposed in Table 10, over the study areas. These can be properly deployed for the transmission of TVWS equipment over the study area thereby maximizing the frequency spectrum.

5. Conclusion

In this work, we investigated the propagation curves, coverage areas and TVWS of some selected DTTBS over four climatic zones in Nigeria for a period of three years (2016–2018). Results revealed that DTTV signal do not reduce generally with distance as expected by the theoretical inverse square law. Rather it undulates with distance due to its interaction with terrain and tropospheric components along its path of propagation. The uniqueness of this work over previous study is highlighted: For the purpose of effective networking and spatial arrangements of DTTBS by system engineers that will ensure optimum coverage over study areas DTTBS can be sited as follows:

i. 8 km (LOS) from each other in Lagos and by extension in any other urban city in the coastal climatic zone of Nigeria.

ii. 12 km (LOS) from each other in Akure and by extension in any other sub urban city in the tropical rain forest climatic zone of Nigeria.

iii. 8 km (LOS) from each other in Kaduna and by extension in any other urban city in the Sudan Savannah of Nigeria.
iv. 15 km (LOS) from each other in Katsina and by extension in any other sub urban city in the Sahel Savannah of Nigeria

Another finding from the propagation curves is that RSS reduces to about half of its base station’s value at about 8 km, and 12 km LOS from the base stations in the two sub urban stations of Akure and Katsina respectively. However, it drops to about half of its base station's value (AHD) at about 6 km from the base stations in urban cities of Lagos and Kaduna. The implication of this is that Digital Terrestrial Television signal experiences lower attenuation in the Sahel compared to the

Figure 18. Radial Map of Coverage Areas and their Grades for Katsina DTTBS.

Table 8. Characteristics of the estimated coverage areas over the study location.

| Location of DTTBS | Characteristic of primary coverage area | Characteristic of secondary coverage area | Characteristic of fringe coverage area |
|-------------------|----------------------------------------|-----------------------------------------|--------------------------------------|
| Ikorodu-Lagos     | 0 ≤ d ≤ 6km, RSS > -53dBm              | 6 ≤ d ≤ 8km, -53 ≤ RSS ≤ -70dBm        | 8 ≤ d < 15km, -70 ≤ RSS ≤ -116dBm   |
| Akure             | 0 ≤ d ≤ 8km, RSS > 53                  | 8 ≤ d ≤ 12km, -53 ≤ RSS ≤ -70dBm       | 12 ≤ d < 18km, -70 ≤ RSS ≤ -116dBm  |
| Kaduna            | 0 ≤ d ≤ 6km, RSS > -53dBm              | 6 ≤ d ≤ 8km, -53 ≤ RSS ≤ -70dBm        | 8 ≤ d ≤ 15km, -70 ≤ RSS ≤ -116dBm   |
| Katsina           | 0 ≤ d ≤ 10km, RSS > -53dBm             | 10 ≤ d ≤ 15km, -53 ≤ RSS ≤ -70dBm      | 15 ≤ d ≤ 19km, -70 ≤ RSS ≤ -116dBm  |

Table 9. Percentage of coverage area as a function of the radial distance covered by DTTBS over the study locations.

| Location of DTTBS | Estimated primary coverage area (%) | Estimated secondary coverage area (%) | Estimated fringe coverage area (%) |
|-------------------|-------------------------------------|--------------------------------------|-----------------------------------|
| Ikorodu-Lagos     | 16.50                               | 28.50                                | 55.00                             |
| Akure             | 19.75                               | 24.69                                | 55.60                             |
| Kaduna            | 11.11                               | 33.30                                | 55.59                             |
| Katsina           | 27.70                               | 34.60                                | 37.70                             |
tropical rainforest zone. It also experiences lower loss of signal strength in the sub urban compared to urban cities.

On coverage areas’ classification and proposed TV white spaces, the following were obtained.

i. Lagos/coastal zone: The percentage of coverage areas as a function of the radial distance covered by the DTTBS was calculated as 16.50, 28.50 and 55.00 % for primary, secondary and fringe respectively. This is based on 15.0 km radial distance from DTTBS. The proposed TV spatial white spaces are locations beyond 15 km (LOS) radial distance from the DTTBS in Kotonu.

ii. Akure/Tropical rain forest zone: The percentage of coverage areas as a function of the radial distance covered by the DTTBS was calculated as 19.75, 24.69 and 55.60 % for primary, secondary and fringe respectively. This is based on 18.0 km radial distance from DTTBS. The proposed TV spatial white spaces are locations beyond 18 km (LOS) radial distance from the DTTBS in Akure.

iii. Kaduna/Sudan Savannah: The percentage of coverage areas as a function of the radial distance covered by the DTTBS was calculated as 11.11, 33.33 and 55.56 % for primary, secondary and fringe respectively. This is based on 19.0 km radial distance from DTTBS. The proposed TV spatial white spaces are locations beyond 19 km LOS from the DTTBS in Kaduna.

iv. Katsina/Sahel Savannah: The percentage of coverage areas as a function of the radial distance covered by the DTTBS was calculated as 27.70, 34.60 and 37.70 % for primary, secondary and fringe respectively. This is based on 19.0 km radial distance from DTTBS. The proposed TV spatial white spaces are locations beyond 19 km LOS from the DTTBS in Katsina.

v. Highest primary coverage area of 27.70 % was recorded in Katsina (a sub urban city in the Sahel) whereas the least of 11.11 % was recorded in Kaduna (an urban city in the Sudan). On the other hand, the least of fringe coverage of 37.70 % was also recorded in the Sahel and the highest of 55.60 % in the tropical rain forest zone. The implication of this is that, DTTV signal experienced the least level of attenuation in the Sahel compared to other climatic zones.

vi. The fringe coverage areas have the highest coverage in all the study locations, meaning that a good number of the citizens do not have access to quality of service from this service provider. The service providers with relevant stakeholders should take necessary steps by establishing repeater stations at the fringe or increase transmitter power to enhance QoS. For DTT networking in Nigeria and country with similar terrain, DTTBS can be sited at transmitter power to enhance QoS. For DTTV networking in Nigeria and country with similar terrain, DTTBS can be sited at transmission antenna and gain amongst others) across various climatic zones.

Declarations

Author contribution statement

A. Akinbolati: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
M. O. Ajewole: Conceived and designed the experiments.
A. T. Adediji & J. S. Ojo: Analyzed and interpreted the data; Wrote the paper.

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Additional information

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