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*Research Article*

# Radio Refractivity Impact on Signal Strength of Mobile Communication

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This research investigated radio refractivity impact on signal strength of mobile communication. The mobile communication signal strengths of two popular networks in Nigeria, 9Mobile and MTN, were considered. In the 2100 MHz-3 G band, 9Mobile transmits in the downlink spectrum of 2130.00–2140.00 MHz, while MTN transmits in the downlink spectrum of 2110.00–2120.00 MHz. Also, 9Mobile transmits in the downlink spectrum of 791–821 MHz in the 800 MHz band and 1805–1880 MHz in the 1800 MHz, while MTN transmits in the downlink spectrums of 2620–2690 MHz in the 2600 MHz band; all in the 4 G band. Using the instrument of a mobile station in each station (location) in some selected cities in southern Nigeria, the signal strengths were measured. A cell signal monitor (version 5.1.1) mobile application installed in an Android (transceiver) device (having two SIM slots) constituted the mobile station. To achieve high accuracy, there was a restriction in measuring transmission from specific cells. Hourly measurement of signal strengths was carried out and instantaneously corresponding weather parameters were recorded. Weather parameters for this investigation; atmospheric temperature and pressure; and relative humidity were excerpted online from the Nigeria Meteorological Agency (NIMET) hourly weather report for the various cities where the stations were situated. The hourly radio refractivity was computed using the 2015 International Telecommunication Union–Radio-communication sector (ITU-R) recommended model. Overall, the results indicate that there was no established linear relationship between signal strength and radio refractivity since the overall average $R$ value is 0.0123691 and the overall average standard deviation of $R$ values is 0.1112165. The inconsistencies in the linear relationships obtained from different locations and cells could be due to variations in topography, antenna properties, seasonal variations, wind and position, and distance of the receiver from the transmitter.

## 1. Introduction

The atmosphere is a channel for wireless (also called over-the-air) communication. Every wireless communication technology, be it radio and television broadcast, radar communication, global positioning system (GPS), satellite communication, cellular communication, wireless fidelity (Wi-Fi), radio frequency identification, and Bluetooth, employs the atmosphere in its communication. The atmospheric channel is influenced by weather [1–15]. Weather is the condition of the atmosphere within a particular period and place. The parameters that influence the weather of a place are atmospheric temperature, atmospheric pressure, relative humidity, and wind [16–22]. The variations of the quartet weather parameters mentioned above affect the properties of the atmosphere as a communication channel and invariable the propagation of radio waves [23–35]. One of the important properties of the atmosphere that varies with changes in the weather is its density [36–38]. Changes in the density of the atmosphere can affect the properties of propagating electromagnetic waves, mainly its refraction [1, 39–43]. Refraction is just the deviation in the path of a propagating wave as a result of the dissimilarity in the density of the media or medium which it propagates through. Hence, radio waves undergo refraction as they propagate through the atmospheric channel as a result of changes in the weather which varies the densities with the vertical position in the atmosphere [44–53].

Refractivity is the physical property of a medium as determined by its index of refraction. In short words, it is the measure or degree of refraction of a wave through a medium or media. All members of the electromagnetic waves that propagate through the atmosphere experience atmospheric refraction [1, 54–57]. The refraction experienced by radio waves mainly in the troposphere of the atmosphere is better quantified in terms of radio refractivity (International Telecommunication Union–Radio-communication sector [58]). Out of the basic quartet parameters of interest to meteorologists or weather scientists, the triplet: atmospheric temperature, atmospheric pressure, and relative humidity are required for the computation of refractivity [59–65]. Nonetheless, wind can also affect radio refractivity, since it affects the composition of the atmosphere and a lot of research has shown that wind affects radio communication in the atmosphere [66–70].

The knowledge of radio refractivity is of importance to radio scientists, technologists, and engineers as this enables them to design, construct, and implement radio equipment for efficient communication through the troposphere [1, 71–75]. Research has shown that radio refractivity has a significant effect on radio waves at ultrahigh frequency (UHF) [3, 59, 76–83]. Also, radio waves sometimes have been enhanced to reach distant locations which were impossible through tropospheric ducting (a consequence of radio refractivity), often after a temperature inversion [84, 85].

In the light of abovementioned theory, this research intends to ascertain the effect of radio refractivity on mobile communication signal strength as the radio waves propagate through the troposphere during the downlink. Worthy of note is that the atmosphere is divided into spheres. The sphere that governs the weather and is of utmost importance to weather scientists or meteorologists is the troposphere [86]. Hence, the focus will be on the troposphere in discussion of the atmosphere in this study.

## 2. Literature Review of Similar Research Studies

Ali et al. [87] in Islamabad, Pakistan, studied “Various meteorological parameters effect on GSM radio signal propagation for a moderate area.” In their review, they said the remote systems of the coming-generation such as the 5 G cellular networks focus on supporting applications of different kinds, e.g., interactive media on interchanged packet systems, information, and voice. Individual-to-individual correspondence can be enhanced in these systems with high-quality video and images and access to data and services will be enhanced by quality of service, security efforts, productivity of vitality, higher information rates, and new adaptive communication capabilities in public and private systems. However, particularly in the moderate areas, the channel continues to be a challenge. To determine a relationship that exists between refractivity and radio waves signal in the moderate zone at the confinement points of the observable pathway, Ali et al. [87] were able to carry out factual investigations of the generation of GSM radio waves signal. From their results, they evaluated the correlation between propagation of the GSM radio signal and refractivity as a −0.98 which infers opposite relationship. In other words, the greater refractivity, the lower the signal quality and vice versa (i.e., refractivity mitigates signal quality).

Osahenvemwen and Omatahunde [88] studied the “Impacts of weather and environmental conditions on mobile communication signals” in Benin city, Nigeria. They considered a mobile communication network of Glo operating in the 900 MHz band. Glo-world in Benin city is the location of the Glo fixed base transceiver station (BTS) considered. Relevant data of parameters were hourly obtained from 200 meters from the Glo BTS within a period of three (3) months in 2016 by means of a notebook Intel palm top with a frequency-signal tracker software, version 2.5.1 installed and configured. Rainy weather, dry weather, and fog weather as well as, morning, afternoon, and evening conditions were based on the statistical central tendency parameters. −61.3 N/km was the observed average refractivity gradient. It was observed that the variation of rain was within the 38 dBm range, in fog, variation was within the 34 dBm range, while in dry weather, signal strength variation was within 32 dBm, indicating a lower variation. The duo observed that refractivity gradient and air temperature had 0.42 and 0.50 positive correlations with received signal strength, respectively, and air pressure and relative humidity possess −0.50 and −0.44 negative correlations, respectively, with received signal strength. More so, there was a higher signal loss as the mobile station is moved away from the BTS.

Usman et al. [89] studied “Instantaneous GSM signal strength variation with weather and environmental factors” in Bauchi, Northern Nigeria. They carried out an experiment focusing on refractivity-related effects. First, at a fixed location on a live GSM network operating in the 900-MHz band, hourly measurement of signal strength was made and the fluctuations were observed. Second, from Bauchi meteorological center, data on variable parameters of the troposphere–relative humidity, pressure, and temperature were simultaneously obtained. The radio refractivity, as well as the refractivity gradient, and effective earth radius factor were calculated using the meteorological data available. −61.3-N/km was the average refractivity gradient (dN/dh) obtained from the hourly measurement taken at a fixed location for seven days. This average propagation conditions corresponds to the normal mode. However, at about 10-am and 8-pm, super refraction was often expected. They concluded that on the whole, temporal variations did not show any meaningful impact of radio refractivity gradient on received signal since the 0.091 correlation value between the variables is very low. Also, they said, receiver location has a dominating impact on signal strength fluctuations amongst the environmental factors investigated.

Familusi et al. [1] in Osun State Nigeria studied “assessment of radio refractivity and frequency modulated radio signal strength variability with time in the broadcasting system using Osun State Broadcasting Co-operation (OSBC), FM 104.5 MHz as a reference station." Frequency modulated radio signal strength (FMRSS) and radio refractivity (RF) meters were self-developed for the acquisition of data for the research. The meters were installed in a station in the state capital; Osogbo within the OSBC–FM coverage. The FMRSS meter was tuned to OSBC–FM operating at 104.5 MHz. Results indicate that better reception is achieved when radio refractivity is lower. In other words, high radio refractivity impacts negatively frequency modulated radio signals. Familusi et al. [1] observed that receptions are good under normal meteorological conditions.

Adisa [90] worked on "refractivity variation effect on radio wave propagation" in Akure, South-West Nigeria. He made use of the meteorological data of tropospheric parameters acquired from the Nigeria Metrological Agency (NIMET) in a month in 2013 (March precisely) to compute the radio refractivity. In addition, on daily basis, UHF broadcast signal strength was taken both in the daylights and at night at the same point of observation (3.7-km line-of-sight with GPS) using the UNAOHM model EP742A field strength meter with a Yagi array antenna connected also simultaneously corresponding meteorological data of tropospheric parameters were recorded. In conclusion, he put forward that each meteorological parameters have effect on radio refractivity, but relative humidity is strongest. In addition, he said that seasonal and latitudinal variations have some effect on surface refractivity and generally, −0.81 and −0.97 for day and night, respectively, were the correlations obtained between radio refractivity and broadcast signal strength.

Ayantunji et al. [91] in Gusau, North West, Nigeria, carried out an empirical analysis of atmospheric radio refractivity effect on signal quality at UHF band in a tropical environment. Surface values of temperature, pressure, and relative humidity as well as UHF signal strength used for this study was extracted from the measurements made using Davis Vantage PRO2 automatic weather station and UHF signal strength measuring device located at the ground surface of Federal University, Gusau (60° 78′N, 120° 13′E) North West Nigeria. The weather stations have a thirty-minute integration time while the UHF signal strength measuring device has a five-minute integration time. Data collected for the year 2018 for both weather parameters and signal strength were averaged over each hour to give twenty-four data points representing diurnal variations for each day and averages were taken over the month to give 24 data points for the month. The data acquired were used to analyze the diurnal variations of refractivity and signal strength as well as the correlation between weather parameters and signal strength. The refractivity values were computed using the ITU-R model. The results from the empirical analysis showed that the average daily variation of refractivity is large due to variations in humidity, while refractivity curves revealed seasonal variations with high values in the rainy season (from April to October) and low values in the dry season (from November to March). Regression analyses gave UHF signal strength and relative humidity correlations of 0.633 and 0.85 for December and January, and −0.728 and −0.639 for August and September. Also, the correlation between UHF signal strength and temperature was −0.597 and −0.890 for December and January, and 0.782 and 0.556 for August and September, respectively. Lastly, the correlation between UHF signal strength and radio refractivity was 0.530 and 0.864 for December and January and 0.311 and 0.364 for August and September, respectively. They concluded that environmental factors have effects on signal quality.

Famoriji and Oyeleye [92] in Akure, Ondo state, Nigeria, investigated "a test of the relationship between refractivity and radio signal propagation for dry particulates." Hourly averages of radio refractivity for dry particulates during the dry season (January) were calculated from the data obtained from the Nigeria Meteorological Agency (NIMET) when UHF broadcast signal measurement was taken for each hour throughout the whole day. They concluded that "the statistical correlation (with a correlation coefficient of −0.97) reveals that at different points when the refractivity was high (most especially at night and in the morning when the humidity was high) the signal strength was low and at the points when the refractivity was low (most especially during the day when the humidity was low due to high temperature) the signal strength was higher. Therefore, the higher the refractivity, the lesser the signal strength at the point of observation in the troposphere; i.e., they are inversely proportional to each other."

Amajama [80] studied the "association between atmospheric radio wave refractivity and UHF radio signal" in Calabar, Nigeria. Signal strengths measurements were obtained half hourly at a residential area in Calabar, Cross River State, Nigeria, for over 24 hours, and simultaneously, the meteorological components: atmospheric temperature and pressure, relative humidity, and wind (direction and speed) were recorded to probe the impact of the atmospheric radio wave refractivity on the radio signal. The measurement of the signal strength was made using a Digital community Access (Cable) Television (CATV) analyzer with 24 channels, spectrum 46–870 MHz, connected to a domestic receiver antenna of height 4.23 m. Signal was transmitted from the Cross River Broadcasting Co-operation Television (CRBC-TV) at the strength of 35 mdB and a frequency of 519.25 MHz: defined by the International Telecommunication Union (ITU) as ultra-high frequency (UHF). Results erected that signal strength has a partially inverse relationship with atmospheric radio wave refractivity. The correlations of the association between signal strength and refractivity when the wind speed and direction were observed to be constant and when wind speed and direction were not considered are −0.62 and −0.43, respectively.

Yekeen and Micheal [48] in Ondo state, Nigeria, probed "signal strength dependence on atmospheric particulates." A series of readings of television broadcast signal strength were carried out in the UHF band (470–862 MHz) using a Yagi array antenna coupled through a 50-ohm feeder to the UNAOHM model EP742A field strength meter, during the dry periods and after a heavy downpour. In addition, dry and wet temperatures, saturated water vapor, and relative humidity measurements were collected from selected open spaces. This series of measurements allowed the duo to study the atmospheric effect before and post-rain, particularly the effect of hydrometeors and particulates on radio signals. They voiced that there is a marked improvement in propagation signal strength corresponding to clear sky conditions. The dependence of refractivity on the physical structure of the atmosphere implies that changing metrological conditions can lead to changes in radio wave propagation.

Bhattacharjea [93] in Georgia, United States of America, studied "the effects of atmospheric refractivity in near-earth UHF channels." They carried out measurements to determine the effects of varying key parameters in the near-ground channel, including atmospheric conditions, ground conditions, and frequency. More so, simulations, modeling, and analysis of UHF propagation in atmospheric refractive structures near the surface of the earth were carried out. The primary practical result obtained from the study is a body of evidence that suggests that UHF propagation over hundreds of meters near the surface of the earth is not significantly affected by near-earth atmospheric refractivity, at least for vertical wire antennas, or any antenna that emits radiation of the same polarization as a vertical wire antenna. In addition, a measurements-based model of the near-ground atmosphere was derived, and the results of modeling the atmosphere were used to predict the performance of an ultrahigh-frequency radio system operating near the ground surface. However, the methods developed do show that atmospheric refractivity is more of a factor at higher frequencies approaching millimeter waves. The developed techniques might find future use in studies involving the 24 GHz or 61 GHz bands, which have both been identified as available industrial, scientific, and medical radio bands by the International Telecommunication Union (ITU).

Alam et al. in 2017 examined "refractivity variations and propagation at ultra-high frequency (UHF)" in Leicester, England. They said to deal with such kinds of effects, many researchers proposed several methodologies. One common method is to use the parameters from meteorology to investigate the effects of variations in refractivity on propagation. These variations are region specific. In this research, they selected a region of one kilometer in height over the English Channel. They constructed different modified refractivity profiles based on the local meteorological data. They recorded more than 48 million received signal strength from communication links of 50-km operating at 2015-MHz in the ultra-high frequency (UHF) band giving path loss between transmitting and receiving stations of the experimental setup. They used the parabolic wave equation method to simulate an hourly value of signal strength and compared the obtained simulated loss to the experimental loss. The analysis was made to compute the Refractivity Distribution of Standard (STD) and International Telecommunication Union (ITU) refractivity profiles for various evaporation ducts. In their conclusive words, "standard refractivity profile is better than the ITU refractivity profiles for the region at 2015-MHz." Furthermore, it was inferred from the analysis of results that 10-m evaporation duct height is dominant among all evaporation duct heights considered in the research. They added that "the best match of the simulated losses along the path by the experimental observation was in the month of August; hence, both simulated and experimental results have identical fluctuations at times and identical smooth behaviors at other times during the month of August."

All the aforementioned studies made a tremendous effort to reach a valid conclusion on the effect of radio refractivity on mobile communication signals. The methodologies adopted were appropriate for the investigations. However, the studies were conducted in single stations and measurements of signal strengths were not restricted to transmission from specific cells but base station(s) comprising different transmitting cells.

## 3. Methodology

The campaign to investigate the effect of radio refractivity on mobile phone communication signal strength was carried out in the following cities: Calabar, Uyo, Portharcourt, Yenagoa, and Warri in southern Nigeria. This southern portion of Nigeria has a tropical monsoon climate, which is classified as "Am" by the Köppen climatic classification. The monsoons, which originate in the "South Atlantic Ocean," are delivered into the country by the "Maritime Tropical (MT) airmass": a warm wet ocean to land seasonal wind that influences the climate. Because of its high humidity and warmth, the MT airmass has a strong inclination to rise and create a lot of rain, which is caused by water vapor condensation in the quickly rising air.

The mobile communication signal strengths of two popular networks in Nigeria, 9Mobile and MTN, were considered. In the 2100 MHz-3 G band, 9Mobile transmits in the downlink spectrum of 2130.00–2140.00 MHz while MTN transmits in the downlink spectrum of 2110.00–2120.00 MHz. Also, 9Mobile transmits in the downlink spectrum of 791–821 MHz in the 800 MHz band and 1805–1880 MHz in the 1800 MHz while MTN transmits in the downlink spectrums of 2620–2690 MHz in the 2600 MHz band; all in the 4 G band (Nigerian Communication Commission [94]).

Using the instrument of a mobile station in each station (location) in some selected cities in southern Nigeria were the signal strengths measured. A cell signal monitor (Version 5.1.1) mobile application installed in an Android (transceiver) device (having two SIM slots) constituted the mobile station. The application has a signal strength data logger which was set at a minute interval. The average signal strength level at the strike of the first fifteen (15) minutes every hour was registered. To achieve high accuracy, there was a restriction in measurements to transmission from specific cells. In all, measurements were taken from eighty eight (80) cells.

Weather parameters for this investigation; atmospheric temperature and pressure, and relative humidity were excerpted online from the Nigeria Meteorological Agency (NIMET) hourly weather report for the various cities where the stations were situated. Hourly measurement of signal strengths was carried out and instantaneously corresponding weather parameters were recorded. The hourly radio refractivity was computed using the 2015 International Telecommunication Union–Radio-communication sector (ITU-R) recommended model (International Telecommunication Union–Radio-communication sector [58]).

The 2015 "International Telecommunication Union-Radio sector (ITU-R) model" for radio refractivity, $N$, is as shown in the following equation [58]:

$$N = 77.6\,\frac{P_d}{T} + 72\,\frac{e}{T} + 3.75 \times 10^5\,\frac{e}{T^2}\ (N - \text{units}). \tag{1}$$

The radio refractivity's dry term, $N_{\text{dry}}$, is given in the following equation:

$$N = 77.6\,\frac{P_d}{T}. \tag{2}$$

Also, as stated in equation (3), the wet term for radio refractivity, $N_{\text{wet}}$, is as follows:

$$72\,\frac{e}{T} + 3.75 \times 10^5\,\frac{e}{T^2}, \tag{3}$$

where $P_d$: dry atmospheric pressure (hPa), $P$: total atmospheric pressure (hPa), $e$: water vapor pressure (hPa), and $T$: absolute temperature (K).

Also, total atmospheric pressure, $P$, is as shown in the following equation:

$$P = P_d + e. \tag{4}$$

Since $P_d = P - e$, equation (4) can be rewritten following the International Telecommunication Union–Radio-communication sector (ITU-R) [58]:

$$N = 77.6\,\frac{P}{T} - 5.6\,\frac{e}{T} + 3.75 \times 10^5\,\frac{e}{T^2}\ (N - \text{units}). \tag{5}$$

Equation (5) may be approximated with reduced accuracy as shown in the following equation:

$$N = \frac{77.6}{T}\left[P + 4810\,\frac{e}{T}\right]. \tag{6}$$

For the temperature range of −50°C to +40°C, $N$ values generated from equation (6) are within 0.02 percent of the value derived from equation (1).

The link between water vapor pressure, $e$, and relative humidity, $H$, is seen in the following equation:

$$e = \frac{H.e_s}{100}, \tag{7}$$

where $e_s$ is deduced from the following equation:

$$e_s = \text{EF}.a.\exp\left[\frac{(b\ - t/d).t}{t + c}\right]. \tag{8}$$

Also, EF for ice and water can be evaluated using equations (9) and (10), respectively.

$$\text{EF}_{\text{ice}} = 1 + 10^{-4}\left[2.2 + P.\left(0.00382 + 6.4 * 10^{-7} * t^2\right)\right], \tag{9}$$

$$\text{EF}_{\text{water}} = 1 + 10^{-4}\left[7.2 + P.\left(0.00320 + 5.9 * 10^{-7} * t^2\right)\right], \tag{10}$$

where $e_s$ is saturation vapor pressure (hPa) at the temperature, $t$ (°C) $H$ is relative humidity (%), $p$ is pressure (hPa), and $t$ is temperature (°C).

For water, valid between −40°C and +50°C, the coefficients $a, b, c$, and $d$ are $a = 6.1121$; $b = 18.678$; $c = 275.14$; and $d = 234.50$.

For ice, valid between −80°C and 0°C, the coefficients $a$, $b$, $c$, and $d$ are $a = 6.1115$; $b = 23.03$; $c = 279.82$; and $d = 333.70$.

The vapor pressure, $e$, is computed from the water vapor density, $\rho$, using the following equation:

$$e = \frac{\rho T}{216.7}\ \text{hPa}, \tag{11}$$

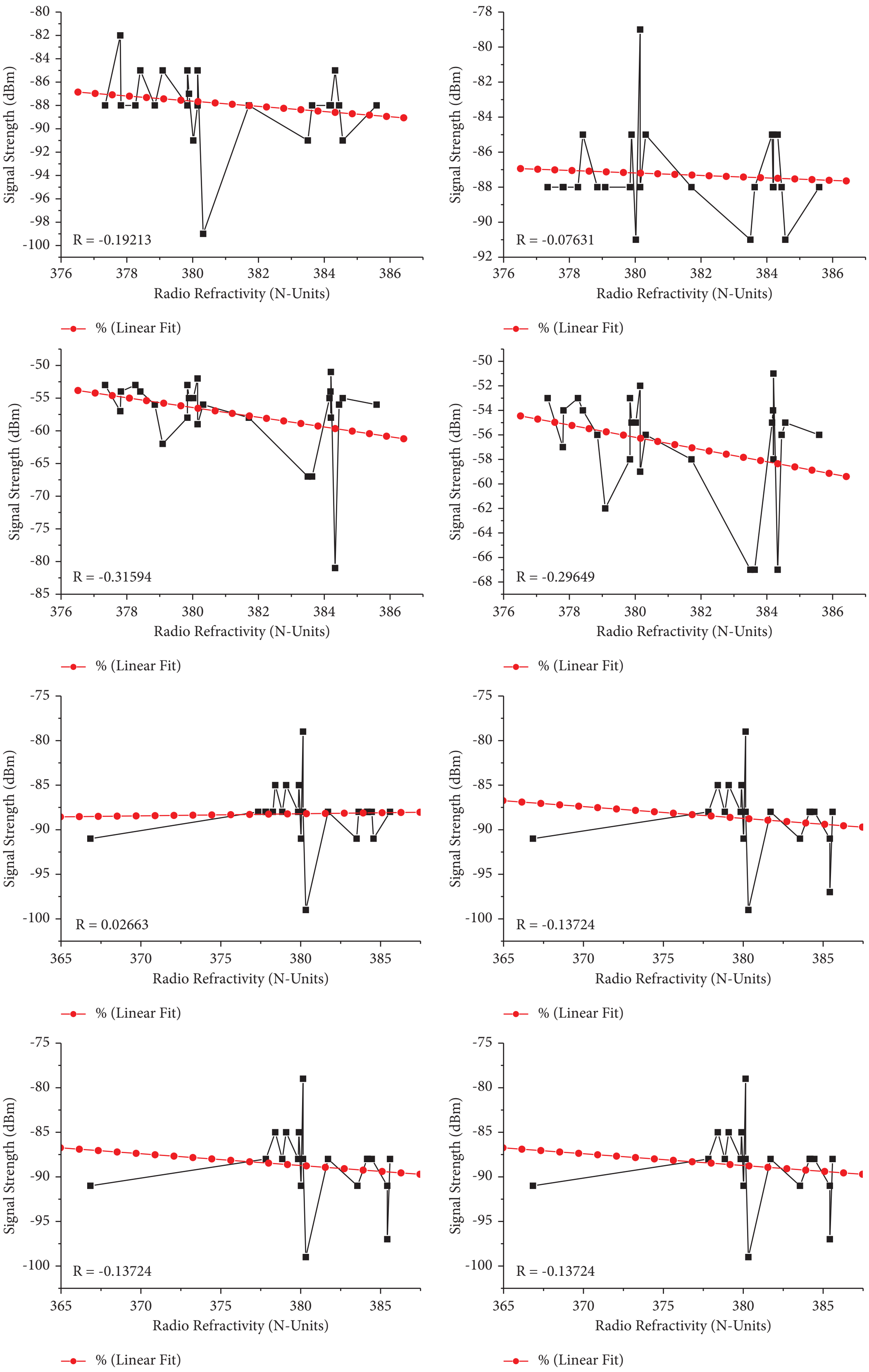
where $\rho$ is given in $g/m^3$.

## 4. Results and Discussion

From the linear graphs (Figures 1–5) between received signal strength and radio refractivity, for the eighty (80) cells considered, out of all, 38 cells showed that the correlation between received signal strength and radio refractivity is negative while 42 cells were contrary. The correlation between received signal strength and radio refractivity ranged between −0.48748 and 0.68129.

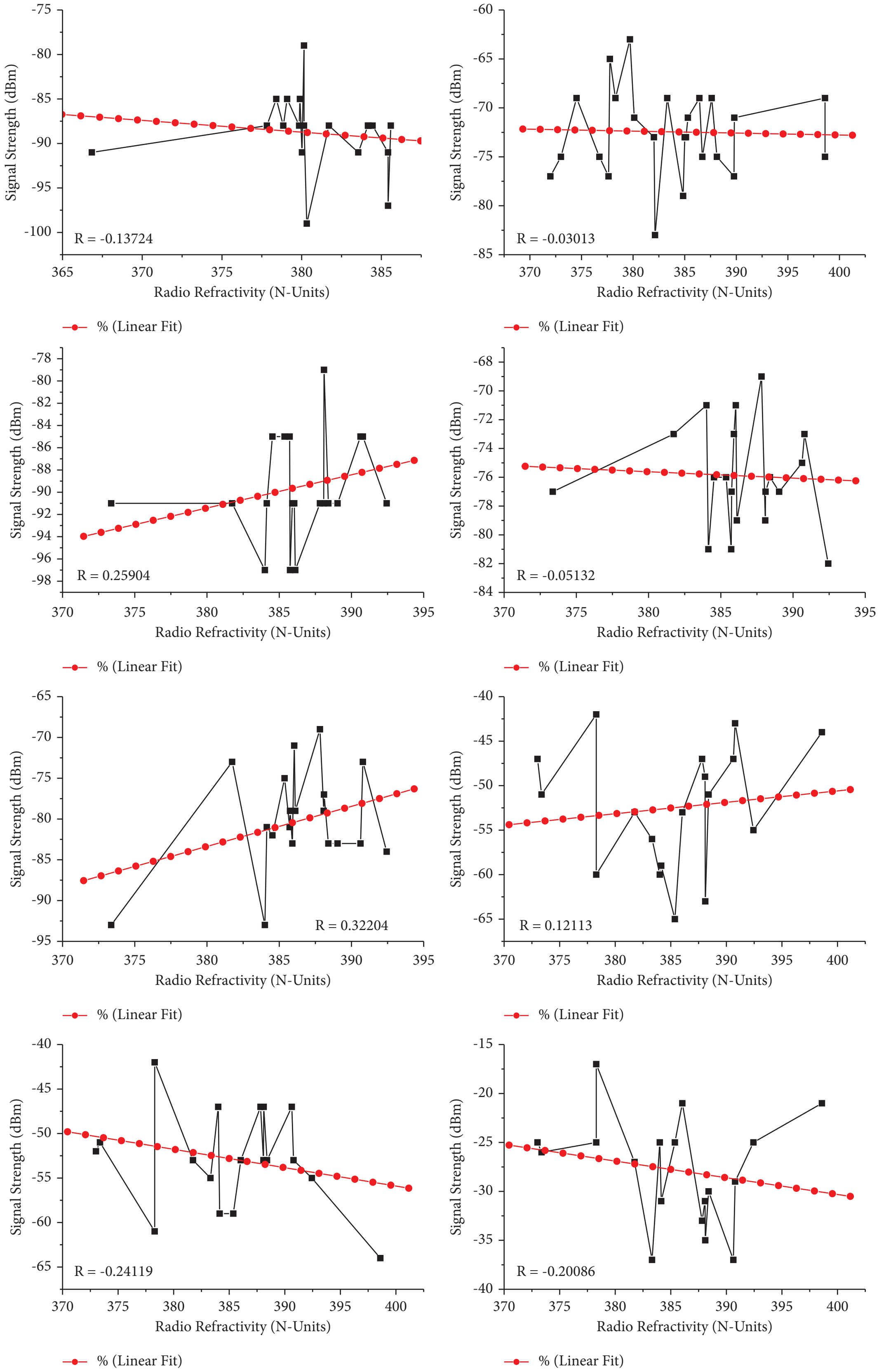
Table 1 shows the summary of results, that is, the average R value in each location, average standard deviation of R value in each location, overall average R value and overall average standard deviation of $R$ values.

Overall, there was no established linear relationship between signal strength and radio refractivity since the overall average $R$ value is 0.0123691 and the overall average standard deviation of $R$ values is 0.1112165. In the comparison of findings with similar works, Usman et al. [89] said that overall, the variation in refractivity gradient with signal strength does not explain the temporal variations in the received signal strength, since the correlation between the variables is as low as 0.091. Their conclusion converges with the findings from this study. Divergently, Osahenvemwen and Omatahunde [88] observed that the refractivity gradient had a 0.42 positive correlation with GSM signal strength. Ali et al. [87] discovered that there exists a relationship between refractivity and propagation of GSM radio signal with a correlation coefficient of −0.98 that infers the opposite relation; in other words, refractivity mitigates signal strength and generally signal quality. This is, the greater the refractivity the lower the signal strength and generally signal quality and vice versa. Adisa [90] said that each atmospheric parameter has a role to play in radio refractivity with humidity as the most dominant or influential factor than any other. In addition, surface refractivity is also influenced by latitudinal and seasonal



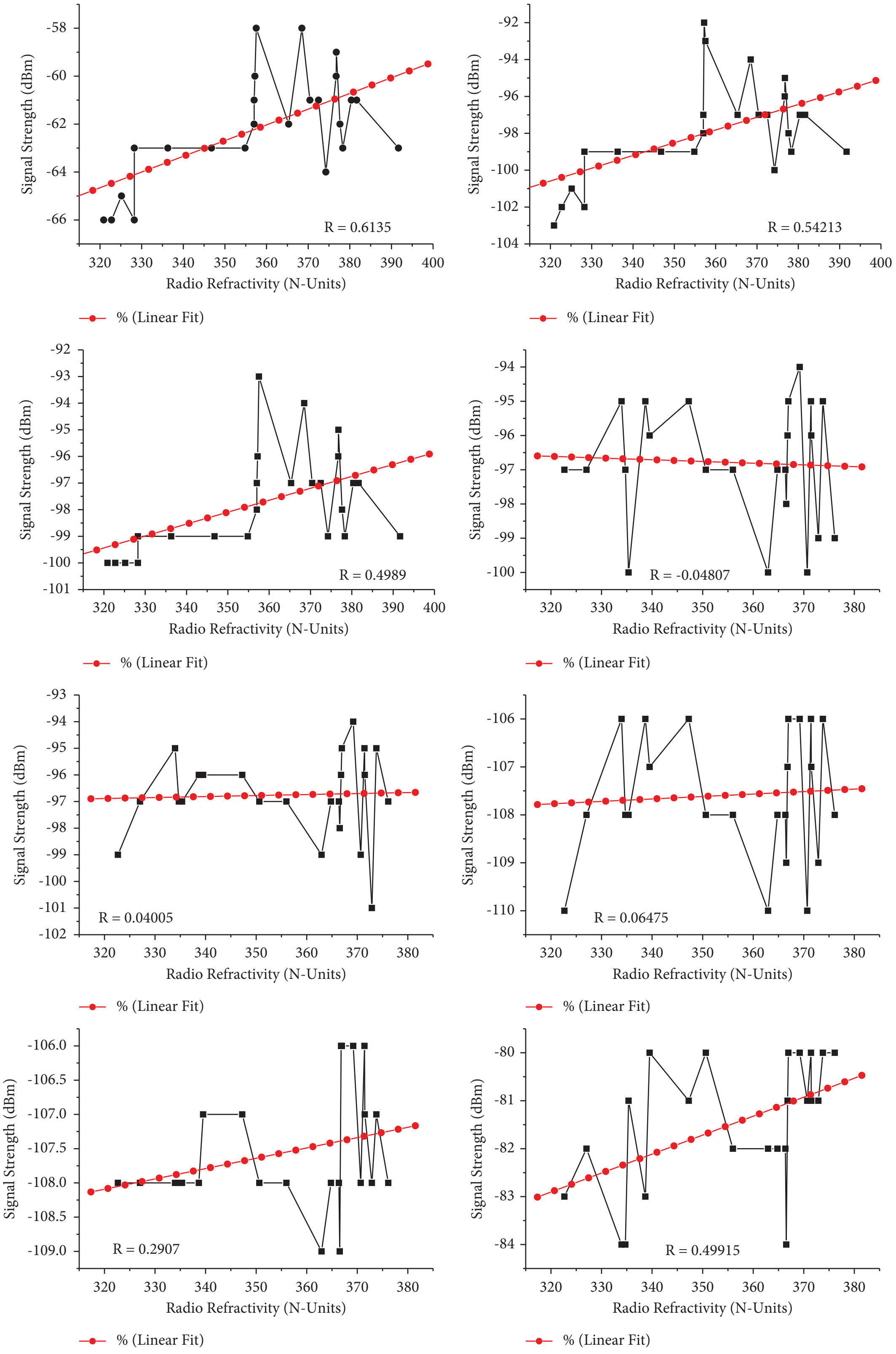
(a)

Figure 1: Continued.



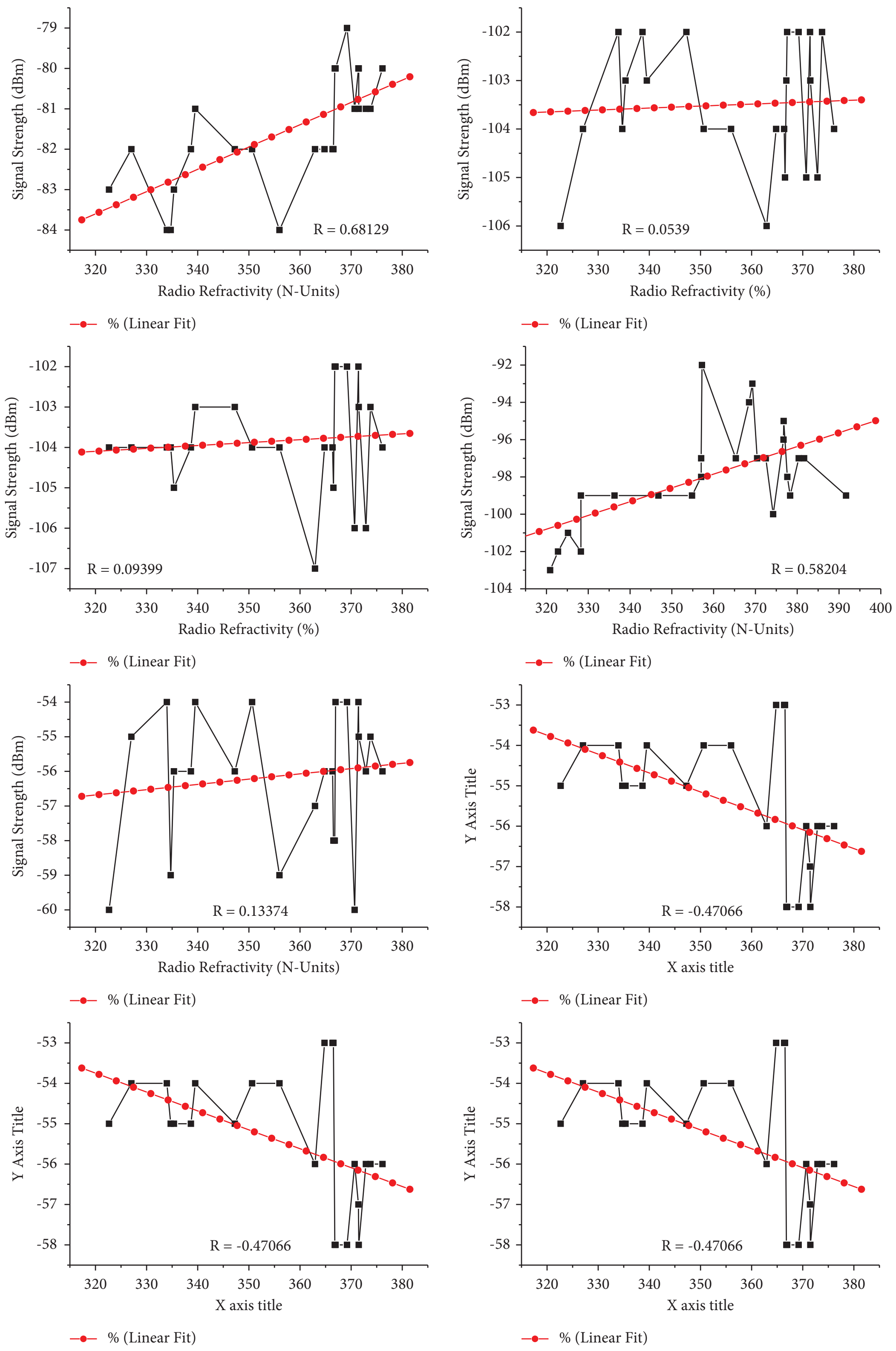
(b)

Figure 1: Signal strength vs. radio refractivity from some selected cells in Calabar.



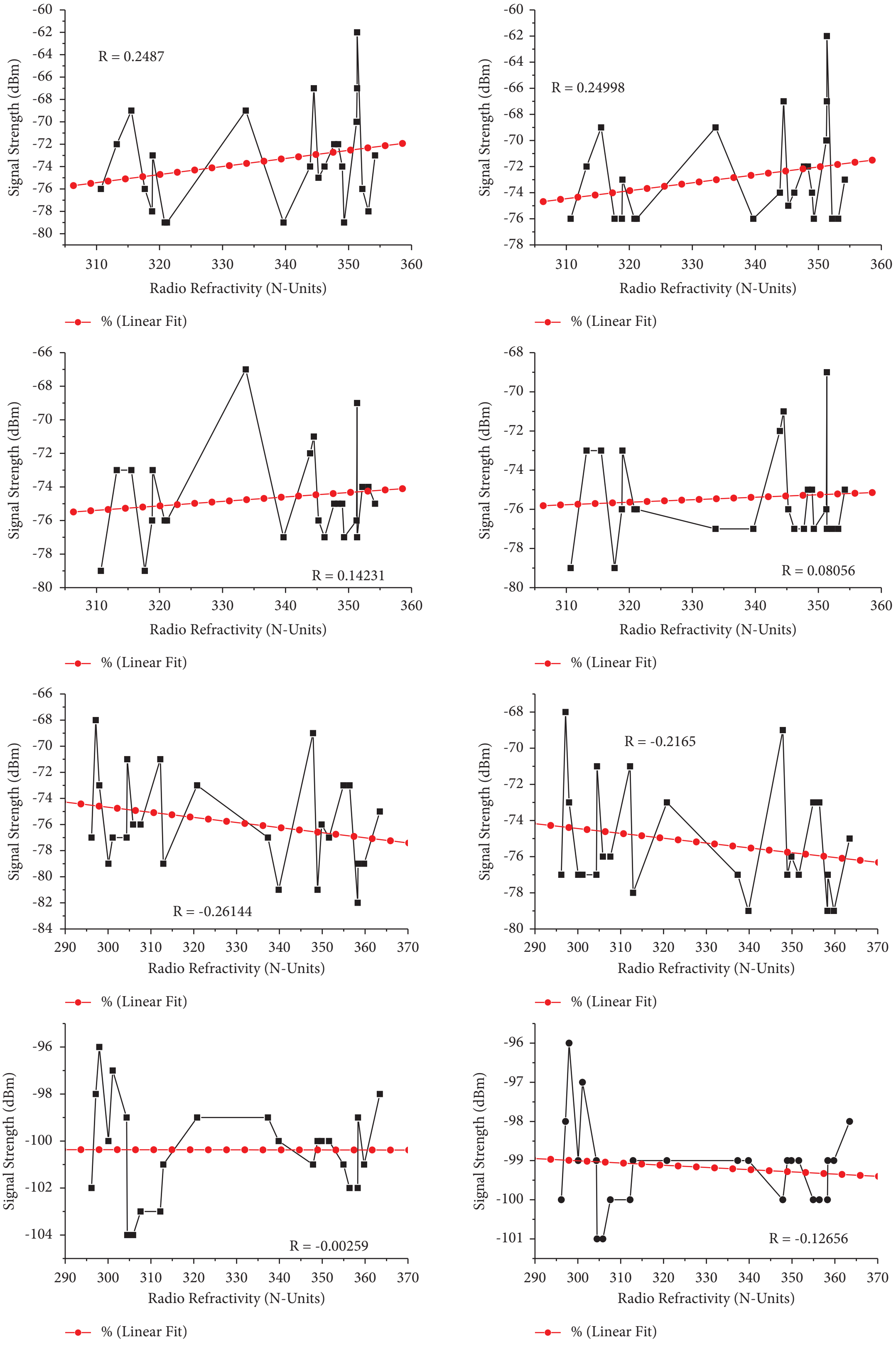
(a)

Figure 2: Continued.



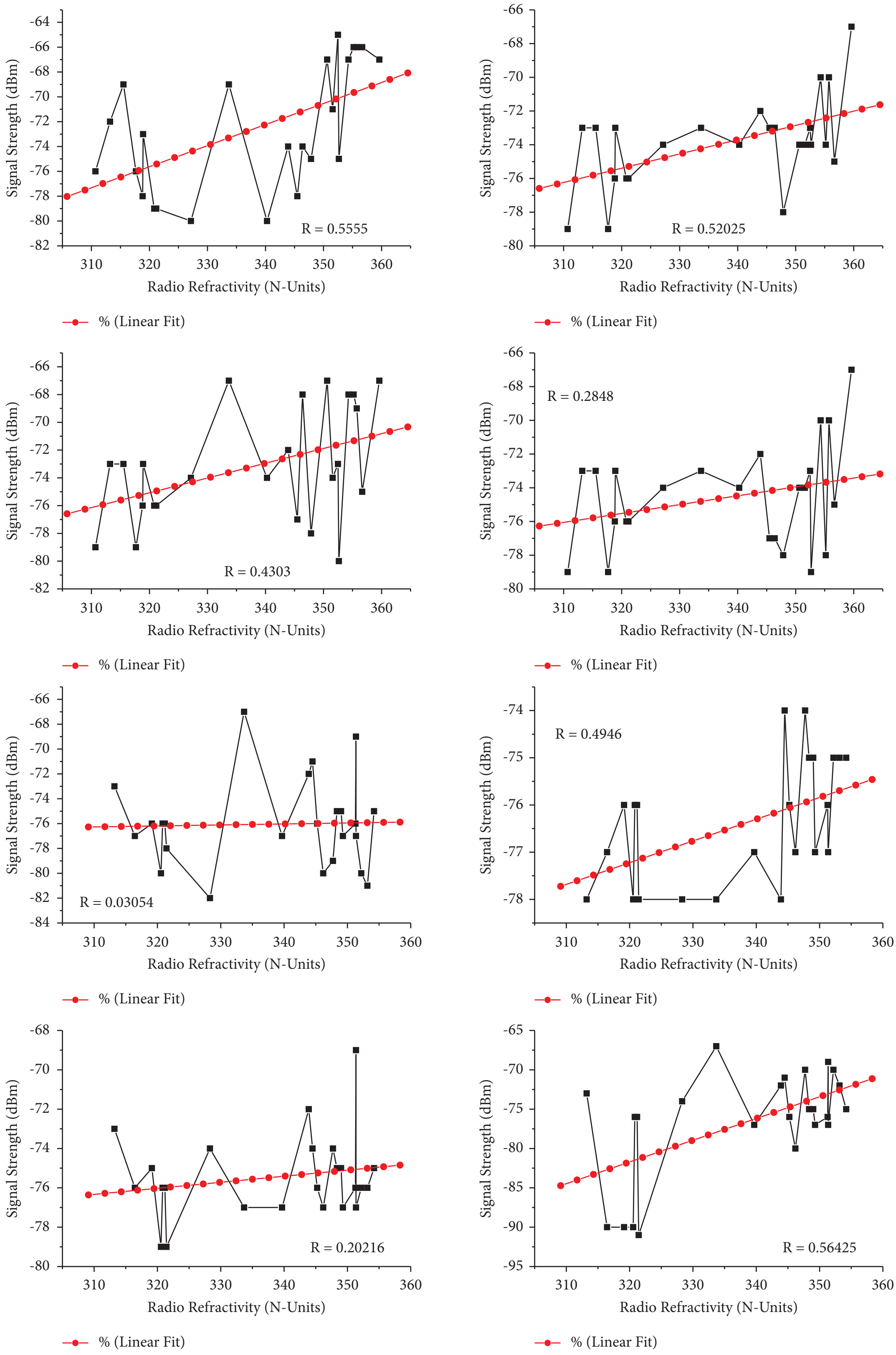
(b)

Figure 2: Signal strength vs. radio refractivity from some selected cells in Uyo.



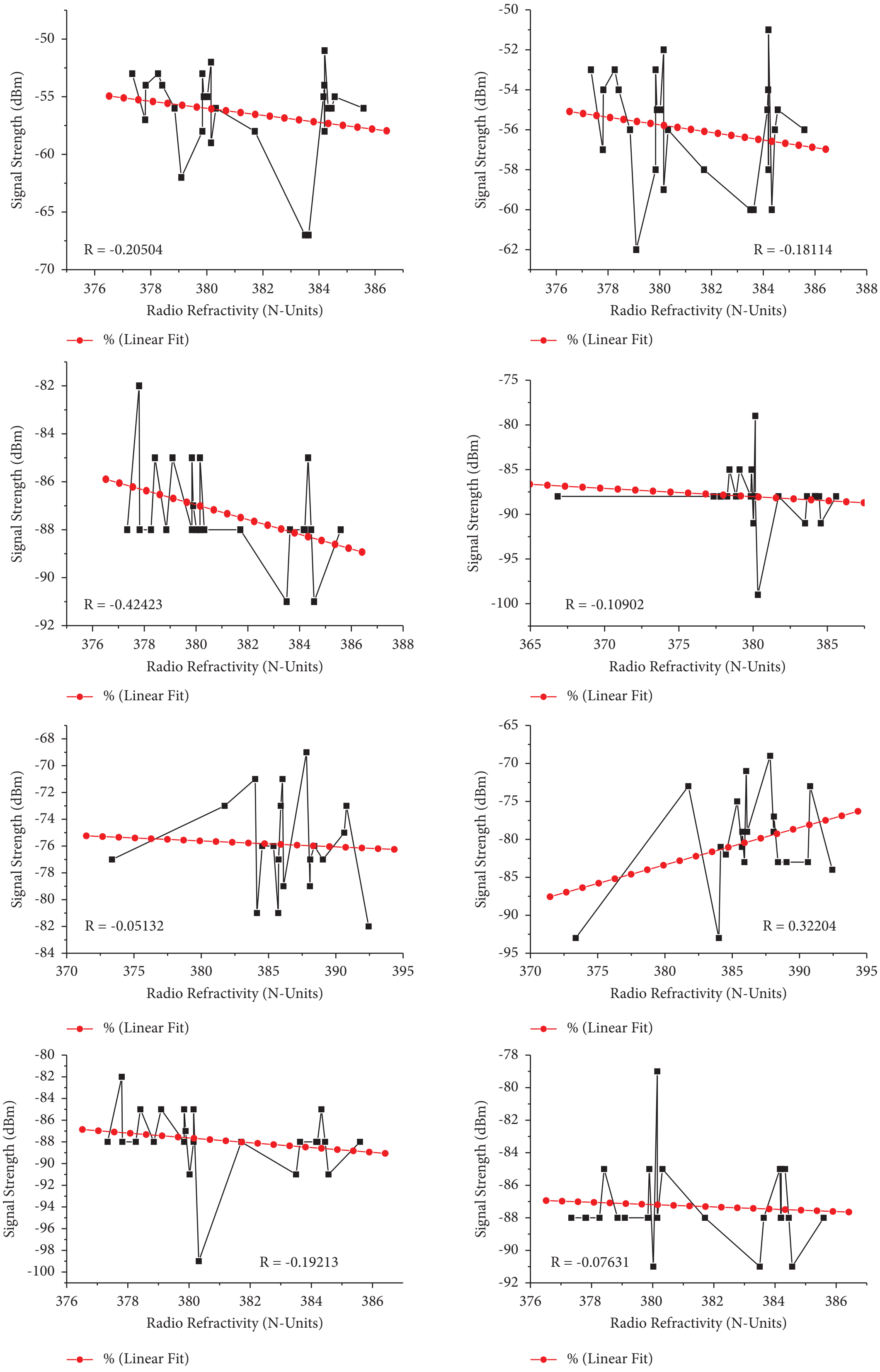
(a)

Figure 3: Continued.



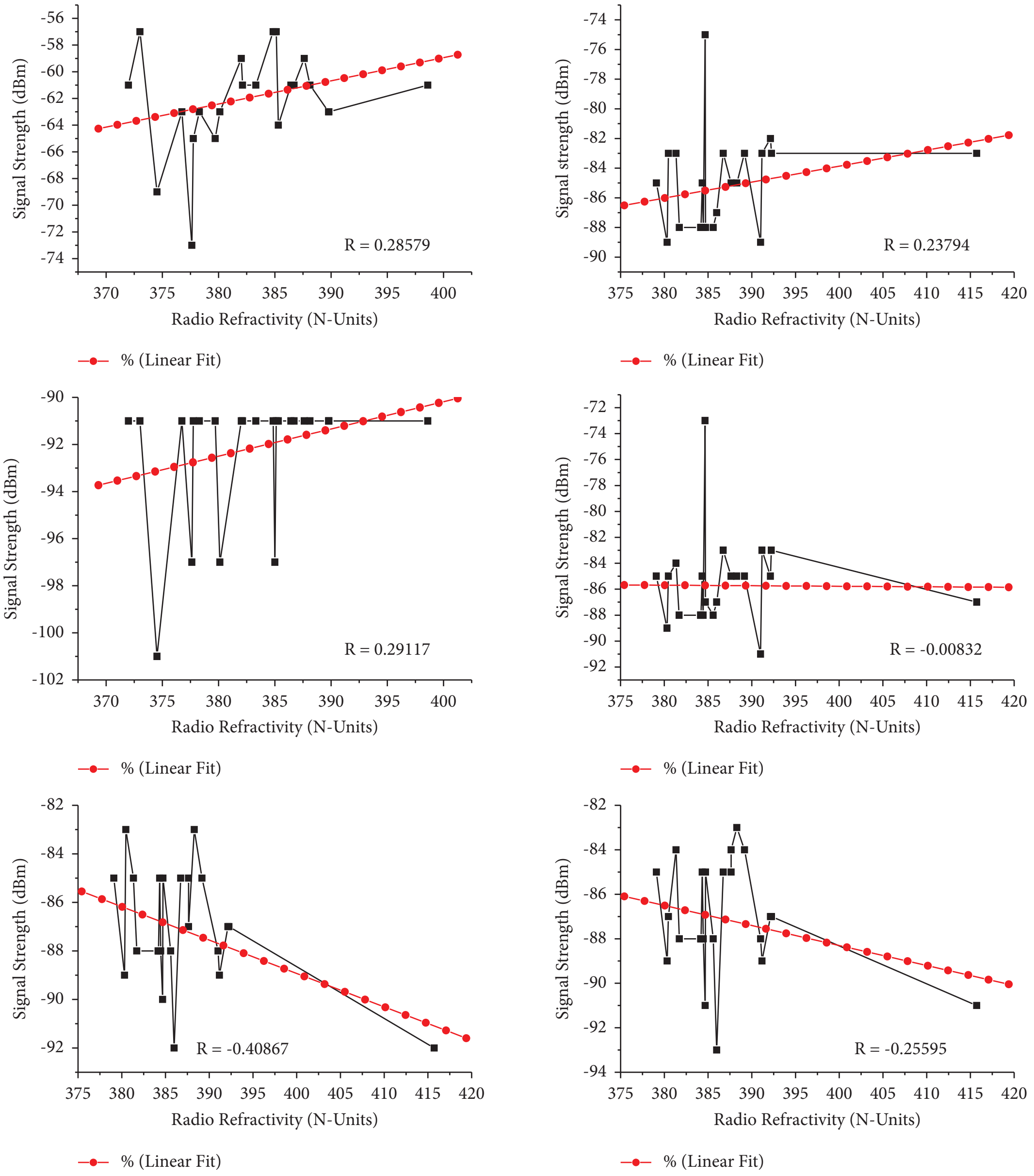
(b)

Figure 3: Signal strength vs. radio refractivity from some selected cells in Portharcourt.



(a)

Figure 4: Continued.

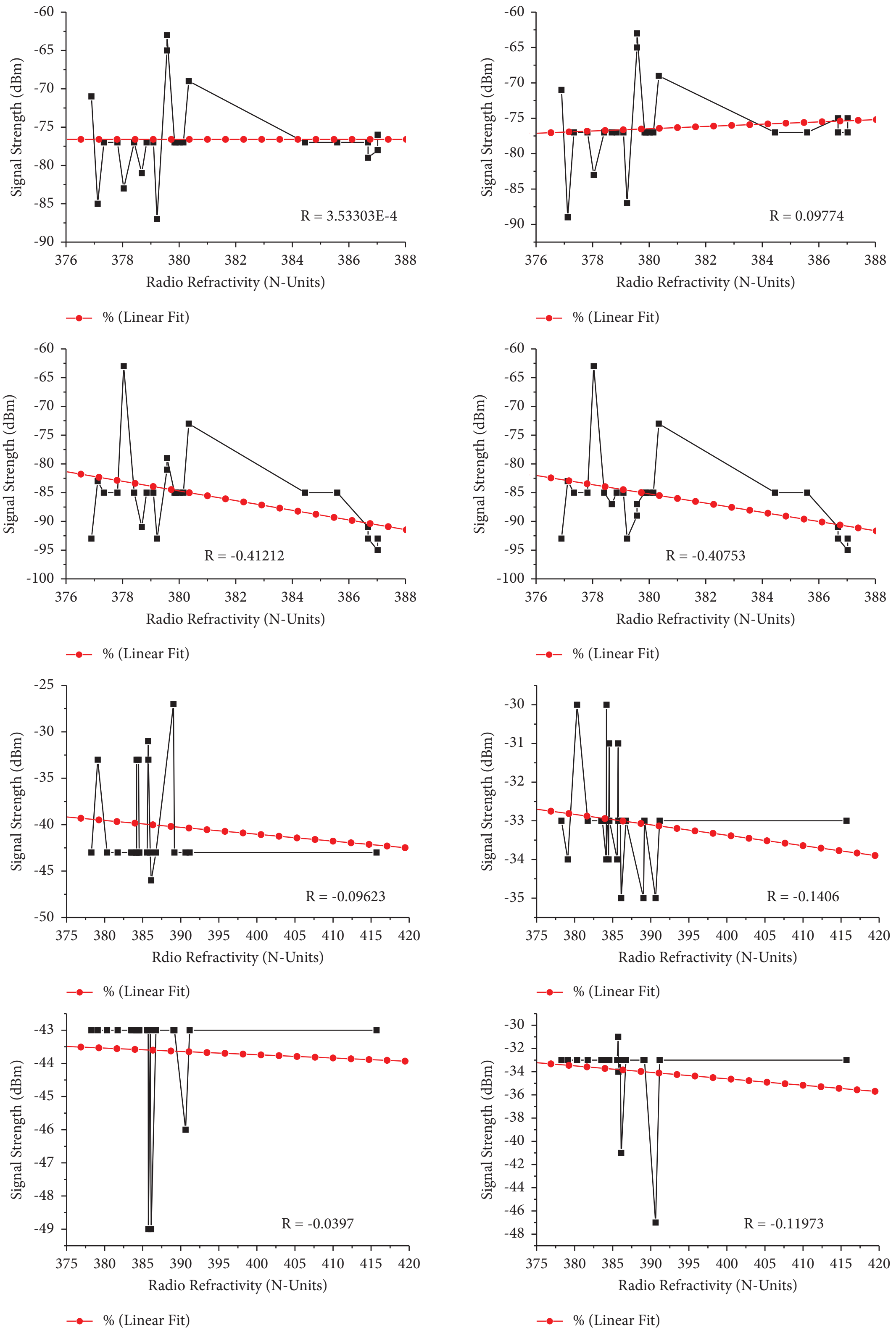


(b)

Figure 4: Signal strength vs. radio refractivity in from some selected cells in Warri.

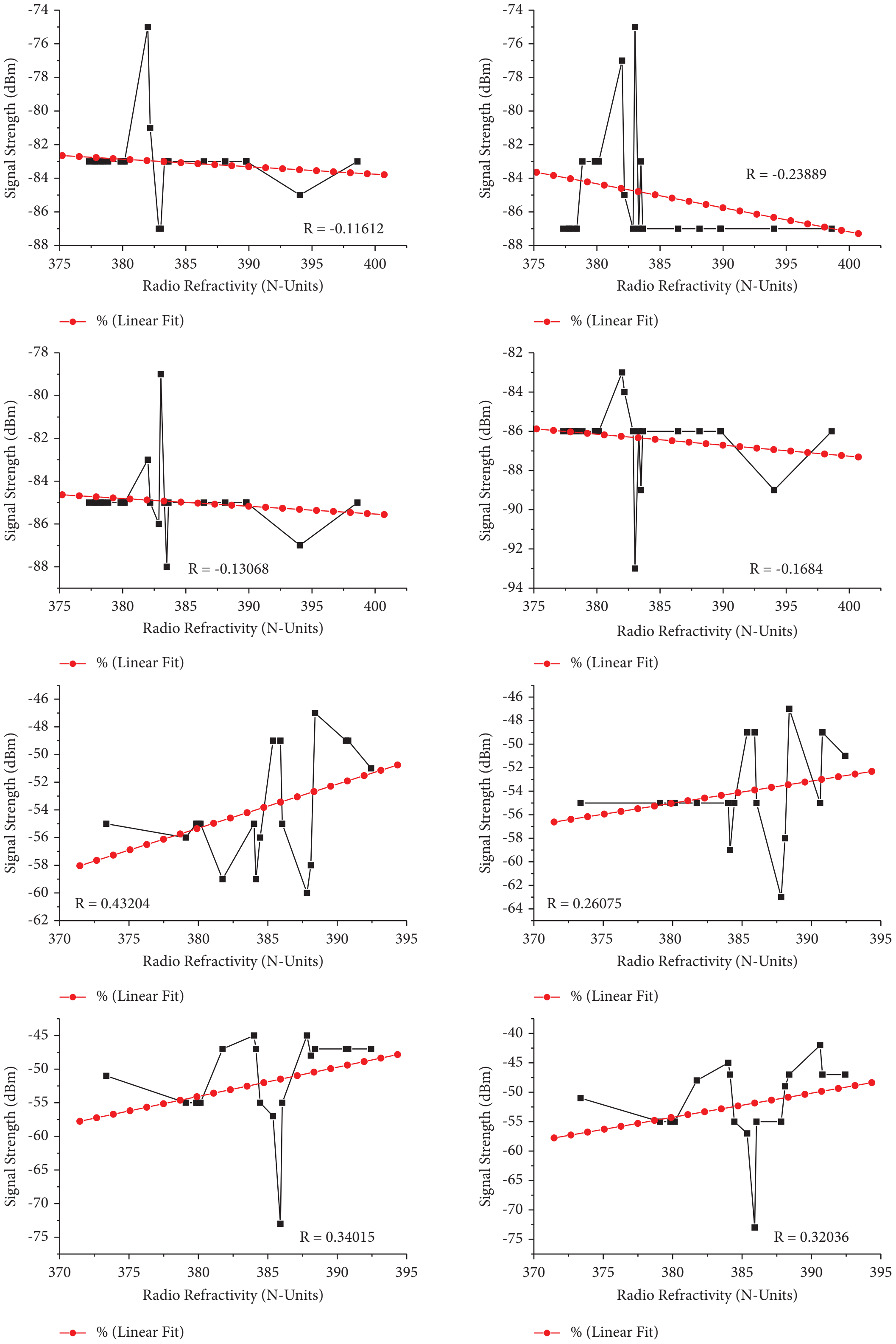
variations. He concluded that generally, radio refractivity and broadcast signal (UHF) are inversely related with correlation factors of −0.81 and −0.97 for day and night, respectively. Famoriji and Oyeleye [92] reported that the statistical correlation of −0.97 between signal strength and UHF broadcast signal reveals that at different points when refractivity was high (mostly at night and morning with high humidity) the UHF broadcast signal strength was low and at points when the refractivity was low (mostly during the day when the humidity is low and the temperature is high) the signal strength was higher. Therefore, the higher the refractivity the lesser the signal strength at the point of observation in the troposphere, that is, they are inversely proportional to each other.

The inconsistencies in the linear relationships from the graphs in Figures 1–5 could be due to topological differences between the locations of the base and mobile stations where measurements were taken since the communication between the base station transmitter and the mobile station receiver is majorly point-to-point or line-of-sight. This is in agreement with the work of Dalip and Kumar [95]. They said at higher height levels, GSM receivers provide better signal strength because at higher heights fewer obstacles interfere. In locations or stations of lowland with the base station on a higher plane or highland; radio refractivity and signals strength showed a positive correlation. In other words, an increase in radio refractivity enhanced signal strength to some extent. However, in locations situated on a higher



(a)

Figure 5: Continued.



(b)

Figure 5: Signal strength vs. radio refractivity in from some selected cells in Yenagoa.

Table 1: Summary of results.

| Location | Average $R$ value | Average standard deviation of $R$ values | Overall average $R$ value | Overall average standard deviation of $R$ values |
|---|---|---|---|---|
| Calabar | −0.0396523 | 0.2363366 | 0.0123691 | 0.1112165 |
| Uyo | 0.2573125 | 0.2609118 | | |
| Portharcourt | 0.2054338 | 0.2533071 | | |
| Yenagoa | −0.0198363 | 0.2626848 | | |
| Warri | −0.0261629 | 0.2460226 | | |

plane or highland with the base stations on a lowland or lower plane, radio refractivity was detrimental to some degree to the signal strength.

By and large, wind speed and direction not being considered in this research could also have influenced inconsistencies in the linear relationships from the graphs in Figures 1–5, since water vapor (the major substance) in the atmosphere that contributes to the variation in the density of the vertical layers of the atmospheric channel can be transported and concentrated or deconcentrated in any region of the atmosphere at a specific place and time and could influence radio refraction and invariably signal strength. More so, radio waves double as particles; hence, the direction of these particles could still be influenced by the wind since the received signal strength by an antenna is proportional to the amount of the particles that fall on it. To buttress the before-mentioned claim, Chima et al. [66] observed in their research that wind may not have a direct effect on propagating signal but it has an effect on the refracting (bending) capability of the wave, thus a slight variation in the wind can cause a considerable effect on the received signal strength. Meng et al. [69] experimentally showed that wind and rain can impose an additional attenuation on signal propagating within an environment. This additional attenuation increases as the strength of the wind and rain and frequency increase. More so, they observed that there is a large power of variation and deep fades in received signal as the strength of the wind and the intensity of the rain increase. Syed Zafar et al. [70] said that strong wind speed and rain could contribute to the attenuation of radio signals. In their analysis, results showed that between the wet and dry seasons, the former season showed a significantly stronger negative correlation between received signal strength and wind speed. Syed Zafar et al. [70] in a further analysis suggested that a fresh breeze had brought high rainwater due to the high rain rate and caused the absorption and scattering of radio signals which increased the attenuation of received signal strength. However, they forwarded that wind speed without rain and a decrease in humidity during the dry season were found to increase the received signal strength. More so, they said, refraction of radio waves was found not to have a negative impact on the signal strength in the dry season but increased received signal strength. Joseph and Oku [67] hypothesized that at uniform atmospheric temperature, relative humidity, and atmospheric pressure, the wind has a marked effect on radio signal strength. They said the signal received is better if the wind propagates in a similar path as the radio waves but is worse on the contrary direction.

Also, at UHF, radio propagation tends to be more of the line of sight, however not all the time [96, 97]. Hence, position away from the transmitter and antenna height may have also been responsible for the inconsistencies in the linear relationships from the graphs in Figures 1–5. This is owed to the fact that in a terrestrial environment, signals undergo multiple reflections and as such reach the receiver through several different paths. The received signal may superpose constructively or destructively depending on the relative phases of the signal. If the receiver is moved, the situation changes, and the overall received signal is found to vary with position. Receivers of mobile communication devices are subject to this kind of effect termed Rayleigh fading. Also, the height of the antenna affects the received signal strength. An increase in the height of an antenna betters the received signal strength; however, it is dependent upon the plane between the receiver and transmitter. In general, the positioning of an antenna system higher in the sky enhances communication capabilities and reduces the chances of RF exposure and electromagnetic interference. This corroborates the finding from Anyasi and Uzairue [98]. The duo submitted that the location of a mobile station affects received signal strength in addition to antenna factors or properties.

More so, the directivity or radiation pattern of the antenna could also have influenced the inconsistencies in the linear relationships from the graphs in Figures 1–5. This is because not all the antennas are omnidirectional, some are directional (e.g., unidirectional and bidirectional), depending on the intention of the transmission [96, 97]. Thus, the position of the mobile station may affect the strength of the signal received.

Seasonal weather changes could also have been responsible for the inconsistencies in the linear relationships from the graphs in Figures 1–5, since the research was conducted throughout the year. In some locations (Calabar and Bayelsa), the research was conducted predominantly in the wet season, while in some other locations (Uyo, Portharcourt, and Warri), it was during the dry and wet seasons. The refractivity in this region of the study is usually high during the wet season but slightly lower during the dry season. This is owed to the fact that the entire region is a tropical monsoon climate with a very narrow range of temperature and relative humidity between the wet and dry seasons. In another word, the refractivity of this region is near constant throughout the year and it is highly dependent on the humidity during the rainy season and on atmospheric temperature during the dry season. The effect of atmospheric pressure is almost insignificant since the range of average atmospheric pressure throughout the year is inconsiderable. Oku et al. [99] said the average radio refractivity of Calabar for the rainy season is higher than that of the dry season for a better part of the year; however, there are overlapping points in the radio refractivity profile of the two seasons. They said this is an indication that the climatic condition of Calabar contributes to just a slight variation in seasonal refractivity as compared to studies in other regions of the country with a clear difference between the rainy and dry season refractivity. Also, Edet et al. [100] said that there is very little variation in the seasonal radio refractivity for both seasons in Calabar. Bawa et al. [101] in a study on radio refractivity of Lagos state, Nigeria (a tropical monsoon climate as well) put forward that refractivity result reveals seasonal variations with high values in the rainy season and low values in the dry season over the location and the seasonal variation of refractivity of the troposphere is a function of climatic condition.

## 5. Conclusion

Overall, there was no established linear relationship between signal strength and radio refractivity, since the overall average $R$ value is 0.0123691 and the overall average standard deviation of $R$ values is 0.1112165. The inconsistencies in the linear relationships obtained from different locations and cells could be due to variations in topography, antenna properties, seasonal variations, wind, and position and distance of the receiver from the transmitter.

## 6. Recommendations

Findings from this research will enable engineers and scientists in the radio world (most especially, radio transmission through the atmosphere); to compensate for refractivity or refraction loss in the atmosphere during link budgeting, for effective implementation of mobile phone communication systems, minimize interference due to overbudgeting in the reuse of frequency owing to limitations in communication band [102–105]. Thus, results from this study may be used to develop effective link margins and budget for the study area rather than using margins developed from the data of other regions.

Furthermore, the information from this research will provide meaningful and useful information that could help enhance optimal signal power control to enable the transmission of the needed power to support a given data rate or sustain a call in a mobile communication link. This is because, if the power transmitted is too high, it causes unnecessary interference, but if the power is low, it increases the error rate which causes the call to drop or requires retransmission–which invariably causes large transmission delays and lower throughputs [106–109].

Future research and measurements from refractometers should be compared with that of the refractivity from the ITU model. Also, the topography of the study location should be put into account to ascertain its effect on the radio signal. More so, future studies could be carried out on the effect of atmospheric parameters on the signal strength at different frequencies or bands, and wind effects should be incorporated into the refractivity model.

## Data Availability

The data used to support the study are available from the corresponding author upon request.

## Additional Points

*Highlights*. (i) To achieve high accuracy, there was a restriction in measurements to transmission from specific cells. (ii) The overall average $R$ value between signal strength against radio refractivity in the stations across the study is 0.0123691 with an overall average standard deviation of $R$ values of 0.1112165. (iii) Overall, the results indicate that there was no established linear relationship between signal strength and radio refractivity.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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