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Rain Attenuation Mitigation using Frequency Diversity Improvement for Lagos at 15-45 GHz

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Received: September 14, 2024 Accepted: November 28, 2024

Abstract: Rain fade at microwave radio frequencies by atmospheric occurrences is predominant at frequencies above 11GHz, especially in tropical regions like Nigeria characterized by high rainfalls. In this study, a comprehensive analysis of rain fade for Ikeja, Lagos in Nigeria was carried out. Monthly rainfall data were acquired from the Nigerian Meteorological Agency (NIMET) and analyzed to extract rainfall rates for different percentage of time exceedances. ITU-R rain attenuation prediction model was adopted to compare the performance of the existing proposed Frequency Diversity Improvement Factor (FDIF) and rain attenuation values for different frequencies ranging between 15-45GHz using MATLAB. The predicted data obtained were carefully examined to arrive at a prediction for the calculated improvement factor. The fade depth was examined for different improvement factors at 5 GHz apart, and the results showed that this frequency diversity improvement technique is more effective at higher frequencies (at 25 to 45GHz), as desired. Frequency diversity technique is effective for reducing the effect of rain fade at higher frequencies by switching from a high frequency to a lower frequency in order to circumvent attenuation; hence, ensuring better designed terrestrial and earth-space communication systems, improving link availability and quality of service during rain occurrence.

Keywords: Communication links, fade depth, Frequency Diversity Improvement Factor (FDIF), Rain fade, Tropical regions.

Introduction

In the transmission of any signal from source to destination in a satellite system, the quality or authenticity of services to be provided by the source to the destination is a major factor to be considered. In an attempt to transmit any signal (either voice or data) to a particular destination, some fundamental constraints such as cost, time and labor, atmospheric influences (wind, rain, hail, etc.) and the required technology needed in order to realize a quality satellite system must be considered. For atmospheric influences, attenuation is a common occurrence or consequence of transmitting signals over long distances. It denotes any decline in the strength of a payload or signal during transmission. Rain fade can affect any type of signal either digital or analog depending on what type is used for transmission. Rain attenuation is the decadence of the power level of a signal as a result of rain rate which also results towards a reduction in the quality of the system. It is a critical problem of microwave link and telecommunication design employed in tropical stations like Nigeria, where the intensity of rain is extensively high (Asen and Tjelta, 2003; Burszta-Adamiak et al.,2023). When it comes to the transmission of any signal, consideration is mostly centered around the wide spread of waves in the microwave link via mm-wave spectrum of frequency (0.3-300 GHz) and since they lie within the various high bands such as UHF (0.3-3 GHz), SHF (3-30 GHz), and EHF (30-300 GHz) bands, any of these bands may be utilized for transmission (Crane, 2003).

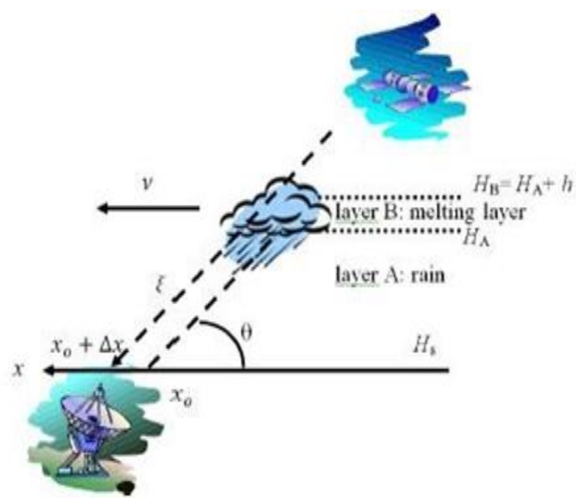


Figure 1: Schematic for Slant Path Rain Structure for SST (Yussuff, 2016)

Electromagnetic waves re degraded due to fade between the Satellite-Earth stations mostly in the presence of slight droplets of clouds and rain drops as the attenuation of rain occurs by virtue of the absorption of a radio frequency by either rain or ice (snow) which is most exclusively common at frequencies ranging beyond 10 GHz (Dahman et al., 2018). Basically, in addressing the issue of capacity in satellite communication, the primary step to consider is the multi-beam spectrum with a higher amount of beams which permits a considerably large amount of the re-use of frequency, and in an attempt to adjust the capacity to be able to accommodate higher payloads, the next step will be to employ frequency bands that are higher such as Ka, EHF or Q/V bands which ranges between (20-30), (20-45), or (40-50) GHz respectively, where 1, 2 and 3 GHz can be allotted to the appropriate Satellite System (Castanet et al., 2003). The link affected by rain occurs as a result of rain, temperature, angle of elevation, intensity of rain, angle of polarization, rain drop size distribution (DSD) and frequency. The variability that results from the rain DSD alone (all other parameters being fixed) spans between 5-33% standard deviation (SD) around the mean (Yussuff and Khamis, 2014; Vidyarthi et al., 2012). The dispersal of rain that drops in the path of any radio propagation could be inhomogeneous as weighty drops of rain are frequently restrained to a lesser space when compared to lighter rain, and the rain area, or rain cells, may take on any shape (Asen and Tjelta, 2003). Microwave link's fading is defined as the change in relative phase, intensity (or both) of any frequency component of an incoming radio signal as a result of the changes of the propagation path with time (Freeman, 1997). Rain attenuation being measured at all terminal points on ground in an operational network is not practicable and so, the only effective way by which one can achieve or realize a better estimation of expected attenuation is through the use of modeling and prediction methods (Shrestha and Choi, 2017; Mardani et al.,2024). Due to a high level of congestion and limited bandwidth in the C and Ku bands and the fact that this are the most frequently used bands in satellite communication, the satellite communication society has transited to millimeter-wave band (30/20 GHz). This switching has its advantage as well as disadvantages. The advantages are less congestion, large bandwidth which causes adequate allowance of transmission in the communication link and makes the reuse of frequency possible thereby increasing the capacity of a communication system in terms of data rate and throughput; with these benefits, the frequencies of millimeter waves (where most signal experience fading) encounter some limitations (Jassal, 2011; Bohren and Huffman, 2012). This limitation arises due to the influence of rain particles, either through scattering or absorption of the electromagnetic signal that descends along the propagation path (Mukesh et al., 2014). Attenuation of signals as a result of rain fade is intense especially in areas with high rain rate where convective rainfall is prevalent. In order to mitigate this shortfall, various ain fade mitigation techniques (FMT) is being employed in achieving a stable efficient transmission of signal along the path of propagation.

Diversity protection scheme, Effective Isotopic Radiated Power (EIRP) control methods, and Adaptive transmission strategies are three categories of mitigation techniques (Athanasios et al., 2004; Jiang et al, 2024). uplink power control (ULPC), downlink power control (DLPC), end-to-end power control (EEPC), and on-board or spot beam shading are subsets of the EIRP control technology. UPLC aims at matching the conveying earth station's output power with uplink losses. EEPC aims at matching a transmitting Earth station's output power with either uplink or downlink impairments (Patra and Sil, 2017). DLPC comes into realization by raising the satellite's transmit power. In contrast to ULPC, DLPC is incredibly difficult to implement as a result of the limitations encountered due to the size and weight of the satellite and the restricted capacity of regulating the satellite operation (Athanasios et al., 2004). On-board or spot beam shading seeks to correct for rain attenuation on spot beams where rain is anticipated to occur by radiating more power. It implements the use of active antennas allowing the spot beam strengths to be adjusted in response to propagation conditions (Patra and Sil, 2017). When the link quality of a satellite network depletes, adaptive waveform is used to change how signals are sent by nodes. However, this idea can be broken down into three different processes: adaptive modulation (AM), adaptive coding (AC), and data rate reduction (DRR). Diversity aims at re-routing information in the network to avoid network disruptions caused by an atmospheric agitation. Site diversity (SD), frequency diversity (FD) and orbital diversity (OD) are the three basic mechanisms that make up diversity technique. FD is a concept of switching payloads between two (higher and lower) frequency bands that are available on board (di Toma et al, 2024; Graf et al., 2024). In this technique, when there is a fade occurring at the higher frequency, the links are re-directed utilizing a lower frequency band signal that is less affected by atmospheric propagation issues (Athanasios et al., 2004; Patra and Sil, 2017; Jiang and Schotten, 2023). Several authors have conducted studies on rain attenuation using different approaches. FD technique, though less common, have shown potential for achieving efficient and reliable satellite communication links. Yussuff (2016) investigated earth-space rain attenuation models for tropical regions, concluding that empirical models, based on real-time measurements and simplified assumptions, were the most effective. Similarly, Patra and Sil (2017) developed a frequency diversity improvement factor (FDIF) prediction model for mitigating rain fade from 50–90 GHz, investigating a 10 GHz frequency separation. In tropical climates, this model was found to be particularly valuable for reliable microwave communication. Islam et al. (2016) extended this approach by developing an FDIF prediction model for rain fade mitigation between 5–40 GHz. With FD, a higher frequency band carries most of the traffic, while a lower band is used during periods of severe rain attenuation. This strategy supports the communication link but can increase the likelihood of outages in high-frequency lines, reducing the rain margin. By applying these FD models, rain fade mitigation can be optimized, especially in tropical environments where rain-induced signal degradation is significant.

Materials and Method

The data used in this study were collected from Nigerian Meteorological Agency (NIMET). Measured rain rate data for five years (January 2015 to December 2019) for Ikeja were used. The need of one-minute rainfall frequency led to the utilization of the empirical model formulated by Chebil and Rahman (1999). Chebil and Rahman's suggested rain rate conversion model for conversion of these hourly data to the equivalent one-minute rainfall rate values as follows:

$$CF60 = 0.772p^{-0.041} + \exp(-2.570 * p) \quad (1)$$

$$CF60 = R_{1(p)} / R_{60(p)} \quad (2)$$

$$R_{1(p)} = CF60 * R_{60(p)} \quad (3)$$

where CF_{60} as the ratio of rain rates $R_{1(p)}$ and $R_{60(p)}$ for a given percentage of time p with an integration time of 1 min and 60 min, respectively. p lies between the constraints $0.001\% \leq P \leq 1.00\%$. $R_{1(p)}$ is the one-minute rain rate values and $R_{60(p)}$ is the hourly rain data.

Figure 2 shows the analog channel diversity schematic diagram for a typical FD set up.

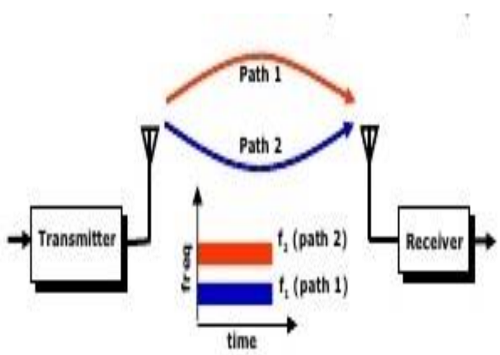


Figure 2: Schematic of Analog Channel Diversity (Schweber, 2018).

The variation of rain fade is a determinant factor in carrying out this investigation. MATLAB codes were employed in plotting relationship between the rain rate at different percentages of time and attenuation and other parameters.

Model Description

The Recommendation ITU-R P.838-3 (2005) prediction model was used adopted since it is necessary to determine the attenuation due to rain utilizing rain rate information. The input parameters required are as follows:

$$\gamma_R = k(R_{0.01}) \propto \text{dB/km} \quad (4)$$

$$k = (k_H + k_V) + ((k_H - k_V) * (\text{Cos}2(\theta) * \text{Cos}(2\tau))/2 \quad (5)$$

$$\alpha = [(k_H \alpha_H + k_V \alpha_V)(k_H \alpha_H - k_V \alpha_V) \text{Cos}2\theta\text{Cos}2\tau]/2k \quad (6)$$

Equations (4) to (6) were generated from the curve-fitting to power-law coefficients that were derived from scattering simulations and used to determine values for the coefficients k and ∝, which is a function of frequency which lies within the range of 1-1000 GHz.

Frequency Diversity Improvement Factor Calculation

The improvement factor formula is given as:

$$I = a\,(f_d)^{-b} + c \quad (7)$$

The coefficients employed in fading are a, b, and c were obtained from Islam et al. (2015) and f_d represents the diversity frequency. This was used to calculate the Improvement factor for each frequency between 15 GHz to 45 GHz at 5 GHz separation, considering the fade margin between 3dB to 7dB.

Results and Discussion

Separating the frequency by 5 GHz, the improvement factors are determined and shown in Table 1, by employing the equation (7) and the relationship is plotted as shown in Figure 3. The best fitting curves for coefficients a and b are displayed in Figure 4 for varied fade margins diversity frequencies from 3-7dB/km and the measured rain rate of 65.22mm/hr for Ikeja extrapolated for 0.001-1% of time exceeded. This was employed to forecast the rain fade for frequencies between 15-45 GHz utilizing equations (4) to (6) as shown in Figure 5. Figure 5 shows how the outage percentage of time varies in accordance with the system's required fade margin, which is determined by the specific rain fade. It is clearly seen that at different percentage of time exceeded, the attenuation values gotten when transmitting at various frequencies differ. The variation of this rain fade is a determinant factor in carrying out this investigation from definition with 5GHz separation using the selected fade margin to calculate the given values.

Table 1: Calculated Improvement Factor showing the base and diversity frequencies.

F_d (GHz)	F_b (GHz)	IMPROVEMENT FACTOR $I_D(P)$				
		3dB	4dB	5dB	6Db	7dB
15	20	2.231	2.656	2.695	2.592	2.645
20	25	1.596	1.886	1.790	1.715	1.614
25	30	1.345	1.483	1.502	1.554	1.556
30	35	1.225	1.242	1.386	1.512	1.550
35	40	1.160	1.084	1.331	1.500	1.549
40	45	1.122	0.975	1.302	1.493	1.549

Figure 3 showed how the improvement factor was higher at lower frequencies and vice-versa. Also, at different fade margins, we obtain different curves for each as the greater the fade margin, the greater the gain and the lower the fade margin, the lower the improvement factor (gain). In actualizing frequency diversity, we consider and used two frequencies at once, given a particular frequency separation (in this case we use 5 GHz) where the first one is termed the diversity frequency and the other is named the base frequency which is shown above in Table 1. Hence, when transmitting on a signal on the higher frequency and interference occurs, we can easily switch to the lower frequency to mitigate rain attenuation.

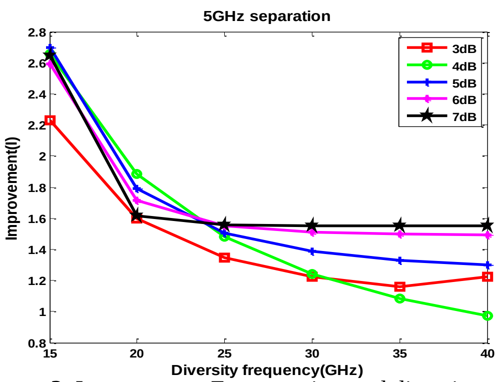
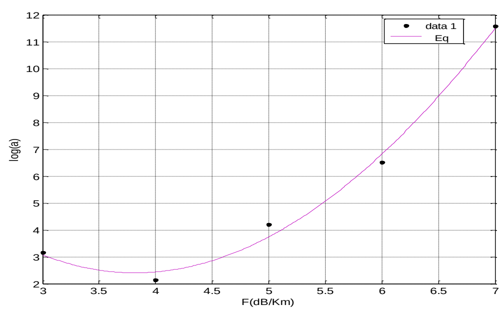
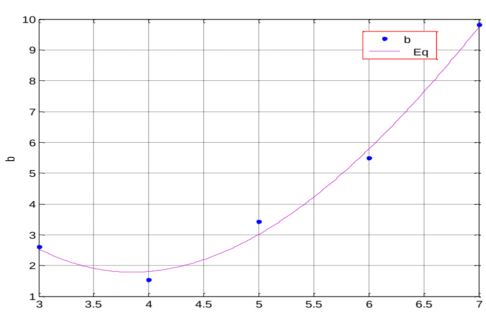


Figure 3: Improvement Factor against and diversity frequency



(a)



(b)

Figure 4 (a) and (b): Best fitting curve for coefficients a and b

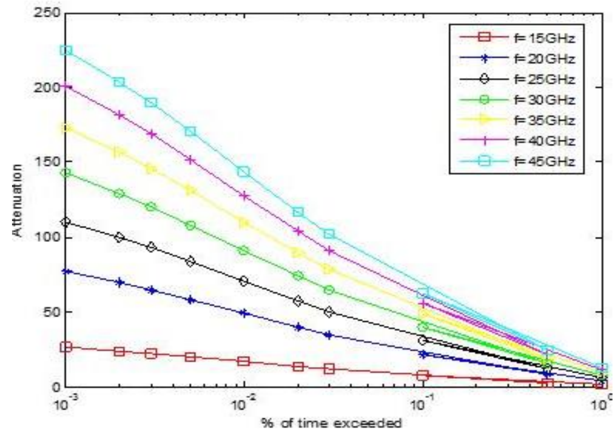


Figure 5: Attenuation (dB/km) expected for 15-45GHz due to the Rain rate measured in Ikeja Lagos Nigeria.

In Figure 4 (a), the logarithmic value of coefficient a is plotted against the fade margin. The equation that defines the graph is given as:

$$y = -0.028x^3 + 1.3x^2 - 8.7x + 18 \qquad (8)$$

The nature of the graph is such that the logarithmic value of coefficient increases exponentially as the fade margin increases.

Also, the equation that defines the graph for b (see Figure 4 (b)) is given as:

$$y = -0.062x^3 + 1.7x^2 - 10x + 20 \qquad (9)$$

The values of coefficient b start to rise exponentially from 3dB/km to 7dB/km, however there is a drop in the coefficient at 4dB/km; this is one of the reasons why it is used as the estimated factor fitting for the existing model.

Figure 6 depicts the Fade depth against the Improvement when a payload is transmitted at separate frequencies between 15-45 GHz respectively. At 15 GHz, there was an increase in the improvement from 3dB to 5dB and then a decrease in the improvement as the fade margin increases above 5dB fade and there was further in above 6dB. Similarly, at 20 GHz, there was a remarkable increase in the improvement from 3dB to 4dB and also a drastic decrease in the improvement for fade depth above 4dB. At 25 GHz, there was a progressive increase in the improvement from 3dB to 7dB and no decrease at all in the improvement for this particular frequency; this is because attenuaton is more predominant at higher frequencies and a higher improvement is needed in order to circumvent degradation.

At 30, 35, 40 and 45 GHz, it indicated that there were slight decrease in the improvement from 3dB to 4dB and then an increase in the improvement factor above 4dB/km attenuation.This is due to the high frequencies used in the transmission, which later readjusted showing an increase in the improvement factor, although at slightly different margins at these different frequencies.

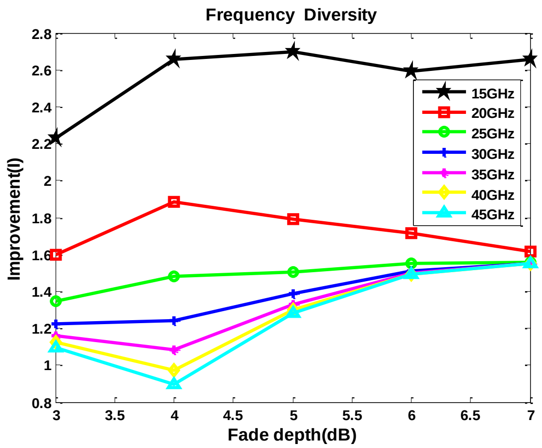


Figure 6: Combined Improvement showing comparison for frequencies ranging between 15-45 GHz at 5 GHz separation

Conclusion

In this study, the rain rate and rain attenuation from 15GHz to 45GHz radio wave frequencies over earth to space links were assessed and analyzed for a period of five years for Ikeja, Nigeria. ITU-R P.838-17 model was adopted and Frequency Diversity Improvement Factor technique was applied to it using frequency diversity rain attenuation mitigation approach. $R_{0.01}$ (rain rate with one-minute integration time) of 65.22 mm/hr at 0.01% of time was extrapolated to obtain the rain rates for other percentages of time exceeded using the empirical model formulated by Chebil and Rahman. The specific attenuation estimated at different fade margins indicated that the improvement factor increased as the fade margin increases, the improvement factor reduced with the reduction in the fade margin due to the frequency diversity technique applied.

Furthermore, it was observed that the best performances were observed at higher frequencies, between 25 to 45GHz; where rain attenuation is more pronounced, and of course where intervention is critically required. It can be firmly concluded that the frequency diversity technique is effective for reducing the effect of rain fade at higher frequencies by switching from a high frequency to a lower frequency in order to circumvent attenuation or outages and also to ensure improved design of terrestrial and earth-space communication systems, higher link availability and improved quality of service during rain occurrence.

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