Intersystem interference on horizontally polarized radio signals in tropical climate

J S Ojo*,1,2, *, S K Sarkar1 & A T Adediji2

1Radio and Atmospheric Sciences Division, National Physical Laboratory, New Delhi 110 012
2Department of Physics, Federal University of Technology, Akure, Ondo State, Nigeria

*E-mail: josnno@yahoo.com

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The nature and characteristics of tropical rainfall have called for the need to investigate horizontally polarized radio signals from Earth-to-Satellite link and to estimate intersystem interference due to hydrometeor in the tropical climate. Two rain cells, Awaka and Capsoni models, are used and results obtained from these models are compared. A difference of 5 dB has been observed between effective transmission loss (Le) and transmission loss (L) for Awaka model, whereas it is about 8 dB for Capsoni model at 0.01% of time unavailability (outage time). This suggests higher interference level in Awaka model for terrestrial and satellite communication operating at frequency above 10 GHz. The statistics of effective transmission loss over frequencies variation, station separation and terrestrial antenna gains have also been considered.

Keywords: Intersystem interference, Horizontal polarization, Tropical climate, Effective transmission loss.
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1 Introduction

The role of satellite communication continues to increase in the field of atmospheric sciences as well as some vital areas of life, viz. telemedicine, defence, internet, banking, fixed and mobile telephony among others. The trends to make use of frequencies above 10 GHz by terrestrial and earth satellite radio links are well established1, 2. However, at those frequencies, the most serious problems in system design emanated from attenuation, depolarization and scattering interference by precipitation particles along the radio path1. Interference hampers coverage and capacity, and limits the effectiveness of both new and existing systems. Assessing the extent of such interference on statistical terms is extremely important for the correct design of communication systems operating at microwave and millimeter wave frequency.

In the tropical region, the quality of signals received is often affected by high intensive rainstorms that are characterized by large size raindrops on the path of communication satellite2. Although the work has been already carried out on the evaluation of bistatic interference on communication paths at temperate region, which include the work of Crane3, Capsoni et al.4, Awaka5, Olsen et al.6, Holts et al.7, Capsoni and D’Amico8, Sitorus and Glover9, etc. However, the results obtained in such studies cannot be applied directly on tropical paths. This is due to the nature and characteristics of tropical rainfall which are often convective, and characterized by large raindrop sizes with high intensity and often accompanied by severe lightning and thunderstorm. In addition, most of these studies are based on estimation of transmission loss arising from hydrometeor scattering on vertically polarized microwave signals into the receiver of earth-space communications systems operating at the same frequency. The horizontal polarization is usually not investigated because coupling (transmission loss) between the transmitting and receiving systems is much less than in vertical polarization10. However, the nature and characteristics of tropical rainfall, which are quite distinct from the temperate rainfall, call for the investigation of the horizontal polarization of transmitted signals. The level of interference in a communication channel depends on several factors such as length and geometry of the interfering path; electrical parameters of transmitting and receiving systems; and meteorological variables associated with propagation medium.

The present paper is based on evaluating the intersystem interference in terms of effective transmission loss (Le) on the transmission of horizontally polarized signals in tropical climate by using and comparing the results of two models4,5. Capsoni and D’Amico8 models reveal that transmission loss statistics alone, is not sufficient to characterize the interference problem and hence effective transmission loss is used in this work. The effective transmission loss is due to the additional rain
attenuation \( (A_w) \) on the path of satellite signal, which further reduces the signal-to-noise ratio at the satellite terminal (Fig.1). The study is also based on thunderstorm rainfall type, which is peculiar to the tropical region.

2 Theoretical concepts

The transmission loss is estimated in terms of simplified bistatic radar equation (SBRE) using the expression

\[
L = P_t - P_r = K_T + A_g - M + (S - Z + A) \quad \ldots(1)
\]

All the terms in equation (1) are in decibel (dB) units. \( P_t \) and \( P_r \) are, respectively the mean power (in watts) transmitted and received along the axis of the main antenna beams; \( A_g \), extra attenuation due to gaseous absorption; \( Z \), reflectivity factor; \( M \), polarization decoupling factor; \( S \), allowance for Rayleigh scattering at frequencies greater than 10 GHz; \( K_T \), contains the link geometry with the system parameters; and \( A \), slant path rain attenuation from the transmitter to the common volume and from the common volume to the satellite receiver and can be estimated from power law relationship between rain rate and attenuation\(^{11}\) which is expressed as

\[
A_H = k_H R^{\alpha_H} \quad \ldots(2)
\]

The subscript \( H \) refers to horizontal polarization and the constant parameters \( k_H \) and \( \alpha_H \) for calculating attenuation \( A \) are shown in Table 1 for the frequencies investigated in the present study. This study assumes that both \( M \) and \( S \) of equation (1) are equal to 1. This assumptions means that reflectivity factor \( Z \) is isotropic. In evaluating total or scattering cross-section per unit volume of the precipitating particles, it is important to use appropriate drop size distribution (DSD) irrespective of the shape factor adopted over the frequency spectrum. In this study, the lognormal distribution is employed while Rayleigh scattering correction takes care of shape factor at frequencies higher than 10 GHz\(^{12}\). The detailed description for estimating \( L \), is not included here, but can be found from the Refs 2-4.

Effective transmission loss is usually evaluated in terms of a joint transmission loss, \( L \) and additional rain attenuation \( A_w \) as

\[
L_e = L - A_w = P_t - (P_r + A_w) \quad (dB) \quad \ldots(3)
\]

The result of the point rain rate measured during the joint African radiometric measurement campaign in Ile- Ife, Nigeria (4.34°E, 7.33°N) is used in this study\(^{13}\). The details of assumed parameters for the study are summarized in Table 2, which can be found in the work of Ajewole\(^{14}\) and Ajewole and Ojo\(^2\). Also, reflectivity-rain rate relationships proposed by Ajayi and Owolabi\(^{15}\) were used with reflectivity factor \( Z-R \) \( (Z = a R^b) \). For tropical thunderstorm rainfall, \( Z = 461R^{1.31} \), where \( a = 461 \) and \( b = 1.31 \) (Table 2). The study covers the frequency range 4-35 GHz while effective transmission loss and transmission loss are evaluated for probability of occurrence ranging from 0.001 to 1%. The terrestrial station path lengths to common volume distance, ranging 50-250 km and additional parameters used are also summarized in Table 2.

The earth satellite system receiver is characterized with elevation angle of ~55° (This is the look angle of most satellite receiver systems over Atlantic ocean region in Nigeria), beam width ~0.18° and a gain of ~59 dB. Aside from the elevation angles, the system parameters stated in Table 2 are similar to those utilized along some propagation geometries having the same characteristics with tropical region in Cost

Table 1 — Regression coefficients \( k \) and \( \alpha \) of the power law expression for horizontally polarized states

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>( k_H )</th>
<th>( \alpha_H )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>6.51×10^{-4}</td>
<td>1.072</td>
</tr>
<tr>
<td>6.0</td>
<td>1.85×10^{-3}</td>
<td>1.214</td>
</tr>
<tr>
<td>8.0</td>
<td>4.72×10^{-3}</td>
<td>1.273</td>
</tr>
<tr>
<td>10.0</td>
<td>1.10×10^{-2}</td>
<td>1.252</td>
</tr>
<tr>
<td>12.0</td>
<td>2.20×10^{-2}</td>
<td>1.204</td>
</tr>
<tr>
<td>16.0</td>
<td>4.10×10^{-2}</td>
<td>1.128</td>
</tr>
<tr>
<td>20.0</td>
<td>8.20×10^{-2}</td>
<td>1.083</td>
</tr>
<tr>
<td>35.0</td>
<td>2.76×10^{-1}</td>
<td>0.970</td>
</tr>
</tbody>
</table>
Table 2 — Characteristics of the station, terrestrial satellite and earth satellite

<table>
<thead>
<tr>
<th>Station</th>
<th>Ile-Ife, Nigeria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>4.34°E, 7.33°N</td>
</tr>
<tr>
<td>Frequency range</td>
<td>4-36 GHz</td>
</tr>
<tr>
<td>Altitude</td>
<td>274 m</td>
</tr>
<tr>
<td>Rain climatic zone</td>
<td>N and P</td>
</tr>
<tr>
<td>( h_{FR} )</td>
<td>4.54 – 4.79 km</td>
</tr>
<tr>
<td>Transmitting antenna</td>
<td></td>
</tr>
<tr>
<td>Elevation angle</td>
<td>1°</td>
</tr>
<tr>
<td>Gain</td>
<td>40.5 dB</td>
</tr>
<tr>
<td>Beam width</td>
<td>1.6(^{\circ}), Gaussian radiation pattern</td>
</tr>
<tr>
<td>Polarization</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Receiving antenna</td>
<td></td>
</tr>
<tr>
<td>Elevation angle</td>
<td>55°</td>
</tr>
<tr>
<td>Gain</td>
<td>59 dB</td>
</tr>
<tr>
<td>Beam width</td>
<td>0.18(^{\circ}), Gaussian radiation pattern</td>
</tr>
<tr>
<td>Polarization</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Z-R relation</td>
<td>461 R(^{1.31})</td>
</tr>
</tbody>
</table>

Project 210\(^{16}\). The vertical structure of precipitation is assumed constant up to 0°C isotherm height, below which is the rain region where attenuation and scattering of the wanted and interfering signals occur. Beyond 0°C, is the ice region where \( Z \) decreases at the rate of 6.5 dB/km. In Nigeria, during raining conditions, the mean freezing height (\( h_{FR} \)) is nearly constant and hence equal to \( h_0 \). Its value lies between 4.54 and 4.79 km from the coast to the arid region of the country\(^{17}\). These parameters, however, show a strong seasonal variation. To assess the height variation impact on the predictions; simulations have been carried out using \( h_{FR} \) as proposed by Cost 210\(^{16}\). The effect of using \( h_{FR} \) instead of its median height \( h_0 \), brings a better estimation of interference statistics since height of the common volume is well above the median \( h_0 \). The effect of the atmosphere has been taken into account by complex propagation constant in the bistatic radar equation\(^{8}\). The intersystem interference prediction has been carried out using extra attenuation due to rain (with respect to the free space) that the signal experiences along the path towards and from the common volume. The two main contributions to attenuation come from precipitation and to a lesser extent, the atmospheric gases. In the earlier work of Ajewole et al.\(^{12}\), intersystem interference has been estimated over different rainfall types (thunderstorm, widespread and shower) and their effects have been considered on vertically polarized radio signal. In this work, gaseous absorption is calculated using the relation provided by the International Telecommunication Union (ITU)\(^{18}\) with an average water vapour density of ~ 20 g/m\(^3\), as recommended in Cost 210\(^{16}\). Raindrop shapes are assumed to be oblate spheroids at ~ 20°C using lognormal distribution, which has been proved to fit better in describing the rain drop size distribution in the tropical region\(^{10,11}\). The value was used to evaluate the refractive index of water using the method described by Ray\(^{19}\).

The horizontal structure of rain rates are assumed to be exponentially distributed with peak intensity inside the rain cells and are expressed as

\[
R(r) = R_M e^{-\frac{r}{R}} \quad \text{...(4)}
\]

where, \( r \) is radial distance from the rain cell center; \( R_M \) maximum rainfall rate; and \( r_0 \), distance of the point from the centre of rain cell for which rain rate decreases by a factor \( e^2 \) with respect to the rain rate value inside the cell, and this corresponds to minimum rain rate in the cells. For Capsoni\(^{4}\) and Awaka\(^{5}\) rain cell models \( r_0 \) is expressed respectively as

\[
r_0 (R_M) = 1.7 \left[ \left( \frac{R_M}{6} \right)^{-10} + \left( \frac{R_M}{6} \right)^{-0.26} \right] \text{ km} \quad \text{...(5)}
\]

\[
r_0 (R_M) = \frac{10 - 1.5 \log_{10} R_M}{\ln \left( \frac{R_M}{0.4} \right)} \text{ km} \quad \text{...(6)}
\]

Equations (5) and (6) differentiate the two models from each other. The probability of occurrence of a rain cell is defined in terms of the total number of rain cells \( N^* (R_M) \) for a given area per unit rain rate \( R(r) \). A general retrieval algorithm for \( N \) as proposed by Awaka\(^{5}\) can be expressed as

\[
N^* (R_M) = \frac{-1}{2\pi R_m r_0^2 (R_M)} \left| \frac{d^3 P(R)}{d(lnR)^3} \right|_{R=R_M} \quad \text{...(7)}
\]

For the Capsoni model\(^4\), the denominator of the first term on the right is two times higher. By using third order differentiation, this equation is solved in terms of a power law relationship for the cumulative distribution of measured rain rate \( P(R) \) at the location of interest as

\[
P(R) = P_o \ln \left( \frac{R'}{R} \right)^k \quad 0 < R < R' \quad \text{...(8)}
\]

\( P_o \) and \( k \) can be obtained by interpolation from cumulative distribution of the measured point rain rate \( P(R) \). \( R' \) is normally assumed to be about four times the highest rain rate at the location of interest.
3 Results and discussion

Table 3 shows typical results of attenuation due to water vapour over the location where water vapour concentration varies between 8 g/m$^3$ and 24 g/m$^3$. Table 4 gives typical results on attenuation due to rain at different rainfall intensity. It is seen in Table 3 that attenuation due to water vapour increases as the water vapour density increases. Also, Table 4 shows that rain attenuation increases with increase in rain intensity. The signal at the receiving end decreases when attenuation of the radio wave due rain and water vapour increases. Therefore, due to decrease of the received signal, the interference from the other system increases.

The results of effective transmission and transmission loss for frequency of 16 GHz, path lengths of 50 km and at some percentages of time are presented in Fig. 2. The results show that both effective transmission loss and the transmission loss increases as outage time (% time probability) increases, though the transmission loss statistics show a fairly increase for the two models. For 0.01% of time unavailability, a difference of 5 dB exits between effective transmission loss and transmission loss for Awaka model, while it is about 8 dB for Capsoni model. The results also show that these differences decrease with increasing outage time (% time probability).

Figure 3 shows variation of effective transmission loss at different frequencies, 0.01% of time and at both short (50 km) and long (200 km) path lengths. Generally at short path length, effective transmission loss decreases with frequency except at frequency window of 16-20 GHz there is a slight increase. Also, Awaka model predicts high effective transmission loss for frequencies less than 20 GHz. The effect of $Z$ is conspicuous when path length is large and frequency is more than 16GHz. The common volume at this distance is in the ice region, hence, ice scattering predominates over rain scattering. However, for frequency greater than 16 GHz and at path length of 200 km, both models could not produce values for the effective transmission loss results for horizontally polarized signal due to the practical limit set for computation of coupling around -180 dB. Apart from the fact that convective rainfall plays a major role in the tropical region which called for a need to investigate the level of interference on horizontally polarized signal, it could also be observed from the result that $L_e$ decreases with frequency except at frequency window 16-20 GHz for lower probability of 0.01% even at a relatively large distance from a transmitting station. This means that for a given link, higher the frequency, the stronger the interference’s effect. Hence, system outages may be a frequent problem in this kind of location whenever a convective rainstorm intercepts the signal path.

In Fig. 4, results show the variation of $L_e$ with terrestrial antenna gain at 0.01% of time unavailability, frequency of 16 GHz for both short and long path lengths. Generally, effective

![Fig. 2 — Comparison of effective transmission loss and transmission loss for frequency of 16 GHz, path length of 50 km and at some percentages of time](image)

![Fig. 3 — Comparison of the frequency characteristics of effective transmission loss for the two models at 0.01% of time, for both short and long path lengths](image)
transmission loss decreases with increasing terrestrial antenna gain. There is also more spread values of $L_e$ with distance. However, there is a difference of 2 dB for short path length between the models, while it is just 1 dB for long path length. The decrease in $Z$ may further enhance high $L_e$ in the terrestrial system when frequency is low at long path length.

The variation of effective transmission loss with percentage time unavailability at frequencies 8, 16, 20 and 34.8 GHz is presented in Fig. 5. The propagation path length from terrestrial antenna to the common volume is 50 and 200 km (short and long path length). The result shows that effective transmission loss increases as outage time (percentage time probability) increases. Also $L_e$ increased with increasing terrestrial to common volume distance (or terrestrial to satellite antenna separations). At 50 km and time probability of 0.01% for lower frequency of 8 GHz, $L_e$ is about 121.27 and 120.27 dB, respectively for Awaka and Capsoni models. The effective transmission loss is down to 118.27 and 117.27 dB at 0.001 time percentage. However, this trend is slightly noticeable at long path length. It is also noticed that $L_e$ is consistently poor at high frequency of 34.5 GHz, when compared with the frequency of 20 GHz (50 km path length) for both models and for all percentages time unavailability, which means that there will be stronger interference effect on propagation paths at this frequency.

Figure 6 presents the comparison of results obtained for $L_e$ with $L$ at an elevation angle of 45°, frequency of 16 GHz and by varying the distance between earth station and terrestrial station antenna systems at 0.01% and 0.001% unavailability of time. For the two outages time, both $L_e$ and $L$ increased with increase in the positions of the two links (antenna separation). The effect of the extra attenuation due to rain along the earth station is quite significant (Fig. 1). The closer the station, the higher is the interference received in the satellite channel since weaker interfering signal arrives and contribution from rain scattering is dominant to the interference. At longer path length, the difference between $L$ and $L_e$ statistics becomes very small because the contribution from ice scattering is dominant to the interference.

4 Conclusions

The effective transmission loss due to hydrometeors scatter on horizontally polarized signal from terrestrial communication link operating at the same frequency in a tropical environment has been estimated by using two rain cell models. The results have been compared over some unavailability of time, frequencies variation, and terrestrial antenna gain and station separation. For 0.01% unavailability of time (outage time), a difference of 5 dB exists between effective transmission loss and transmission loss for Awaka model, whereas it is about 8 dB for Capsoni model. This suggests that Capsoni rain cell model predicts higher values of effective transmission loss and may, therefore, predict lower interference levels in Nigeria.
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