QoS In Weather Impacted Satellite Networks

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***Abstract*—Rain and snow can have a distorting effect on Ku and Ka bands signal fidelity resulting in excessive digital transmission errors. This loss of signal attenuation is commonly referred to as rain fade. Rain fade impacts the Quality of Service (QoS) in wireless and satellite networks. Accurately predicting rain fade can enable mitigation planning by adaptively selecting appropriate power level, coding and modulation. This paper computes rainfall rate and Rain Attenuation (RA) at any location on earth using ITU-R models combined with bi-linear interpolation and frequency extrapolation. In addition since RA is considered a dominant impairment for wireless signal [1]-[6], we are introducing a novel method for accurately determining RA as function of frequency based on proceeding results from a predicted weather database. Finally, a three dimensional relationship is proposed among RAs with both frequency and rainfall rate, which is a function of probability. These results are key factors in adjusting and improving satellite signal power, modulation and coding schemes, and frame size, monitored and controlled altogether by a powerful and efficient intelligent system in order to improve QoS.**

***Index Terms*—International Telecommunications Union - Radiocommunications (ITU-R), Quality of Service (QoS), Rain Attenuation (RA), and Service Level Agreements (SLA).**

I. INTRODUCTION

Propagation impairments include RA, gaseous absorption, cloud attenuation, and tropospheric scintillation, which affect satellite links at Ku and Ka bands. RA is considered a dominant impairment for satellite signals. It becomes particularly severe at frequencies higher than 10 GHz, especially for small aperture antenna such as Very Small Aperture Terminal and Television Receive Only [3] and [5].

A number of prediction models are available for the estimating individual components. However, methodologies that attempt to combine them in a cohesive manner are not widely available yet [7]-[10]. Furthermore, it is extremely hard to optimally manage satellite-available network resources that are impacted by rain fade, with link traffic engineering only - "Goldilocks Link Budgeting". It is then absolutely necessary to correctly identify and predict the overall impact of every significant rain-attenuation factor on QoS, be it location, transmission or propagation characteristics along any given path between satellite and ground terminals.

In the absence of detailed knowledge of occurrence probabilities for different impairments, empirical approaches are taken by estimating their combined effects. Once the amounts of expected impairments are established, appropriate methods for mitigating impairments must be invoked. Some of these include up-link power control, adaptive coding, antenna beam shaping, and site diversity [11]-[14].

In view of these analytical approaches, dealing with weather-impacted QoS and reliable satellite communications are currently non-existent. Other thrusts in satellite service providers are shifting their resolution towards intelligent-based computationally efficient prediction methods. These types of methods accurately predict relevant rain metrics; by adaptively applying the prediction methods to regulate transmit power, modulation schemes and channel coding. Consequently, these methods will promptly adjust to new signal changes, through the inter-connected network entities, before rain problems actually manifest themselves to maintain end-to-end QoS requirements.

In this paper, we use ITU-R models to compute rainfall rate and RA. Then, we introduce a method to accurately determine RA as a function of frequency based on proceeding results from a predicted weather database. Finally, a three dimensional relationship is proposed for RA with both frequency and rainfall rate that will supply the intelligent system with a mechanism to better estimate satellite networking parameters such as link and queuing characteristics. Then these derived parameters would enable the intelligent system to maintain QoS and SLAs by adaptively adjusting signal power, coding, and modulation under unpredictable weather conditions.

The remaining sections of this paper are organized as follows: In section II, we describe the existed, approximated and proposed methods along with statistical analysis of RA as a function of frequency. It is then followed, in section III, by a simulation and analysis of RA as a function of both frequency and rainfall rate at different locations. Finally, conclusions are outlined in section IV.

II. THEORY AND RESULTS

Data files collected from ITU-R for *PR*, *MC* and *MS* contain numerical values for the variables: P_R (*Lat, Long*), M_C (*Lat, Long*) and M_S (*Lat, Long*) respectively. These data files represent a weather characteristic model to derive rainfall rate at different X (Longitude degree) and Y (Latitude degree) locations. Data files *Lat* and *Long* contain latitude and longitude for each data entry in all files [1]-[2], [4] and [6].

II.1 Rainfall Rate Calculation

Rainfall rate, which is a function of probability, is used as a factor to determine rain fade. Rain fade seems to correlate very closely with the volume of raindrops along the path of propagation. Therefore, rainfall rate can be computed by:

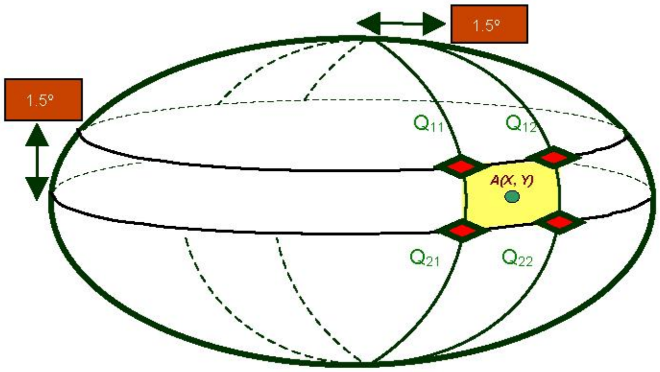

Fig. 1. Grid Point Location

1) Extracting variables P_R, M_C and M_S for the four points closest in *Lat* and *Long* to the geographical coordinates (*X* and *Y*) of the desired location. Latitude grid range: 90°N to -90°S, and longitude grid range: 0 to 360° both for 1.5° steps. If the location falls on the grid, we will take these values as is from the given ITU-R tabulated data. Otherwise, we perform a bi-Linear interpolation to the four closest grid points as shown in Fig. 1.

2) Deriving percentage probability of rainfall rate in an average year, P_0, based on calculated data collected from previous steps, where:

$$P_0(Lat,Long) = P_R(Lat,Long)\left(1 - e^{-0.0117(M_S(Lat,Long)/P_R(Lat,Long)}\right). \quad (1)$$

If $P_R = 0$, the result will be undetermined and consequently rainfall intensity will also be zero [1]. In this case we shall stop the procedure. Otherwise, if $P_R \neq 0$, we shall derive rainfall rate (R_p) from the exceeded percentage probability *(p)*, where p should be $\leq P_0$, otherwise $P_0 = 0$ and the following steps will not be required.

$$a = 1.11,\ b = \frac{(M_c(Lat,Long) + M_s(Lat,Long))}{22932\,P_0} \text{ and } c = 31.5 * b. \quad (2)$$

$$A = a*b, B = a + c*\ln(p/P_0(Lat,Long)) \text{ and } C = \ln(p/P_0(Lat,Long)) . (3)$$

Thus, rainfall rate will be:

$$R_p(Lat,\ Long) = \frac{-B + \sqrt{B^2 - 4*A*C}}{2*A} \quad mm/hr. \quad (4)$$

For example, by using (1)-(4), rainfall rate value R_p will be 33.21 mm/hr, for longitude X = 30, latitude Y = 35, and p = 0.01%. If $P_0 = 0 \Rightarrow R_p$ from (4) will also be zero.

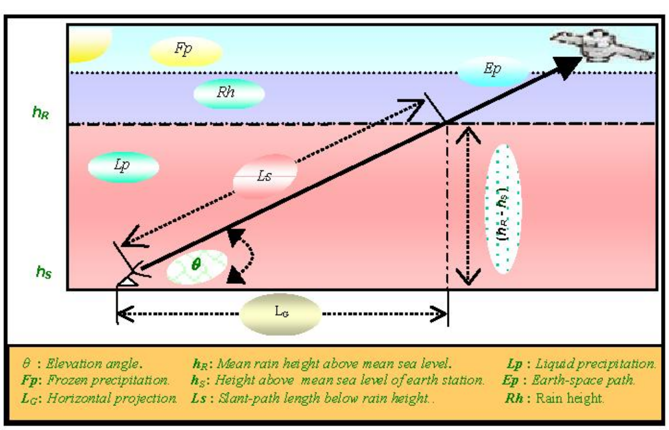

Fig. 2. Earth-Space Path

II.2 Rain Attenuation Calculation

II.2.1 Existed and Approximated Method

The approximated method is derived from the existing one. As described below, we can compute RA's behavior for any location and for the whole range of applicable frequencies up to 55 GHz based on a fixed frequency sample (F_i).

Fig. 2 shows the relationship of signal propagation parameters.

Other required parameters are: Frequency ***f*** *(GHz)*, latitude of earth station ρ *(degree)* and effective radius of Earth ***R*** *(km)*.

With respect to altitude where rain extends during periods of precipitation, the following procedure has been recommended:

1) If no specific information is available: the mean 0°C isotherm height - with resolution of 1.5° in both latitude and longitude - above mean sea level h_0 could be obtained from ITU-R data file *HEIGHT0.txt* [4].

2) Mean rain height above mean sea level, h_R, can be obtained from 0°C isotherm h_0 given in [4] as:

$$h_R = h_0 + 0.36 \quad km. \quad (5)$$

3) To compute slant-path length, L_S, below rain height from [1]-[2], [4] and [6]; the following formulas are used:

i- $\theta < 5°$: $$L_S = \frac{2(h_R - h_S)}{\left(\sin^2\theta + \frac{2(h_R - h_S)}{R_e}\right)^{1/2} + \sin\theta} \quad km. \quad (6a)$$

ii- $\theta \geq 5°$: $$L_S = \frac{(h_R - h_S)}{\sin\theta} \quad km. \quad (6b)$$

if $(h_R - h_S) \leq 0 \Rightarrow$ predicted RA for any time percentage is equal to zero and the following steps are not required.

4) Calculate horizontal projection, L_G, of slant-path length from: $$L_G = L_S \cos\theta \quad km. \quad (7)$$

5) Find rainfall rate, $R_{0.01}$, for exceeded p = 0.01% of an average year. If $R_{0.01} = 0 \Rightarrow$ RA = 0 for any time percentage and the following steps are not required.

6) Compute specific attenuation, γ_R, using frequency-dependent coefficients as given in [2] for k, α and rainfall rate (R_p) calculated in section II.1 for p = 0.01%, determined from (4), by using: $$\gamma_R = K\ (R_{0.01})^{\alpha} \quad dB/km. \quad (8)$$

For linear and circular polarization and for all path geometries, coefficients in (8) can be computed from (9) and (10) as:

$$K = \left[K_H + K_V + (K_H - K_V)\cos^2\theta\cos 2\tau\right]/2. \quad (9)$$

$$\alpha = \left[K_H\alpha_H + K_V\alpha_V + (K_H\alpha_H - K_V\alpha_V)\cos^2\theta\cos 2\tau\right]/2k. \quad (10)$$

where K_H, α_H and K_V, α_V are constants for the coefficients of horizontal and vertical polarizations respectively.

7) Calculate horizontal reduction factor, $r_{0.01}$, for 0.01% of time: $$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G \cdot \gamma_R}{f}} - 0.38\left(1 - e^{-2L_G}\right)}. \quad (11)$$

8) Calculate vertical adjustment factor, $v_{0.01}$, for 0.01% of time: $$\sigma = \tan^{-1}\left(\frac{h_R - h_S}{L_G \cdot r_{0.01}}\right) \quad degrees. \quad (12)$$

For $\sigma > \theta$, the actual slant-path length L_R will be:

$$L_R = \frac{L_G \cdot r_{0.01}}{\cos\theta}, \text{ else } L_R = \frac{(h_R - h_S)}{\sin\theta}\ km. \quad (13)$$

$$\text{if} \left|\rho\right| < 36^\circ \Rightarrow \chi = 36 - \left|\rho\right|, \text{ else } \chi = 0 \text{ degrees.} \quad (14)$$

$$v_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-\left(\theta/(1+\chi)\right)}\right)\frac{\sqrt{L_R \cdot \gamma_R}}{f^2} - 0.45\right)}. \quad (15)$$

9) Effective path length is: $L_E = L_R \cdot v_{0.01}$ $km.$ (16)

10) Predicted RA exceeded for $p = 0.01\%$ of an average year is obtained from: $A_{0.01} = \gamma_R \cdot L_E$ $dB.$ (17)

11) For other exceeding percentages of an average year ranging from 0.001% to 5%, estimations of RA can be computed from (17) for an average year as follows:

if $p \geq 1\%$ or $\left|\rho\right| \geq 36^\circ \Rightarrow \beta = 0,$

else if $p \leq 1\%$ or $\left|\rho\right| < 36^\circ$ and $\theta \geq 25^\circ \Rightarrow \beta = -0.005\left(\left|\rho\right| - 36\right),$

otherwise $\beta = -0.005\left(\left|\rho\right| - 36\right) + 1.8 - 4.25\sin\theta.$ (18)

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655 + 0.033\ln(p) - 0.045\ln(A_{0.01}) - \beta(1-p)\sin\theta)}\ dB. \quad (19)$$

The above RA equation was tested by ITU-R and found to have the most accurate overall results of all tested models [1]-[6]. However, in order to solve RA problem, we have to go through (5) to (19) for every frequency sample. This is a process that requires a large computational load.

Approximated method, on the other hand, can be useful to compute RA's behavior for the whole range of applicable frequencies, by using (20)-(23), based on a fixed frequency sample (F_i) as follows:

$$\varphi(f_n) = \frac{f_n^{\ 2}}{1 + 10^{-4} f_n^{\ 2}}, \quad (20)$$

$$A(F_i) = \gamma_R(F_i) \cdot L_E(F_i)\ dB. \quad (21)$$

$$H(\varphi(F_i), \varphi(f_n), A(F_i)) = 1.12 \times 10^{-3}\left(\varphi(f_n)/\varphi(F_i)\right)^{0.5}\left(\varphi(F_i)A(F_i)\right)^{0.55}. \quad (22)$$

$$A(f_n) = A(F_i)\left(\varphi(f_n)/\varphi(F_i)\right)^{\left(1 - H(\varphi(F_i),\ \varphi(f_n),\ A(F_i))\right)}. \quad (23)$$

where $A(f_n)$ represents RA at any frequency (f).

These empirical formulas, if reliable attenuation data measured at one frequency (F_i) is available (preferably a higher frequency sample since it offers better results for most cases), will then give RA as a function of the chosen frequency [6]. Such attenuation can be applied for frequency ranging from 7 to 55 GHz.

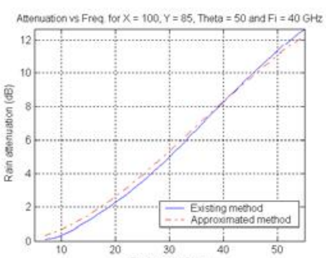

Fig. 3. Existed and Approximated method for small R_p

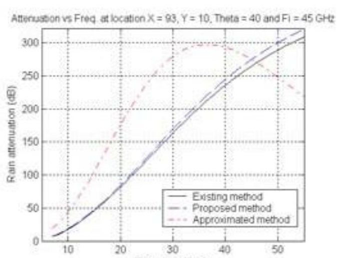

Fig. 4. Existed, Approximated and Proposed method for high R_p

The results will be computed for different specific inputs of prediction of a given percentage of an average year probability (p), for different theta angles (θ), for frequency sample (F_i) and for different (X and Y) locations.

However, it is accurate only under a specific condition: when rainfall rate (R_p), is reasonably small (6.79 mm/hr), as shown in Fig. 3. Thus, high frequency sample (F_i) will not guarantee delivering accurate solutions for all models. Therefore, a novel method will be proposed in the next section.

II.2.2 Proposed method

In order to overcome problems associated with inaccuracies and CPU inefficiencies for estimating RA at different locations, we propose a novel method to maintain and improve QoS by perfectly matching the accurate results up to higher frequencies by solving (24) at any frequency ranging from 7 to 55 GHz and by deriving all other attenuations at any other frequency within the same range recursively merely out of (25)-(26).

Earlier, the approximated method was done according to value of RA calculated at a specific frequency (F_i). By following the empirical formulas (21)-(23), we were able to extrapolate values of RA at any frequency ranging from 7 to 55 GHz based on calculated RA at frequency (F_i).

Equations (24)-(26) compute RA as a function of any frequency (f). Fig. 4 shows a comparison between existed, approximated and proposed methods. The latter being the new technique presented as:

$$A(f_n) = \gamma_R(f_n) \cdot L_E(f_n)\ dB. \quad (24)$$

Also, for any specific frequency ranging from 7 to 55 GHz is obtained from:

$$H(\varphi(f_{n-1}), \varphi(f_n), A(f_{n-1})) = 1.12 \times 10^{-3}\left(\varphi(f_n)/\varphi(f_{n-1})\right)^{0.5}\left(\varphi(f_{n-1})A(f_{n-1})\right)^{0.55}. \quad (25)$$

$$A(f_n) = A(f_{n-1})\left(\varphi(f_n)/\varphi(f_{n-1})\right)^{\left(1 - H(\varphi(f_{n-1}),\ \varphi(f_n),\ A(f_{n-1}))\right)}\ dB. \quad (26)$$

where $A(f_{n-1})$ and $A(f_n)$ are the equiprobable values of excess RA at frequencies (f_{n-1}) and (f_n), respectively.

Methods explained so far, are used to investigate the dependence of RA statistics on elevation angle, rainfall rate, polarization, probability and frequency.

Thus, if reliable attenuation data measured at any specific frequency is available, the previous empirical formulas shown in (24)-(26) will then provide RA as a function of preceding frequency. This means once we have RA at any lower frequency, we can then compute RA of upper level based on it and so on until we reach the maximum desired frequency. Moreover, this method provides high CPU efficiency since we do not have to repeat the entire calculation from beginning for each frequency, as is the case for the existing solution.

On the other hand, approximated method mentioned in the previous section is not accurate for most cases especially when we deal with relatively high rainfall rate ($R_p = 114.28$ mm/hr) even when applying high frequency sample ($F_i = 45$ GHz) as shown in Fig. 4.

III. SIMULATION RESULTS

In this section we present new results for RA as a function of both frequency (f) and rainfall rate (R_p) by combining several equations.

As mentioned earlier, rainfall rate is a function of probability (p). Thus, (27)-(29) show an appropriate technique for calculation of RA for different frequencies and probabilities ranging from 7 to 55 GHz and 0.001% to 5%, respectively.

The predicted RA of an average year for different frequencies and different probabilities can be obtained from:

$$A(f, p) = \gamma_R(f, p) \,.\, L_E(f, p) \; dB. \quad (27)$$

$$H(\varphi(f_1),\varphi(f_2),A(f_1,p_1)) = 1.12\times10^{-3}\left(\frac{\varphi(f_2)}{\varphi(f_1)}\right)^{0.5}\left(\varphi(f_1)A(f_1,p_1)\right)^{0.55}. \quad (28)$$

$$A(f_2,p_2) = A(f_1,p_1)\left(\frac{\varphi(f_2)}{\varphi(f_1)}\right)^{(1-H(\varphi(f_1),\varphi(f_2),A(f_1,p_1)))} dB. \quad (29)$$

Where $A(f, p)$ represents Rain Attenuation (RA) at any frequency (f) and any probability (p).

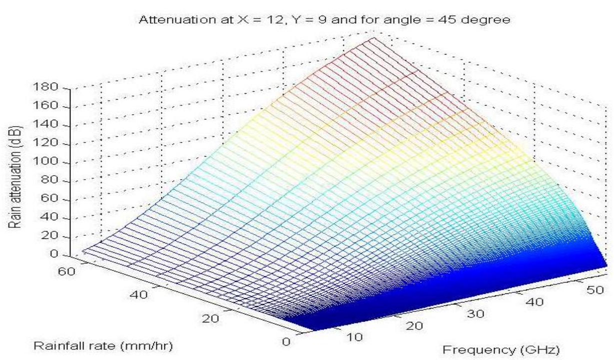

Fig. 5. Rain Attenuation – Function of Frequency and Rainfall rate

This method provides useful general tools for scaling RA according to these parameters. This model helps and provides the designer with a perceptible view of approximate RA values that can be computed at any desired location (X and Y), for all frequency ranges (f), for rainfall rate (R_p) computed at different percentages for the average year probability (p) prediction, and for any angle theta (θ) as shown in Fig. 5.

Therefore, knowing this data will be an immense asset to support analysis for budgeting the operational satellite networking parameters around the world.

IV. CONCLUSIONS

Signal fading caused by rain, limits satellite's QoS links and system availability that operate at frequencies above Ku-band. In most situations, satellite links operating at such frequencies are designed to be up-link limited. Up-link power control is one of the most cost-effective rain fade mitigation techniques. It enhances link availability and performance.

This proposed method improves QoS by providing accurate results for RA in lieu of a wide range of frequencies and probabilities. This is done by periodically computing attenuation that would keep updating our knowledge input to our intelligent system to improve proactive QoS control before weather deteriorates.

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