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Research Note

Rain and Scintillation Fading on Low Availability Ka Band VSAT Satellite Systems

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The relative significance of scintillation fading and rain attenuation on low availability VSAT satellite systems operating at Ka band is examined. The influence of such parameters as signal frequency, path elevation angle, time percentage and climate dependence is discussed. Based on measurement data, a model for prediction of scintillation fading in Ka band is introduced. By using this model and the Simple rain Attenuation Model (SAM), the combined effects of rain and scintillation fade in different climate zones are obtained. It is shown that rain is the predominant degrading factor in high availability satellite communication systems operating at frequencies above 10 GHz. However, scintillation fading becomes a comparatively significant impediment when required system annual availability can be relaxed to 99% or lower. This is especially the case in low availability VSAT satellite systems operating at Ka band frequencies and beyond.

INTRODUCTION

VSAT systems find applications in three broad service areas. They are used with receive-only capability in broadcast services involving one-way transmission from a hub station for applications such as service information, news reports, and direct broadcast television. VSATs are used in transmitted only mode for data collection from mobiles and remote locations. They are also used in interactive configuration with both receive and transmit capabilities for applications such as distance learning, video conferencing, computer networking and information exchange. These emerging applications of satellite communications do not require the high availability specification of Public Switch Telephony Networks (PSTN). The activity ratio (ratio of up time to total time) of some of these systems may be less than 10%. Relatively low-availability (99%) will, therefore, be acceptable. In this paper, comparative evaluation of scintillation and rain attenuation effects on low availability VSAT satellite systems operating at Ka band in tropical and temperate climatic conditions are discussed. It is also shown, that scintillation fade is as important as rain attenuation in such links.

SCINTILLATION

Radiowave scintillation is the condition of rapid fluctuations in the parameters of waves, such as its amplitude, phase, angle of arrival or polarization. These fluctuations are perceived in the receiver as random fade and enhancements of the received signal amplitude about its short-term mean value and are referred to as amplitude scintillation [1,2]. The main cause of scintillation is the random variation in the atmosphere refractive index or propagation constant due to small-scale irregularities in tropospheric humidity, temperature, pressure and ionosphere electron density. Ionospheric effects are negligible on radio signals of frequencies above about 3 GHz.

Scintillation at Ka band, therefore, arises solely from interaction within the troposphere (the lowest layer of the atmosphere extending to a height of about 16 km in the equator and about 8 km at the poles). The tropospheric medium could be a random continuum, such as a turbulent clear atmosphere, or it could be a random particulate medium, such as a cloudy atmosphere.

The main concern in this paper is calculating the random fades which necessitate a scintillation power margin on a satellite communication system

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to avoid repeated outage. It is important to note that scintillation induced signal enhancements can also be a source of performance degradation in the some satellite systems. For example, sufficiently large enhancement could drive a satellite transponder into its non-linear region of operation, thereby causing signal distortion and intermodulation noise [3]. It could also significantly lower the carrier-to-interference ratio of other carriers that share the same transponder.

SCINTILLATION FADING

Several methods have been developed for the prediction of scintillation fade on a satellite link [1-4]. In this paper, a model is used, which is derived by using measurement data. Full details of deriving these formulae are shown in [5]. This model determines scintillation fading as a function of annual time percentages p% and communication link parameters such as signal frequency, antenna diameter, path elevation angle and atmospheric refractivity, namely:

$$\sigma_x^2 = (0.0048 + 1.757 \times 10^{-4} N_{\text{wet}})^2 . G_{HV}(D_e) \times f^{0.7814} . \sin\theta^{-2.094},$$

$$G_{HV}(D_e) = 3.8637.(x^2+1)^{\frac{11}{12}} . \sin\left\{\frac{11}{6}\text{arctog}\left(\frac{1}{x}\right)\right\} - 7.0835.x^{\frac{5}{6}},$$

$$x = 0.0584.D_e^2.\frac{K}{L},$$

$$D_e = \sqrt{\eta}.D,$$

$$L = \frac{2.h}{\sqrt{\sin^2\theta + \frac{2.h}{R_e}} + \sin\theta},$$

$$N_{\text{wet}} = \frac{2730.H.e_s}{(273+T)^2},$$

$$e_s = \frac{5854 \times 10^y}{(273+T)^5},$$

$$y = 20 - \frac{2950}{(273+T)},$$

$$\eta(p) = -0.061(\log p)^3 + 0.072(\log p)^2 - 1.71\log p + 3, \qquad 0.01 < p < 50,$$

$$x(p) = \eta(p).\sigma_x(f, \theta, D_a, t, u). \tag{1}$$

In these formulae, N_{wet} is the wet part of tropospheric refractivity, $G_{HV}(D_e)$ is the aperture averaging factor by which scintillation is reduced in finite aperture antennae compared to point receivers, L is the effective turbulent path in meter, $h = 1000$ m is the height of turbulence, $Re(= 8.5^*10^6$ meter) is the effective earth radius, e_s is the saturated water vapor pressure in mbar and u is the water vapor pressure. T and H are the annual average ambient temperature in Kelvin and relative humidity in %, θ is the path elevation angle in degree, K is the wave number in radian per meter, $\eta \cong 0.75$ is the aperture efficiency of the receiver antenna, f is the signal frequency in GHz and D is the receiver antenna diameter in meters.

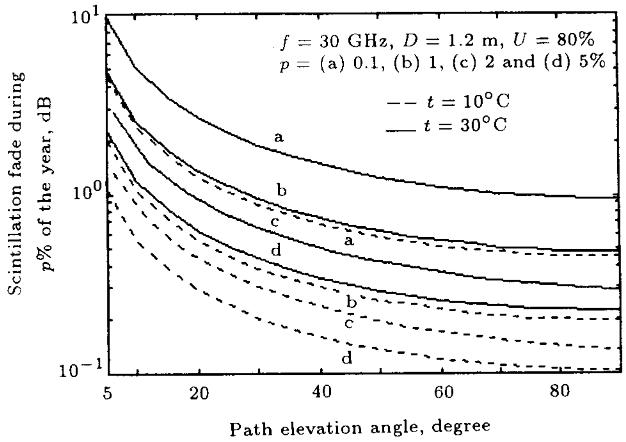

Figure 1. Scintillation fade predicted by Equation 1.

The fade predicted by Equations 1 for a satellite link with $f = 30$ GHz, $D = 1.2$ m, and $H = 80\%$ is shown in Figure 1, as a function of time percentage, p, path elevation angle, θ, and ambient temperature, t°C.

The strong influence of path elevation and ambient temperature on scintillation fade can be seen in Figure 1. For example, during 1% of the year on this satellite link in mild temperatures ($t = 10$°C) and hot tropical ($t = 30$°C) climates, scintillation fade exceeds 1.7 dB and 3.64 dB, respectively, at $\theta = 10°$, compared to thresholds of 0.2 dB and 0.43 dB at zenith elevation ($\theta = 90°$).

RAIN ATTENUATION PREDICTION

Several methods have been developed for the prediction of rain attenuation on a specified satellite link in the form of a cumulative distribution, which gives the rain attenuation levels exceeded at various percentage of time p in an average year. The most prominent methods include the global model, the ITU-R model, the SAM model and the Dutton-Dougherty and the Leito-Watson models [6-9].

In this paper, for comparing the relative importance of rain fade and scintillation fade, the SAM model is used for rain, which determines rain attenuation as a function of the equi-probable rainfall rate and has been found to give better agreement with measurements than other models. In the SAM model, rain attenuation A_p (dB), exceeded during $p\%$ of an average year, is given by [8] as follows:

$$A_p = \begin{cases} aR_p^b L & R_b \le 10 \\ aR_p^b \frac{1-\exp\left\{-\gamma_b \ln\left(\frac{R_p}{10}\right) L\cos\theta\right\}}{\gamma_b \ln\left(\frac{R_b}{10}\right)\cos\theta} & R_b \ge 10 \end{cases},$$

$$L = 2(h_e - h_0)/\left\{\sqrt{\sin^2\theta + 2(h_e - h_0)/a_e} + \sin\theta,\right.$$

$$h_e = \begin{cases} h_i & R_p \le 10 \\ h_i + \log_{10}\left(\frac{R_p}{10}\right) & R_p \ge 10 \end{cases},$$

$$h_i = \begin{cases} 4.8 & |\Theta| \le 30 \\ 7.8 - 0.1|\Theta| & |\Theta| \ge 30 \end{cases},$$

$$\gamma_b = \frac{1}{14}. \tag{2}$$

where, R_p is the equi-probable rain rate in mm/hr, the rainfall rate exceeded during $p\%$ of the year, L is the physical propagation path length through rain in km, h_e is the effective rain height in km, h_i is the 0°C isotherm height in km and a and b depend on polarization, signal frequency and temperature, Θ is the earth station latitude in degrees and θ is elevation angle.

Note that $p \le p_c$, where p_c (given in Table 1 from [7] for the 15 ITU-R rain climate zones) is the percentage time at which rainfall rate is assumed to decrease to zero, according to the expression:

$$R_p = R_1 \left\{\log\left(\frac{p_c}{p}\right) / \ln(p_c)\right\}^2, \quad 1 \le p \le p_c, \tag{3}$$

where R_1 is the exceeded rain rate at 1% time in mm/hr.

COMPUTATION AND DISCUSSION

The scintillation fade model of Equation 1 and the SAM rain attenuation model (with rain rate given by Equation 3) is now applied to study the relative magnitudes of scintillation and rain fading occurring on various tropical and temporal links for annual time percentages of at least 1%. Note that the values of parameters such as temperature, relative humidity and rain rate used in this computation are approximate. More accurate values of these parameters can be determined for a given earth station by long-term local measurements. Figures 2 and 3 give the rain attenuation for horizontally polarized radiation exceeded in various rain climatic zones at percentages of 1 and 5% as a function of link frequency and path elevation angle. It is observed that rain effects are negligible on high elevation paths at percentages above 1% in nearly all temperature climates. On the other hand, rain attenuation remains significant in tropical

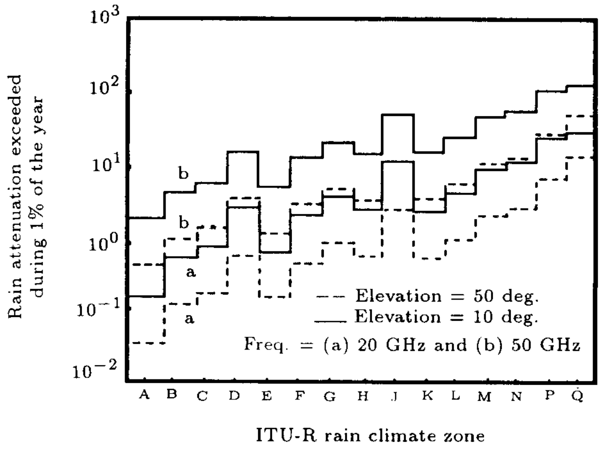

Figure 2. Rain attenuation exceeded during 1% of the year.

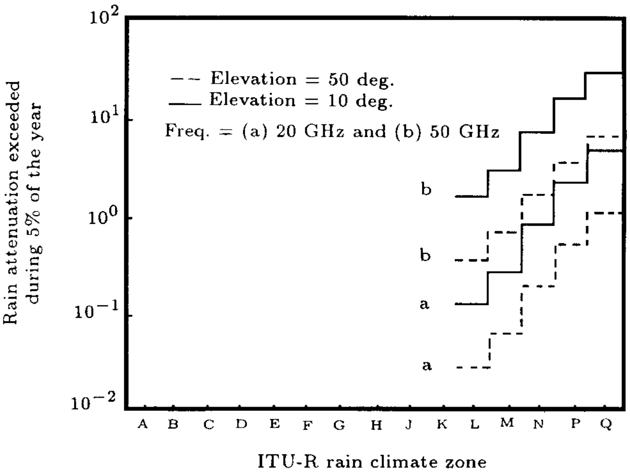

Figure 3. Rain attenuation exceeded during 5% of the year.

Table 1. 15 ITU-R rain climatic zones. R_p is the rain rate during $p\%$ of the time and $p_c(\%)$ is the percentage time at which rain rate decreases zero.

Zone	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*J*	*K*	*L*	*M*	*N*	*P*	*Q*
$R_{0.01}$	8	12	15	19	22	28	30	32	35	42	60	63	95	145	115
R_1	0.1	0.5	0.7	2.1	0.6	1.7	3	2	8	1.5	2	4	5	12	24
p_c	2	2	3	3	3	5	5	5	5	5	7.5	7.5	10	10	10

climates (e.g. zones N, P and Q) beyond 5% of the year. For example, Figure 3 shows that during 5% of the year on a 50 GHz link in zone Q, rain attenuation exceeded 28.9 dB at 10° elevation and 6.6 dB at 50° elevation. Thus, low margin systems requiring link availability of up to 95% may be difficult to implement in some tropical climates except where a high path elevation can be guaranteed. This is usually the case since tropical stations are located near the equator and can, therefore, view geostationary satellites at high path elevation angles.

The relative magnitude of scintillation fade and rain attenuation is now examined. It is clear that this depends on a number of parameters. The most significant of which are path elevation angle, link availability, climate and signal frequency [10].

To examine the relative importance of scintillation and rain attenuation, a function F, is introduced which is defined as follows:

$$F = \frac{x_p}{x_p + A_p} \times 100, \tag{4}$$

where x_p and A_P are the scintillation fade and rain attenuation exceeded during p% of the year. Now the scintillation model introduced in Equation 1 and the SAM model for rain is used to compute x_p and A_P as a function of p, θ and f in a tropical zone A (with $H =$ 90%, $t = 28°\text{C}$, $\theta = 25°$) and zone E (with $H = 80\%$, $t = 10°\text{C}$, $\theta = 50°$). In this calculation, horizontal polarization and antenna diameter are assumed as 0.28 m. The results are plotted in Figures 4 and 5. These figures confirm the following important features:

1. The relative significance of scintillation is larger at high path elevation angles. It should be emphasized that the above situation applies only to low rain rates. At higher rain rates the effective rain path is reduced by an exponential shaped rain rate profile. In this case, scintillation fading increases more rapidly than rain attenuation as path elevation decreases;

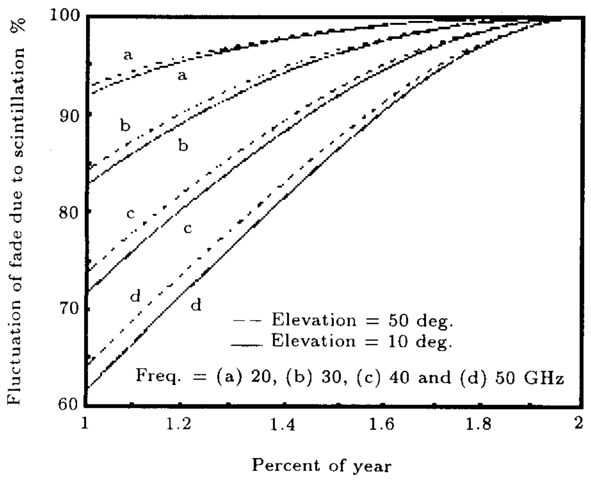

Figure 4. Relative magnitude of scintillation fading in zone A.

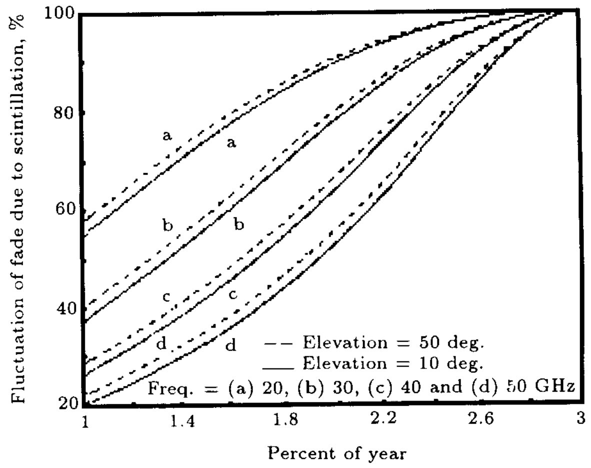

Figure 5. Relative magnitude of scintillation fading in zone E.

2. Both x_p and A_p decrease as time percentage increase, however scintillation fading decreases less rapidly and is never non-existent on a link. This is apparent in Figures 4 and 5 where F rises steadily with increasing p to a value of 100% at $p = p_c$. Thus, while rain attenuation is the predominant degradation at high link availability, scintillation fading becomes a very significant factor at low-availability;

3. The relative importance of scintillation at time percentages $\geq$ 1% depends crucially on climate and signal frequency. For example, it is observed from Figures 4 and 5 that at p = 1% and 2%, F = 92.7% and 100% in zone A and F = 58.3% and 90.4% in zone E, on a 50° elevation and 20 GHz link. That means scintillation effects are more dominant in zone A than zone E at high time percentages. Furthermore, it is observed that with other link parameters being equal, F is lower at higher frequencies. For example, in Figure 5, at $p =$ 1% and $\theta = 50°$, F = 58.3% at 20 GHz and 22.8% at 50 GHz. The gap between F at the two frequencies, however, gradually closes as p increases, until at p = 3%, F is 100% at both frequencies in zone E. Therefore, rain attenuation is comparatively more significant at higher frequencies. However, F increases more rapidly with p at higher frequencies, because tropospheric scintillation increases less rapidly with frequency than rain attenuation;

4. Finally, it is noted that scintillation degradation exhibits marked climatic dependence on both high and low availability links. At path elevation not less than 20°, tropospheric scintillation fade exceeded during 1% of the year, is, at most, 0.8 dB in a

typical temperature climate ($t = 10°\text{C}$, $H = 80\%$) at frequencies not exceeding 50 GHz, but is up to about 1.5 dB in a warm tropical climate ($t = 25°\text{C}$, $H = 90\%$). At $\theta = 5°$, scintillation fade level increases to 2.7 dB and 5.3 dB, respectively, in the two climates.

CONCLUSION

Rain attenuation increases more rapidly with frequency and poses a serious obstacle to the utilization of the large bandwidths available at Ka band. Mass-affordable interactive satellite systems, may, however, be designed at these frequencies provided they can operate satisfactorily at low availability when rain attenuation is negligible. Although rain attenuation at these frequencies can be significantly reduced or even eliminated by lowering required link availability, scintillation degradation remains significant. So, at low and high availability, an appropriate power margin must always be included in the link budget to prevent repeated scintillation-induced outage, especially on low elevation tropical paths.

This study has shown that the relative importance of rain attenuation and scintillation fading depends in a complex manner on various climatic and link parameters. The situation on a given link must be carefully analyzed to assess the feasibility of low-margin VSAT systems and the maximum realizable link availability.

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