ATLANTIS PRESS
Atlantis Highlights in Intelligent Systems (AHIS), volume 1
3rd International Conference on Control, Automation and Artificial Intelligence (CAAI 2018)

Research and Exploration on Computation and Countermeasures on Cloud, Fog and Rain Attenuation in Ka-band Satellite Communication

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***Abstract*—Satellite communication system design engineers are often concerned with the attenuation caused by propagation in rainfall while ignoring the influence on microwave propagation on satellite-earth link in satellite communication on cloudy, foggy or rainy days. This paper comprehensively gives a calculation method in satellite communication attenuation in the Ka-band. The method can be used as reference for researchers engaged in similar work. In this paper, we analyze the effects of cloud, fog and rain attenuation in Ka-band satellite communication. We also suggest real-time dynamic compensation uplink and fixed rain compensation downlink by rate diversity technology. As a result, this method compensates for cloud, fog and rain attenuation and simplifies satellite control.**

Keywords—attenuation; Ka-band; link; compensation

I. INTRODUCTION

In the design of satellite-earth link, engineers are often concerned about the rainfall in where the ground station is located. Then, they could calculate the appropriate link margin, and ensure the stable connection of the link under certain climatic conditions. However, most engineers do not consider the impact of cloud, rain and fog have on the radio wave propagation. The impact has become a forgotten area in satellite-earth link design in satellite communication. This paper aims to analyze the impact cloud, rain and fog have on satellite-earth link in satellite communication, especially in Ka-band.

II. ANALYSIS OF CLOUD AND FOG ATTENUATION IN RADIO WAVE TRANSMISSION

A. Cloud and Fog Attenuation Coefficient

Cloud and fog attenuation coefficient can be expressed by K_l. The absorption of radio waves by the cloud and fog is mainly related to liquid water in cloud and fog. Therefore, cloud and fog attenuation is mainly related to the dielectric constant of liquid water in the cloud and fog.

Dielectric constant of water [1]:

$$\varepsilon^{'}(f)=\frac{f(\varepsilon_0-\varepsilon_1)}{[1+(f/f_p)^2]}+\frac{f(\varepsilon_1-\varepsilon_2)}{[1+(f/f_s)^2]}+\varepsilon_2$$

$$\varepsilon^{n}(f)=\frac{f(\varepsilon_0-\varepsilon_1)}{f_p[1+(f/f_p)^2]}+\frac{f(\varepsilon_1-\varepsilon_2)}{f_s[1+(f/f_s)^2]} \quad (1)$$

Where, ε_0=77.6+103.3(θ-1),ε_1=5.48,ε_2=3.51,$\theta=\frac{300}{T}$,T is temperature(K),f_p=20.09-149(θ-1)+249(θ-1)^2,f_s=590-1500(θ-1)

(2)

According to Recommendation of ITU-R 840.3,K_l can be expressed as equation (3) [1]

$$K_l=\frac{0.819f}{\varepsilon^n(1+\eta^2)} \quad (3)$$

Where f is frequency(GHz), and $\eta=\frac{2+\varepsilon^{'}}{\varepsilon^n}$

B. Calculation of Cloud and Fog Attenuation

The cloud and fog attenuation of the satellite-earth link is related to the antenna elevation angle of the ground station. Supposing the antenna elevation angle of the ground station is θ, the cloud and fog attenuation of the satellite-earth link is: [1]

$$A=\frac{LK_l}{\sin\theta}\text{ dB for } 90°\geq\theta\geq5° \quad (4)$$

Where θ is the elevation angle, L is water vapor content in gas column in(kg/m^2)

III. RAIN ATTENUATION VALUE ON SATELLITE-EARTH LINK IN KA-BAND SATELLITE COMMUNICATION

From (4),

$$\theta=\arcsin\frac{LK_l}{A} \quad (5)$$

Rain attenuation coefficient γ_R can be obtained from (6) [2]

$$\gamma_R=kR^{\alpha} \quad (6)$$

k and α are related to the operating frequency and polarization,

For circular polarization and arbitrary linear polarization

$$k=\frac{[k_H+k_V+(k_H-k_V)\cos^2\theta\cos 2\tau]}{2} \tag{7}$$

$$\alpha=\frac{[k_H\alpha_H+k_V\alpha_V+(k_H\alpha_H-k_V\alpha_V)\cos^2\theta\cos 2\tau]}{2K} \tag{8}$$

Substituting (5) into (7) (8),

$$k=\frac{\left[k_H+k_V+(k_H-k_V)(1-(\frac{LK_l}{A})^2)\cos 2\tau\right]}{2} \tag{9}$$

$$\alpha=\frac{[k_H\alpha_H+k_V\alpha_V+(k_H\alpha_H-k_V\alpha_V)[1-(\frac{LK_l}{A})^2]\cos 2\tau}{2K} \tag{10}$$

Where τ is the angle between the polarization direction of the link line and the horizontal plane. When the link polarization is circularly polarized, τ is 45°. k_H, k_V, α_H are the values of horizontal and vertical linear polarization, respectively. θ is the working station elevation angle

The effective path length of the electric wave L_E passing through the rain zone can be obtained by the formula (11) [2]

$$L_E=L_P v_P \tag{11}$$

Where L_P is the attenuation path of the electric wave passing through the rainfall zone, v_p is the vertical height adjustment coefficient at the availability (1-p%), p% is the probability of the link interruption.

At the availability of 99.99%, the vertical height adjustment coefficient v_s can be obtained from (12) [2]

$$v_s=\frac{1}{1+\sqrt{\sin\theta}\left(31\left(1-e^{-\left(\frac{\theta}{1+\chi}\right)}\right)\frac{\sqrt{L_P\gamma_R}}{f^2}-0.45\right)} \tag{12}$$

Substituting equation (5) into equation (12)

$$k=\frac{1}{1+\sqrt{\frac{LK_l}{A}}\left(31\left(1-e^{-\left(\frac{\arcsin\frac{LK_l}{A}}{1+\chi}\right)}\right)\frac{\sqrt{L_P\gamma_R}}{f^2}-0.45\right)} \tag{13}$$

Where f is the link operating frequency; χ is related to the latitude of the earth station. When the latitude is $|\varphi|<36°$, $\chi=36-|\varphi|$ (unit: degree)

When the earth station latitude $|\varphi| \geq 36°$, $\chi = 0°$

The attenuation path length of the electric wave L_P (unit: km) passing through the rainfall zone can be obtained from equations (15) (16) [2]

When

$$\zeta>\theta(\zeta=\arctan(\frac{h_R-h_s}{L_s r_s})),\ L_P=L_s r_s \tag{14}$$

When

$$\zeta\leq\theta,\ L_P=\frac{h_R-h_s}{\sin\theta} \tag{15}$$

h_R is the height of the rainfall zone through which the link traverses, and h_s is the altitude of the earth station.

When the elevation angle of the earth station $\theta\geq5°$, the path of the electric wave passing through the rainfall zone L_s can be obtained by equation (16)[2]

$$L_s=\frac{h_R-h_s}{\sin\theta} \tag{16}$$

At link availability of 99.99%, horizontal path attenuation coefficient r_s can be obtained from equation (17) [2]

$$r_s=\frac{1}{1+0.78\sqrt{\frac{L_P\gamma_R}{f\cos\theta}}-0.38(1-e^{-2L_S\cos\theta})} \tag{17}$$

Substituting equation (5) into equation (17)

$$r_s=\frac{1}{1+0.78\sqrt{\frac{L_P\gamma_R}{f\sqrt{1-(\frac{LK_l}{A})^2}}}-0.38(1-e^{-2L_S\sqrt{1-(\frac{LK_l}{A})^2}})} \tag{18}$$

Then, total rainfall attenuation at availability 99.99% [2]

$$L_{Rs}=\gamma_R L_P v_s \tag{19}$$

For the availability of 99.999% to 95%, rain attenuation L_R can be obtained from equation (18)[2]:

$$L_R=L_{Rs}(\frac{p}{0.01})^{-(0.655+0.033\ln p-0.045\ln L_{Rs}-\beta(1-p)\sin\theta)} \tag{20}$$

Substituting equation (5) into equation (21) comes out a cloud, fog and rain attenuation with the availability of 99.999% to 95%.

$$L_R=L_{Rs}(\frac{p}{0.01})^{-(0.655+0.033\ln p-0.045\ln L_{Rs}-\frac{\beta(1-p)LK_l}{A})} \tag{21}$$

β is related to the link availability and the latitude of the earth station.

When the availability is not more than 99% or the latitude of the earth station $|\varphi| \geq 36°$, $\beta = 0$.

When availability is greater than 99%, and the latitude of the earth station $|\varphi|<36°$:

when the earth station's elevation angle $\theta\geq25°$, $\beta=-0.05(|\varphi|-36)$;

otherwise

$$\beta=-0.05(|\varphi|-36)+1.8-4.25\sin\theta=-0.05(|\varphi|-36)+1.8-4.25\sin\theta$$

IV. Cloud, Fog and Rain Attenuation Compensation Strategy

A. *Rate Diversity Technology*

The signal to noise ratio is expressed by equation (22) [3]

$$I=\frac{P_T G}{N_0 R} \tag{22}$$

Where P_T is the transmit power, G is the channel gain, N_0 is unilateral power spectral density of noise (can be taken as 1), and R is the symbol rate. QPSK modulation is used, so the symbol rate is 1/2 of the information rate R_b. If R_b reduces, the signal-to-noise ratio will increase, and the bit error rate will reduce. Since the cloud, fog and rain fading channel is uncertain, we should estimate the gain G. Its estimation formula is [3]

$$\widehat{G}=e^{m+\frac{a^2\sigma^2}{2}} \tag{23}$$

In the formula, the parameters m and σ^2 are the mean and variance of the random variable X= lnG, respectively, a is the fading factor, $a=e^{-w_d T_d}=e^{-\Pi f_d T_d}$, f_d is Puls frequency shift in fading channel. T_d is the symbol sampling interval, $0 < a < l$.

To let the difference between the estimated channel gain and the real channel gain as small as possible, a correction margin K is introduced, and its expression is [3].

$$K=[e^m/G_{out}]^{\sqrt{1-a^2}} \tag{24}$$

Where G_{out} is the threshold of channel gain, $G_{out}=e^{m-\sigma Q^{-1}|P_{out}|}$, $Q(x)=1/2\mathrm{erfc}(x/\sqrt{2})$, and P_{out} is the outage probability of the system.

The estimated value of the signal-to-noise ratio is [3]

$$\hat{I}=\frac{2P_T\widehat{G}}{N_0 R_b K} \tag{25}$$

Let the maximum transmission rate of the Ka-band satellite communication system be R_{max}, and we can obtain the estimated signal-to-noise ratio $\hat{I}_{R_{max}}$ from equation (26) at the maximum information rate under the cloud-fog-rain channel under adaptive power control.

$$\hat{I}_{R_{max}}=\frac{2P_T\widehat{G}}{N_0 R_{max} K} \tag{26}$$

Outage probability of the satellite system should be 0.01%. According to [4], the bit error rate should be 10^{-7}. Assuming that the corresponding signal-to-noise ratio is $\hat{I}_o$, the signal-to-noise ratio after rate diversity compensation should be no less than $\hat{I}_o$. According to [4], [5], $\hat{I}_o$ can be obtained by simulating the error rate of the channel under adaptive power compensation. Then, we can calculate the ratio of SNR [6].

$$\Delta\hat{I}=\frac{\hat{I}_o}{\hat{I}_{R_{max}}}=\frac{\frac{2P_T\widehat{G}}{N_0 R_b K}}{\frac{2P_T\widehat{G}}{N_0 R_{max} K}}=\frac{R_{max}}{R_b} \tag{27}$$

From equation (27), we could obtain that the adjustment of the information rate R_b is related to $\Delta\hat{I}$

B. *Dynamic Compensation Achieved by Speed Diversity Technology*

From equation (27) we can obtain,

$$N_0=\frac{2P_T\widehat{G}}{R_b K\hat{I}} \tag{28}$$

Let the demodulation threshold of the link transmission error rate p_e be $(C/N_o)_{min}$.

When the link availability is A_T, the rain attenuation is L_r, and the lowest level is [7].

$$C_{min}=(C/N_o)_{min}-L_r+N_o+M_c \tag{29}$$

M_c is the link margin under clear-sky conditions. N_o is the link noise power spectral density. C is the link signal level.

Substituting equations (22) and (28) into (29)

$$C_{min}=\left(\frac{CR_b K\hat{I}}{2P_T\widehat{G}}\right)_{min}-L_{Rs}\left(\frac{p}{0.01}\right)^{-(0.655+0.033\ln p-0.045\ln L_{Rs}-\frac{\beta(1-p)LK_1}{A})}+\frac{2P_T\widehat{G}}{R_b K\hat{I}}+M_c \tag{30}$$

Fixed compensation is applied in downlink, and dynamic rain attenuation compensation can be used in uplink.

From [3], we know that if the rainfall attenuation of the frequency f_1 is A_1, the rainfall attenuation A_2 of the frequency f_2 can be obtained from the formula.

$$A_2=A_1(\varphi_2/\varphi_1)^{1-H(\varphi_2*\varphi_1*A_1)} \tag{31}$$

where φ_2, φ_1 are the frequency, and f_1, f_2 are rainfall attenuation parameters.

$$\varphi(f)=\frac{f^2}{1+10^{-4f^2}} \tag{32}$$

$$H(\varphi_2,\varphi_1,A_1)=1.12*10^{-3}*(\varphi_2/\varphi_1)^{0.5}(\varphi_1 A_1)^{0.55} \tag{33}$$

The value of f_1,f_2 range from 7 to 55 GHz. The Ka-band link frequency ranges from 19 to 31 GHz.

Therefore, this formula can be used for uplink rain attenuation compensation. However, the statistical formula in [3] is a fitting of the rainfall attenuation relationship, of all frequencies from 7 to 55 GHz and of various environments. There are fitting errors and statistical errors in specific frequencies and positions.

According [8], channel interference, noise, satellite transmitter gain variation, earth station device gain variation might also change in the downlink level. Regardless of changes in downlink level caused by these factors, false compensation might occur when compensating the uplink by the cloud, fog and rain attenuation. What's worse, the satellite transponder may be saturated or damaged.

While downlink level measured in real time compensates the variation in earth station downlink device gain in the telemetry determination, we can compare the reception level and the level change threshold L_t, the level threshold S_t and level change duration threshold T. If the level is changed by the cloud, fog and rain attenuation, the uplink level compensation value A_u can be obtained from the downlink level attenuation value, and the uplink power is adjusted.

The value of L_t is determined by the satellite power stability L_s, channel interference L_i, noise L_n, and multipath attenuation L_m. The threshold is set to avoid adjusting the uplink power caused by downlink level fluctuation from channel interference, noise, multipath fading, etc. [8]

$$L_t=(L_s^2+L_n^2+L_i^2+L_m^2)^{1/2} \tag{34}$$

S_t is the minimum level value of start control with uplink compensation. It is determined by the link demodulation threshold $(C/N_o)_{min}$ and the link margin M_c. By setting the threshold people can avoid adjusting the uplink power caused by downlink level fluctuations caused by tracking errors, ionospheric changes, etc. People only adjust the uplink power only when the link signal-to-noise ratio is close to or lower than the demodulation threshold that affects the link transmission error rate [8]

$$S_t=(C/N_o)_{min}+N_o+M_c \tag{35}$$

Substitute equations (22) and (28) into equation (35)

$$S_t=(\frac{CR_bK\hat{I}}{2P_T\hat{G}})_{min}+M_c+\frac{2P_T\hat{G}}{R_bK\hat{I}} \tag{36}$$

Frequent adjustment of uplink power caused by short-term fluctuations in the downlink can be avoided by setting the threshold of the minimum time interval T for compensation [8]

$$T=\max(T_m,T_n,T_i,\ldots) \tag{37}$$

Where T_m is the maximum value of the level fluctuation duration caused by multipath, T_n is the random interference duration, and T_i is the duration of the flicker noise.

The dynamic compensation accuracy is mainly related to the measurement error of the downlink level σ_{dm}, conversion error $\sigma_c$from cloud, fog and rain attenuation value in downlink level and the cloud, fog and rain attenuation value in uplink level, short-term stability in satellite power σ_s, control error in uplink power σ_{uc} and so on. They can be determined by experiment, while σ_c is determined by long-term statistic data. The total compensation error σ is [8]

$$\sigma=(\sigma_{dm}^2+\sigma_c^2+\sigma_s^2+\sigma_{uc}^2)^{1/2} \tag{38}$$

In general, σ_{dm} is 0.1~ldB, $\sigma_s$is 0.2~ldB, σ_c is 0.1~ldB, and σ_{uc} is 0.1~0.5dB. According to the maximum value, the total error of cloud and rain attenuation compensation of this method σ is 1.8dB.

V. APPLICATIONS

With the cloud, fog and rain attenuation compensation strategy obtained above, the uplink rain attenuation compensation can be performed with data of a Ka-band communication earth station in Beijing on July 3rd, 2016. The measured data of the uplink and downlink rain attenuation is shown in Figure 1. From 6:58 to 8:53, the highest link level attenuation value was 18.63Db. The link level attenuation value was no more than 3Db when there was no rain. According to [8], in dynamic compensation, when L_t = 1dB, S_t = 0dB, and T = 60s. The uplink cloud, fog and rain attenuation compensation result is shown in Figure 2.

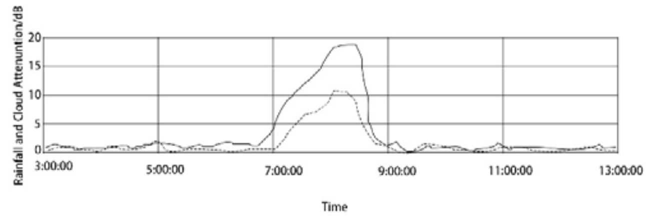

FIGURE. I. CLOUD, FOG AND RAIN ATTENUATION ON THE UPLINK AND DOWNLINK OF KA-BAND EARTH STATION IN A CERTAIN AREA OF BEIJING. SOLID LINE INDICATES UPLINK, DASHED LINE INDICATES DOWNLINK

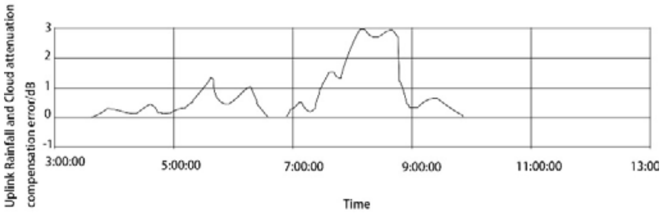

FIGURE. II. UPLINK CLOUD FOG RAIN ATTENUATION COMPENSATION

FIGURE. I and FIGURE. II indicate that, when no compensation is performed, the uplink cloud, fog and rain attenuation is up to 18.64 Db. When compensation is performed, the uplink attenuation is 2.91 Db. This is the compensation error.

It can be obtained from [9] that this compensation has better effect than the compensation of the American Advanced Communication Satellite System (ACTS), whose compensation error is 5dB.

VI. CONCLUSIONS

This paper describes the calculation method of cloud, fog and rain attenuation in Ka-band satellite communication link and applies rate diversity technology for dynamic compensation. In practice, it can effectively reduce the compensation error and ensure reliable transmission of information.

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