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SATELLITE COMMUNICATION: SIGNAL ATTENUATION BY RAIN AND CLOUDS

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Abstract - Satellite Communication has been the most versatile modes of communication among modern communication systems since couple of decades. Despite being high-quality system, it lacks cent efficiency. The signal sent through uplink and downlink suffers attenuation on account of many factors. Two major factors of the medium of propagation are Rain and Clouds. These two factors share water droplets as their common constituent. Electromagnetic waves get scattered due to differential refractive index of water droplets and get attenuated. ITU (International Telecommunication Union) has specified highly precise models to reconstruct the original incident signals. This paper provides basics of how attenuation causes deviation in the net energy of the wave.

Keywords - Directivity, Attenuation, Specific Attenuation, Lin's Model, Faraday Effect, Depolarization, Scintillation.

I. INTRODUCTION

Signal is carried and communicated on EM waves of particular frequencies. Beams of waves are transmitted from satellite and received by ground antenna. Due to the inherent disturbances in the propagation medium, the beam looses directivity. Directivity is a focusing characteristic of wave. Antenna's directivity is given by:

$$D(\theta,\phi) = \frac{P(\theta,\phi)}{P}$$

Here θ is the elevation, ϕ is the azimuth, $P(\theta,\phi)$ is the radiation intensity in the direction (θ,ϕ) and P is the average radiation Intensity. As the propagation path increases, the wave beam travels in a much larger solid angle due to the uncertainties in θ and ϕ.

$$D(\theta,\phi) \propto P(\Delta\theta,\Delta\phi)$$

Due to this deviation in directivity, the antenna receives the signals of different strength from different directions in downlink communication (Henceforth, I shall deal with downlink communication). The transmitted signal is the vector sum of these components. The wave directly received on the antenna is termed as root component or r(t). Other characterization of components are diffused component d(t) and specular component s(t).

$$\psi(t) = r(t) + s(t) + d(t)$$

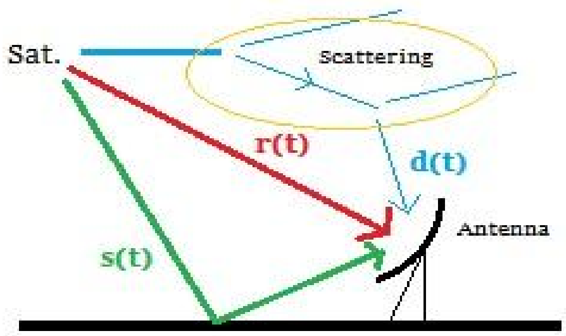

Fig. 1. Components of Signal Received

Diffused component is caused by scattering from nearby objects.[1] $\psi(t)$ reaching at the antennas also depend uponthe availability of link between the satellite and receiver. Availability refers to the percentage of time that the link guarantees a specified link quality.[1] Hence we may include a factor called environment dependent attenuation factor or $\alpha(h)$.

$$\psi(t) = \alpha(h)[r(t) + s(t) + d(t)]$$

Here "h" represents the altitude. $\alpha(h)$ being 0 indicates that satellite is in shadow and $\alpha(h)$ being 1 indicates that the satellite is in total visibility of receiver and hence, link is established perfectly. Since the diffused component carries small energy as compared to the other two components, we can introduce a Kronecker Delta operator with the term $d(t)$.

$$\psi(t) = \alpha(h)[r(t) + s(t)] + d(t)\delta[\alpha(h),1] \quad (1)$$

This is the generic solution for the signal wave. If $\alpha(h)$ is any value other than 1, eq.1 will get rid of the diffused component altogether. Besides $\alpha(h)$, rain and cloud attenuations affect the magnitude of energy being received. It is necessary to consider other attenuation causing factors like ice, ionospheric effects, gaseous composition of medium and antenna configuration. Energy, after being attenuated, can be found out using the following two equations:

$$A = 10log_{10}\frac{I_0}{I} \quad (2)$$

$$I = kE^2 \quad (3)$$

Here "I_0" is input intensity, "I" is output intensity and "E" is Energy. E in terms of input energy (E_0) can be given using eq. 2 and eq. 3.

$$E = E_0 10^{\frac{A}{20}} \quad (4)$$

II. ATTENUATION DUE TO RAIN

Hydrometer is a general name for referring to condensed water vapors existing in atmosphere to condensed water existing in the atmosphere.[1] Rain is the major hydrometer which affects the signal. The most generalized representation of attenuation is given by:

$$A_r = aR^bL(r)$$

Here
"a" is frequency dependent constant
"b" is temperature dependent constant
"R" is the surface rain rate at the given location
"L(r)" is the effective length of the rain at that particular location. Total attenuation is the summation of specific attenuations.

$$A_r = \int_0^{L(r)} a_s da_s$$

Here "a_s" is coefficient of specific attenuation. It depends on the radius of rain droplets, refractive index gradient and frequency of signal wave.

The most preferred expression for obtaining "L(r)" is a derivative of Lin's model. Lin performed many experiments at US locations in 5 minute averaged rain. The rationale behind choosing 5 minute averaged rain is because 5 minute rains are very common not only in US, but also in the spectrum of neighboring longitudes.[1]

$$L(r) = 2636/[R - 6.2 + \frac{2636sin(\theta)}{4 - G}]$$

ITU-R specifies 20% as expected variability in rain attenuation from year to year.[2] The energy deviation due to such attenuation is:

$$E(r) = E_0 10^{\frac{aR^bL(r)}{20}}$$

This equation is derived by substituting eq. 5 in eq. 4. Since clouds are above the rain altitudes, here E_0, the input energy for rain attenuation, is already altered due to cloud attenuation.

III. ATTENUATION DUE TO CLOUDS

It is possible to measure specific attenuation of the cloud (a_s) by the liquid content present in it.[3]

$$a_s = k_c\rho$$

Here k_c is specific attenuation coefficient and ρ is the liquid content density of cloud.
Clouds have liquid content upto 5g/m^3. Calculations of the specific attenuations shows that for frequencies less than 30 GHz, the largest attenuation from clouds in fair weather (liquid content ~ 2.5g/m^3) is equivalent to attenuation caused by light rain (~ 10mm/h).[1]
Total attenuation is given by summation of specific attenuations of discrete patches over the cloud base area above the region over which clouds are present. Let the length and breadth of the cloud's base be "n" and "m" respectively.

$$A_c = \sum_0^{nm} a_s$$

$$\Rightarrow A_c = k_c \sum_0^{nm} \rho$$

$$\Rightarrow A_c = k_c \sum_0^{nm} \frac{w(\Delta V)}{\Delta n \Delta m \Delta h}$$

Here $w(\Delta V)$ is the mass of liquid content in an unit volume and "h" is altitude.

$$\Rightarrow A_c = k_c W \frac{1}{nm} \frac{\sum}{\Delta h} (7)$$

Here "W" is the total mass of liquid content of cloud. $\frac{\sum}{\Delta h}$ represents varying altitude over each discrete patch of cloud. Mathematical operation to obtain eq. 7 can be justified analytically. It is well known that, unlike rain, clouds are present in discrete patches. Hence we used discrete summation over integration. Summation of differential base area $(\frac{1}{\Delta n \Delta m})$ gives the total base area. The only variable is "h" as it may be different for each patch of cloud. Using eq. 7 and eq. 4, energy deviation due to cloud attenuation is obtained as:

$$E(c) = E_0 10^{k_c W \frac{1}{20nm} \frac{\sum}{\Delta h}} \qquad (8)$$

The signal reaches to clouds through ionosphere. Therefore, E_0 is already altered due to ionospheric effects.

IV. ATTENUATION DUE TO OTHER FACTORS

A. Ionospheric Effects

Faraday Effect and scintillation are two major ionospheric effects. Faraday Effect refers to the twisting of EM wave in Earth's magnetic field. This twisting angle is inversefunction of the square of signal frequency. Angles at 4GHz and 6GHz are 9^o and 4^o respectively. Scintillation refers to gaining fluctuations in amplitude, frequency and phase of the signal wave. It occurs due to electron densities in the ionosphere. It is insignificant for frequencies over 7GHz. As we can see, these are minor attenuation factors. Signals affected by Faraday Effect can be reconstructed by assigning specific predicted polarization angles of antenna.

B. Depolarization

Interference between orthogonal components of wave is the reason for depolarization. As the wave strikes an oblate rain drop at particular angles, signals get coupled between the field vectors. The magnitude of depolarization can be unpredictable and imprecise due to randomness in canting angle of rain drops. Similarly, depolarization due to ice is insignificant.

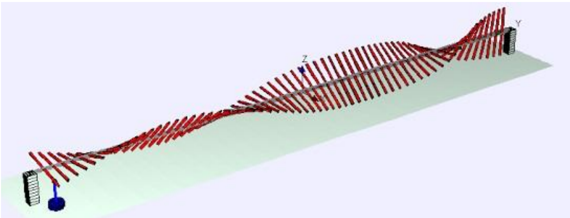

Fig. 2. Twisting of EM Wave [4]

We can see that these effects can be neglected while analyzing the basic energy configuration of receiving wave. Nevertheless, ITU has complex models to analyze the slightest depressions.

V. ENERGY ANALYSIS

We have seen that the wave energy is altered due to rain and cloud attenuation. The equations corresponding to energy depression due to each factor are derived (eq. 6 & eq. 8). The fundamental approach for energy analysis is to calculate net energy of the signal reaching to receiver antenna. Clearly, irrespective of signs of the energy deviations, individual energy deviations would be subtracted from the transmitted energy.

$$E_{net} = E_T - \Delta E(r) - \Delta E(c) \qquad (9)$$

Here, E_T is transmitted energy. Substituting the values of individual energy deviations (eq. 6 and eq. 8) in eq. 9:

$$E_{net} = E_T - E_T 10^{K_c W \frac{1}{20nm} \sum_{\Delta h} (1 - 10^{\frac{aR^b L(R)}{20}}$$

We know that the signal wave getting received by antenna has three components. The energy carried by the three components is:

$$E_T = \lim_{t \to \infty} \int_{-\infty}^{\infty} [\psi(t)]^2 dt$$

Therefore,

$$E_{net} = \lim_{t \to \infty} \int_{-\infty}^{\infty} [\psi(t)]^2 dt [1 - 10^{K_c W \frac{1}{20nm} \sum_{\Delta h} (1 - 10^{\frac{aR^b L(R)}{20}})}] \qquad (11)$$

We know that $[1 - 10^{K_c W \frac{1}{20nm} \sum_{\Delta h} (1 - 10^{\frac{aR^b L(R)}{20}})}]$ is less than one. Therefore, we can conclude that E_{net} will always be less than E_T. The energy depression can be calculated as $E_T - E_{net}$.

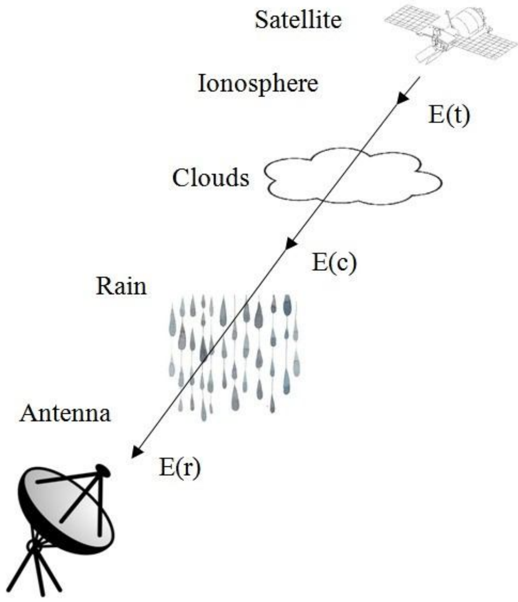

Fig. 3. Energy Diagram

CONCLUSION

Energy of signal being received by antenna is formulated (eq. 11) considering two major attenuation factors - Rain and Clouds. Although derived from downlink communication, this energy depression is not specific to it. This depression is the characteristic of the medium. Hence, keeping it in consideration, desired energy of signal sent to satellite in uplink communication can be adjusted.

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