Comparative Study of Cloud Attenuation for Millimeter Wave Communications

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Summary
The loss of signal in terms of attenuation is very common problem. Signal attenuation can cause degradation in the Quality of service (QoS) in wireless communication. Networks operating over high frequency bands are highly affected by signal attenuation. This is particularly trivial in the millimeter (mm) wave bands. The number of climatic factors which cause signal attenuation include fog, cloud, rain, gas but attenuation due to clouds is a complex study because of the structure of clouds and higher probability of occurrence. It is important to investigate the effect of clouds on electromagnetic waves and to study the models of cloud attenuation as its role at mm is significant. This research work presents the comparative study of such empirical models which provides the cloud attenuation considering frequency, elevation angle and liquid water content as input parameters. Simulated results showed that liquid water content and frequency are directly proportional to cloud attenuation while at lower elevation angle the cloud attenuation is higher. Moreover, Dissanayake-Allnutt-Haidara (DAH) model has the lowest attenuation loss as compared to other models.

Key words: Cloud attenuation, prediction models, millimeter (mm) wave

1. Introduction

Signals are attenuated when traversing through the atmosphere by parameters such as water vapor, oxygen, rain, cloud, scintillation, fog and dust. Above 10 GHz the most dominant propagation impairment is cloud attenuation, and it is present under more than 95% of time [1]. With increasing operating frequency, the additional impairments such as gaseous absorption, rain attenuation, melting layer attenuation and tropospheric refractive effects become increasingly important. Cloud attenuation is directly proportional to the frequency up to about 100 GHz in microwave region and depends on mass of the water in clouds in a specified amount of air across the propagation path which is measure per volume of the air [2]. Cloud attenuation is a function of mainly liquid water content, temperature, frequency and elevation angle which can be measure through different available resources. For calculation of cloud attenuation many prediction models already exist in the literature. Due to diversity and not easily redeemable of inputs to such models it's also difficult to find the dependable data against which the accuracy can be checked.

Clouds are of different types and are formed when moist air goes upward. When the air rises it becomes colder. Finally, the air can't hold all of the vapors in it, so some of the water vapor goes to the condensation process to form water droplets. The fog is formed in the same way when the process occurs close to the ground. Clouds physical features are not stationary which means they change all the time. At any given time, the earth's surface is covered 50% with clouds statistically [3] which leads us to the impact that they have. The fog is similar to clouds but the only difference between these two is the place of formation. Clouds are present under more than 95% of time so attenuation occurs due to clouds became an important factor.

From the list of factors affecting the signal, prediction of both rain attenuation and cloud attenuation is important for mm wave frequency bands [4], [5]. The initial efforts to develop mathematical models for cloud attenuation were put forward by Mie and Rayleigh and initiated by [6]. These initial models are based on mathematical equations and hence can't accommodate empirical data. Mainly two alternative approaches i.e. physical based and semi empirical models are typically presented in literature [7].

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The physical models are most precise method and depends on individual particles microphysics as well as electromagnetic properties. First, the propagation path is divided into horizontal homogenous layers for computing specific attenuation of each layer. The total attenuation can be calculated by adding all the layers contribution. The main drawback of physically based models is the difficulty in finding the knowledge of vertical profile of air pressure, humidity and temperature in any site [7].

Later the empirical models were independently developed, such as those proposed by Dintelmann and Ortgies [8] and Altshuler and Marr [9], [10], calculating the cloud attenuation using the surface absolute humidity as an input parameter. The coefficients of these model expressions depend on actual measurements. The methodology to predict cloud attenuation proposed by Dissanayake et al. [11] is the worth mentioning and is based on occurrence probability of four different cloud types which come from cloud cover atlas [12]. The model proposed by Salonen and Uppala in [13] also known as Teknillinen KorkeaKoulu (TKK) which shows the good prediction accuracy also accepted in Recommendation ITU-R P.840-6. Mass absorption coefficients Model which is an alternative approach of Salonen and Uppala proposed by Luini and Capsoni [14], [15].

Nikolaos K. Lyras et al. in [16] presented a model that includes the spatial and temporal behavior of Integrated Liquid Water Content. Two-year statistical results of cloud attenuation on a Ka-band satellite link have been reported in [17] and the results are compared to the ITU-R model. Lorenzo Luini in [18] developed an extensive methodology to access tropospheric fade altering the earth-space communication system is given which combines the synthetic fields of rain rate, water vapor and clouds. The authors in [19], presented the comparison between two cloud models on the basis of prediction of cloud liquid water content and cloud attenuation in a tropical region.

Many experimental studies have been conducted on mm wave atmospheric attenuation. Based on these studies cloud cover statistic and cloud attenuation for the African tropical rain forest climate is investigated [20]. The use of meteorological data available worldwide are used for estimation due to clouds, water vapor and oxygen in Belgium and India [21]. It is well known that the water vapor plays an important role in Earth's cycle [22] therefore in [23] for cloud vertical structure detection is used in tropical region and its improved approach for determining the cloud attenuation is presented in [24]. In [25], [26] different aspect of clouds e.g. drop size, temperature, liquid water content and dielectric constant with respect to cloud attenuation is discussed and its effects on satellite communication is given, while in this research work the effect of frequency, elevation angle and liquid water content on cloud attenuation is presented. Moreover, the attenuation loss results are analyzed with theoretical Empirical Cumulative Distribution Function equation.

Rest of the paper is organized as follows: section II, presents the mathematical analysis of cloud attenuation for commonly used prediction models namely Salonen and Uppala, Mass Absorption and Dissanayake-Allnutt-Haidara (DAH). Section III, demonstrates the simulated results of the models with different parameters. Finally, section IV, comments on conclusions of this research.

2. Cloud Attenuation Models

2.1 Dintelmann and Ortgies Model

It is the initial model developed by Dintelmann et al in [8] to calculate the attenuation of clouds. The basic idea of this model was the clouds formation. At a certain height, h, when water vapours in the atmosphere increase than the quantity that the air can hold potentially which is called the saturation density, ρ_S, the condensation process starts and small tinny droplets of water form which combine to form clouds. The water vapour concentration at that height $\rho(h)$ can be measured at ground and is given as

$$(h) = \rho \frac{T_o}{T}\left(1 - \frac{k-1}{k}\frac{gh}{RT_o}\right)^{\frac{k}{k-1}} \quad (1)$$

where ρ_o is the water vapor concentration at ground level in g/m^3 measured from ground temperature, T_o, T is the absolute temperature in K which is assumed to be 270K, k is specific heat ratio for water vapor molecule which is 4/3, g is the acceleration due to gravity i.e. 9.8 m/s^2, R is the fundamental gas constant which is 0.4615 J(kg) for water vapor and height, $h = 0.89 + 0.165(T_o - 273)$ is related to ground temperature. The water vapor concentration, $\rho(h)$, given in (1) can be used to calculate the liquid water content, w, as:

$$w(h) = \begin{cases} 0 \\ \rho(h) - 3.82 \end{cases} \quad (2)$$

If the water vapor concentration ρ is equal or less than saturation density , ρ_S, whose value is about 3.82 g/m^3, then the liquid water content, w, in clouds is zero and if the ρ is greater than ρ_S, then w in clouds is the difference of water vapor concentration ρ and saturation density ρ_S. The slobin expression's using the w is

$$\alpha = \frac{5.038\, w\, 10^{-0.744}}{\lambda^2} \text{ (dB/Km)}$$

where λ is the wave length in cm. The final equation to calculate the attenuation along with the elevation angle θ is given by [8]:

$$A = \alpha \frac{\Delta}{sin\theta} \quad (4)$$

where Δ is the vertical extent of clouds. Due to scare knowledge on Δ, authors made use of radiometer measurements carried out at 20 GHz and 30 GHz.

2.2 Salonen and Uppala Model (ITU-R P.840-6)

Salonen and Uppala developed a model which was adopted in Recommendation ITU-R P.840-6 (ITU-R P.840-6). It is also known as Teknillien KorkeaKoulu (TKK) model. This model estimates the cloud attenuation using the vertical profile of temperature, pressure and liquid water content. The specific attenuation, γ_c, due to clouds is given by following equation [27]:

$$\gamma_c = k_1 w \quad (5)$$

where w is the liquid water content in g/m^3 and k_1 is the coefficient of liquid water content and is given by

$$k_1 = \frac{0.819\, f}{\epsilon''(1+\eta^2)} \quad (6)$$

where $\eta^2 = \frac{2+\epsilon'}{\epsilon''}$ is the constant, ϵ' and ϵ'' are the real and imaginary parts of electric permittivity of water respectively which are valid for upto 1000GHz frequencies and -10°C to 30°C temperature. The liquid water content, w, in clouds is given as [27]:

$$w = \begin{cases} w_o(1+cT)\left[\frac{h_c}{h_r}\right] p_w(T) & T \geq 0°C \\ w_o e^{cT} \frac{h_c}{h_r} p_w(T) & T < 0°C \end{cases} \quad (7)$$

where c is the factor of temperature dependence and is equal to 0.041/°C, T is the temperature in °C, h_c is the height from cloud base in m, w_0 = 0.14 g/m^3, h_r= 1500m and $p_w\,(T)$ is the liquid water/ice fraction. Salonen and Uppala introduced a reduced liquid water content w_R to a fixed temperature T_R such that $\gamma_c' = k_1(T_R) w_R(T_R)$. The change from actual values of T is taken into account by converting w to w_R. The term $k_1(T_R)$ can be used for all the cloud layers but for the calculation of whole path attenuation integrated liquid water content w_R reduced is considered. The equation for the slant path attenuation is given by [13]

$$A = \frac{k_1 w_R}{\sin(\theta)} \quad (8)$$

The approach proposed by Salonen and Uppala to calculate the attenuation using the reduced liquid water content w_R has adopted in Recommendation P.840-6 (ITU-R P.840-6) using the Pressure-Relative Humidity-Temperature (P-RH-T) profiles extracted from ERA-40 database.

2.3 Mass absorption coefficients Model

The main drawback of Salonen and Uppala model is that it can only receive reduced integrated liquid water content as an input from ERA40 and cannot accept input from any other source of cloud data. To overcome this problem Luini and Capsoni in [14], [15], derived an expression of mass absorption coefficient $a_W(f)$ as a function only of frequency operating in 20 GHz to 200 GHz from RAOBS data. The cloud attenuation $A(f)$ is given by [15]:

$$A(f) = \frac{a_w(f) w_R}{\sin(\theta)} \quad (9)$$

where $a_W(f)$ is given as

$$a_W(f) = \frac{0.819\,(af^b + cf^d + e)}{\epsilon''(1+\eta^2)} \quad (10)$$

According to authors, the knowledge of a_W and w is enough to calculate cloud attenuation. This solution introduces to work with physical quantity w not with w_R.

2.4 DAH Model

This model was proposed by Dissanayake et. al [11] which gave better prediction of cloud attenuation as it depends on average properties of different cloud types and their occurrence probabilities which come from cloud cover atlas. The atlas provides the characteristics of six different clouds which are; Cirrus, Cumulus, Cumulonimbus, Stratus, Nimbostratus and Altostratus. The specific attenuation is related to cloud water content and is given by

$$\gamma_c = 0.4343 \left(\frac{3\pi}{50\lambda P_d}\right) Im\left(\frac{-(\epsilon-1)}{(\epsilon+2)}\right) \quad (11)$$

where ϵ is the complex dielectric constant of water and P_d is the density of water as a function of temperature, its value can be taken as 1. The liquid water content varies from cloud to cloud and their vertical and horizontal extent is also different. The total attenuation through the clouds can be obtained as [11]:

$$A_i = A_Z^i L_i \quad (12)$$

where i is the type of cloud, $A_Z^i = 0.52\gamma_C w^i L_v^i$ is the zenith path attenuation of i-th cloud and L_i is path length of i-th cloud [11].

3. Simulation Results

This section presents the simulated results obtained from Salonen and Uppala model, Mass absorption model and DAH model. The attenuation loss results are achieved by considering the frequency range of 30 to 60 GHz, elevation angle of 10 to 90 degree and liquid water content from 0.1 to 0.9 mm as preliminary input parameters. In addition, the efficiency of these models is theoretically verified by using the Empirical Cumulative Distribution Function (ECDF) equations.

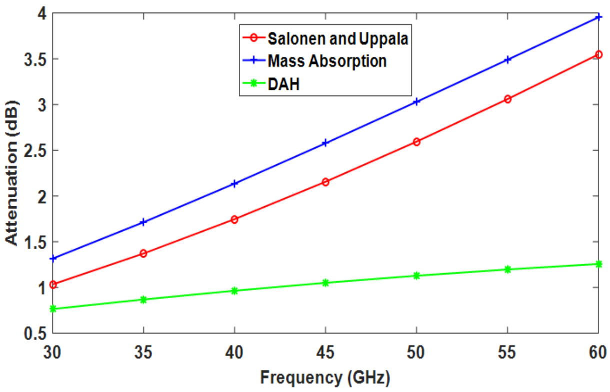

Fig. 1. Cloud attenuation for varying frequency at elevation angle of 40°

3.1 Cloud Attenuation

Fig. 1 shows the cloud attenuation of three models given in equation (2.20), (2.21) and (2.31) for a frequency range of 30 to 60 GHz with 40° elevation angle and liquid water content 1mm. It can be seen that the cloud attenuation is directly proportional to operating frequency. At lower frequency 30 GHz almost all the models show a similar attenuation loss in dB and as frequency increases the attenuation loss also increases for all models. While comparing the models, the mass absorption coefficient model shows a significant attenuation as compared to other two models, especially at higher frequency band. DAH model gives a low attenuation loss among all due to the fact that it uses the cloud coverage parameters that to calculate fairly accurate predictions and it based on factors which has less dependency on frequency. Moreover, similar pattern of attenuation loss is observed for elevation angle of 50° and 60° for frequency range of 30 to 60 GHz and liquid water content of 1mm as shown in Fig. 2 and Fig. 3.

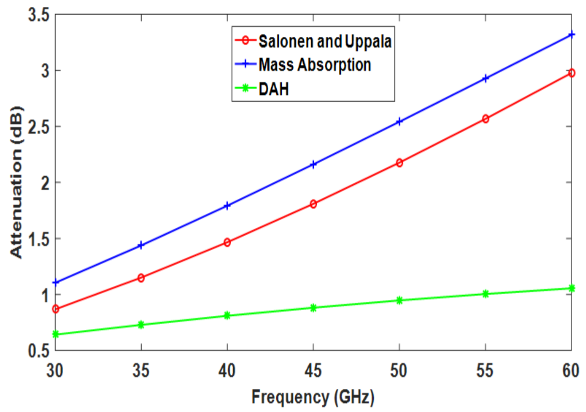

Fig. 2. Cloud attenuation for varying frequency at elevation angle of 50°

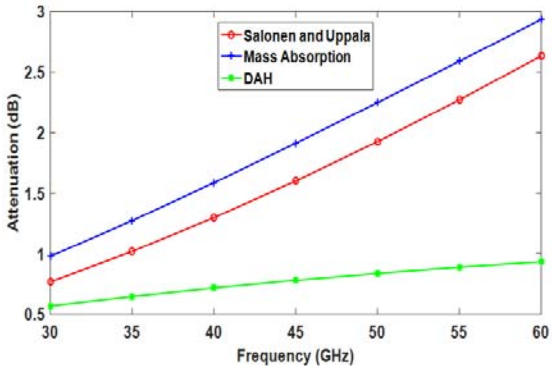

Fig. 3. Cloud attenuation for varying frequency at elevation angle of 60°

The observation of the Fig. 4 and Fig. 5 suggests the preference of higher elevation angles for frequency of 30GHz and 40GHz, respectively and 1mm liquid water content. It can be seen that elevation angle is inversely proportional to the attenuation i.e. by increasing elevation angle the attenuation decreases. For the lower elevation angle of 10°, the attenuation is high, and for higher elevation angle of 100°, the attenuation can be seen very low as around 0.5 dB for all the three models. Further, DAH model gives a low attenuation loss then the other models due to the fact that its elevation angle depends on the dimension of each cloud type. The model will give more accurate result if more factors are included.

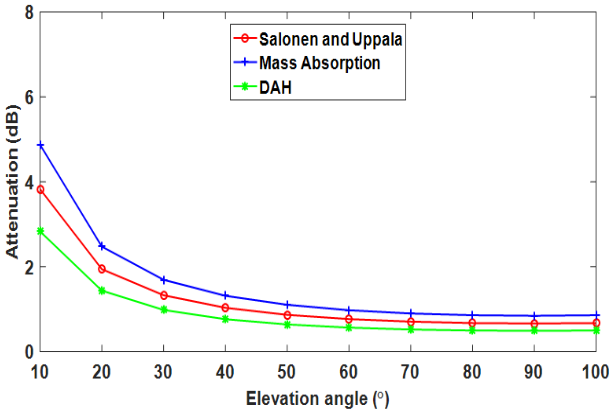

Fig. 4. Cloud attenuation for varying elevation angle at 30 GHz frequency.

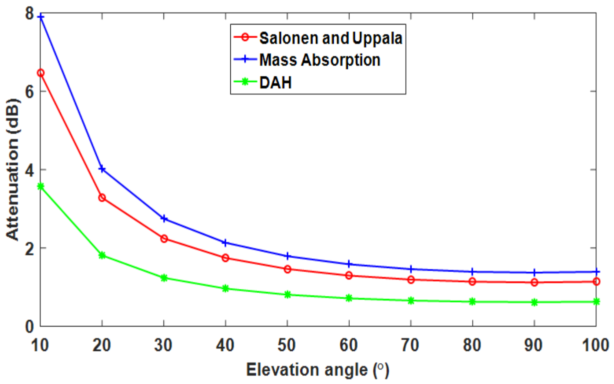

Fig. 5. Cloud attenuation for varying elevation angle at 40 GHz frequency.

Figures 6 and 7 present the impact of liquid water content on the magnitude of cloud attenuation for three models. It can be seen from the figures that the liquid water content is directly proportional to the attenuation. For all the three models by increasing the frequency with liquid water content the attenuation increases. More water, the more signal losses its strength. DAH model gives the better results because it depends on horizontal and vertical extent of cloud as well as on their average liquid water content.

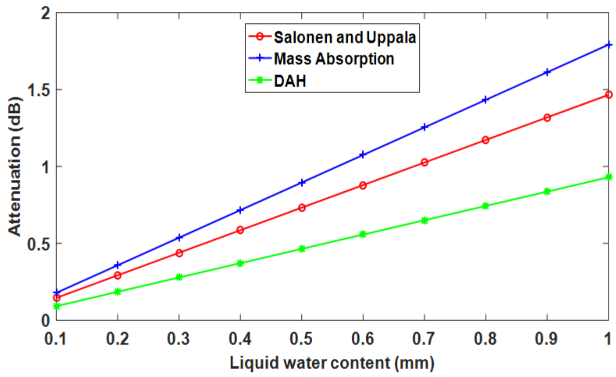

Fig. 6. Cloud attenuation for liquid water content at elevation angle of 40º and 40 GHz frequency.

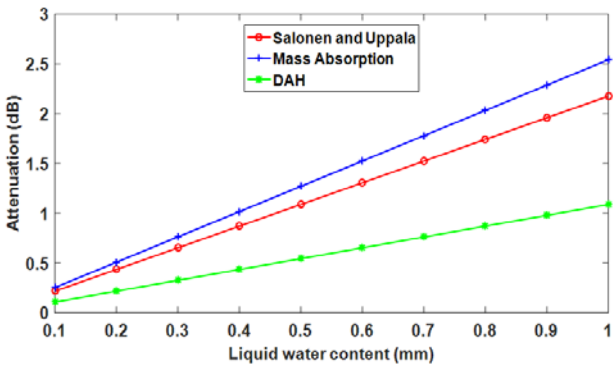

Fig. 7. Cloud attenuation for liquid water content at elevation angle of 40º and 60 GHz frequency.

3.2 Empirical Cumulative Distribution Function

Figure 8 depicts the efficiency of the models theoretically by using the Empirical Cumulative Distribution Function (ECDFs) equation which is calculated at a frequency of 30 GHz with 40° elevation angle and a range of liquid water content. The ECDF showed the probability of link communication which is less than or equal to 1. Here the probability of 1 means good condition and 0 means worst condition. It is calculated as [28]:

$$F_n(t) = \frac{k}{n}\sum_{j=k}^{n} I_{\{z_{j\leq t}\}} \tag{13}$$

where I is the indicator function, k is the k-th observation and n is the total number of observations.

The attenuation predictions of three different models depending on the cloud coverage i.e. from clear sky to partially cloudy and to the full cloud coverage are shown in Fig. 8. It can be seen from DAH model when 80% of the sky is clear the attenuation to the signal will be about 0.2 dB while at worst condition which is when only 10% of the sky is clear or we can say at cloudy day the highest value of attenuation that a signal can experience is about 0.85 dB. Similarly, it can be observed that for Salonen and Uppala model when 80% of the sky is clear the attenuation to the signal will be about 0.21 dB while at worst condition of 10% clear sky it is 1.05 dB. Furthermore, at 80% the attenuation to the signal for Mass Absorption model is 0.4 dB and at 10% it is almost 1.31 dB.

By comparing all the three models it can be concluded that DAH is the most accurate among the three models because it has low attenuation even in the worst scenario that is when the cloud coverage is to the fullest.

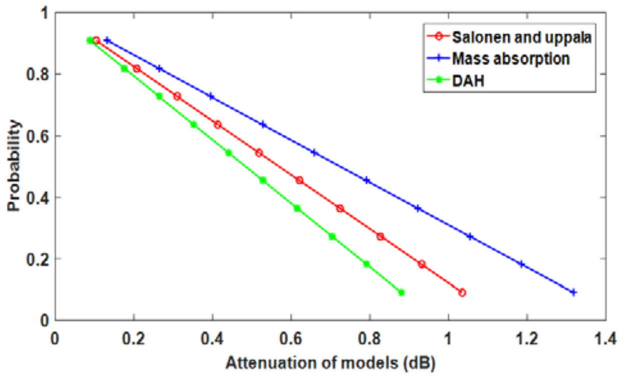

Fig. 8. Communication link probability of cloud attenuation models

4. Conclusion

In this study a detailed comparison of empirical cloud attenuation models is presented. The calculations of the cloud attenuation models are specifically relying on the liquid water content, elevation angle and frequency. The results by comparing the models indicate that liquid water content and frequency is directly proportional to cloud attenuation while at lower elevation angle the cloud attenuation is higher. All the models approximately show same attenuation, but the DAH model is more accurate as compare to the other models because it gives the lower attenuation.

For future work, the results obtained can be combine with the effect of haze (vapors, mist, fog, smog) and clouds having ice particles for the better estimation of cloud attenuation. Cloud attenuation can also be calculated for various location of Pakistan with these models using real time data and the result will be useful for future satellite communications in cloudy conditions.

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