Research on 6G characteristic attenuation rate

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Abstract. The terahertz band characteristic attenuation rate in 6G mobile communication system is studied. Through the model building and simulation, the results show that 6G radio wave fluctuates greatly with the increase of frequency in dry air, and there are multiple peaks. The characteristic attenuation rate of radio wave in water vapor at low frequency band is smaller than that in dry air, and adverse at high frequency band. The results also show that the characteristic attenuation rate increases with the increasement of rainfall, and is faster than that of frequency. The characteristic attenuation rate has little effect on the visibility. For frequency above 150GHz, the characteristic attenuation rate is greatly affected by snowfall intensity, while the frequency below 150GHz is relatively less affected by snowfall intensity. Under the frequency band of 20GHz, the characteristic attenuation rate increases obviously with the increase of frequency, and the characteristic attenuation rate is relatively gentle with the increase of frequency when it is above 20GHz. Meanwhile, the change is not obvious with the water content in the dust. For a certain water content, frequency from 0 to 350 GHz and temperature from 0 to 60 ℃, the characteristic attenuation rate mainly increases with the increase of frequency, almost does not change with temperature.

1. Introduction
Terahertz wave will be used for short-range communication by mobile communication system, and can also provide backhaul link for 6G mobile communication system[1][2]. Due to the widely available frequency bandwidth and beam concentration of terahertz wave, it can improve energy efficiency, directivity, and is less affected by interference[3][4]. However, the characteristic attenuation rate of radio waves in its frequency band is also different in various environments, such as dry air, air humidity, rainfall, snow and dust environment, etc., which affect the line of sight characteristic attenuation rate. In the network sites planning, the intensity characteristic attenuation rate should be analyzed to guide the sites planning in future.

2. Frequency characteristic attenuation rate model and simulation

2.1. Characteristic attenuation rate of communication signal in Atmospheric
When radio wave propagates in the air, it is affected by air pressure, water vapor pressure and temperature etc. Let dry air pressure be $p$, water vapor pressure be $e$ ($e = \rho T / 216.7$), where $\rho$ is water vapor density in g / m$^3$, $T$ is temperature in K, total air pressure is $p_{tot}$ ($p_{tot} = p + e$), $p$, $e$ and $p_{tot}$ in hPa. The calculation of characteristic attenuation rate $\gamma_o$ in dry air and $\gamma_w$ ($f, r_p, \rho, r_t$) of radio waves in water vapor are shown in formulas (1) and (2), respectively, in dB / km.
The air characteristic attenuation rate parameters in formulas (1) and (2) are shown in Table 1.

Table 1 air characteristic attenuation rate and horizontal and vertical polarization parameters

| i | $k_i$ | $a_i$ | $b_i$ | $c_i$ | $d_i$ | coefficient | $p_i$ | $q_i$ | $l_i$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.0717 | -1.8132 | 0.0156 | -1.6515 | $k_H$ | -5.33980 | -0.10008 | 1.13098 |
| 2 | 1 | 0.5146 | -4.6368 | -0.1921 | -5.7416 | | -0.35351 | 1.26970 | 0.45400 |
| 3 | 1 | 0.3414 | -6.5851 | 0.213 | -8.5854 | | -0.23789 | 0.86036 | 0.15354 |
| 4 | 1 | -0.0112 | 0.0092 | -0.1033 | -0.0009 | | -0.94158 | 0.64552 | 0.16817 |
| 5 | 1 | 0.2705 | -2.7192 | 0.3016 | -4.1033 | | 3.80595 | 0.56934 | 0.81061 |
| 6 | 1 | 0.2455 | -5.9191 | 0.0422 | -8.0719 | | 2.44965 | -0.22911 | 0.51059 |
| 7 | 1 | -0.1833 | 6.5589 | -0.2402 | 6.131 | | -0.39902 | 0.73042 | 0.11899 |
| 8 | 1 | 2.192 | 1.8286 | -1.9487 | 0.4051 | -2.8509 | | 0.50167 | 1.07319 | 0.27195 |
| 9 | 1 | 12.59 | 1.0045 | 3.561 | 0.1388 | 1.2834 | | 1.43418 | 1.82424 | -0.55187 |
| 10 | 1 | 15.0 | 0.9003 | 4.1335 | 0.0427 | 1.6088 | | 0.29591 | 0.77564 | 0.19822 |
| 11 | 1 | 14.28 | 0.9886 | 3.4176 | 0.1827 | 1.3429 | | 0.32177 | 0.63773 | 0.13164 |
| 12 | 1 | 6.819 | 1.432 | 0.6258 | 0.3177 | -0.5914 | | -0.75670 | -0.96230 | 1.47828 |
| 13 | 1 | 1.908 | 2.0717 | -4.1404 | 0.491 | -4.8718 | | 1.61721 | -3.29980 | 3.43990 |
| 14 | 1 | 0.00306 | 3.211 | -1.94 | 1.583 | -16.37 | | -0.07771 | 2.33840 | -0.76284 |

Where $f$ is frequency in GHz, $r_p=p_i p_o/1013$, $r_t=288/(273+t)$ is temperature in °C.

\[
\xi_i = k_i \cdot p_i \cdot a_i \cdot b_i \cdot c_i \cdot d_i \cdot e^{[1-(r_p)+(1-r_t)]} \]

\[
g(f, f_i) = 1 + \left( \frac{f - f_i}{f + f_i} \right)^2 \]

The air characteristic attenuation rate parameters in formulas (1) and (2) are shown in Table 1.
According to the characteristic attenuation rate parameter in Table 1. When the temperature is 20 °C, the water vapor density is 7.5g/m³ and the atmospheric pressure is 1013hPa, the characteristic attenuation of different frequency shown in Fig. 1 (a) (obtained through simulation). Among them, the radio wave characteristic attenuation rate fluctuates greatly with the increase of frequency in dry air, and there are multiple peaks. The characteristic attenuation rate of radio wave in water vapor at low frequency band is smaller than that in dry air, and the characteristic attenuation rate at high frequency band is larger than that in dry air, and there are multiple peaks with frequency variation. The total characteristic attenuation rate in air caused by dry air and water vapor are added together, the multi peak fluctuation occurs.

![Graph showing characteristic attenuation rate](image1)

(a) The characteristic attenuation rate varies with different frequency caused by dry air

![Graph showing characteristic attenuation rate with water vapor](image2)

(b) The characteristic attenuation rate varies with frequency and water vapor density

Fig. 1 The characteristic attenuation rate caused by air

The total characteristic attenuation rate of radio waves in the air varies with the water vapor density. The characteristic attenuation rate caused by water vapor density and frequency, as shown in Fig. 1 (b), it can be seen that the characteristic attenuation rate increases more obviously with the increase of water vapor density.

2.2. Characteristic attenuation rate of communication signal in Rain

In addition to characteristic attenuation in the air, the radio wave will also encounter the characteristic attenuation of rain when transmitting in line of sight. If the radio wave propagates in rain, the characteristic attenuation rate $\gamma_R$ caused by rainfall is shown in formula (5).

$$\gamma_R = KR^4 \tag{5}$$

Where $R$ is rainfall in mm / h, $K$ and $A$ are obtained from formulas (6) to (9) and parameters in Table 1. Take $K$ and $\alpha$ as shown in formulas (6) and (7).

$$k = 10^{\sum_{j=1}^{4} p_j e^{\left(\frac{\left|\log_{10} f - q_j\right|^2}{l_j}\right) + m_k \log_{10} f + n_k}} \tag{6}$$

$$\alpha = \sum_{j=1}^{5} p_j e^{\left(\frac{\left|\log_{10} f - q_j\right|^2}{l_j}\right) + m_k \log_{10} f + n_k} \tag{7}$$

In horizontal polarization, $k$ is represented by $k_h$, $\alpha$ is represented by $\alpha_h$, $m_k = -0.18961$, $n_k = 0.71147$, $m_k = 0.67849$, $n_k = -1.95537$ in formula (6) and (7). In vertical polarization, $k$ is expressed in $k_v$, $\alpha$ is
expressed in $\alpha, m_k = -0.16398, n_k = 0.63297, m_e = -0.053739, n_e = 0.83433$ in formula (6) and (7). $p_i, q_i, l_i$ are shown in Table 1. $K$ is shown in formula (8), and $A$ is shown in formula (9)

$$K = \frac{[k \alpha + k_i + (k_i - k) \cos^2 \theta \cos 2\tau]}{2}$$

(8)

$$A = \frac{[k \alpha + k_i + (k_i - k) \cos^2 \theta \cos 2\tau]}{2k}$$

(9)

According to formula (5) and taking different frequency and rainfall, the relationship among characteristic attenuation rate, frequency and rainfall is obtained through simulation, as shown in Fig. 2 (a). It can be seen that the characteristic attenuation rate increases with the increase of rainfall, and the growth rate is fast.

![Fig. 2 The characteristic attenuation rate caused by air and rainfall](image)

(a) Relationship among characteristic attenuation rate, frequency and rainfall

(b) Characteristic attenuation rate of radio waves in the air varies with frequency and rainfall

In rainy environment, the characteristic attenuation rate $F_r$ of line of sight radio wave is

$$F_r = \gamma_w + \gamma_w + \gamma_R$$

(10)

The relationship among the line of sight characteristic attenuation rate, rainfall and frequency is shown in Fig. 2 (b). It can be seen that the characteristic attenuation rate increased with the increase of rainfall faster than that caused by the increase of frequency.

2.3. Characteristic attenuation rate of communication signal in cloud and fog

Cloud and fog characteristic attenuation $\gamma_{c&f}$ can be calculated by formula, as shown in formula (11):

$$\gamma_{c&f} = 0.148 f^{2} / V_{m}^{1.43} \text{ dB/km}$$

(11)

Where $f$ is the operating frequency in GHz and $V_m$ is the visibility in m.

The international regulations on visibility are: very dense fog, $V_m < 50$ m; dense fog, $50$ m $< V_m < 200$ m; light fog, $200$ m $< V_m < 500$ m. The relationship among characteristic attenuation rate, frequency and visibility is shown in Fig. 3. The visibility range of simulation in the Fig. 3 is 20 m ~ 500 m. As can be seen from Fig. 3, the change of characteristic attenuation rate with visibility has relatively little effect. At the same visibility, when the frequency is below 100GHz, the characteristic attenuation increases obviously with the increase of frequency. When the frequency is higher than 100GHz, the characteristic attenuation increases not obviously with the increase of frequency at the same visibility.

2.4. Characteristic attenuation rate of communication signal in snow

The characteristic attenuation rate $\gamma_s$ caused by snowfall can be approximately expressed as
\[ \gamma_s = 7.47 \times 10^{-5} f \sqrt{I (1 + 5.77 \times 10^{-5} f^{3.6})} \text{ (dB/km)} \] (12)

Where \( f \) is the working frequency, in GHz; \( I \) is the snowfall intensity in mm/h, which is the height of snow melting into water in unit volume per hour. The relationship among characteristic attenuation rate, frequency and snowfall intensity is shown in Fig. 4. When frequency above 150GHz, the characteristic attenuation rate is greatly affected by snowfall intensity, while the frequency below 150GHz is relatively less affected by snowfall intensity.

2.5. Characteristic attenuation rate of communication signal in dust climate

2.5.1. Dust size distribution

The Northwest and North of China are relatively dry, and there are often sand dust environment, which has three kinds of environment conditions, such as floating dust, blowing sand and sandstorm, which have obvious impact on the characteristic attenuation of communication signals. There are larger dust particles and smaller dust particles in the sandstorm environment, which have a greater impact on the transmission of millimeter wave and terahertz wave. Sand and dust can be divided into natural formation and artificial formation, such as explosion dust or vehicle movement dust. The shape of sand particles has complex diversity, and the shape of sand particles is also different due to the different regional environment and the causes of sand dust. The distribution of dust particle size is close to lognormal distribution, as follow[5][6]:

\[ N(D) = N_0 p(D) = \frac{N_0}{\sqrt{2\pi\sigma D}} \left[ -\frac{(\ln D - m)^2}{2\sigma^2} \right] \] (13)

Where \( N_0 \) is the bulk density of sand dust (1/m\(^3\)); \( D \) is the diameter of dust particles, \( p(D) \) is the density function of the size distribution of dust particles; \( m \) is the mean of \( \ln D \), and \( \sigma \) is the standard deviation of \( \ln D \).

2.5.2. Analysis of permittivity constant and characteristic attenuation of sand dust

The complex permittivity of sand dust is a function of water content and frequency. The permittivity can be obtained by substituting the permittivity of dry sand and water into the mixture equivalent method. The complex permittivity of dry sand and water can be obtained by formula. The formula for the complex permittivity \( \varepsilon_s \) of dry sand is shown in formula (14)

\[ \varepsilon_s = \varepsilon_s' + i \varepsilon_s'' \] (14)

Where \( \varepsilon_s' \) (equal to 3) is the real part of the complex permittivity of sand dust, and \( \varepsilon_s'' \) is the imaginary part of the complex permittivity of sand dust, and it’s values are as follows.
The formula for the complex permittivity of water was proposed by Ray, as shown in formula (15).

\[
\varepsilon_w = \varepsilon_{\infty} + \frac{(\varepsilon_{ws} - \varepsilon_{\infty})[1 - \left(\frac{\lambda}{\lambda_s}\right)^{1-a} \sin \frac{\alpha \pi}{2}]}{1 + 2\left(\frac{\lambda}{\lambda_s}\right)^{1-a} \sin \frac{\alpha \pi}{2} + \left(\frac{\lambda}{\lambda_s}\right)^{2(1-a)}} + \frac{(\varepsilon_{ws} - \varepsilon_{\infty})\left(\frac{\lambda}{\lambda_s}\right)^{1-a} \cos \frac{\alpha \pi}{2}}{1 + 2\left(\frac{\lambda}{\lambda_s}\right)^{1-a} \sin \frac{\alpha \pi}{2} + \left(\frac{\lambda}{\lambda_s}\right)^{2(1-a)}} + \frac{\sigma_w \lambda}{18.8496 \times 10^{10}} \tag{15}
\]

Where \(\varepsilon_{\infty}=78.54 \times [1-4.579 \times 10^{-3}(t-25)+1.19 \times 10^{-5}(t-25)^2-2.8 \times 10^{-8}(t-25)^3]\), \(\sigma_{\infty}=12.5664 \times 10^{8}(S \cdot m^{-1})\), \(\varepsilon_{ws}=5.27137+0.0216474t-0.00131198t^2\), \(\alpha=-16.8129/(t+273)+0.0609265\), \(\lambda_{\infty}=0.00033836 \exp[2513.98/(t+273)]\). \(\varepsilon^*\) is the real part of complex permittivity of water, \(\varepsilon^*\) is the imaginary part of complex permittivity of water, and \(t\) is temperature in °C.

The equivalent complex permittivity of wet sand dust can be obtained by Maxwell-Garnett formula as follow:

\[
\varepsilon_{eff} = \varepsilon^* + i\varepsilon^* = \varepsilon^* \left[1 + \frac{3\rho_{per}(\varepsilon_w - \varepsilon^*)/(\varepsilon_{ws} + 2\varepsilon^*)}{1 - \rho_{per}(\varepsilon_w - \varepsilon^*)/(\varepsilon_{ws} + 2\varepsilon^*)}\right] \tag{16}
\]

Where \(\varepsilon^*\) is the real part of the complex permittivity of the wet sand dust, \(\varepsilon^*\) is the equivalent complex permittivity of the wet sand dust, \(\varepsilon^*\) is the complex permittivity of the dry sand, \(\varepsilon_w\) is the complex permittivity of the water, \(\rho_{per}\) is the volume percentage of the water content.

If the real part and imaginary part of the complex permittivity of the wet sand dust are taken respectively, the characteristic attenuation rate \(L_R\) is as follows:

\[
L_R = 0.4288 \times 10^{10} \frac{\varepsilon}{(\varepsilon^* + 2)^2 + \varepsilon^*} f N_0 \exp(3m + 4.5\sigma^2)
\]

The bulk density \(N_0\) of \(\text{ID}^\prime\)s mean \(m\) and standard deviation \(\sigma\) of natural and artificially formed dust samples are shown in Table 2.

| type           | \(m\)  | \(\sigma\) | \(N_0\)     |
|----------------|--------|------------|-------------|
| Explosion dust | -8.489 | 0.663      | 6.272×10^6  |
| Natural dust   | -9.718 | 0.405      | 1.630×10^5  |
| Vehicle dust   | -9.448 | 0.481      | 1.880×10^6  |

For the civil mobile communication system is mainly faced with the natural dust (such as sand dust, haze environment) characteristic attenuation. Here we use natural dust parameters for simulation. At 20 °C temperature, the characteristic attenuation rate corresponding to frequency from 0 to 350 GHz and water content from 0 to 0.3 is shown in Fig. 5(a). It can be seen that under 20GHz frequency band, the characteristic attenuation rate increases obviously with the increase of frequency, and above 20GHz, the characteristic attenuation rate is gentle with the increase of frequency, and the change is not obvious with the water content in dust. For a certain water content, frequency from 0 to 350 GHz and temperature from 0 to 60 °C, the corresponding characteristic attenuation rate is shown in Fig. 5(b). The characteristic attenuation rate mainly increases with the increase of frequency, and almost does not change with temperature.
3. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) It is shown that the characteristic attenuation rate of radio wave in water vapor is smaller than that in dry air at low frequency band, but it is larger at high frequency band than that in dry air, and fluctuates greatly with frequency, and there are multiple characteristic attenuation rate peaks. The sum characteristic attenuation rate in air caused by dry air and water vapor, leads to multi-peak fluctuation. the characteristic attenuation rate increases with the increase of water vapor density more obviously than that of frequency.

(2) The characteristic attenuation rate increases with the increase of rainfall. With the increase of rainfall, the increase of characteristic attenuation rate is faster than that of frequency.

(3) The characteristic attenuation rate is little affected by the visibility.

(4) The characteristic attenuation rate is related to the frequency and snowfall intensity. The frequency above 150GHz is greatly affected by the snowfall intensity, and the frequency below 150GHz is relatively less affected by the snowfall intensity.

(5) Under the frequency band of 20GHz, the characteristic attenuation rate increases obviously with the increase of frequency, and the characteristic attenuation rate is relatively gentle with the increase of frequency when it is higher than 20GHz. Meanwhile, the change is not obvious with the water content in the dust. For a certain water content frequency from 0 to 350 GHz and temperature from 0 to 60°C, the characteristic attenuation rate mainly increases with the increase of frequency, and almost does not change with temperature.

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