Cloud Attenuation Prediction at High Frequency by Using ITU-R Model for Satellite Links in Ulaanbaatar, Mongolia

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Abstract: Satellite communication systems operating at high frequencies are significantly affected by atmospheric impairments, particularly cloud-induced attenuation. As Mongolia advances its national satellite program at the 113.6°E geostationary orbital position allocated by the International Telecommunication Union, accurate estimation of propagation losses becomes essential for reliable link design. This study evaluates cloud attenuation for C-, Ku-, and Ka-band satellite links in Ulaanbaatar, Mongolia, using the internationally standardized ITU-R P.840-5 methodology. Seasonal atmospheric temperature data obtained from radiosonde measurements (2015–2020) and statistical liquid water content values were incorporated to determine the specific attenuation coefficient (Ki) and total path attenuation. Results indicate that attenuation increases significantly with frequency and is strongly influenced by seasonal temperature variations, with maximum values observed in winter due to enhanced dielectric interaction of liquid water. The Ka-band exhibits the highest sensitivity, reaching peak attenuation under high liquid water content conditions. The findings provide essential technical insight for satellite link budgeting, system reliability assessment, and sustainable satellite network planning under Mongolia's extreme continental climate conditions.

Keywords: *Cloud Attenuation, Liquid Water Content, ITU-R P.840-5*

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I. INTRODUCTION

A cloud is consisting of mass of very small water droplets, ice crystals, super cool water or some suspended particles present in atmosphere. The formation of clouds is due to saturation of atmospheric air, which is the results of cooling of air at dew point. It is also formed when it gets sufficient moisture from its surroundings in order to raise due point to ambient temperature. There are different types of clouds available in atmosphere. These are divided into three main type namely low level, middle level and high-level clouds.

Low level clouds consist of cumulus, cumulonimbus, stratus and stratocumulus. Middle level clouds consist of Altocumulus, Altostratus and nimbostratus. The high-level clouds consist of cirrus, cirrocumulus and cirrostratus.

Cumulus clouds are generally found at the height of 2000 to 3000 feet. It can be found at whole part of globe except poles due to extremely cold climate. They rarely cause rain except fewer light showers. Cumulonimbus is found at the height of 2000 to 4500 feet. They are very common at temperate and tropical regions. They are cause of heavy rains ad hails. They are consisting of liquid water and ice crystals at top. Stratus clouds are found at the height of 0 to 6500 feet. They are very common at coastal areas and mountains. It causes only light drizzle. Stratocumulus clouds are generally found at the height of 2000-6500 feet. They are very common clouds which causes rain and snow.

Altocumulus is found at 6500 to 18000 feet. They are also found worldwide with light rain. Altostratus clouds are found at the height of 6500 to 16500 feet. They are causing light rain and snow. They contain both snow and liquid. Nimbostratus is found at 200 to 18000 feet. Table 1. Approximate heights each level, and the genera occurring in each.

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Table 1 Types of Cloud

Level	Genera	Polar region	Temperate region	Tropical region
High	Cirrus Cirrocumulus Cirrostratus	3-8 km	5-13 km	6-18[m
Middle	Altocumulus Altostratus Nimbostratus	2-4 km	2-7 km	2-8 km
Low	Stratus Stratocumulus Cumulus Cumulonimbus	From the earth`s surface to 2 km		

Cirrus clouds are highest of all clouds and are found at the height of 16500 to 45000 feet. They are composing of ice crystals. Cirro-cumulus is found at the height of 16500 to 45000 feet. They are usually consists of ice crystals.

II. METHOD OF CLOUD ATTENUATION CALCULATION

➢ *Atmospheric Attenuation Due to Clouds and Fog-P.840-5*

Recommendation ITU-R P.840-5 provides an internationally standardized method for predicting atmospheric attenuation caused by clouds and fog. This recommendation is particularly important for radio systems operating above 10 GHz, including satellite communications and high-frequency terrestrial links Ku, Ka and millimeter-wave bands) and the model defines:

- The specific attenuation (dB/km) as a function of frequency and temperature,
- The dependence on liquid water content (LWC),
- The calculation of total path attenuation through vertical integration,
- Statistical estimation methods for attenuation exceeded for a given percentage of time.

The total attenuation is determined from the product of the specific attenuation coefficient and the integrated liquid water density along the propagation path. ITU-R P.840-5 is widely applied in satellite link design, high-frequency terrestrial systems.

➢ *Mathematical Equations and Model*

A mathematical model based on Rayleigh scattering, which uses a Double-Debye model for the dielectric permittivity ε (f) of water, can be used to calculate the value of K_i for frequencies up to 1000 GHz [6].

$$K_i = \frac{0.819f}{\varepsilon''(1+\eta^2)} \text{ (dB/km)/(g/m}^3\text{)} \quad (1)$$

Where f is the frequency (GHz), and

$$\eta = \frac{2+\varepsilon'}{\varepsilon''} \quad (2)$$

The complex dielectric permittivity of water is given by;

$$\varepsilon''(f) = \frac{f(\varepsilon_0-\varepsilon_1)}{f_p\left[1+(\frac{f}{f_p})^2\right]} + \frac{f(\varepsilon_1-\varepsilon_2)}{f_s\left[1+(\frac{f}{f_s})^2\right]} \quad (3)$$

$$\varepsilon'(f) = \frac{(\varepsilon_0-\varepsilon_1)}{\left[1+(\frac{f}{f_p})^2\right]} + \frac{(\varepsilon_1-\varepsilon_2)}{\left[1+(\frac{f}{f_s})^2\right]} + \varepsilon_2 \quad (4)$$

Where:

$$\varepsilon_{(0)} = 77.6 + 103.3(\theta-1) \quad (5)$$

- $\varepsilon_{(1)} = 5.48$
- $\varepsilon_{(2)} = 3.51$
- $\theta = 300/T$

With T is the temperature (K)

The principal and secondary relaxation frequencies are:

$$f_p = 20.09 - 142\ (\theta-1) + 294\ (\theta-1)^2 \quad (6)$$

$$f_s = 590 - 1500\ (\theta-1) \quad (7)$$

Cloud attenuation

$$A = \frac{LK_i}{\sin\theta} \text{ [dB] for } 90^0 \geq \theta \geq 5^0 \quad (8)$$

Where:

- θ is the elevation angle
- K_i is specific attenuation coefficient
- L is total columnar content of liquid water

III. DATA COLLECTION

The total of attenuation caused by clouds in the C, Ku and Ka frequency bands of national satellites in Ulaanbaatar, Mongolia is calculated using certain basic parameters and a methodology based on international standards.

This calculation uses basic technical parameters such as the liquid water content in the cloud, air temperature of four seasons of year, satellite and ground station locations, and antenna vertical angle orientation. These parameters are summarized in Table 2.

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Table 2 Data of parameters

Parameters	Data	Calculation methods
Geometry parameters of satellite communication		
Satellite position	113.6° E	ITU-R
Longitude of ES	106.92°E	timegenie.com
Latidute of ES	47.92°N	
Elevation angle of ES	34.5°	Result of calculated satellite geometry parameters
Azimuth angle of ES	171.04°	
Related others parameters		
liquid water content. (0.1-20 % of year)	0.2 g/m^3-2 g/m^3	ITU-R P.840-5
Temperature	Four season	Monthly and annual average air temperature of the Ulaanbaatar (1991-2020)

These baseline data and international standard models, as shown in Table 2, provide an opportunity to assess and accurately calculate the attenuation caused by clouds on satellite communication signals in Ulaanbaatar, Mongolia in real conditions.

➢ *Geography and Climate of Ulaanbaatar in Mongolia*

Ulaanbaatar is the capital and largest city of Mongolia, located in the north-central part of the country at an elevation of approximately 1.350 meters above sea level. Situated along the Tuul River and surrounded by four sacred, forested mountains-Bogd Khan, Songino Khairkhan, Chingeltei, and Bayanzurkh the city experiences an extreme continental climate.

Also, Ulaanbaatar city is the world's coldest national capital. Winters are long, sunny, and frigid (Nov-Apr, often below -30°C). Summers (July-Aug) are short, mild, and relatively warm, with most precipitation falling during this period. It is shown in Fig.1

Fig 1 Lacation and Geography of Ulaanbaatar

The Ulaanbaatar Department of Water, Meteorology and Environment (DME) launch radiosonde stations twice a day to determine the vertical structure of the atmosphere and the state of the weather. Radiosonde stations are launched to measure basic meteorological elements such as air pressure, temperature, humidity, and wind speed at altitudes up to 30 km above the ground. These data are widely used in weather forecasting, numerical modeling, and climate research. The seasonal trend of air temperature in the region was analyzed using vertical atmospheric measurement data from the radiosonde station (WMO code: 44242) of Meteorological and Environmental Research Agency in Ulaanbaatar, between 2015 and 2020. The results of the radiosonde station measurements determined temperature changes at an altitude of 3700-4400 m in the atmosphere of Ulaanbaatar city, and the results are summarized by season in Table 3.

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Table 3 The Seasonal Average Air Temperature Determined by Measurements from the Ulaanbaatar City Radiosonde Station from 2015 to 2020.

Parameters			**Surface Latitude & Temperature**		**Air Latitude & Temperature**	
Station WMO	**Season**	**Period of Month**	**Surface Latitude-[m]**	**Surface Temperature-[C°]**	**Air Latitude-[m]**	**Air Temperature [C°]**
44242	Winter	XII-II	1310	-18.8	4123	-17
44242	Spring	III-V	1310	2.2	4292	-1.9
44242	Summer	VI-VIII	1310	17.4	3700	7
44242	Autumn	IX-XII	1310	0.1	4400	-6.1

The table shows that the temperature at the surface and the upper atmosphere of Ulaanbaatar fluctuates seasonally. The temperature at the surface is the coldest in winter, reaching an average of (-18.8°C), and warms up to +17.4°C in summer, while the temperature at the upper atmosphere at an altitude of 3700-4400 meters is relatively stable, but it varies depending on the season. For example:

- In winter: (December-February) the air temperature at the surface is very cold (-18.8°C), but at an altitude of 4123 m the temperature has increased slightly to (-17°C), indicating the presence of an air inversion.
- In spring: (March-May) the temperature has increased, reaching +2.2°C at the surface and -1.9°C at an altitude of 4292 m. This indicates that the temperature is gradually decreasing vertically.
- Summer: (June-August) +7°C temperature is observed in the upper layer (3700 m), indicating that normal conditions for temperature decrease in the vertical direction prevail.
- Autumn: (November-December) temperature drops, reaching 0.1°C at the surface and -6.1°C at an altitude of 4400 m.

The atmospheric temperature in Ulaanbaatar varies depending on the season, with a tendency for temperature inversion in the vertical direction in winter, and a normal decrease in other seasons.

➤ *Annual Statistics and Assessment of Cloud Liquid Water Content Affecting Radio Wave Propagation*

The ITU-R P.840-5 document provides statistical estimates of the probability of cloud liquid water content (LWC) formation at a given location over a given year at 0.1%, 0.5%, 1%, 5%, 10%, and 20% of the annual cloud water content (LWC).

This statistical data is an important parameter used to assess the conditions for satellite radio transmission, and these annual values indicate the trend of cloud liquid water content in different parts of the world. Using the annual statistical values of cloud liquid water content contained in the ITU-R P.840-5 document, relevant data for the regions of Mongolia between 70°-120° east longitude and 40°-60° north latitude were selected and summarized in Table 4.

Table 4 Annual Specific Values of Cloud Liquid Water Content (g/m³)

Coverage of Longitude and Latitude		Exceeded of Year				
		0.1 %	0.5 %	1 %	5 %	10 %
		[g/m^3]				
Longitude	70-120 E	2	2	1	0.2	0.2
Latitude	40-60 N					

Table 4 shows that in Mongolia, the cloud liquid water content is relatively high at 2 g/m³ at very low annual percentages (0.1% and 0.5%). However, at 1% of the annual frequency, the liquid water content decreases to 1 g/m³, indicating a relatively reduced cloud density. In addition, the values observed at 5%, 10% and 20% of the annual frequency are the same at 0.2 g/m³, indicating that the cloud liquid water content remains stable and low at these frequencies. This statistical data is an important parameter used to assess the conditions for satellite radio transmission, and these annual values indicate the trend of cloud liquid water content in different parts of the world.

IV. CLOUD ATTENUATION RESULT IS CALCULATED BY ITU-R METHODOLOGY

➤ *Calculated Results of Ki Coefficient of Liquid Water Attenuation in Ulaanbaatar*

The temperature-dependent Ki coefficient of liquid water attenuation was calculated for radio waves of various frequencies in Mongolian conditions. Using the seasonal average temperature values measured by radiosonde stations, the effect of temperature changes on Ki values was calculated, and the results are shown in Table 5.

Table 5 Cloud Liquid Water Attenuation Coefficient (Ki) (Seasonal)

Parameters		**Winter**	**Spring**	**Summer**	**Autumn**
Air Temperature -[C°]		**-17**	**-1.9**	**7**	**-6.1**
Air Temperature [K]		**256.15**	**271.25**	**280.15**	**267.05**
The Specific Attenuation Coefficient-(Ki)					
C-Band	4 GHz	0.028	0.016	0.012	0.018
	6 GHz	0.063	0.036	0.027	0.041
Ku-Band	12 GHz	0.245	0.142	0.107	0.164

	18 GHz	0.521	0.313	0.239	0.361
Ka-Band	26 GHz	1.0	0.63	0.489	0.72
	40 GHz	1.97	1.39	1.093	1.55

In winter, when the temperature is lowest (-17°C), Ki values are highest at all frequencies. This is due to the fact that water molecules are more concentrated in cold conditions. However, in summer, when the temperature is 7°C, Ki values are lowest, which means that the dielectric permittivity of water decreases and radio waves penetrate more easily. In spring and autumn, Ki values fluctuate at an average level. It is clear from the calculations that both temperature and frequency have an effect on the dielectric properties of liquid water. It is necessary to take into account temperature and wave frequency in the calculation of radio wave propagation, and this calculation shows that high-frequency bands (especially Ka and Ku) are more sensitive to temperature changes.

➤ *Calculated Results of Cloud Attenuation in Ulaanbaatar, Mongolia*

Using air temperature measurement data from the Ulaanbaatar city radiosonde station and the Ki coefficient calculation results, the total of attenuation caused by clouds in the propagation of radio waves from national satellites was calculated for each season using the ITU-R P.840-5 modeling. The total of attenuation (dB) from clouds in Ulaanbaatar for each season was calculated in the 4 GHz-40 GHz radio frequency band, and the results are shown in Table 6.

Table 6 Calculated Results of Cloud Attenuation in Ulaanbaatar, Mongolia

Parameters		**Winter**	**Spring**	**Summer**	**Autumn**
Air temperature -[C°]		-17	-1.9	7	-6.1
Air temperature [K]		256.15	271.25	280.15	267.05
Satellite position		113.6° E			
Elevation angle of ES		34.5°			
Cloud Attenuation-[dB/km] Total Columnar Content of Liquid Water-2 (g/m^3)					
C-Band	4 GHz	0.099	0.056	0.429	0.063
	6 GHz	0.222	0.127	0.095	0.145
Ku-Band	12 GHz	0.865	0.501	0.378	0.579
	18 GHz	1.85	1.105	0.849	1.275
Ka-Band	26 GHz	3.53	2.224	1.73	2.54
	40 GHz	6.96	4.908	3.86	5.47

The table presents the calculated seasonal cloud attenuation values in Ulaanbaatar, Mongolia for satellite communication links operating in the C-band (4-6 GHz), Ku-band (12-18 GHz), and Ka-band (26-40 GHz). The calculations are based on seasonal atmospheric temperatures, a satellite position of 113.6°E, an earth station elevation angle of 34.5°, and a cloud liquid water content of 2 g/m³. The results show that attenuation increases with frequency, with the Ka-band experiencing the highest attenuation, particularly during winter conditions, while the C-band is the least affected across all seasons.

In Fig.2, Fig.3 and Fig.4 show the calculated cloud water content at 2 g/m³, 1 g/m³, and 0.2 g/m³, respectively, using four-season measurement data from the Ulaanbaatar city radiosonde station in the C (4-6 GHz), Ku (12-18 GHz), and Ka (26-40 GHz) frequency bands.

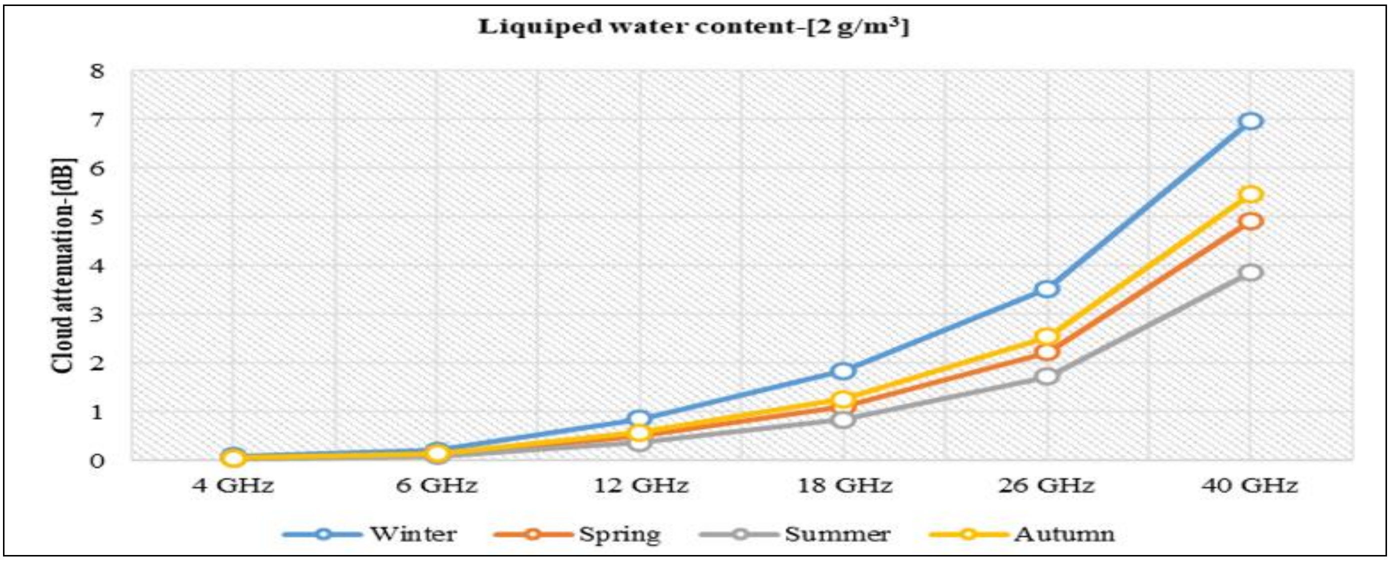

Fig 2 Seasonal Variation of Cloud Attenuation for LWC = 2 g/m³ in Ulaanbaatar

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Cloud attenuation as a function of frequency for different seasons at a liquid water content of 2 g/m³. The results show that attenuation increases with frequency, reaching the highest values in winter and the lowest in summer.

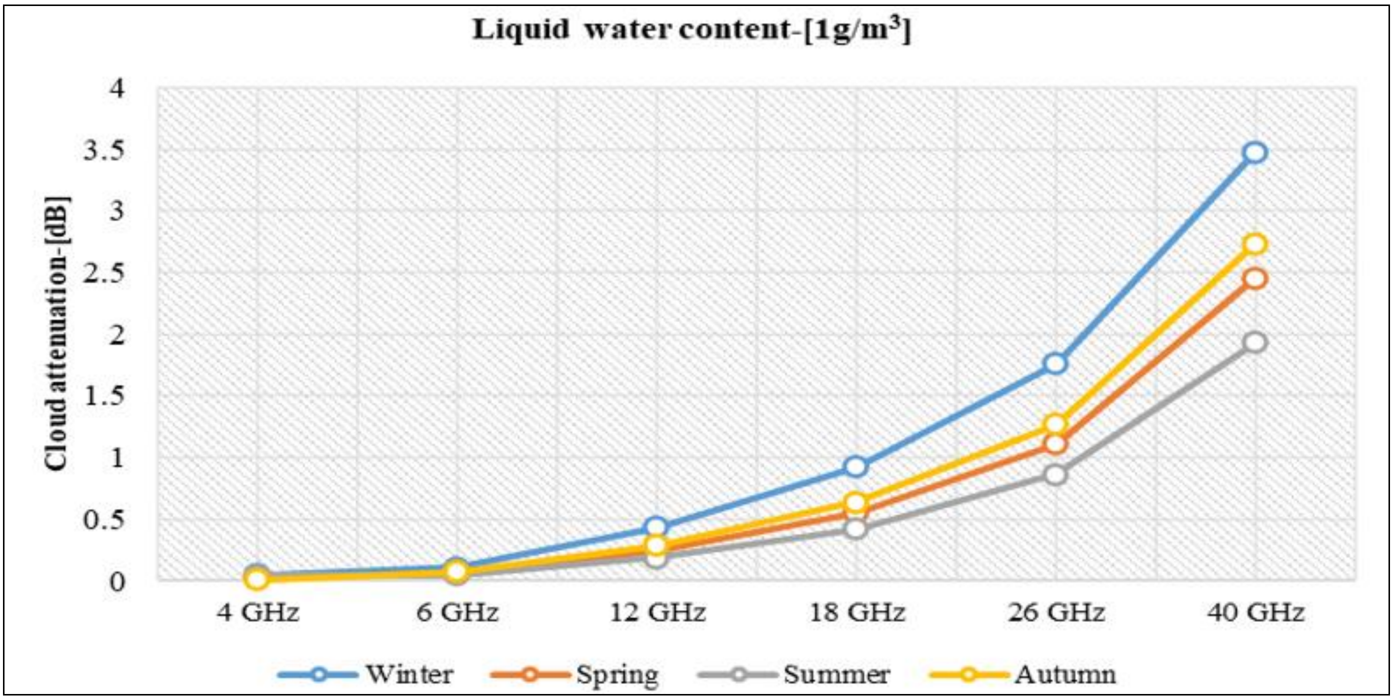

Fig 3 Seasonal Variation of Cloud Attenuation for LWC = 1 g/m³ in Ulaanbaatar

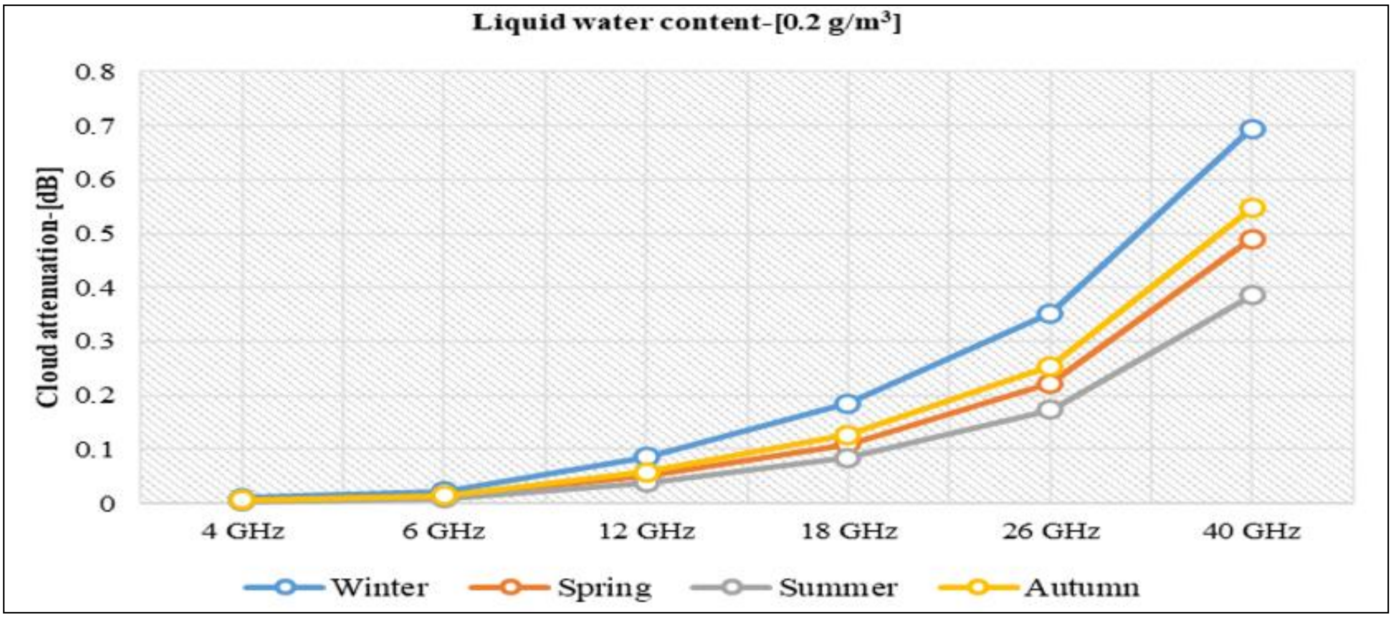

Fig 4 Seasonal Variation of Cloud Attenuation for LWC = 0.2 g/m³ in Ulaanbaatar

The results presented in Fig.2-Fig.4 illustrate the seasonal variation of cloud attenuation in Ulaanbaatar for different levels of cloud liquid water content (LWC), namely 2 g/m³, 1 g/m³, and 0.2 g/m³, across the C-band (4-6 GHz), Ku-band (12-18 GHz), and Ka-band (26-40 GHz) frequency ranges. The results show that attenuation increases significantly with frequency and liquid water content, with the Ka-band experiencing the highest attenuation levels, while the C-band remains relatively stable and less affected. Seasonal effects are also evident, where winter conditions produce the highest attenuation values due to lower atmospheric temperatures and stronger dielectric interaction of water droplets, whereas summer shows the lowest attenuation. These results demonstrate that both frequency and cloud liquid water density play critical roles in determining satellite link performance in Mongolia's continental climate.

V. RESULT

The cloud attenuation for satellite communication links in Ulaanbaatar was evaluated using the ITU-R P.840-5 model by considering seasonal atmospheric temperature variations and different cloud liquid water content (LWC) levels. The analysis was conducted for C-band (4-6 GHz), Ku-band (12-18 GHz), and Ka-band (26-40 GHz) frequencies.

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The calculated results show that the attenuation increases significantly with frequency. The C-band experiences the lowest attenuation values across all seasons, while the Ka-band shows the highest sensitivity to cloud effects. For example, at 40 GHz and LWC=2 g/m³, the cloud attenuation reaches approximately 6.96 dB in winter, while the corresponding values in spring, summer, and autumn are lower.

Seasonal variation also plays an important role in attenuation characteristics. Due to lower atmospheric temperatures, the highest attenuation values occur during winter, whereas the lowest values are observed in summer. Additionally, the results demonstrate that higher cloud liquid water content leads to increased attenuation, confirming that both frequency and atmospheric conditions strongly influence satellite signal propagation.

VI. CONCLUSION

This study analyzed the effect of cloud attenuation on satellite communication links in Ulaanbaatar, Mongolia, using the ITU-R P.840-5 propagation model and seasonal atmospheric temperature data obtained from radiosonde measurements. The results indicate that cloud attenuation strongly depends on frequency, liquid water content, and seasonal temperature variations.

Among the examined frequency bands, the Ka-band is the most affected by cloud attenuation, while the C-band remains relatively stable and less sensitive to atmospheric conditions. The study also shows that winter conditions produce the highest attenuation due to lower atmospheric temperatures and stronger dielectric interaction of water droplets.

These findings provide useful technical guidance for satellite link budget design, propagation analysis, and reliability planning for Mongolia's national satellite system operating at 113.6°E. The results are particularly important for the development of high-frequency satellite communication systems in regions with extreme continental climates such as Mongolia.

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