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Atmospheric Challenges Affecting Satellite-to-Ground Station and Ground-station-to-satellite Communications

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ABSTRACT

Satellite communication systems are affected by atmospheric conditions at one point or another, and this can cause degradation or attenuation of quality. This study discussed the impact of atmospheric conditions such as temperature, humidity, rainfall, atmospheric pressure, and ionospheric electron density on satellite-to-ground and ground-to-satellite communication links as being the major challenges. The research work, which made use of the review research method, in which several research works from reputable journals and sources were studied. The research result showed that some of the effects of these challenges affecting satellite-to-ground station and ground-station-to-satellite communications are signal attenuation, propagation delay, scintillation, noise, and interference, as well as complete link outages. The result also reported some methods of mitigating atmospheric challenges to satellite-to-ground and ground-to-satellite communication, such as adaptive modulation and coding, frequency diversity and power control mechanisms, site diversity using multiple ground stations, advanced error correction algorithms, and atmospheric prediction models for proactive link management. In conclusion, it was said that satellite-to-ground station as well as ground station-to-satellite communications links are faced with several atmospheric challenges, which can result in many negative ways; such challenges can be prevented or reduced to manageable levels. The results will be valuable for designing resilient satellite networks, particularly in high-frequency bands and regions prone to severe weather disturbances.

KEYWORDS: *Attenuation, Adaptive modulation and coding, scintillation, Satellite, communication links.*

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1. INTRODUCTION

The communication from the satellites in space and ground stations, as well as from the ground stations to the satellites in space, depends on reliable electromagnetic wave propagation through the atmosphere of the Earth. But this atmospheric medium also presents the satellite communications links with some challenges that can degrade signal quality and affect the overall system performance. The work by Olla et al. (2023) reported that gaseous absorption significantly reduces signal strength in fixed satellite links, particularly in tropical environments like Nigeria, where the level of humidity is high. According to Matricciani et al. (2024), rain attenuation strongly affects Earth–space radio links, and this can result in link degradation as well as potential communication outages during heavy precipitation events. In the same way, Abadi et al. (2024) emphasized that tropospheric scintillation becomes very critical and more severe at higher frequency bands such as Ku and Ka bands, thus impacting broadband satellite services. This was also complemented by Zhang, Liu, et al. (2024), who, in their work, investigated ionospheric scintillation using space-based observations and discovered that irregular electron density structures in the ionosphere can distort satellite signals, especially in equatorial regions. In the views of Broumandan et al. (2024), ionospheric disturbances are associated with solar activity to positioning errors in satellite navigation systems. In the same way, emerging high-frequency wireless systems are also vulnerable to these atmospheric gases' effects, as reported by Sudhamani et al. (2025), who found that atmospheric gases and rain intensity significantly influence terahertz wave propagation, posing challenges for next-generation satellite networks.

2. Research Methodology

This study adopts a review research method approach to investigate atmospheric challenges to satellite-to-ground station communication and vice versa, as well as some of the effects of these challenges. This involves collecting recent peer-reviewed published works and analyzing their results, including their methodologies. The research focus was on key atmospheric parameters such as temperature, humidity, atmospheric pressure, rainfall, and ionospheric electron density as regards their effects on satellite-to-ground and ground-to-satellite signal propagation. The study also looked at the communication challenges arising from atmospheric effects such as signal attenuation, propagation delay, scintillation, link outages, and noise and interference. This methodology allows for a holistic understanding of atmospheric impacts and communication challenges or consequences of these atmospheric challenges on satellite communication links, aiming to enhance the performance of satellite communication systems in various environmental conditions.

3. Results and discussion

3.1. Atmospheric Parameters affecting Satellite-to-Ground Station and Ground Station-to-Satellite Communications

3.1.1. Atmospheric temperature

Temperature is the measure of the degree of coldness or hotness of an environment. It is also the measure of the average kinetic energy of the particles in an object or an environment. Temperature affects air density and atmospheric refractive index, which directly determine how electromagnetic waves propagate through the atmosphere. According to Wang et al. (2013), during both uplink and downlink operations, the transmitted beam propagates through the atmosphere where environmental factors such as clouds, fog, snow, and rainfall may significantly degrade or even terminate the communication link through photon absorption and scattering. Atmospheric turbulence is largely caused by temperature and pressure variations along the transmission path, and this turbulence affects signal propagation (Maharjan, 2022).

Turbulence occurs when the Earth’s surface absorbs solar radiation, heating nearby air layers. The warmer air rises and mixes with cooler surrounding air, creating random temperature fluctuations that form turbulent cells or eddies. These eddies behave like refractive prisms with varying refractive indices, producing constructive or destructive interference with the propagating beam (Ghassemlooy, 2018; Maharjan, 2022). When turbulent eddies become larger than the satellite beam diameter, beam wandering may occur, causing misalignment with the ground receiver and reduced signal quality. Ayantunji et al. (2018) investigated the impact of atmospheric temperature and wind speed on Ku-band satellite signals using five months of observational data. It was observed by them that there was an inverse relationship between temperature and signal strength. In the same way, Opara et al. (2018) reported that variations in tropospheric temperature and relative humidity change atmospheric refractive index, thereby affecting received signal strength in downlink satellite communication systems. Furthermore, Sudhamani et al. (2025) demonstrated that temperature variations influence molecular activity within the atmosphere, increasing absorption losses at microwave and terahertz frequencies. Higher temperatures enhance molecular motion, strengthening interactions between electromagnetic waves and atmospheric gases, which leads to measurable signal attenuation.

3.1.2. Atmospheric Pressure Effect

Atmospheric pressure is defined as the pressure exerted by the force or weight of air in an area. According to Chima et al. (2020), in their work, *“Investigating the Impact of Weather Parameters on Signal Strength of Satellite Dish in Enugu Metropolis,”* it was reported that signal strength is inversely proportional to atmospheric temperature, pressure, and humidity when other parameters remain constant. According to Opara et al. (2021), changes in atmospheric pressure alter air density, thereby modifying electromagnetic wave propagation characteristics, which can contribute to signal fading. In the view of Czerwinski (2025), pressure variations influence atmospheric transmission behavior in satellite downlinks and optical communication systems. Also, Shivkant et al. (2025) reported that atmospheric pressure affects propagation loss through its influence on atmospheric density and refractive conditions along Earth–space communication paths. As reported by Olla et al. (2023), atmospheric pressure contributes to tropospheric gaseous absorption, which results in signal strength reduction over long propagation distances.

3.1.3. Humidity

Humidity is defined as the amount of moisture in the atmosphere. Relative humidity quantifies the amount of water vapor present in the air. Bragin et al. (2024) reported that variations in water vapour density significantly influence microwave link attenuation. Also, Srinivas and Sudha (2025) reported that atmospheric moisture, particularly in tropical regions, causes degradation of signal quality in high-frequency systems. In the work by Obiyemi and Moloi (2024), the results showed that moisture in Nigeria's atmosphere contributes to signal attenuation via absorption and scattering mechanisms, especially in microwave frequency bands used for satellite TV and data transmission. This was further confirmed by Olla et al. (2023), as they reported that water vapour affects atmospheric refractivity and signal bending to take a different direction from the intended one, resulting in a multipath scenario.

3.1.4. Rainfall and Precipitation

Rainfall is defined as the amount of precipitation (mm or inches) measured over a specific period. According to Obiyemi and Moloi (2024), heavy rainfall in Nigeria can weaken signals substantially, causing path loss, fading, and temporary service interruptions. Matricciani et al. (2024) confirmed that attenuation increases nonlinearly with rain intensity and frequency, making precipitation a dominant limiting factor in high-frequency systems. In the work by Srinivas and Sudha (2025), it was stated that dense rain clouds increase signal attenuation and that rainfall rate is a key parameter affecting satellite communication link availability. Furthermore, Olla et al. (2023) reported that rainfall does not only cause attenuation of signals but also raises atmospheric moisture content, which will further enhance absorption signals along the propagation path.

3.1.5. Ionospheric Electron Density

Ionospheric electron density is defined as the number of free electrons per unit volume in the earth's atmosphere. According to Adebiyi et al. (2024), in equatorial regions, such as Nigeria, increased electron concentrations cause signal refraction and phase delay, and this affects the accuracy and stability of satellite communication and navigation systems. Also, Zhang et al. (2024), in their work, observed that electron density changes can produce scintillation, causing rapid fluctuations in signal amplitude and phase, and these can cause disruption of communication links, particularly at low latitudes where ionospheric irregularities are frequent. In the same way, Kumar and Singh (2025) reported that the variations in electron density can alter signal propagation delay and bending, especially in lower frequency bands like L-band and VHF, leading to timing errors and path prediction inaccuracies. Furthermore, Oladipo et al. (2023) observed that seasonal and diurnal variations in the West African ionosphere can reduce signal reliability, in which a critical impact is observed during geomagnetic disturbances causing fading and phase instability.

3.2. Communication Challenges Caused by Atmospheric Effects

The interaction between atmospheric parameters and electromagnetic signals introduces several challenges to the communication signal. Some of these are as follows.

3.2.1. Signal Attenuation Effect

Attenuation is defined as the reduction in signal power as electromagnetic waves travel through the atmosphere from the source to the destination. Modibbo et al. (2025), in their work on Ku-band satellite links in Abuja and Kaduna, stated that rainfall significantly reduces signal strength, causing signal attenuation due to scattering and absorption. Also, Giannetti et al. (2025) observed that atmospheric particles weaken microwave signals and increase the natural noise, as well as reduce communication reliability when there is a heavy rainfall. In the work by Rahman et al. (2025), in which a machine learning technique was used to predict rain-induced signal loss in systems above 10 GHz, it was reported that though other factors can cause signal attenuation, rain is a dominant factor in high-frequency link degradation. Confirming this, Czerwinski (2025) reported in the work that beam spreading and turbulence also contribute to communication signal attenuation, especially for satellite downlinks.

3.2.2. Propagation Delay Effect

Propagation delay in satellite-ground station communication occurs when atmospheric conditions slightly slow electromagnetic signals as they travel between satellites and ground stations. In satellite communication, signals must travel long distances through multiple atmospheric layers before reaching receivers. During this propagation process, atmospheric conditions influence the speed and phase of electromagnetic waves, thereby introducing transmission delays. According to Adebiyi (2024), ionospheric variability over equatorial regions significantly alters radio wave propagation by modifying electron density levels.

Similarly, Kumar and Singh (2025) investigated the effects of ionospheric electron density variations on satellite communication systems, and the results indicated that propagation delay increases during periods of high solar activity. It added further that increased ionization leads to signal refraction and group delay, which affects signal arrival time at ground stations. In addition, Bragin et al. (2024), in their work, stated that variations in atmospheric water vapor density influence microwave signal propagation by altering refractivity within the lower atmosphere. Supporting these findings, et al. (2024) used space-based observations to examine ionospheric scintillation effects on satellite signals; they discovered that irregular ionospheric structures create rapid signal phase changes and variable propagation paths, leading to inconsistent signal arrival times at ground receivers.

3.2.3. Scintillation Effect

Scintillation is defined as the rapid fluctuations in signal amplitude and phase due to atmospheric refractive index irregularities, caused by tropospheric turbulence and ionospheric electron density variations. These fluctuations can result in signal fading, increased bit error rates, and reduced communication reliability. In the views of Broumandan et al. (2024), ionospheric scintillation during solar cycle 25 causes rapid phase and amplitude changes, especially in equatorial regions. Also, Zhou et al. (2025) reported the impact of tropospheric turbulence on optical satellite links, adding that it causes severe fluctuations that reduce the reliability of communication links. In the same ways, Abadi et al. (2024) revealed that when scintillation increases, it causes the increase in frequency and lowering of elevation angles, resulting in the vulnerability of Ku- and Ka-band systems. It is also important to note, as stated by El-Nabawy and Kamel (2025), that even clear-sky conditions can produce significant scintillation, emphasizing its persistent nature; hence, important measures are always to be put in place.

3.2.4. Atmospheric Noise

Atmospheric noise is defined as the unwanted electrical disturbances in the atmosphere of the earth, caused by natural electromagnetic phenomena such as lightning discharges and thunderstorms. Atmospheric noise primarily originates from natural processes within the troposphere and ionosphere. According to Giannetti et al. (2025), rainfall or precipitation increases antenna noise, and this causes the degrading of communication signals. Furthermore, Singh and Sharma (2024), in their work, highlighted lightning and tropospheric disturbances and discovered these to be significant contributors to impulsive noise, especially in tropical regions. In the same way, in the work by Rahman et al. (2025), the result showed that humidity, rainfall, and cloud density variations increase background noise, and this affects the link margins by causing its reduction. Confirming this, Khan et al. (2024) observed that atmospheric noise combined with external interference can severely reduce communication efficiency and network performances, especially in integrated networks. Variations in temperature, humidity, and atmospheric gases create random electromagnetic emissions that interfere with transmitted signals. Singh and Sharma (2024) developed atmospheric noise models and demonstrated that environmental electromagnetic disturbances significantly affect satellite communication systems, especially at microwave frequencies. Their study revealed that atmospheric noise increases background signal power, making it more difficult for receivers to distinguish useful information from unwanted signals. In equatorial and tropical regions, ionospheric activity plays a major role in interference generation. Adebiyi, Adeniyi, and Adimula (2024) observed that ionospheric irregularities alter radio wave propagation paths and introduce fluctuations that manifest as signal distortion and interference at receiving stations. Their findings showed that changes in ionospheric electron density produce random amplitude and phase variations, thereby increasing communication noise levels and reducing signal quality. These effects are particularly noticeable during periods of intense solar radiation when ionospheric ionization increases.

3.2.5. Atmospheric Interference Effect

Atmospheric interference is defined as the disruption of radio signals by the electromagnetic disturbances in the earth’s atmosphere. Atmospheric gases and precipitation also contribute to interference through absorption and scattering mechanisms. Sudhamani et al. (2025) investigated the effects of atmospheric gases and rain intensity on electromagnetic wave propagation and found that molecular absorption and rain scattering introduce additional signal disturbances. These disturbances generate fluctuations that behave like interference within communication channels, especially at higher-frequency bands such as millimeter-wave and terahertz communications. Rainfall-induced interference has also been widely documented in tropical communication environments. Obiyemi and Moloi (2024) described rainfall as a complex atmospheric phenomenon that simultaneously causes attenuation and random signal fluctuations. Their review highlighted that raindrops scatter electromagnetic waves in multiple directions, creating multipath interference that distorts received signals. Such interference reduces communication efficiency and may result in temporary loss of data during heavy precipitation events common in regions like Nigeria. Furthermore, El-Nabawy and Kamel (2025) investigated clear-air scintillation effects on communication signals and reported that atmospheric turbulence introduces rapid fluctuations in signal amplitude and phase. These fluctuations act as interference sources by continuously altering signal characteristics during propagation. It was further reported by the authors that turbulence-induced interference becomes critical for high-capacity satellite systems where stable signal quality is required for accurate data transmission.

3.2.6. Link Outages Due to Severe Weather and Ionospheric Disturbances

Link outage is defined as a situation when severe weather or ionospheric disturbances completely disrupt satellite communication. In the work by Obiyemi and Moloi (2024), it was reported that tropical regions in Nigeria are highly vulnerable to Ku- and Ka-band signal loss during prolonged heavy rainfall. Also, Matricciani et al. (2024), in their work, reported that severe precipitation combined with atmospheric turbulence can cause a full blockage of high-frequency signals, and this outage can be caused by ionospheric storms, as reported by Broumandan et al. (2024), that ionospheric storms during Solar Cycle 25 can cause temporary signal outages due to induced phase errors and amplitude fading.

3.3. Methods of mitigating atmospheric effects on satellite-to-ground station and ground station-to-satellite Communication signals

3.3.1. Adaptive Modulation and Coding

The adaptive modulation and coding (AMC) technique is defined as a method that allows a satellite communication system to automatically adjust its transmission parameters according to prevailing atmospheric conditions, such that instead of transmitting signals using a constant modulation format, the system evaluates channel quality in real time and selects an appropriate modulation level and coding rate. In this, during favourable weather conditions, higher-order modulation schemes are applied to increase data transmission efficiency, while during heavy rainfall or atmospheric turbulence, stronger coding schemes are activated to protect signal integrity. From the work by Zhang et al. (2022), it was stated that adaptive modulation significantly improves link reliability because transmission parameters continuously align with atmospheric channel variations, thus reducing communication outages caused by weather disturbances while maintaining efficient spectrum utilization. In the same way, Elsayed et al. (2025), in their work, explained that adaptive transmission techniques effectively counter atmospheric turbulence by dynamically modifying modulation formats and coding redundancy, thereby stabilizing signal reception during fluctuating atmospheric conditions. Ayegba et al. (2024) examined the relationship between atmospheric components and television signal strength in Abuja and found that temperature, humidity, and atmospheric pressure significantly influence received signal levels throughout the year. Earlier work by Ayegba, Ojo, and Adediji (2022) also confirmed that atmospheric parameters directly correlate with signal fluctuations, suggesting that fixed communication configurations are inadequate for regions with rapidly changing climatic conditions. These studies reinforce the need for adaptive modulation and coding strategies in satellite communication systems operating in tropical regions.

3.3.2. Frequency diversity and power control mechanisms

Frequency diversity is the process of transmitting information across multiple frequency bands so that when one frequency experiences severe atmospheric attenuation, either due to rain or other factors-induced fading at higher microwave frequencies, another frequency maintains acceptable signal quality. In the work by Modibbo et al. (2025), which investigated the impact of rain-induced attenuation in Abuja and Kaduna, it was observed that rainfall intensity significantly reduces signal strength at higher frequencies. Their findings indicated that communication reliability improves when systems employ multiple frequency options alongside adaptive transmission power adjustments. Power control mechanisms work by automatically increasing transmit power when atmospheric attenuation rises and reducing power during clear conditions to conserve energy and minimize interference. Power control mechanisms enable communication signals, like radio or television signals, to reach their designed horizon at any given time irrespective of the atmospheric conditions.

3.3.3. Site Diversity Using Multiple Ground Stations

Site diversity is defined as the process of deploying multiple ground stations at different geographical locations to communicate with the same satellite. Research carried out by Olla, et al. (2022) reported that atmospheric gas absorption and refractivity vary considerably across locations, which implies that signal performance differs even within the same country. Also, supporting this observation, Ayegba (2025) conducted a comparative analysis of atmospheric components affecting signal strength between Abuja and Plateau State and reported noticeable geographical differences in signal degradation patterns. These findings confirm that relying on a single ground station increases vulnerability to atmospheric disturbances, whereas distributed ground infrastructure enhances communication availability. By distributing ground stations geographically, communication systems can automatically switch transmission to the station experiencing more favourable atmospheric conditions. Descriptively, site diversity improves link availability because the probability of severe atmospheric attenuation occurring simultaneously at multiple distant locations is very low. Consequently, this strategy enhances communication reliability, especially in tropical regions where weather conditions change rapidly.

3.3.4. Advanced Error Correction Algorithms

"Error correction" is defined as the techniques used to detect and correct errors in data transmission or storage in order to maintain the integrity of the data. Advanced error correction involves the use of sophisticated techniques like forward error correction to add redundancy to data or information, thereby allowing the correct information to be received without retransmission. These algorithms add controlled redundancy to transmitted data so that the receiver can detect and correct errors caused by atmospheric conditions without requesting retransmission. According to Atser et al. (2024), advanced error correction techniques substantially reduce bit-error rates during rain attenuation events. Their study revealed that combining coding redundancy with adaptive communication strategies maintains data integrity even when signal strength temporarily drops below optimal thresholds. Furthermore, Zhang et al. (2022) explained that adaptive coding schemes dynamically adjust redundancy levels depending on channel quality. During adverse atmospheric conditions, stronger error correction improves reliability, while reduced redundancy during clear conditions maintains transmission efficiency. Ayegba et al. (2024) also observed that atmospheric parameters such as humidity and temperature strongly influence signal fluctuations in Abuja, reinforcing the need for intelligent digital correction techniques capable of maintaining data integrity under varying environmental conditions. In summary, error correction algorithms add controlled redundancy to transmitted information, allowing receivers to detect and reconstruct corrupted data without retransmission. This implies that advanced error correction algorithms serve as a protective digital layer that ensures communication continuity even when atmospheric disturbances temporarily weaken signal strength.

3.3.5. Atmospheric Prediction Models for Proactive Link Management

This involves the use of historical data of some independent variables, like meteorological data, to forecast signal degradation before it occurs. **Atmospheric prediction models** use historical meteorological data, statistical analysis, and real-time environmental monitoring to forecast signal degradation before it occurs. Predictive atmospheric models allow satellite operators to implement proactive link management strategies such as adjusting transmission power, switching modulation schemes, or activating alternative ground stations ahead of severe weather conditions. Ayegba, et al. (2022) established statistical correlations between atmospheric variables and signal strength variations, showing that predictable environmental patterns influence communication reliability. In the same way, Modibbo et al. (2025) observed that rain attenuation in tropical regions follows seasonal trends, and this enables the estimation of expected signal losses in order to design appropriate fade margins. In the same way, Elsayed, et al. (2025) stated that the integration of atmospheric forecasting with adaptive communication technologies significantly reduces unexpected outages as well as enhancing link stability. In simple terms, proactive link management helps the satellite communication systems to have the capability of anticipating atmospheric disturbances and maintaining consistent service quality.

4. Conclusion

The work on the assessment of atmospheric challenges affecting satellite-to-ground station and ground-station-to-satellite communications has been carried out using the review research method. This study discussed the impact of atmospheric conditions such as temperature, humidity, rainfall, atmospheric pressure, and ionospheric electron density on satellite-to-ground and ground-to-satellite communication links as being the major challenges. It was observed from the analysis that some of the effects of the atmospheric challenges affecting satellite-to-ground station and ground-station-to-satellite communications are signal attenuation, propagation delay, scintillation, noise and interference, as well as complete link outages. The result also reported some methods of mitigating atmospheric challenges to satellite-to-ground and ground-to-satellite communication such as adaptive modulation and coding, frequency diversity and power control mechanisms, site diversity using multiple ground stations, and advanced error correction algorithms. In conclusion, it can be said that satellite-to-ground station as well as ground station-to-satellite communications links are faced with several atmospheric challenges, which can result in many negative ways; such challenges can be prevented or reduced to manageable levels. The results will be valuable for designing resilient satellite networks, particularly in high-frequency bands and regions prone to severe weather disturbances.

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