2024 4th International Conference on Emerging Smart Technologies and Applications (eSmarTA) | 979-8-3503-5413-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/eSmarTA62850.2024.10638931

Resilient Skies: Advancing Climate-Resilient UAVs for Energy-Efficient B5G Communication in Challenging Environments

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***Abstract*—Due to severe climatic circumstances exacerbated by climate change, deploying Beyond Fifth Generation (B5G) networks is critical. Unmanned Aerial Vehicles (UAVs) have become indispensable for B5G connectivity in inclement weather conditions such as snow, fog, and rain. This paper investigates energy-efficient B5G connectivity and climate-resilient UAVs. We evaluate the performance of UAV coverage and energy efficiency at different elevation angles under various weather conditions, including snow, fog, and rain. Additionally, we discuss the challenges environments and propose solutions to improve climate-resilient and energy-efficient B5G communication. Emphasizing the adverse effects of climate change on communication networks, The paper's findings highlight the significant impact of weather conditions on UAV coverage, B5G communication networks, and energy efficiency. This research paves the way for a more resilient and sustainable future.**

***Index Terms*—UAV-assisted communication, Harsh environments, Meteorological impacts, Energy efficiency, Outage probability, Spectrum efficiency, B5G.**

I. Introduction

A MAJOR advancement in contemporary communication systems, The launch of Beyond Fifth Generation (B5G) networks came to emulate the rapid development in communications systems and pave the way for a renaissance era characterized by high speed and power. Modern wireless communication networks play an important role in improving network latency, throughput, and capacity [1]. B5G networks play an important role in improving several applications, such as IoT connectivity, providing mission-critical communications for autonomous vehicles and industrial automation, and providing immersive augmented reality experiences [2]. The growing frequency and intensity of unfavourable climatic circumstances, made worse by climate change, is one of the most urgent problems. Intense precipitation, thick fog, and snowfall are environmental phenomena that significantly challenge the reliable functioning of wireless communication networks [3], [4]. For example, rain attenuates radio transmissions, reduces the Unmanned Aerial Vehicles (UAVs) coverage area, and degrades the strength of the signal. Similarly, fog scatters signals, leading to loss of signal and deterioration of the quality of communication connection. The accumulation of ice and snow on communication equipment after snowfall obstructs signal transmission and results in equipment failure.

UAVs have arisen as a disruptive technology in response to these issues, providing a viable means of improving communication in challenging areas [5]. UAVs are an emerging solution to improve communication in difficult environmental conditions since they can quickly traverse and adjust to difficult meteorological conditions [6], [7]. As a result, UAVs are excellent candidates for covering and supporting GNs in need [8]. UAVs are perfect for providing vital coverage and assistance to GNs operating in challenging areas, as they are extremely agile and adaptable [6]. Unlike conventional fixed communication infrastructure, UAVs can instantly self-adjust to enhance signal reception and transmission. This function guarantees a continuous connection even during bad weather, such as snowstorms, heavy fog, or torrential rain. In challenging circumstances, maintaining a dependable and high-quality connection is essential, and this feature significantly increases network dependability [9]. UAVs can reduce route overhead considerably. Traditional GNs often depend on intricate routing strategies in difficult situations to bypass barriers and maintain connectivity. UAVs simplify routing and lessen the complexity of data transmission thanks to their direct line-of-sight capabilities and agility, which promotes more effective network operation [9]. Furthermore, a UAV-aided communication cellular network is vital to serve the requirements for dynamic communication [10]. Drones can enable quick recovery in disaster areas and uninterrupted communication services [11]. Additionally, UAVs' adaptability and resilience extend to scenarios where unplanned spikes in network traffic cause temporary overloading or incapacitation of communication infrastructure, as frequently happens during significant events or catastrophes. Under such circumstances, UAVs can be quickly deployed to unload traffic, guaranteeing uninterrupted operation of vital communication services, such as emergency calls and data transfer [12]. This article explores the relationship between UAVs, unfavorable weather, and B5G communication, assessing how UAVs could improve energy-efficient communication in the face of rain, fog, and snow. Numerous performance measures are included in the evaluation, such as route loss, energy efficiency, probability of outage, and spectrum efficiency. By addressing the challenges, we highlight the potential for drones to support communication in difficult environments and serve as reliable replacements for failing ground communication stations.

A. Motivation and contributions

The development of B5G networks offers the potential to bring about significant advancements in communication, allowing up applications such as seamless connectivity for IoT devices and ultra-low latency for autonomous vehicles. The impact of harsh environmental conditions brought on by climate change, such as heavy rain, fog, and snow, which present significant obstacles to dependable wireless communication, is limiting the effectiveness of B5G networks. By examining how climate-resilient UAVs could improve energy-efficient B5G communication during inclement weather, this article seeks to close this gap and unleash the full potential of B5G networks for various game-changing applications. Although 5G networks are up and coming, there still needs to be a significant gap in ensuring that communication infrastructure is resilient to the unfavorable weather conditions exacerbated by climate change. Rain, fog, and snow can severely degrade wireless communication quality, disrupting services, and hindering the deployment of the B5G network. This paper fills this gap by examining how climate-resilient UAVs can improve energy-efficient B5G communication in harsh environments. It offers crucial insights and solutions to keep communication services running in bad weather, ensure critical applications do not stop working, and make B5G communication systems more climate-resilient. The paper aims to increase knowledge on how, in challenging environmental circumstances, UAVs may significantly improve the resilience and energy efficiency of B5G communication networks. The contributions include quantifying the impact of UAVs on energy efficiency and important performance measures, as well as showcasing them as a climate-resilient option. The contributions of the paper are summarized as follows:

- The paper investigates how energy-efficient B5G connectivity and climate-resilient UAVs, evaluate their performance in terms of coverage and energy efficiency under various adverse weather conditions (snow, fog, and rain).
- We discuss the challenges posed by disaster environments to B5G communication networks and UAVs, proposing solutions to enhance climate-resilient and energy-efficient communication.

B. Related work

Recent research has examined the interaction of UAVs, unfavorable weather, and wireless communication. Several studies have established the groundwork for understanding UAVs' ability to lessen the difficulties presented by hostile environments. The pioneering study on wireless communications with UAVs clarified the advantages and disadvantages of UAV-assisted communication [9]. The authors emphasized that UAVs can significantly provide on-demand wireless communications with agility and adaptability when traditional infrastructure is disrupted [13]. Despite concentrating on conventional UAV applications, their study offered insightful information about the viability of UAVs in challenging environmental settings. A thorough tutorial on the uses, difficulties, and unsolved issues related to UAVs in wireless networks was provided in [6]. The authors of [14] investigated how fog and haze affect communication using visible light. Although their research was not focused on UAVs, it did emphasize the necessity of robust communication systems during inclement weather. In line with our research goals, the study focused on how weather affects communication quality and dependability.

The use of UAVs in 6G communication networks was investigated by the authors of [15], who emphasized how quickly they could be deployed and how they could extend coverage in the case of harsh weather. The effect of rainfall on millimeter wave communication, a crucial part of B5G and 6G networks, was examined in [16]. The results emphasized how significant weather-induced signal attenuation is and how UAVs might serve as dynamic relays to lessen the impact of rain on high-frequency transmission. In addition, in [17], the authors explored the difficulties associated with energy-efficient communication in inclement weather. The study focused on energy-conscious routing strategies for UAV-assisted networks functioning in cloudy environments, highlighting the significance of energy conservation in difficult weather situations. Our paper adds to this changing landscape by thoroughly assessing UAV performance in B5G networks under the combined influence of rain, fog, and snow. Although the above studies have made significant strides in understanding the role of UAVs and weather effects in communication networks, in this context, this paper continues to expand on this understanding. Our article addresses difficulties related to energy-efficient and climate-resilient B5G communication in severe locations, including information on energy efficiency, probability of outage, spectrum efficiency, and route loss.

C. Paper Structure

It has been added to Section I. The remainder of the paper is organized as follows: Section II presents the proposed system model. Section III provides the simulation results of the key performance indicators and their discussion. Section IV presents the conclusion

II. Proposed System Model

The system model is designed to handle situations where GNs have significant difficulties sustaining wireless connectivity. We intentionally use UAVs to restore and maintain vital communication links with GNs in these difficult situations to address this widespread problem. Innovative solutions are required for conventional wireless coverage services, which ground base stations usually supply. We strategically deploy UAVs to reinstate and sustain essential communication links with GNs in these demanding scenarios to overcome this pervasive issue. In our proposed model, UAVs have advanced directional antennas, a critical feature designed to optimize network coverage performance. Furthermore, the UAVs employ dynamic altitude adjustments, responding to factors such as antenna beamwidth and the density of nearby structures, as quantified by the number of installations [18].

The altitude adaption ensures Adequate GN coverage, particularly in challenging climatic circumstances. In difficult situations, the ability of UAVs to dynamically assign GNs and user devices inside the coverage area dramatically increases the likelihood of reliable and continuous connectivity. Even in bad weather, the allocation technique improves coverage and connection. Path loss, energy efficiency, and coverage area are just a few of the performance metrics we use to evaluate the effectiveness of our suggested system. These parameters are essential for assessing the system's performance in various weather scenarios, guaranteeing dependable connectivity even in the most hostile settings.

A. Attenuation Models for Rain, Fog and Snow

The issue of using UAVs for telecommunications services in bad weather is considerable. Investigating attenuation models for various everyday weather situations, such as rain, fog, and snow, is crucial to laying the groundwork for the deployment of UAV communications in such dynamic environments. The following is the expression for the attenuation models under certain weather conditions [19]:

$$\gamma = \begin{cases} kR^{\alpha} & \text{Rain model} \\ K_1(f,T)M \quad (\mathrm{dB/km}) & \text{Fog model} \\ 0.00349\dfrac{R_{\mathrm{s}}^{1.6}}{\lambda^4} + 0.00224\dfrac{R_{\mathrm{s}}}{\lambda} \quad (\mathrm{dB/km}) & \text{Snow model} \end{cases} \tag{1}$$

Rain Model: The rain attenuation model is characterized by the equation $\gamma = kR^{\alpha}$, where R represents the rain rate in millimeters per hour exceeded for 0.01% of an average year. The parameters k and α are functions of polarization, and their values are determined by equations derived from experimental data fitting to power-rate coefficients accessible from ITU-R [19].

Snow Model: The snow attenuation model is described by the equation $0.00349\frac{R_{\mathrm{s}}^{1.6}}{\lambda^4} + 0.00224\frac{R_{\mathrm{s}}}{\lambda}$, where λ is the wavelength and R_{s} is the snowfall speed.

Fog Model: The attenuation coefficient is given by $\frac{4.34f^2}{\lambda^2}$ in units of $(dB/km)/(g/m^3)$. where η is defined as $\frac{2+\varepsilon'}{\varepsilon''}$, and the complex permittivity of water is expressed as $\varepsilon''(f)$ and $\varepsilon'(f)$. For fog attenuation modeling, the equations governing the complex permittivity of water ($\varepsilon''(f)$ and $\varepsilon'(f)$) are provided, with temperature (T) and various constants that determine their values. The specific attenuation coefficient ($K_1(f,T)$) is essential to quantify fog-induced attenuation and is directly related to the density of liquid water in the cloud or fog (M) [19].

$$K_1(f,T) = \frac{0.819f}{\varepsilon''\left(1+\eta^2\right)} \quad (\mathrm{dB/km})/\left(\mathrm{g/m^3}\right), \tag{2}$$

where $\eta = \frac{2+\varepsilon'}{\varepsilon''}$ and $\varepsilon''(f)$ is given as:

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

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

Where ε_0 is calculated as $77.66+103.3(\theta-1)$, ε_1 is derived as 0.0671 times ε_0, and ε_2 is a constant with a value of 3.52. Here, θ is determined as $300/T_{\mathrm{fog}}$, where T_{fog} represents the temperature during foggy weather conditions and is set at 293.15K. Additionally, we define the primary relaxation frequency, f_p, as $20.20-146(\theta-1)+316(\theta-1)^2$, and the secondary relaxation frequency, f_s, as 39.8 times f_p (in GHz).

where m and α , are determined [19], T represents the temperature of liquid water, K_1 stands for the specific attenuation coefficient (dB/km per g/m^3), and M denotes the density of liquid water in the cloud or fog (g/m^3), as documented in [20]. Additionally, Rs corresponds to the snowfall speed measured in millimetres per hour, and λ indicates the wavelength measured in centimetres

When UAVs are deployed in challenging meteorological environments, attenuation models are important to understand and mitigate the effects of rain, fog, and snow on wireless communication. They also provide valuable insights into how environmental conditions impact communication performance and direct the development of resilient communication systems.

B. Path Loss for Rain, Fog and Snow

The propagation of path loss in the air-to-ground (A2G) channel is a critical factor in determining the wireless communication channel between UAVs and GNs. Environmental factors significantly impact signal path loss, such as separation between UAVs and GNs, GN elevation angles, and UAV heights. We incorporate the route loss models with unique attenuation coefficients for rain, fog, and snow to fully simulate the A2G channel under various weather scenarios. The A2G channel models that are obtained can be stated as follows [19]:

$$PL_{\text{UAV}} = (PL_{\text{LoS}} \times P_{\text{LoS}} + PL_{\text{NLoS}} \times P_{\text{NLoS}}) + \frac{(\beta+\gamma)d}{1000}$$
$$= \left(\frac{A}{1+a\exp\left(-b\left(\frac{180}{\pi}\tan^{-1}\left(\frac{h}{r}\right)-a\right)\right)} \right.$$
$$\left. +20\log\frac{r}{\cos\left(\frac{180}{\pi}\tan^{-1}\left(\frac{h}{r}\right)\right)} + B \right) + \frac{(\beta+\gamma)d}{1000}, \quad (5)$$

Where, PL_{UAV} represents the UAV path loss, PL_{LoS} and PL_{NLoS} are path loss components for Line-of-Sight (LoS) and Nonline-of-Sight (NLoS) conditions, respectively. where β unique attenuation coefficient, d is the distance between the UAV and the Ground Node (GN) and a and b these are constants used in the path loss model. in anddtion , h is the height of the UAV , r is the horizontal distance between the UAV and the GN and B: is a constant used in the path loss model.

C. Connectivity in UAV coverage area

To determine the optimal coverage area of the UAV, we derive the first derivative of equation (16) in [19] concerning the variable r as follows:

$$\begin{aligned}
0 = &-\frac{Aah}{r^2}(b)\left(\tan^{-1}\left(\frac{h}{r}\right)-a\right) \\
&\times\left(e^{-b\left(\tan^{-1}\left(\frac{h}{r}\right)-a\right)}\right) \\
&\times\left(1+ae^{-b\left(\tan^{-1}\left(\frac{h}{r}\right)-a\right)}\right)^{-2} \\
&\times\left(\frac{h^2}{r^2}+1\right)^{-1} \\
&+20\log\left(\cos\left(180\frac{1}{\pi}\arctan\left(\frac{h}{r}\right)\right)\right)^{-1} \\
&-3600\frac{(\log h)\,h}{r\pi}\sin\left(180\frac{1}{\pi}\tan^{-1}\left(\frac{h}{r}\right)\right) \\
&\times\left(\cos\left(180\frac{1}{\pi}\arctan\left(\frac{h}{r}\right)\right)\right)^{-2} \\
&\times\left(\frac{h^2}{r^2}+1\right)^{-1}
\end{aligned} \quad (6)$$

This derivative is instrumental in determining the optimal coverage area of the UAV, taking into account critical parameters such as altitude, distance, and environmental factors. Based on the findings of [21], we combine the propagation attenuation effects of rain, fog, and snow under various weather conditions to model wireless channels effectively. This integrated model aids in our comprehension of how bad weather affects communication, especially when UAVs are being deployed.

Several important factors are included in the performance criteria intended to evaluate GN communications assisted by UAVs, such as reaching faster data speeds, improving energy efficiency, increasing network capacity, and guaranteeing service availability in the case of extreme weather [22]. Interestingly, especially in difficult circumstances, network capacity is determined by the amount of traffic that can be managed with the lowest possible bit error rate. Effective wireless communication system design is based on a thorough understanding of weather-induced attenuation and the derivative-based optimization approach to achieve optimal performance metrics in UAV-assisted GN communications, even under challenging environmental conditions.

D. Energy Efficiency

The UAV assumes the critical function of a temporary communication relay in challenging environmental communication scenarios, guaranteeing the prompt and dependable essential interchange of information. Nevertheless, unfavorable meteorological phenomena like precipitation, mist, and snowfall substantially affect the UAV's energy reserves, especially when recharging. The circumstances waste time and exhaust the UAV's energy supply. Therefore, improving the energy efficiency of UAV-assisted communication systems is imperative. Energy efficiency in UAV-assisted communication is evaluated holistically by considering the UAV's complete instantaneous transmission vector, EE^k_{UAV}. This vector represents every component that makes up the connection between the UAV and the ground nodes. It functions as a thorough metric to evaluate and enhance the system's energy efficiency, tackling the difficulties presented by severe weather and guaranteeing efficient use of the UAV's resources for dependable communication [7].

$$\text{EE}_{\text{UAV}} = \frac{B \cdot \log_2\left(1 + \frac{p_i h_i}{\sum_{m=1}^{M} p_m h_{m,i} + p_j h_j + \sigma^2}\right)}{P_{tx} h}, \quad (7)$$

Where, B is the bandwith, h_i represents the number of hops from the UAV to GN communications, and P_{tx} stands for the maximum transmission power the UAV uses for downlink communications with GNs.

Algorithm 1 Climate-Resilient UAV Communication Model

```
1:  Input: Rain rate: rain_rate_mm_hr
2:  Frequency: frequency_GHz
3:  Temperature: temperature_Kelvin
4:  Snowfall speed: snowfall_speed_mm_hr
5:  Wavelength: wavelength_cm
6:  t_max: Maximum number of iterations
7:  P_max: Maximum transmission power of UAV
8:  d_{u,i}: The distance between UAV and GNS
9:  θ_{j,k}: Elevation angles of GNs
10: N: length(weather_conditions) ('Rain', 'Fog', 'Snow') for
    t = 1 to t_max do
        for i = 1 to N do
            for j = 1 to N do
                Calculate Path Loss Based on Eq(5)
              Calculate UAV Coverage Area Based on Eq. (6)
              Calculate Energy Efficiency Based on Eq(7)
            end
        end
    end
11: Output: Energy efficiency and UAV Coverage in conditions of ('Rain', 'Fog', 'Snow')
```

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Bandwidth	5 MHz
σ^2	-174 dBm/Hz
f_c	$[28\ GHz, 60\ GHz]$
Urban area factors	$a = 9.61$, $b = 0.16$, $\eta_{\text{LoS}} = 1$, $\eta_{\text{NLoS}} = 20$
Medium rain	$R = 12.5$ mm/h
Medium fog	$M = 0.05$ g/m^3
Snow	$Rs = 5$ mm/h
Weather conditions [dB/km] attenuation coefficient [23]	Clear air = 0.43, Haze = 4.2, Moderate rain (12.5 mm/h) = 5.8, heavy rain (25 mm / h) = 9.2, Light fog = 20, moderate fog = 42.2, Heavy fog = 125
UAV altitude	120 m
UAV TX power	5 W
GN	$0°$ to $90°$

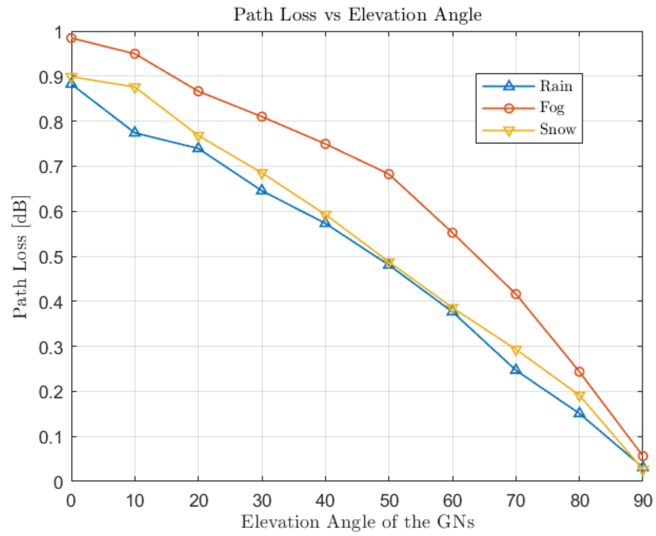

Fig. 1. Variation in Path Loss with GN Elevation Angle in Different Harsh Environments (Rain, Fog, Snow)

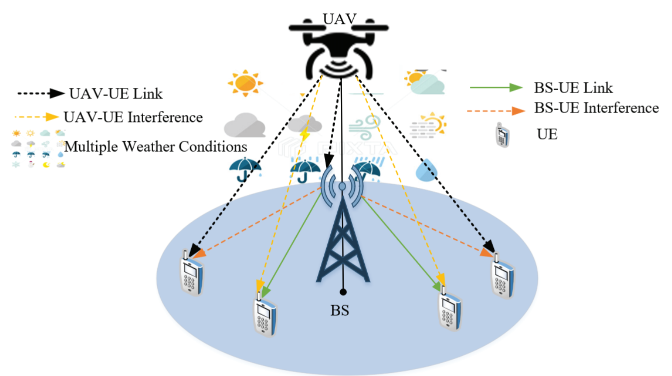

Fig. 2. Architecture of the UAV to GN communication in harsh environments

III. Results and Discussion

We provide a wide range of simulation results that clearly show how well the suggested solutions work. We evaluated key performance indicators and characteristics, paying particular attention to route loss, energy efficiency, and likelihood of failure in UAV-to-ground node communication. These tests are carried out in challenging weather conditions, including rain, fog, and snow. To simulate real-world situations, we consider a scenario where ground nodes are dispersed randomly throughout the UAV's coverage region. We alter the ground node elevation angles and modify the UAV elevations correspondingly to attain a thorough assessment. We assume that the ground nodes are dispersed randomly in each case based on the UAV's coverage area. The ground nodes and the UAV have a transmission distance between 100 and 1000 meters between their source and destination. In addition, we investigate various elevation angles, from 0 to 90 degrees, for the ground nodes. By executing meticulous simulations, we aim to offer a thorough understanding of the performance of our suggested schemes in different scenarios and settings. These empirical data will support the effectiveness of our methods and provide information on how they can be used in practice.

A. Path Loss

Path loss propagation is an essential factor to consider when evaluating communication performance, and it is crucial to comprehend how it changes depending on the circumstances. As the elevation angle of the ground nodes (GN) increased from $0°$ to $90°$ in hostile settings, we noticed a significant trend in route loss, as shown in Fig. 1. Rain, fog, and snow are the main meteorological factors responsible for the fluctuation. Specifically, the route loss increases significantly when the GNs are located in inclement weather; it can range from 0 to 310 dB, depending on the angle of elevation of the GN. The sharp change in route loss shows the difficulties caused by bad weather. Interestingly, the path loss increases subtly in a wet setting, going from 0 dB to 51 dB. In comparison, the path loss in the fog environment increases from 100 to 175 dB. Lastly, due to the unique properties of a single city model, the loss of route increases significantly in the snow environment, from 0 dB to 310 dB, when the elevation angle of the GN varies from $0°$ to $90°$.

B. Energy Efficiency

We examine the energy efficiency of both the GN and the UAV in this setting, providing insight into the behavior of these efficiency measures in different scenarios. Our research is visually shown in Fig. 3. We find that energy efficiency decreases with increasing distance between the GNs and the UAV; this is an important finding, since it indicates that more energy is needed to maintain communication across longer distances. However, an exciting finding emerges when we look at energy efficiency in various contexts. With increased ground node transmission distance, the energy efficiency numbers for

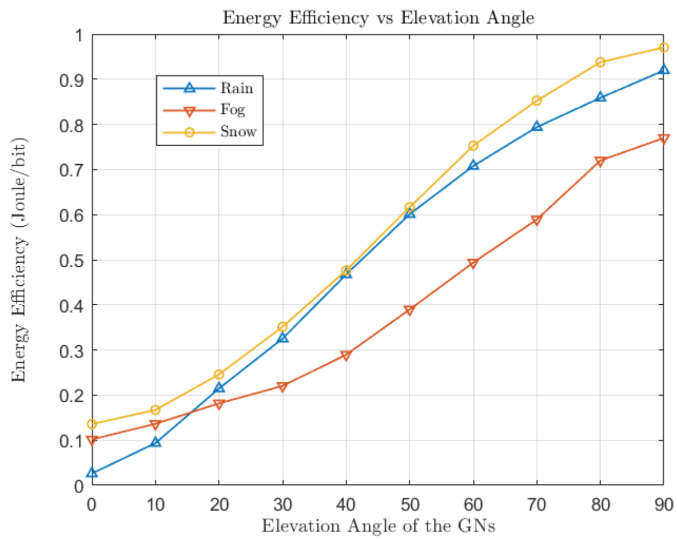

Fig. 3. Variation in Energy Efficiency with Ground Node Distance Across Different Scenarios (Rain, Fog, Snow)

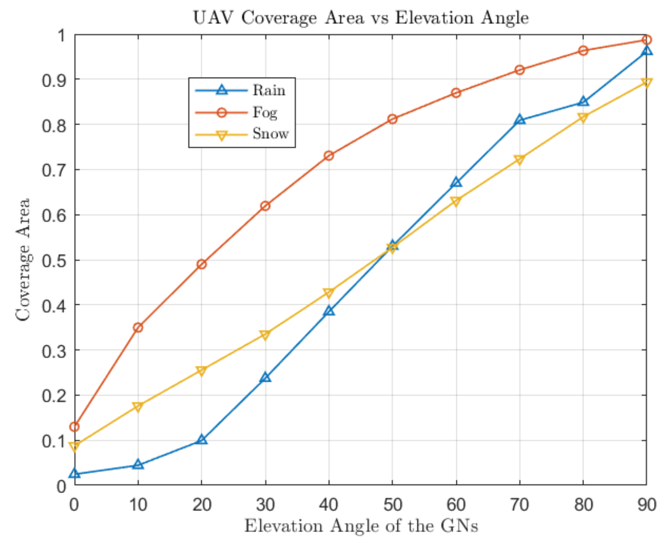

Fig. 4. Variation in UAV Communication Coverage Radius with Altitude Across Different Harsh Weather Conditions (Rain, Fog, Snow)

every scenario converge and align closely. According to the phenomena, interference's adverse effects on energy efficiency decrease with increasing ground node distance. When GNs are farther apart, interference plays a less significant role in reducing energy efficiency.

Increasing transmission power is one effective way to counteract this reduction in energy efficiency due to interference, particularly in scenarios with longer transmission distances [24]. The signal may more effectively withstand interference and increase energy efficiency by supplying additional power. It is also crucial to emphasize that co-channel interference, which occurs when many communication channels overlap and interact, mainly impacts energy efficiency. Directed antennas can be a helpful tactic in this situation. Directional antennas can reduce interference and improve overall efficiency by concentrating and focusing the signal in a particular direction. Therefore, using directional antennas in UAV-to-GN communication scenarios is a helpful way to minimize the negative impacts of interference on energy efficiency.

C. UAV Communication Coverage

The effect of inclement weather, such as rain, fog, and snow, on the radius of the cell and the operating altitude of UAV communication systems is shown in Figure 4. The coverage radius and the ideal UAV height are pretty modest in situations with moderate rainfall, suggesting that lower operation altitudes are required for sufficient coverage. On the other hand, when there is less snow, the coverage radius significantly increases, allowing UAVs to fly at more significant elevations and still cover a large area. This indicates that the trade-off between coverage area and UAV altitude in UAV communication is primarily determined by the severity of the weather, with milder conditions permitting higher altitudes and more extensive coverage areas than situations with more moderate rain.

IV. Conclusion

This paper has investigated the critical function of UAV-assisted ground node communication in difficult weather conditions, such as rain, fog, and snow. Key performance measures such as energy efficiency, outage probability, spectrum efficiency, and route loss have been the focus of our evaluation. According to our suggested system model, UAVs provide GNs operating in challenging situations with critical coverage assistance, resulting in improved network scalability, less routing overhead, optimized throughput, and increased coverage. As cellular communication becomes more dynamic and diversified, UAV-assisted communication is set to become a cornerstone technology that meets the ever-changing needs of communication scenarios. In addition, UAVs are critical in providing rapid recovery if traditional communication infrastructure fails due to natural catastrophes or unfavorable climate conditions. The findings highlighted the significant impact of weather conditions on UAV coverage, B5G network performance, and energy efficiency, emphasizing the necessity for resilient and sustainable communication systems in the face of climate change. In weather conditions, findings showed that UAVs are a suitable substitute for malfunctioning GNs, providing communication services with fast restoration and dependability in emergencies.

Acknowledgment

This research is supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot Q444).

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