Development and Analysis of Outage Probability and Achievable Rate for UAV Relay Implementation in Disaster Areas

Mia Galina *, Muhamad Asvial, Muhammad Suryanegara, and Naufan Raharya
Department of Electrical Engineering, Universitas Indonesia, Depok 16424, Indonesia;
Email: asvial@eng.ui.ac.id (M.A.), m.suryanegara@ui.ac.id (M.S.), naufanraharya@ui.ac.id (N.R.)
*Correspondence: mia.galina91@ui.ac.id(M.G.)

***Abstract*—Unmanned aerial vehicles (UAV) coupled with wireless networks have offered the potential for forthcoming mobile communications networks. The UAV-assisted wireless communication technology approach is an option for maintaining communication services, one of which is for disaster areas. This study aims to investigate the deployment of UAV-assisted communications in disaster areas. The simulation in this work is focused on investigating the relationship between the UAV's height or radius and the outage probability and achievable rate. We identifies a UAV that behaves as a relay in a disaster area connected to two users, identified several critical parameters, such as UAV height, radius, and SNR value, and investigated the impact of changing each of them on outage probability and achievable rate values. Finally, we simulates the effect of these critical parameters on outage probability and achievable rate to maximize the use of UAV-assisted communication as a disaster management solution. According to the simulation results, as the signal to noise (SNR) increases, the probability of network communication interference decreases, and the achievable level increases. Moreover, increasing the range of UAVs can improve communication performance by reducing the probability of outages and increasing the achievable rate.**

***Keywords*—Unmanned aerial vehicles (UAVs), outage probability, achievable rate, wireless communications**

I. Introduction

The development of unmanned aerial vehicle (UAV) technology has given rise to UAVs in various shapes, dimensions, capabilities, and roles. UAVs are aerial platforms with mobility, flexibility, and low energy consumption, that are commonly employed in wireless communication [1, 2]. It is small, and an adjustable altitude supports the UAV's ability to increase line-of-sight (LoS). This condition can increase capacity and coverage, support connectivity efficiently, and even integrate with current telecommunications backhaul services. Other advantages include lower latency, a better signal-to-noise ratio (SNR), and more cost-effectiveness than satellite communications. All these advantages are encouraging for UAVs to emerge as an alternative to complement current cellular systems.

UAVs can be used for wireless backhaul infrastructure demands, traffic offloading, and as an alternate solution for fast service recovery after natural disasters, emergency response, and search and rescue. It can also disseminate and transmit information and collect sensor data in machine-type communication. Using UAV-based wireless services is the ideal solution for rapid service recovery following natural disasters, emergency responses, and search and rescue operations [3, 4].

Disaster conditions can occur at any time and affect a large area. This is frequently followed by situations in which telecommunications infrastructure services are entirely paralyzed. In such circumstances, the first 72 hours (the first three days) are a crucial window that must be carefully considered to maximize search and rescue operations. At the same time, the rise in the frequency of telecommunications traffic to and from the disaster area will increase due to the large number of damaged telecommunications infrastructures [5, 6]. This is one of the considerations in disaster-affected areas; deploying UAV-based wireless communication can contribute to the availability of a communication network connecting disaster survivors and rescue teams to the nearest cellular infrastructure [7].

Several interesting challenges to implementing UAV-assisted communication in disaster areas have prompted researchers to investigate unmanned aerial systems (UAS) technology. This not only relates to disaster situations, but also underlines its scalability, robustness, agile response performance, high throughput capabilities, and technical issues related to low communication latency [8–10]. Moreover, Saif and Dimyati *et al.* [11] have shown that UAVs provide ground node coverage in post-disaster scenarios and evaluate the optimal relay hops of a device-to-device (D2D) wireless network. Finally, the authors of [12–14] investigated a UAV as a base station (BS) communicating with two ground users via NOMA. In [12], the authors discussed UAV-assisted NOMA network's throughput performance and optimization for disaster management. Le and Nguyen *et al.* [13] focused on the closed-form formula of outage probability for two ground

Manuscript received April 12, 2023; revised May 19, 2023; accepted June 27, 2023.

users by providing the simulation impacts of system parameters on outage behavior, while Lima and Fachada *et al*. [14] focused on creating models in Python. Rician fading was considered in this study because communication is line-of-sight (LoS) on the air-to-ground (A2G) communication link between the UAV and ground users. This study explored two secondary users who experienced hardware failure at different levels, which describing network conditions that are not ideal. According to the research, the varying levels of SNR values for the two users determine the probability of an outage occurring.

Motivated by recent work [8–14], this study will enhance previous research by focusing on the analysis of outage probability and achievable rate if UAV technology is used as relay communication in the disaster area. By changing the altitude and radius of the UAV, it is possible to observe the SNR value, as well as the extent to which they affect the outage probability parameter values and the achievable rate to maximize the application of UAV-assisted wireless communication technology as a disaster management solution.

This work adds to prior studies in which UAV relaying has been extensively studied in various settings. Section I begins by presenting the disaster zones and how UAVs can be used as alternative solutions. We also introduce similar studies to give an indication of how far research in this area has progressed and which areas still require further investigation. Section II discusses the theoretical underpinnings of this topic and review previous studies to improve the theoretical foundation. Part of the debate about UAVs that can be used as relays is the essential aspect of UAVs becoming a solution for communication services in disaster areas. Section III describes the methods employed in this study, including the system parameters and algorithms. This section also goes through some of the technical factors that will be used in the simulation, such as the signal-to-interference-and-noise-ratio (SINR), outage probability, achievable rate in UAV-assisted cellular communications, and path loss and channel models. Section IV describes simulations that explore the relationship between UAV height and radius, outage probability and achievable rate and their analysis based on the algorithms and system models provided in Section III. Given the context of deploying UAVs in a disaster region, it is critical to understand which scenarios are most ideal for UAV positioning. Finally, Section V will summarize some essential points.

II. Related Work

A. *Appropriate Positioning of UAVs as Relaying*

Unmanned aerial vehicles can function as a relay of communication services in specific places, boosting the accessibility of the current communication infrastructure to the end users (communication consumers) who require it. This arrangement will likely connect two (or more) sites, which could be end users, access stations, or other relays [15]. Several studies have previously been undertaken to explore and synthesize ideal UAV locations. The authors of [8] simulated the ideal placement of the UAV-BS in a device-to-device communication scenario, developing a controlled framework to examine data coverage and speed by analyzing numerous scenarios using simulation and analytical results. In other research [16], the authors investigated the impact of the UAV-BS height over an area where a UAV-BS provides user coverage. The Authors analyzes the best UAV-BS height (if available) by considering Rician Fading to optimize coverage area.

The critical point of this study is the extent to which UAV height, radius, and SNR value influence outage probability and achievable rates in a disaster area. This is important to investigate because in the event of a disaster, the telecommunications infrastructure is probably affected, although still not completely paralyzed, or may be down. However, telecommunications service traffic will be extremely high at that time. One of the essential technical parameters determining the extent to which telecommunications access can be fulfilled is outage probability and achievable rate, which are the focus of this study. UAV-Assisted Cellular Communications

According to [17], drones can act as hovering user equipment (UE) or as base stations (BS), as shown in Fig. 1. A UAV equipped with cameras and other relevant sensors can be used as an aerial user equipment (AUE) on drones for surveillance, inspection, and dispatch. Connections with landline users are made by transferring the collected data to operators via the existing cellular network infrastructure. In this scenario, a link connecting the AUE to at least one of the BSs is required. If another BS is nearby, it can be a nuisance that interferes with and reduces performance.

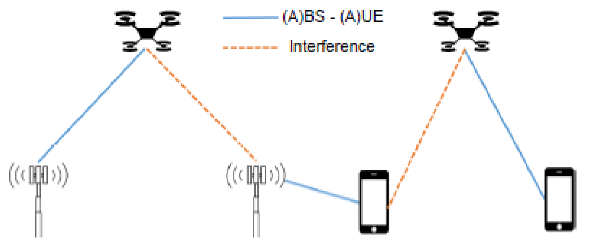

Figure 1. Aerial user equipment and aerial base station configuration [17].

Interference with UAVs will become more complex if it is applied to systems that demand interoperability between the UAS and fixed service (FS), or where both employ shared frequency spectrum allocations. This is described in research [18], which simulated the circumstances and found that interference from FS is not harmful to UAVs. Compatibility and interference issues are also discussed in research [19], where the authors developed a simulation by configuring interference parameters for signal ratio, protection distance, and protection limit criteria. The results were visualized into several graphs indicating the safe compatibility of wireless avionics observed infra-communication (WAIC) and FS.

According to various prior studies, the simulation method promises to be very effective in describing the effect of interference on the overall signal quality of communication services. As a consequence, this study employed the same approach.

UAV technology can be utilized to boost terrestrial communications by acting as a wireless access point in the air or a relay node. This function can send payloads over narrowband or wideband communication channels. UAVs enable terrestrial wireless communication by providing data access for wireless backhaul infrastructure demands, traffic offloading, and as an alternative solution for emergency response, rapid recovery services following natural disasters, and search and rescue.

According to this study [20], the UAV can be a relay, forwarding data to users far from the base station. Furthermore, using UAVs as relays can improve communication quality on visible lines, reduce the effects of fading shadows caused by obstacles, and overcome the problem of severe path loss due to long communication distances with vehicle users outside base station cells [21]. However, the author of [22] has shown that by combining duplex technology, UAVs as air base stations can also help ensure uplink communication quality and increase downlink data communication speeds.

B. UAV-Assisted Communication Implementation in Disaster Areas

Technology provides several options (each with its own advantages) which can play a role in replacing paralyzed infrastructure in disaster areas. In [7], the following WSN and UAV-assisted disaster management applications: (a) monitoring, forecasting, and early warning systems (b) disaster information fusion (c) situational awareness and logistics (d) damage assessment (f) search and rescue missions.

As illustrated in Fig. 2, when applied to disaster areas, WSN- and UAV-based technologies have varying degrees of effectiveness. This is determined by the stage to which it is applied. The UAV surveys pre-disaster events providing static WSN-based threshold sensing and creating EWS during the disaster preparedness stage.

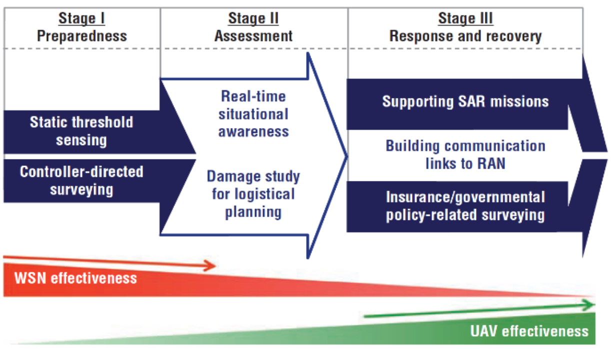

Figure 2. Disaster stages and UAV-assisted operations [23].

However, during the disaster assessment stage, the UAV's primary role is to provide real-time situational awareness and a complete damage assessment for logistical planning. Furthermore, during the disaster recovery and response phases, UAVs are critical in assisting SAR missions by becoming the communication backbone.

III. SYSTEM MODEL

The perspective of this study is based on challenges and limited communication access after a disaster occurs in a specific place. This section offers the simulation findings used to assess the impact of UAV coverage services in the aftermath of a disaster. The implementation of UAVs in disaster zones is the subject of this research. To reflect a catastrophic circumstance in which a large amount of telecommunication equipment may be unavailable, in our scenario, the UAV is in a network model in non-ideal conditions, as studied by [14].

In these circumstances, we define a UAV as an air base station communicating with two users. As illustrated in Fig. 3, we consider the UAV continues to fly in a circular route at a constant speed with an altitude of H.

The UAV's elevation may affect the signal's coverage and quality. UAVs have better coverage and lower signal strength at higher altitudes, however at lower altitudes, signal strength is good, but coverage diminishes. This relationship is critical for deployment as:

$$UAV\ altitude = \propto \frac{Coverage\ area}{Signal\ strength} \quad (1)$$

At the same time, users are randomly assigned within a radius of r. The location of the UAV user (x_N, y_N, 0) with $N \in \{1, 2\}$ based on three-dimensional in-nature cartesian coordinates. Furthermore, the Euclidian distance between the UAV and the N-th user can be calculated as follows:

$$D_N = \sqrt{(x_N - x)^2 + (y_N - y)^2 + H^2} \quad (2)$$

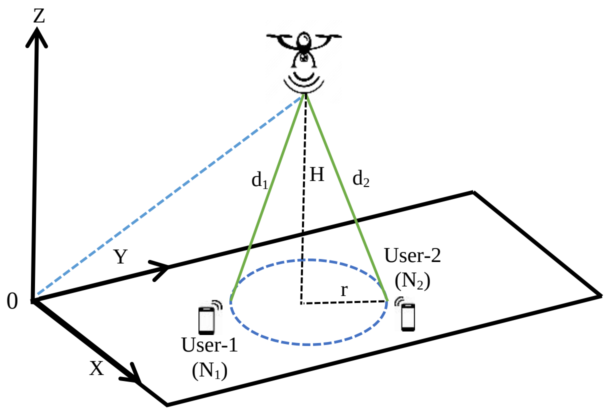

Figure 3. Illustration of UAV- BS in a disaster-affected area.

The ground user, UAV, and remote station are assumed to operate in a three-node relay system in this model, with the UAV serving as a relay in both directions connecting the two ground users. Depending on the communication direction, these two ground users operate as source or destination nodes, while the remote station acts as a destination or source node. These two users experience hardware failure at different levels, which describes network conditions that are not ideal, as a consequence of the disaster affected area.

In the present research, a different perspective than prior investigations have been proposed. The authors of [13] investigated the phenomenon of outage probability for two ground users, and authors of [14] investigated the impact of two secondary users experiencing hardware failure on the probability of outage and achievable rate occurring.

Moreover, since the communication path between the UAV and the ground users is an LoS line, we assume that the communication channel between the UAV and the user follows the Rician distribution. The Rician fading channel in this scenario is expressed by the Rician factor (K) and the total direct and scattered path power (P_{LOS}).

The primary findings from this study are that with UAV-limited energy sources, an examination of the effective placement of the UAV height and radius is essential to reduce outage probability and effectively maintain an achievable rate. The simulation was carried out in two scenarios. The first simulation involved adjusting the UAV's altitude and assessing the impact on outage probability and achievable rate. The second simulation, on the other hand, followed the same approach as the UAV radius change. Table I presents the simulation parameters.

TABLE I. SYSTEM PARAMETERS FOR NUMERICAL SIMULATION

Parameter	Value	Note
UAV Height	10 m, 30 m, 50 m	Scenario-1
Radius UAV	5 m, 10 m, 20 m	Scenario-2
Average UAV flight height	20 m	
Number user	2	
Power LoS	2	
Pathloss Exponent	2.2	
SNR value (min, max)	10 dB , 60 dB	
Target Rate (Primary User, Secondary User)	0.5, 0.5	
Power coefficient (Primary User, Secondary User)	0.8, 0.2	

The effect of adjusting the height of the UAV-BS at three different elevations (10 m, 30 m, and 50 m) and the UAV radius (5 m, 10 m, 20 m) on changes in outage probability and achievable rate values were investigated to determine which factors have the most impact on outage probability and achievable rate. In order to fulfill the requirements of this simulation, we defined the algorithm of this work as follow.

A. Performance Metrics

Metrics generated from the SINR are used to estimate system performance When determining the SNR value, researchers need to consider LoS or NLoS conditions, which are heavily reliant on the obstructions in an area, using the formula given [24]:

Algorithm: Outage Probability and Achievable Rate Simulation of UAV Relay in Disaster Area

Initialization	
Input:	the simulation parameter
	number of samples (Monte Carlo samples, i=50000)
	number of users
	UAV flight path
	Identify the Channel model
	Setup the Simulation scenario
	Randomly place users in a 2D area and the UAV flight path at points (x, y, z)
Process:	Calculate the communication UAV - users
	Calculate scenario-1: for each UAV altitude changes (10 m, 30 m, 50 m)
	Calculate Outage Probability
	Calculate Achievable Rate
	with i = 50000 (number of samples)
	Calculate scenario-2: for each UAV radius change (5 m, 10 m, 20 m)
	Calculate Outage Probability
	Calculate Achievable Rate
	with i = 50000 (number of samples)
Output:	Simulate the result:
	Simulate Outage Probability result
	Simulate Achievable Rate result
	Plot the graph of the simulation result

1) Line-of-sight with complying free-space propagation norms

The average SINR for a mobile receiver functioning in a free-space propagation compliant environment and experiencing free-space gain (h_{fs}) is provided by:

$$SINR \cong \left|h_{fs}\right|^2 \frac{P_T}{\sigma^2} \quad (3)$$

2) Line-of-sight under varying fading conditions

The average SINR for a mobile receiver served by the SBS under LoS conditions and observing direct channel gain (h_d) is provided by:

$$SINR \cong |h_d|^2 \frac{P_T}{\sigma^2} \quad (4)$$

3) No line-of-sight under varying fading conditions

The average SINR for a mobile receiver served by the SBS in a wireless terrain with NLoS conditions and observing channel gain (h_{NLOS}) is provided by:

$$SINR \cong |h_{NLOS}|^2 \frac{P_T}{\sigma^2} \quad (5)$$

where h_{fs} represents experiencing the free-space gain, P_T is the transmit power at the SBS, and σ^2 is the noise power of mobile receiver.

B. Outage Probability

An outage occurs when the time allotted to each user cannot decode the data flow or the data flow from weaker users. The point at which the receiver power value falls below the threshold (minimum SNR) is defined as the outage probability. SNR is a measure of the strength of the signal that was received from the surrounding noise. A more excellent SNR indicates a higher signal quality.

The probability describes the possibility that the UAV and the ground station's communication link may break down. This can happen for various reasons, including interference, shadowing, or fading. The UAV communication system must have a low outage probability to ensure that the UAV can reliably transmit and receive data to and from the ground station in a disaster region. As a result, the communication link outage probability between the in-cluster vehicle and the cluster head vehicle is identified as [25]:

$$\text{Pt out (i, o)} = \text{P}(\gamma\text{tC} < \gamma\text{th}) \quad (6)$$

where γtC represent the SNR of the communication link between the in-cluster vehicle (i) and the cluster head vehicle (C), and γth form is the predetermined the SNR threshold below which the communication link is considered down. It specifies the minimum acceptable level of communication quality. The link is considered down if the instantaneous SNR goes below this level.

From the user perspective, the outage probabilities attained by primary and secondary users can be represented as follows:

$$P_1 = \Pr[R1 < r] \quad (7)$$

$$P_2 = \Pr[R2 < r] \quad (8)$$

where P_1 and P_2 are the outage probabilities achieved by primary and secondary users, R1 and R2 are the achievable rates of primary and secondary users, and r denotes the target rate.

C. Achievable Rate in UAV-Assisted Cellular Communications

The achievable rate is an important performance metric in unmanned aerial vehicle communication systems, particularly in disaster areas where accessibility is critical for coordinating rescue and relief efforts. Given the available resources, the maximum average throughput that can be transmitted over a communication link is the achievable rate (e.g., transmit power, bandwidth, and noise level). The average achievable rate of the receiver is defined as [26]:

$$\text{R} \equiv \text{E}[Log_2(1 + \rho)] \quad (9)$$

where ρ is the average SNR value of the mobile receiver.

In this approach, we calculate the average achievable rate by taking the logarithm of (1+ρ) and considering the receiver's average SNR (ρ). This process converts the SNR value to a logarithmic representation of the attainable rate. The formula estimates the average achievable rate of the receiver over time or in a statistical sense by taking this logarithm's expected or average value. Knowing the average achievable rate can help assess the capacity and efficiency of the communication link and provide insight into the system's ability to transmit data under specific resource restrictions.

D. Path Loss Analysis and Channel Model

Path loss is the decrease in the power density of an electromagnetic wave as it travels through space [27]. This is a critical component in creating a link budget for a telecommunications network. Path loss models are used to forecast SNR and estimate the received signal strength as a function of distance in a wireless communication system. A measurement campaign is the primary method for developing a model.

A wireless system's primary components are transmitters, receivers, and channels. The channel between the transmitter and the receiver might be variable or constant over time. The fading can be triggered by discrepancies in received signal strength over time as the channel becomes visible to the broadcast signal as it passes through the traveling path. Additionally, rain, lightning, and atmospheric events, as well as other physical phenomena associated with path loss, transmitters and receivers' movement, have an impact on channel fading:

$$P_{LOS} = \mu^2 + 2\sigma^2 \quad (10)$$

where the average is μ and the standard deviation is σ

IV. Performance Analysis

In this section, we conduct an output analysis of outage probabilities and the achievable rate of UAVs functioning in disaster areas. The investigation was divided into two parts. The first focuses on analyzing the outage probability and achievable rate by modifying the altitude of the UAV during the simulation. In the second simulation, we observed the same values but changed the radius of the UAV.

A. Simulation Result 1: Observing the Outage Probability and Achievable Rate Value by Changing the Altitude of the UAV

One of the main performance measures in communications system services is the probability of an outage. The outage probability indicates the potential that the communication link between the UAV and the base station would fail due to various circumstances, such as fading, interference, or shadowing. In this study, our concern is whether this happens in disaster situations where a good link telecommunication is critical for coordinating rescue and relief operations.

The UAV communication system must have a low outage probability to ensure that the UAV can reliably transmit and receive data to and from the ground station in a disaster region. Rescue and relief activities may be delayed if the UAV has trouble communicating with the ground station due to a high probability of outages. It is crucial to properly design a UAV communication system to reduce the risk of an outage and maintain reliable communication in disaster areas.

As discussed in the system model section, two users are assumed to be in suboptimal network conditions with the parameter values shown in Table I. As seen in Fig. 4, we observed the outage probability and the SNR value in the first simulation by focusing on changes in the UAV's altitude. The x-axis represents the SNR value, while the y-axis represents the outage probability value. There are three conditions, each represented by a unique color, for UAV heights of 10 m, 30 m, and 50 m. According to Eq. (6), the relationship between UAV height and outage probability can be identified by observing the SNR value and the SNR threshold. The UAV elevation influences SNR via its influence on path loss. The greater the UAV's height, the less route loss happens. The route loss will be lower under these conditions, resulting in a higher SNR value.

Based on the calculation and simulation results, it is clear that as the UAV height increases, the probability of the SNR falling below the threshold diminishes. As a result, the probability of an outage lowers, suggesting an increase in the reliability of the communication link.

In this scenario, the greater the distance between the source of disturbance and the damaged disaster area, the lower the outage probability value. As a result, Fig. 4 shows that in the simulation of raising the height of the UAV, the resulting SNR value increases while the outage probability decreases. Finally, this situation may allow for a better connection and successful data transmission. This is because the signal the base station receives from the UAV has more strength and lower losses, thus increasing communication. Furthermore, Fig. 5 demonstrates how the SNR value affects the achievable rate from three distinct UAV altitudes, respectively 10 m, 30 m, and 50 m. According to the simulation findings, the higher the UAV height, the greater the SNR value. A higher altitude provides a more significant viewing angle, which improves the achievable rate that can be obtained.

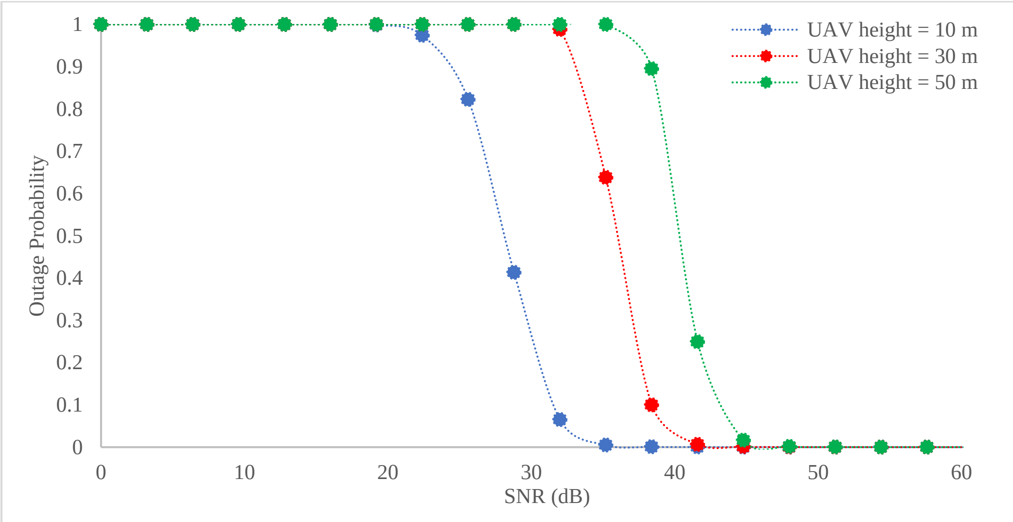

Figure 4. The output of outage probability and SNR value at different UAV altitudes (10 m, 30 m, 50 m).

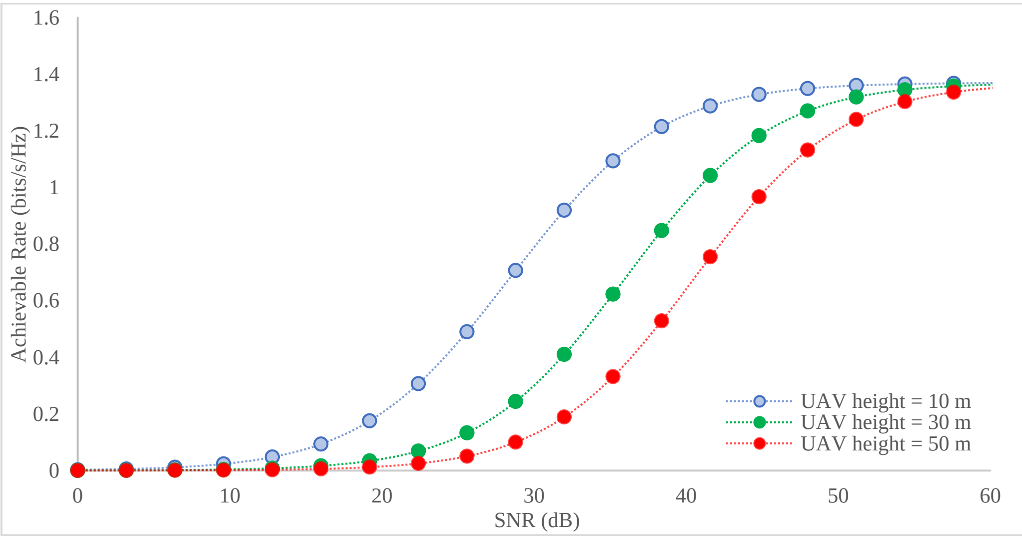

Figure 5. The output of achievable rate and SNR value at different UAV altitudes (10 m, 30 m, 50 m).

B. Simulation Result 2: Observing the Outage Probability and Achievable Rate Value by Changing the Radius of the UAV

The achievable rate is a crucial performance indicator, as seen in Figs. 6–7. The term achievable rate represents the highest data rate that, given the resources available, can be transmitted through a communication link. As shown in Figs. 6–7, the x-axis represents the SNR value, while the y-axis represents the outage probability and achievable value, respectively. In Fig. 6, there are three conditions, each represented by a unique color, for UAV heights of 10 m, 30 m, and 50 m, while in Fig. 7 the unique color identifying the UAV radius changes from 5 m, 10 m, and 20 m. The simulation results demonstrated that increasing the UAV radius can increase the coverage area and reduce the number of UAVs required in the system. However, increasing the radius can also worsen system performance by decreasing the SNR and achievable rate and increasing the outage probability value. Therefore, it is necessary to consider the optimal radius, which balances the coverage area, the number of UAVs, the SNR value, and the achievable rate with outage probability.

Increasing the UAV's height increases the communication distance between the UAV and the user below, increasing the SNR and achievable rate. However, a rise in elevation could affect system performance in poor canal conditions or congested areas by increasing the probability of an outage. Similarly, extending the UAV radius can enhance the coverage area while decreasing the number of UAVs required in the system. Increasing the radius, on the other hand, might degrade system performance by lowering the SNR and attainable rate and increasing the outage probability value. As a result, when determining the best height and radius, it is vital to analyze the system as a whole and consider the trade-off between system performance and implementation costs, as can be shown in future studies.

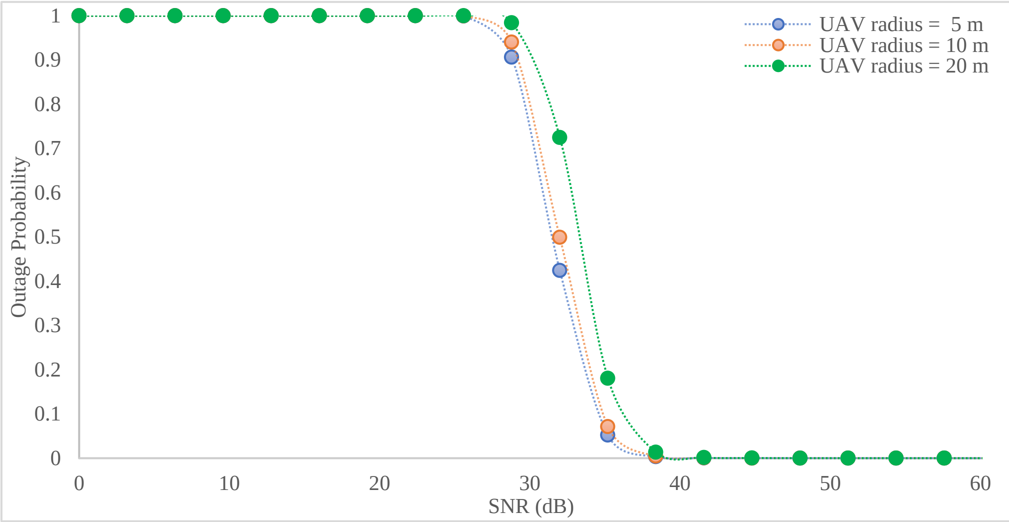

Figure 6. The output of outage probability and SNR value at different UAV radius (5 m, 10 m, 20 m).

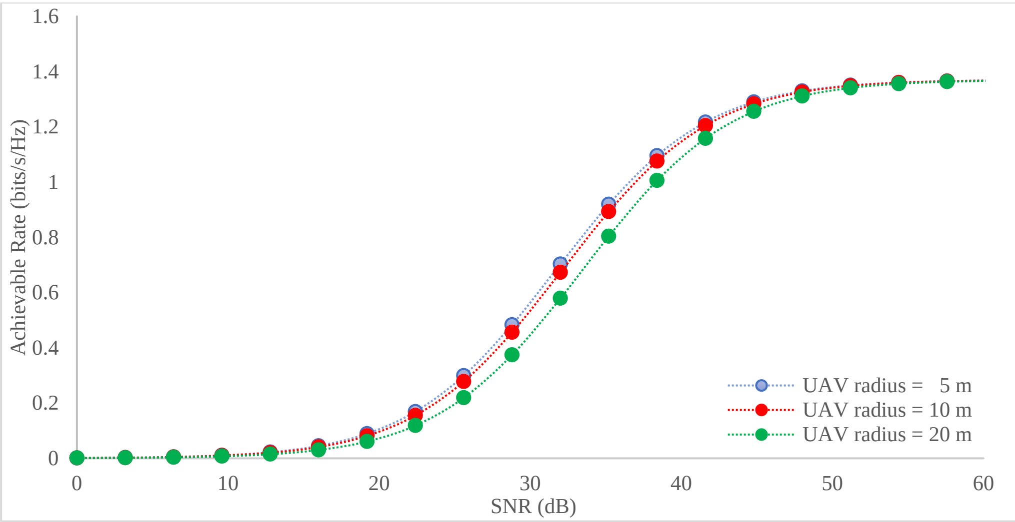

Figure 7. The output of the achievable rate and SNR value at different UAV radius (5 m, 10 m, 20 m).

V. Conclusion

This paper investigates the deployment of UAV-assisted wireless services in disaster areas, focusing on the effects of possible outages and the levels that can be achieved in disaster areas. It shows that in the middle of a macro cell, a UAV flies in a circular trajectory with a set height to provide coverage for two users in the disaster region dealing with hardware problems that impact the outage probability and achievable rate. The outage probability and achievable rate expressions are determined using the Rician air-to-ground channel model, which is then simulated. The simulations were run separately, with the first focused on changes in UAV altitude and their effect on outage probability, SNR value, and the achievable rate. The second simulation followed the same method but focused on changing the radius of the UAV. The first simulation results reveal that as the UAV height increases, the resulting SNR value increases while the likelihood of an outage decreases. It was also discovered that the higher the UAV's height, the higher the level it could reach. Changing the radius of the UAV affects the probability of an outage. The probability of network communication interference diminishes as the SNR increases and the achievable rate increases. It can, however, degrade system performance by lowering SNR and attainable rate and increasing outage likelihood. Evaluating the optimal height and radius for a more precise implementation is critical. Therefore, more comprehensive research is needed to investigate this system, which can be considered for future research development

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

Each of the authors has contributed. MG conducted research, analyzed the model system, wrote the paper, and prepared the simulation; MA, MS, and NR were involved in analyzing the data and simulation results and proofreading the paper; all authors had approved the final version.

Funding

The research was funded by PUTI Universitas Indonesia, with Grants Number: NKB-329/UN2.RST/HKP.05.00/2022.

References

[1] J. Zhang, Y. Zeng, and R. Zhang, "UAV-enabled radio access network: multi-mode communication and trajectory design," *IEEE Transactions on Signal Processing*, vol. 66, no. 20, pp. 5269–5284, 2018.

[2] B. Li, Z. Fei, and Y. Zhang, " UAV communications for 5G and beyond: Recent advances and future trends," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 2241–2263, 2019.

[3] G.Tuna, b.Nefzi and G.Conte, "Unmanned aerial vehicle-aided communications system for disaster recovery," *Journal of Network and Computer Applications*, vol. 14, pp. 27–36, 2014.

[4] G. Peng, Y. Xia, X. Zhang and L.Bai, "UAV-aided networks for emergency communications in areas with unevenly distributed users," *Journal of Communications and Information Networks* , vol. 3, no. 4, pp. 23 - 32, 2018.

[5] M. Erdelj and E. Natalizio, "UAV-assisted disaster management: Applications and open issues," in *Proc. International Conference on Computing, Networking and Communications (ICNC)*, Kauai, HI, USA, 2016.

[6] S. Zhang and J. Liu, "Analysis and optimization of multiple unmanned aerial vehicle-assisted communications in post-disaster areas," *IEEE Transactions o Vehicular Technology*, vol. 67, no. 12, pp. 12049–12060, December, 2018.

[7] S. Li, M. Derakhshani, S. Lambotharan, and L. Hanzo, "Outage probability analysis for the multi-carrier NOMA downlink relying on statistical CSI," *IEEE Transactions on Communications*, vol. 68, no. 6, pp. 3572–3587, 2020.

[8] M. Mozaffari, W. Saad, M. Bennis and M. Debbah, "Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs," *IEEE Transactions on Wireless Communications*, vol. 15, no. 6, pp. 3949–3963, 2016.

[9] M. Mozaffari, W. Saad, M. Bennis, Y. H. Nam and M. Debbah, "A tutorial on uavs for wireless networks: Applications, challenges, and open problems," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2334–2360, 2019.

[10] Q. Huang, A. Razi, F. Afghah and P. Fule, "Wildfire spread modeling with aerial image processing," in *Proc. 2020 IEEE 21st International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)*, Cork, Ireland, 2020.

[11] A. Saif, K. Dimyati, K. A. Noordin, N. S. Shah, Q. Abdullah, M. Mohamad, M. A. Mohamad and A.-S. Am. (April 2021). Unmanned aerial vehicle and optimal relay for extending coverage in post-disaster scenarios. [Online]. Available: https://arxiv.org/abs/2104.06037

[12] L M. Nguyen, V. N. Vo, C. So-In, and V. H. Dang, "Throughput analysis and optimization for NOMA Multi-UAV assisted disaster communication using CMA-ES," *Wireless Networks*, vol. 27, no. 7, pp. 4889–4902, 2021.

[13] A.-T. Le, N. D. Nguyen, and D.-T. Do, "On performance of downlink non-orthogonal multiple access wireless system relying on UAV," *Journal of Communications*, vol. 17, no. 1, pp. 17–21, 2022.

[14] B. Lima, N. Fachada, R. Dinis, D. B.Costa, and M. Beko, "Uavnoma: A UAV-NOMA network model under non-ideal conditions," *Journal of Open Research Software*, vol. 10, no. 1, p. 9, 2022.

[15] G. Alsuhli, A.Fahim, and Y. Gadallah, "A survey on the role of UAVs in the communication process: A technological perspective," *Computer Communications*, vol. 94, pp. 86–123, 2022.

[16] M. M. Azari, F. Rosas, K.-C. Chen, and S. Pollin, "Optimal UAV positioning for terrestrial-aerial communication in presence of fading," in *Proc. IEEE Global Communications Conference (GLOBECOM)*, 2016.

[17] E. Vinogradov, H. Sallouha, S. D. Bast, M. M. Azari, and S. Pollin, "Tutorial on UAVs: A blue sky view on wireless communication," *Journal of Mobile Multimedia*, vol. 14, no. 4, pp. 395–468, 2018.

[18] N. Raharya and M. Suryanegara, "The frequency sharing of unmanned aircraft systems and fixed service at 12.2–12.5 GHz to Support BLOS Requirement," in *Proc. IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob)*, Bandung, Indonesia, 2015

[19] M. Suryanegara, A. Nashirudin, N. Raharya, and M. Asvial, "The compatibility model between the Wireless Avionics Intra-Communications (WAIC) and fixed services at 22–23 GHz," in *Proc. IEEE International Conference on Aerospace Electronics and Remote Sensing Technology (ICARES)*, Bali, Indonesia, 2015.

[20] J. Ji, K. Zhu, D. Niyato, and R. Wang, "Joint trajectory design and resource allocation for secure transmission in cache-enabled UAV-relaying networks with D2D communications," *IEEE Internet of Things Journal*, vol. 8, no. 3, pp. 1557–1571, 2021.

[21] Y. J. Chen, W. Chen and M. L. Ku, "Trajectory design and link selection in UAVassisted hybrid datellite-terrestrial network," *IEEE Communications Letters*, vol. 26, no. 7, pp. 1643–1647, 2022.

[22] A. H. Gazestani, S. Ghorashi, Z. Yang, and M. Shikh-Bahaei, "Joint optimization of power and location in full-duplex UAV enabled systems," *IEEE Systems Journal*, vol. 16, no. 1, pp. 914–921, 2022.

[23] M. Erdelj, E. Natalizio, K. R. Chowdhury, and I. F. Akyildiz, "Help from the sky: Leveraging UAVs for disaster management," *IEEE Pervasive Computing*, vol. 16, no. 1, pp. 24-32, 2017.

[24] T. Dhruvakumar and A. Chaturvedi, "Intelligent reflecting surface assisted millimeter wave communication for achievable rate and coverage enhancement," *Vehicular Communications*, vol. 33 , no. 100431, 2022.

[25] Z. Liu, Q. Tian, Y. Xie and K. Y. Chan, "Outage probability minimization for vehicular networks via joint clustering, UAV trajectory optimization and power allocation," *Ad Hoc Networks*, vol. 140, no. 103060, 2023.

[26] E. Vinogradov, H. Sallouha, S. D. Bast, M. M. Azari, and S. Pollin, "Tutorial on UAVs: A blue sky view on wireless communication," *Journal of Mobile Multimedia*, vol. 14, no. 4, pp. 395-468, 2018.

[27] S. Khan, *Mathematical Framework for 5G-UAV Relay*, vol. 32, 2021 John Wiley & Sons, Ltd., 2021.