RESEARCH ARTICLE

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Performance Analysis of Relay-Based Communication for FANET in 5G and Beyond

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Abstract

Unmanned aerial vehicles (UAVs) have great potential in 5G and 6G networks due to their communication capabilities, low-cost, and adaptable deployment opportunities. The use of multiple Unmanned Aerial Vehicles (UAV) systems is a more cost-effective and operationally efficient approach compared to using a single UAV system. Compared to a large UAV, flying ad hoc networks (FANETs) with small UAVs have many advantages. This UAV-based architecture typically uses clusters of UAVs, where the UAV acts as a cluster head (CH), collecting information from other UAVs and sending it to the emergency communication vehicle (ECV). Although this model works well in open areas, Non-line-of-sight (NLoS) issues caused by tall buildings, trees, places like hills, or other obstacles significantly damage its performance in urban environments. Due to their closeness to ground users, UAVs operating at low altitudes generally provide stronger signals and faster response times; however, they are more likely to encounter NLoS issues. We propose a reliable communication architecture that uses relay drones between CH and ECV to avoid these limitations. To prevent NLoS obstructions and assure a reliable and high-quality connection, these relay drones are deployed at strategic locations and altitudes. Our model dynamically adjusts altitude and position when obstacles arise to provide connectivity in urban environments, overcoming signal obstructions and improving the coverage. Simulation results show that our proposed architecture provides a reliable and adaptive communication framework in urban disaster situations to significantly improve important network performance metrics such as throughput, path loss, and outage probability under Nakagami-m fading channel and relay supported communication compared to traditional UAV clustering models, this improved model assures continuous information flow during critical search and rescue operations.

Keywords: UAVs, relay, low-altitude, maximized coverage, 5G, UAV-based BS, emergency communication, FANET.

1 Introduction

Unmanned aerial vehicles (UAVs), commonly known as drones, are increasingly in demand in various applications. One of the main goals of 5G wireless networks is to support high data capacity [1, 2]. This advanced connectivity is vital for ensuring reliable

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and efficient in mission critical environments. 5G allows UAVs to carry out crucial tasks such as real-time disaster mapping, victim detection, autonomous navigation, and acting as flying base station to restore communication. These UAV operations depend on 5G's low latency, high speed and massive connectivity [3]. Despite its common use, device-to-device (D2D) communications have been used to refer to other things in various fields [2, 4]. With their flexible deployment and aerial wireless coverage that can be adjusted to changing conditions, unmanned aerial vehicles, or UAVs, have become a viable solution [4, 5]. A Cluster Head (CH) UAV gathers data from multiple Cluster Member (CM) UAVs and sends it to an Emergency Communication Vehicle (ECV) or surviving Base Station (BS) in traditional UAV-based emergency communication systems, which frequently rely on cluster-based architectures [2, 6]. While this method performs well in open or rural environments, it suffers in urban settings due to Non-Line-of-Sight (NLoS) conditions caused by tall buildings, dense infrastructure, or natural obstacles such as hills and trees [7, 8]. UAV-based communication systems are typically deployed at altitudes below 10 km. However, when operating at low altitudes, multipath propagation caused by reflections from the ground and surrounding structures can lead to NLoS fading, which degrades the air-to-ground communication link. This results in reduced capacity for a given transmission power and limits the effective coverage area [1, 9].

Therefore, it is worth exploring the flight altitude feature in low-altitude conditions to maximize the coverage size [5, 9]. To overcome these limitations, we propose a novel architecture by using relay UAVs to improve signal strength, reduce the communication gap between ECVs and CH UAVs in NLoS environments and extend the communication coverage area. Relay supported D2D networks utilize the feasible capacity of multi-hop D2D systems over Rayleigh fading channels. The optimal design of D2D systems and the impact of the number of relay hops on system capacity and energy efficiency are evaluated [4, 5]. The role of UAV and multi-hop D2D communication is to provide reliable connectivity in disaster situations and establish communication links with user devices in out-of-coverage situations [6, 7]. Therefore, UAV coverage expansion through relay hop and D2D communication improves wireless coverage services, spectrum, and energy efficiency during public safety communication.

In this paper UAV-based multi-hop D2D relay-supported communication framework for disaster scenario is studied. where drones encounter NLoS conditions, a relay drone is deployed to maintain connectivity by forwarding data to the ECV. The system forward a Medium Access Control (MAC) protocol to enable seamless communication between drones, assuring efficient coordination. Communication takes place over Nakagami-m fading channels within a Flying Ad Hoc Network (FANET) environment. As shown in Figure 1, the system uses several UAVs and clustering also when facing obstacles using relay drones which are at critical locations and altitudes to bridge the communication gap between the base station and the disaster area. This relay-enhanced UAV architecture enables reliable multi-hop communication, which improves signal strength, reduces latency, and increases network coverage in tough urban environments.

The article is organized as follows: Section 2 reviews related work, Section 3 describes the system model, Section 4 presents the Experiments, Section 5 discusses simulation results, and Section 6 provides the conclusions.

2 Related Work

Unmanned Aerial Vehicles (UAVs) have gained lot of attention in recent years for their wireless emergency communication in disaster-affected areas. This is mostly due to UAVs ability to rapidly restore communication in areas where terrestrial infrastructure has been destroyed or damaged [2, 10].

In several studies, such as [1], relay-based UAV architectures have been investigated to improve communication coverage. Specially the use of optimal relay hops in UAV networks to enhance post-disaster connectivity was examined. Their results showed that multi-hop relay communication, particularly when user devices are outside of conventional coverage zones, can lower path loss and boost system capacity [12].

However, they did not thoroughly examine urban NLoS challenges, instead concentrating on general relay optimization.

In order to demonstrate how dynamic cluster formation and optimized MAC protocols can increase throughput and decrease packet delay, Shah [2] proposed a cluster-based FANET for disaster scenarios. Efficient communication between UAVs is assured by MAC protocols. MAC protocols control the wireless

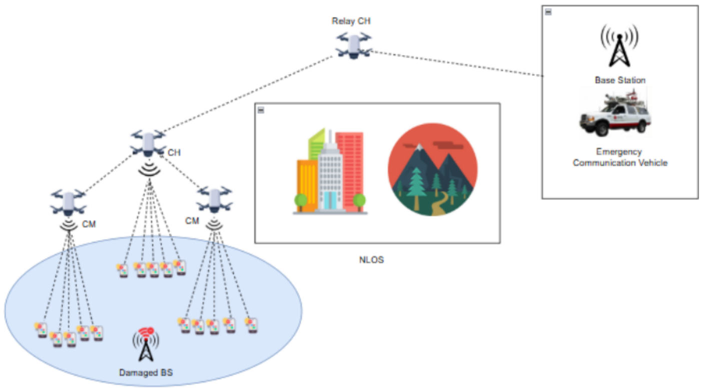

Figure 1. UAV-based emergency communication with relay drones in urban NLoS environments.

communication channels between UAVs to prevent collisions and optimize channel utilization [6].

Other studies have investigated energy efficiency in low-altitude UAVs. For instance, in [12] showed that low-altitude deployment increases signal strength by optimizing UAV coverage by varying the flight altitude and antenna beam angle. However, their approach failed to reduce the NLoS conditions, which became more prominent in lower altitudes.

Additionally, the potential of D2D communication in UAV-supported disaster management has been noted in the literature. UAVs and D2D nodes can work together to enhance network efficiency and dependability, as showed by proposals like [6] and [7]. The use of flying ad-hoc network to provide communication support in disaster situations Where UAVs act as communication gateways between first responders at different locations in the affected area [10]. Although relevant, these works mostly deal with medium access control, rather than the physical deployment techniques or relay deployment required to solve the NLoS problem. To improve UAV deployment in emergency situations, recent studies have also suggested complex relay deployment algorithms that use clustering techniques such as K-means++ [9, 13].

Similarly, trade-offs between UAV altitude, D2D density, and coverage have been balanced using models based on stochastic geometry [10]. Although these techniques offer valuable insights into the behavior of UAV coverage, they do not specifically integrate relay drones at strategic altitudes to reduce NLoS losses in urban areas [4, 13].

3 System Model

The proposed architecture introduces a UAV-based communication network is designed to provide emergency connectivity in urban disaster areas where terrestrial infrastructure is destroyed or damaged. The system is structured into three tiers: ground users, clustered UAVs flying at low altitudes, and high-altitude relay drones connect the CH UAV to the ECV.

Low-altitude UAVs form a cluster to serve mobile users or rescue teams on the ground. Among these, one UAV is selected as the CH responsible for aggregating data from the others. Due to the high probability of NLoS conditions in urban areas, especially at low altitudes, a reliable uplink to the ECV is not guaranteed.

For reliable connection, the proposed system combines a high-altitude relay drones that are dynamically position itself to maintain a LoS path with both the CH and the ECV. Let R denote the total distance between the CH and the ECV, and n be the number of relay drones deployed. The communication path is divided into n equal hops. Each hop spans a distance $d = \frac{R}{n}$ and the elevation angle θ for each hop determines the LoS probability [1]. The free-space path loss (FSPL) and the environment-dependent attenuation are incorporated into the total path loss model:

$$PL = \frac{\mu_{LoS} - \mu_{NLoS}}{1 + a.\exp\left(-b\left[\frac{\pi}{2} - \tan\left(\frac{R}{H}\right) - a\right]\right)}, \quad (1)$$

$$10\lg\left(H^2 + R^2\right) + 20\lg f + 20\lg\left(\frac{4\pi}{c}\right) + \mu_{NLOS}, \quad (2)$$

where μ_{LoS} and μ_{NLoS} are the mean additional losses for LoS and NLoS. Here NLoS is caused by the obstacle between the transceivers under low altitude communications. The value of (μ_{LoS}, μ_{NLoS}) pair is different kinds of scenarios [5, 14, 15].

The probability of Line-of-Sight P_{LoS} is determined by the elevation angle θ, based on the widely accepted urban environment model:

$$P_{LoS} = \frac{1}{1 + a \cdot \exp(-b(\theta - a))}, \quad (3)$$

where a and b are environment specific empirical constants (e.g., $a = 9.61$, $b = 0.16$). This multi-tier, relay-assisted system assures robust, low-latency communication in harsh environments by balancing local coverage (via low-altitude UAVs) and reliable high-altitude relays.

3.1 LoS Probability and NLoS Impact in Urban Environments

Urban disaster areas with their infrastructure and tall buildings which severely impact wireless communication due to signal blockage and reflection. In these environments, low-altitude UAVs suffer from frequent NLoS conditions, which result in increased path loss, higher retransmission rates, and lower throughput.

Accurate modeling the probability of LoS is therefore essential for designing a reliable UAV communication system.

The LoS probability P_{LoS} between a UAV and a target node is modeled as a function of the elevation angle θ, which depends on the relative height H of the UAV and the ground distance d of the link [15]:

$$\theta = \tan^{-1}\left(\frac{H}{d}\right). \quad (4)$$

3.2 UAV to Ground User

U2G communication plays a crucial role in UAV networks, where path loss depends on the environment, obstacle height in disaster areas, and elevation angle [15, 16]. As noted in [17], NLoS communication suffers more from shadowing and diffraction than LoS, resulting in higher path loss. Path loss for urban disaster areas is given by:

$$P_{LoS} = \frac{1}{1} + a.\exp\left(-\beta\left[\theta_n^u - \alpha\right]\right), \quad (5)$$

where α and β two constant values defined based on the environment where the UAVs are deployed and u, n, θ is the time varying elevation angle that is given by $\theta_n^u = \frac{180}{\pi}\arcsin\left(h_u/d_n^u\right)$ [14]. The FSPL follows Friis equation, assuming isotropic transmitter and receiver antennas. The average path loss is given by:

$$\varphi_{UAV2G} = PL_{LoS} + P_{NLoS} \times PL_{NLoS}, \quad (6)$$

where $P_{LoS} = 1 - P_{LoS}$.

3.3 UAV to UAV

UAVs typically rely on free-space LoS propagation, as there are no reflections or obstructions in the air. However, in urban environments with tall buildings, NLoS conditions arise additional path loss due to diffraction and scattering. As described in [14, 17, 18], the path loss between UAV_a and UAV_b is modeled by the following equations.

$$\varphi_{ab}^{UAV\ 2G} = 10\mu_{U2U}^{LoS}\log_{10}\left(\left(4\pi\rho_{U2U}d_a^b/c\right) + \partial_{U2U}, \quad (7)$$

where ∂_{U2U} is an attenuation term and ρ_{U2U} represent as carrier wavelength for U2U channel. In this situation instantaneous SINR U_a to U_b can be calculated as:

$$\begin{aligned} SINR_{nu}^{UAV2UAV} &= (P_r h_a^b)\sum_q^U = 1, q \neq a_{q,b}^{I}{}^{+N_0}) \\ &\geq T_{UAV2G}, \end{aligned} \quad (8)$$

where $h_a^b = 1/\varphi_{ab}^{UAV2G}$ Each pair of UAV_a to UAV_b, if , $\forall_{a,b} \in U$ is assumed to connected if, and only if SINR of U2U is greater than SINER of U2G.

3.4 Outage Probability

In MAC-based adaptive relay communication system, outage probability is the chance that the received signal-to-noise-ratio (SNR) falls below a set threshold γ_{th}, leading to communication failure. To prevent this risk, the MAC layer dynamically selects optimal relay UAVs using channel state information (CSI), distance, and potential blockage predictions. This adaptive strategy helps avoid weak links and improves connection reliability in real time. It is mathematically expressed as [19]:

$$P_{out} = P\left(\gamma < \gamma_{th}\right). \quad (9)$$

For Nakagami-m fading channels, the probability density function (PDF) of the SNR γ is defined as:

$$f_\gamma = \frac{m^m}{\Gamma(m)\Omega^m}\gamma^{m-1}\exp\left(-\frac{m\gamma}{\Omega}\right),\ \gamma \geq 0, \quad (10)$$

where $m \geq 0.5$ is the fading parameter, Ω is the average received SNR and $\Gamma(\cdot)$ is the gamma function.

The outage probability is calculated by integrating the PDF up to the threshold value:

$$P_{out} = \int_0^{\gamma_{th}} f_r(\gamma)d\gamma. \quad (11)$$

This expression can be simplified to a close form solution using the lower incomplete gamma function:

$$P_{out} = \frac{\gamma(m),\ \frac{m_{\gamma th}}{\Omega}}{\Gamma_{(m)}}, \quad (12)$$

where γ is the lower incomplete gamma function, $\Gamma(m)$ is the complete gamma function.

In a decode-and-Forward (DF) relay protocol, an outage happens when either the source-to-relay or the relay-to-destination link cannot support the required data rate R. The outage probability is given by [20]:

$$P_{out} = P_r\left[\min\left(C_{SR,}C_{RD}\right) < R\right]. \quad (13)$$

According to the Shannon capacity formula $C = \log_2(1+\gamma)$, the outage condition is equivalently written as:

$$P_{out} = P_r\left[\min\left(\gamma_{SR,}\gamma_{RD}\right) < \gamma_{th}\right]. \quad (14)$$

For Nakagami-m fading, the closed-form expression becomes:

$$P_{out} = 1 - \left(1 - F_{\gamma_{SR}}\left(\gamma_{th}\right)\right) \cdot \left(1 - F_{\gamma_{RD}}\left(\gamma_{th}\right)\right). \quad (15)$$

This formulation shows that end-to-end communication fails if either the S-R or R-D link is in outage. In our model, the MAC protocol actively evaluates channel quality and selects relay UAVs with the most reliable links. This reduces the comulative distribution functions $F_{\gamma_{SR}}(\cdot)$ and $F_{\gamma_{RD}}$, which represent the Nakagami-m fading on each link, thereby decreasing the total outage probability P_{out}. This formulation enables realistic and efficient performance of cooperative UAV communication in urban environments.

In a cooperative relay-based system, the outage probability is declared to be in outage if one or more of the links are in outage and can be expressed as [21]:

$$1 - \prod_{i=1}^{L}\left(1 - P_{out,i}\right). \quad (16)$$

4 Experiments

To evaluate the proposed relay-supported UAV communication architecture, we conducted simulations using MATLAB. The experiment compares the performance of two communication approaches:

- **Direct Communication:** The CH UAV transmits data to the ECV directly.
- **Relay-Supported Communication:** A series of high-altitude relay drones are deployed between the CH and the ECV, dividing the long-distance transmission into multiple shorter, more reliable hops.

5 Numerical Result

In this section, the proposed method is tested using MATLAB-based simulation comparing the proposed relay-supported UAV communication model to the direct UAV TO ECV transmission model distances from 1 to 1000 meters. The performance is demonstrated using three key metrics: path loss, throughput and outage probability under Nakagami-m fading channel and relay supported communication. Table 1 lists the parameters used in the simulations.

For the path loss analysis, the UAV altitude was set to 300 meters, with a carrier frequency of 1.8 GHz was used. The LoS probability was modeled using an elevation angle based function for urban environments. As shown in Figure 2 simulation results indicate that the path loss increases with horizontal distance due to greater propagation attenuation.

For the throughput analysis in Figure 3, the result show that the relay based communication model usually achieved higher throughput than the direct model, especially at longer distances. This improvement is due to reduced path loss in shorter, multi-hop transmissions.

Figure 4 shows the outage probability for relay-assisted

Table 1. Simulation parameters.

Parameters	Values
f, c, λ	1.8×10^9 Hz, 3×10^8 m/s, $\lambda = c/f$
$P_{tx}, P_{tx}(linear)$	30dBm, 1W
$N, N(linear)$	-100 dBm, 10^{-13} W
B	20×10^6 Hz
μ_{LoS}, μ_{NLoS}	1 dB, 20 dB
a, b	9.61, 0.16
Flight altitude H, Beam angle θ	300 m, 70°
T_{slot}, MAC overhead	5 ms, 1 ms
T_r, γ, η	5 ms, 2, 0.05
Horizontal distance R	1-1000 m
Urban α, β, γ	0.3, 500, 15
m (nakagami)	1 (Rayleigh), 2, 4, 5
$\gamma_{th}, \Omega_{direct}, \Omega_{relay}$	10dB (-10 to 20 dB), 1, 5

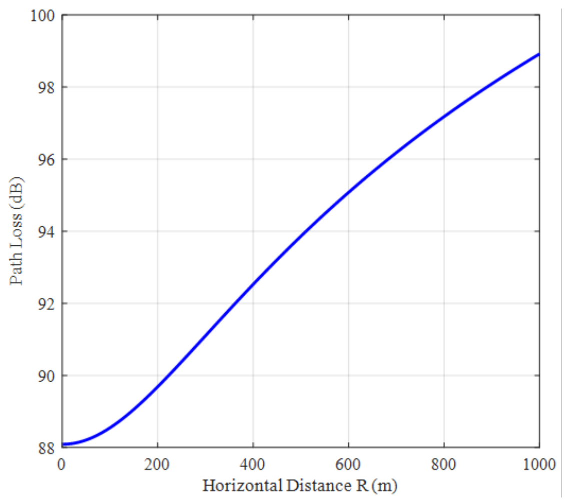

Figure 2. Path Loss vs. Distance.

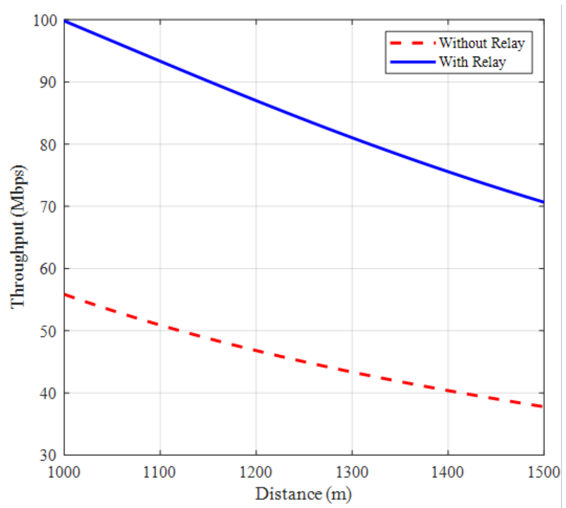

Figure 3. Throughput: direct communication vs with relay.

UAV communication under different Nakagami-m fading scenarios. As the value of m increases from 1 to 5, the outage probability decreases especially at lower SNR. The use of relays indicates that less severe fading leads to more reliable communication.

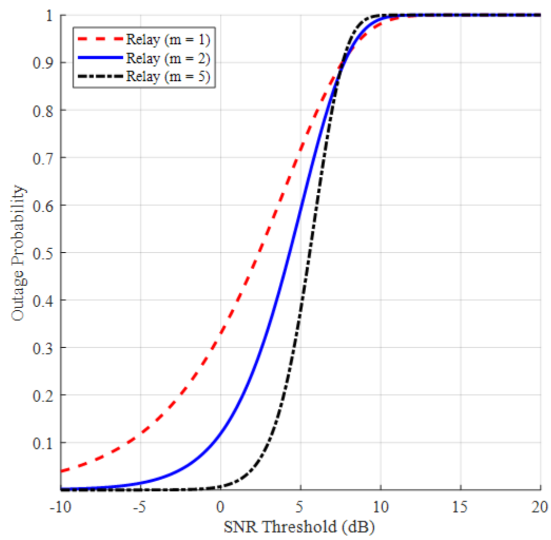

Figure 4. Relay-assisted outage probability for different Nakagami-m value.

Outage probability was simulated in Figure 5 for both direct and relay-supported UAV communication using the Nakagami-m fading model. In the relay-supported case, the average SNR is higher because the communication distance is shorter. The result shows that using relays significantly reduces outage probability compared to direct communication, especially at higher SNR thresholds.

6 Conclusion

In this paper, we suggested an improved UAV-based communication system for urban disaster situations.

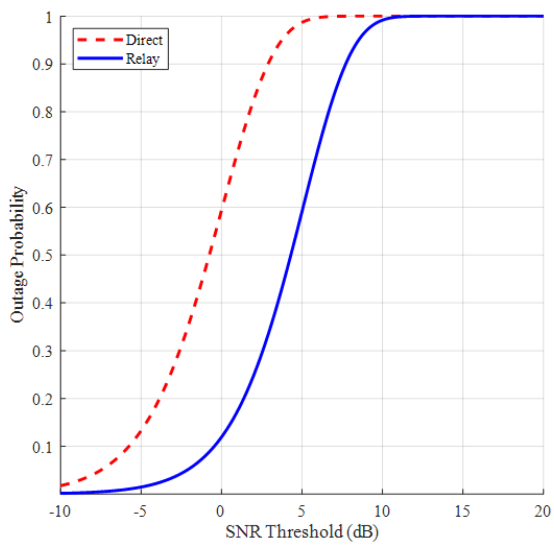

Figure 5. Outage probability: direct vs. relay-assisted communication.

The proposed model ensures real-time adaptation to unexpected obstacles (collapsed buildings, etc.) that may arise during a disaster, thus ensuring uninterrupted information flow throughput rescue operations. Particularly when operating at low altitudes, traditional UAV clustering models suffer significant performance degradation when NLoS obstructions like tall buildings and dense structures are present. Although flying UAVs at low altitudes strengthens signals and improves responsiveness to ground users, it also increases the prevalence of NLoS problems. To solve this challenge, we proposed the idea of placing relay drones in strategic locations between the ECV and the CH UAV to provide reliable and continuous communication. Our proposed architecture not only maintains dependable connectivity in challenging urban environments but also significantly improves metrics like coverage area, throughput, path loss, and and outage probability under Nakagami-m fading channel. Simulation results show that, this model offers a more flexible and reliable solution than conventional UAV deployment techniques.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author declares no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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