Enabling unmanned aerial vehicle to serve ground users in downlink NOMA system

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ABSTRACT

The emergence of internet-of-things (IoT) devices in homes and industry, has resulted in the current and future generation of wireless communications facing unique challenges in spectral efficiency, energy efficiency, and massive connectivity issues. Non-orthogonal multiple access (NOMA) has been proposed as a viable solution to address these challenges as it offers low-latency, spectral efficiency, and massive connectivity capabilities, which are key requirements in upcoming next-generation networks. In addition, another technology that has emerged as a solution to spectral efficiency and coverage is an unmanned aerial vehicle (UAV). Therefore, the combination of UAVs with NOMA has great potential to minimize the challenges and maximize the benefits. Specifically, we investigate the outage performance of the NOMA-UAV network over Nakagami-m channel fading. To this end, we derive a closed-form outage performance metric. The formulated framework is validated using simulations to verify the effectiveness of the proposed solution.

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1. INTRODUCTION

The federal aviation administration (FAA), has reported the rapid adoption of unmanned aerial vehicle (UAV) technology in defense and civilian scenarios [1]-[3]. Recently, the wireless mobile research community has been investigating ways to augment and exploit UAV technology in wireless communication networks as can be seen in the following works [4]-[6]. The major reason UAVs have attracted so much attention is that they can help boost wireless connectivity and enable seamless coverage in dense mobile communication environments. In addition, ultra-reliable low latency communication (URLLC) applications benefit from the short-range line-of-sight (LoS) communication links provided by low-flying UAVs [7]. Furthermore, the flexibility, reliability, and wide coverage of UAVs are useful during times of crowded events as well as in emergencies [4]-[8]. UAVs can offload some of the traffic from a heavily congested multiple access cellular network, thereby, improving the quality of service (QoS). Information security is considered one of the important issues in the information age used to preservesecret information throughout transmissions in practical applications, a lot of schemes related to information security were applied [9].

Due to UAVs sharing the same geographic area and spectral resources with underlay heterogeneousnetworks such as small-cell or device-to-device (D2D) networks, this necessitates interference mitigation and smart resource allocation in such networks [10]-[12]. Recently, a different emerging technology from traditional relaying system to improve the system performance of destinations, it's reconfigurable intelligent surfaces (RIS) that relies on programmable metasurfaces and mirrors [13], [14]. Therefore, an optimized strategy for power control is critical for UAV-enabled networks, as it guarantees acceptable QoS and interference-safe underlay heterogeneous networks.

Non-orthogonal multiple access (NOMA) can provide this optimized power control strategy [15]-[18]. NOMA systems manage the network interference levels by allocating power coefficients to different users based on their channel conditions, this is defined as user fairness [19], [20]. Moreover, the attractive features of NOMA are low latency, spectral efficiency, and connectivity factors. These features satisfy the key requirements of next-generation wireless communications [21]. However, these features increase the intended receiver complexity, as successive interference cancellation (SIC) is utilized to cancel other users' signals before detecting intended transmission signals. Although fairness of users is beneficial to NOMA networks, this results in weak users with poor channel conditions performing poorly due to error propagation [22], [23]. Therefore, for good performance for all users whether weak or strong, massive multiple-input multiple-output (mMIMO) in NOMA has been studied, and the results demonstrate that using mMIMO with good beamforming, can boost throughput and improve QoS of all users [24]-[26].

Nguyen *et al*. [27] introduced NOMA into UAV-aided wireless backhaul networks. Also, the authors derived an algorithm to optimize the UAV position and the transmit beamforming to maximize the sum achievable rate sum. Hou *et al*. [28], derived asymptotic results for outage probability (OP) and ergodic rate (ER) for MIMO-NOMA-aided UAV networks. Studies refer to in [29], [30], the authors jointly optimized, the power allocation and UAV altitude for NOMA-UAV networks to improve the sum rate, coverage, and energy efficiency of these networks. However, all these works designed their systems to operate in microwave bands. Furthermore, in [31], [32] have studied the operation of NOMA-UAV systems in the mmWave bands and have achieved the result that NOMA with distance feedback can provide better outage sum rates than OMA.

Rupasinghe *et al*. [31] proposed a beam scanning approach to maximize the achievable sum rates in [31]. Based on [31], [32] our main contributions are i) we derive closed-form outage performance expressions once Nakagami-m and the location of the UAV are considered and ii) we also present a performance gap among two users. Especially, the improvement of outage performance of the far user can be achieved. All the results are validated using Monte Carlo simulations.

The remainder of this paper is as follows; in section 2, we describe the UAV-based NOMA system; then, section 3 describes our closed-form equations of outage performance; in section 4, we highlight the results and discussion, followed by a summary of our findings in section 5.

2. THE MODEL OF UAV-AIDED SYSTEM

In this paper, we study a cooperative UAV-aided NOMA network, shown in Figure 1. In this case, a base station (S) needs a help of a UAV relay (U) to serve two devices following NOMA (D_1, D_2). Moreover, D_1 is a far user and requires the help of a UAV. Moreover, we denote f_2 is the channel between (S) and D_2, f_U is the channel between (S) and U, and f_1 is the channel between $U$and D_1. In addition, we assume all channels follow Nakagami- m fading channel [33].

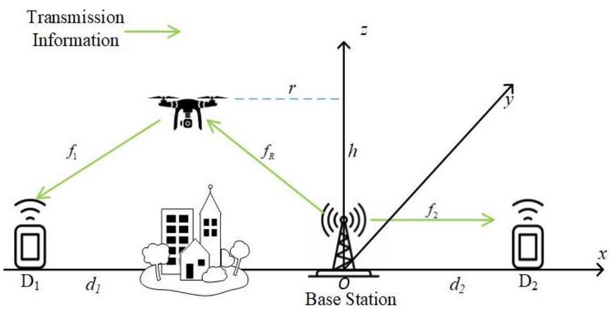

Figure 1. System model of UAV-aided NOMA network

In our work, we consider three-dimensional cartesian coordinates, shown in Figure 1. Next, we assume the (S) located at $S(0,0,0)$, then U is located at $U(-r, 0, h)$. Moreover, we represent the locations of two devises D_1 and D_2 at $D_1(d_1, 0,0)$ and $D_2(d_2, 0,0)$, respectively. As can be seen in Figure 1, we can obtain the Euclidean distance from (S) to U, U to D_1, and S to D_2 respectively as:

$$d_{SU} = \sqrt{r^2 + h^2}, \quad (1)$$

$$d_{UD_1} = \sqrt{(r - d_1)^2 + h^2}, \quad (2)$$

$$d_{SD_2} = d_2 \quad (3)$$

in the first epoch, the source (S) sends the signal $\sqrt{\gamma_1}x_1 + \sqrt{\gamma_2}x_2$ to U and D_2, in which x_1, x_2 are the message of D_1, D_2 respectively, and γ_1, γ_2 are the power allocation coefficient. Thus, the received signal at U and D_2 are shown in:

$$y_U = \frac{\sqrt{P_S}}{d_{SU}^{\tau}}(\sqrt{\gamma_1}x_1 + \sqrt{\gamma_2}x_2)f_U + n_U, \quad (4)$$

and

$$y_{D_2} = \frac{\sqrt{P_S}}{d_{SD_2}^{\tau}}(\sqrt{\gamma_1}x_1 + \sqrt{\gamma_2}x_2)f_2 + n_2, \quad (5)$$

where P_S denotes transmit power at S, τ is the path-loss exponent, n_U and n_2 are the additive white Gaussian noise (AWGN) with zero mean and variance N_0. When U decoding the signal x_1, the signal to interference and noise ratio (SINR) at U as shown in:

$$\Gamma_{U,x_1} = \frac{\gamma_1 P_S |f_U|^2}{\gamma_2 P_S |f_U|^2 + d_{SU}^{\tau} N_0} = \frac{\gamma_1 \delta_S |f_U|^2}{\gamma_2 \delta_S |f_U|^2 + d_{SU}^{\tau}}, \quad (6)$$

where $\delta_S = \frac{P_S}{N_0}$ denotes the transmit signal-to-noise-ratio (SNR) at the source S. Then, the SINR at D_2 is decoded x_1 and can be formulated as:

$$\Gamma_{D_2,x_1} = \frac{\gamma_1 \delta_S |f_2|^2}{\gamma_2 \delta_S |f_2|^2 + d_{SD_2}^{\tau}}. \quad (7)$$

moreover, when D_2 is decoded successfully x_1, by conducting SIC [34] to decode the own signal x_2, the SINR as shown in:

$$\Gamma_{D_2,x_2} = \frac{\gamma_2 \delta_S |f_2|^2}{d_{SD_2}^{\tau}} \quad (8)$$

in the second epoch, U forwards the signal x_1 to D_1. The received signal at D_1 is computed by:

$$y_{D_1} = \frac{\sqrt{P_U} f_1}{d_{UD_1}^{\tau}} x_1 + n_1, \quad (9)$$

where P_U is the transmit power at U and n_1 is AWGN with $CN(0, N_0)$. Next, D_1 is decoded x_1 with SINR which as shown in:

$$\Gamma_{D_1,x_1} = \frac{P_U |f_1|^2}{d_{UD_1}^{\tau} N_0} = \frac{\delta_U |f_1|^2}{d_{UD_1}^{\tau}}, \quad (10)$$

where $\delta_U = \frac{P_U}{N_0}$ is the transmit SNR. In next section, we provide the framework to highlight the system performance of two users which get benefit from the advance of UAV.

3. ANALYSIS OF PERFORMANCE FOR TWO USERS

In this section, we evaluate the closed-form outage probability of D_1 and D_2. To provide more insight, the asymptotic outage probability of D_1 and D_2 are be derived. Considering channel distribution characteristics, put $Z = \{U, 1, 2\}$ and the probability density function (PDF) of f_Z as shown in [33], [35].

$$f_{f_Z}(x) = \frac{\Omega_Z^{m_Z} x^{m_Z - 1} e^{-\Omega_Z x}}{\Gamma(m_Z)}, \tag{11}$$

where $\Omega_Z = \frac{m_Z}{\lambda_Z}$, m_Z is the fading severity parameter, and λ_Z denotes the average power.

3.1. Outage probability of D_1

The outage event occurs when U and D_1 must decode successfully the signal x_1. Thus, the outage probability experienced D_1 is expressed as follows:

$$OP_{D_1} = 1 - Pr\left(\Gamma_{U,x_1} \geqslant \varepsilon_1, \Gamma_{D_1,x_1} \geqslant \varepsilon_1\right), \tag{12}$$

where $\varepsilon_1 = 2^{2R_1} - 1$ is the threshold SNR, R_1 is the target rates of D_1.
Proposition 1: the outage probability of D_2 is expressed by:

$$OP_{D_1} = 1 - \frac{1}{\Gamma(m_U)\Gamma(m_1)} \times \Gamma\left(m_U, \frac{\Omega_U \varepsilon_1 d_{SU}^{\tau}}{(\gamma_1 - \varepsilon_1\gamma_2)\delta_S}\right) \Gamma\left(m_1, \frac{\Omega_1 \varepsilon_1 d_{UD_1}^{\tau}}{\delta_U}\right). \tag{13}$$

Proof: first, (12) can be rewritten by:

$$OP_{D_1} = 1 - \underbrace{Pr\left(\Gamma_{U,x_1} \geqslant \varepsilon_1\right)}_{A_1} \underbrace{Pr\left(\Gamma_{D_1,x_1} \geqslant \varepsilon_1\right)}_{A_2} \tag{14}$$

with the help of (6), the first term A_1 of (14) is calculated by:

$$A_1 = Pr\left(\frac{\gamma_1 \delta_S |f_U|^2}{\gamma_2 \delta_S |f_U|^2 + d_{SU}^{\tau}} \geqslant \varepsilon_1\right) = Pr\left(|f_U|^2 \geqslant \frac{\varepsilon_1 d_{SU}^{\tau}}{(\gamma_1 - \varepsilon_1\gamma_2)\delta_S}\right) = \int_0^{\frac{\varepsilon_1 d_{SU}^{\tau}}{(\gamma_1 - \varepsilon_1\gamma_2)\delta_S}} f_{|f_U|^2}(x)\, dx. \tag{15}$$

Based on (11) and [36], (3.351.2), A_1 can be obtained by:

$$A_1 = \frac{\Omega_U^{m_U}}{\Gamma(m_U)} \int_0^{\frac{\varepsilon_1 d_{SU}^{\tau}}{(\gamma_1 - \varepsilon_1\gamma_2)\delta_S}} x^{m_U - 1} e^{-\Omega_U x}\, dx = \frac{1}{\Gamma(m_U)} \Gamma\left(m_U, \frac{\Omega_U \varepsilon_1 d_{SU}^{\tau}}{(\gamma_1 - \varepsilon_1\gamma_2)\delta_S}\right), \tag{16}$$

where $\Gamma(a, b)$ is the upper incomplete gamma function [36]. Then, with the help of (10) A_2 is calculated by:

$$A_2 = Pr\left(|f_1|^2 \geqslant \frac{\varepsilon_1 d_{UD_1}^{\tau}}{\delta_U}\right) = \int_{\frac{\varepsilon_1 d_{UD_1}^{\tau}}{\delta_U}}^{\infty} f_{|f_1|^2}(x)\, dx = \frac{1}{\Gamma(m_1)} \Gamma\left(m_1, \frac{\Omega_1 \varepsilon_1 d_{UD_1}^{\tau}}{\delta_U}\right). \tag{17}$$

Substituting (16) and (17) into (14). The OP_{D_1} is expressed as (13). The proof is completed.

3.2. Outage probability of D_2

Since D_2 is decoded x_1 first and then D_2 is decode x_2 by using SIC. Thus, the outage probability of D_2 as shown in:

$$OP_{D_2} = 1 - Pr\left(\Gamma_{D_2,x_1} \geqslant \varepsilon_1, \Gamma_{D_2,x_2} \geqslant \varepsilon_2\right), \tag{18}$$

where $\varepsilon_2 = 2^{2R_2} - 1$ is the threshold SNR and R_2 is the target rate of D_2.
Putting (7) and (8), the OP_{D_2} is rewritten by:

$$OP_{D_2} = 1 - Pr\left(\frac{\gamma_1 \delta_S |f_2|^2}{\gamma_2 \delta_S |f_2|^2 + d_{SD_2}^{\tau}} \geqslant \varepsilon_1, \frac{\gamma_2 \delta_S |f_2|^2}{d_{SD_2}^{\tau}} \geqslant \varepsilon_2\right) = 1 - Pr\left(|f_2|^2 \geqslant \frac{\psi d_{SD_2}^{\tau}}{\delta_S}\right) = 1 - \int_{\frac{\psi d_{2}^{\tau}}{\delta_S}}^{\infty} f_{|f_2|^2}(x) dx, \tag{19}$$

where $\psi = max\left(\frac{\varepsilon_1}{\gamma_1 - \varepsilon_1\gamma_2}, \frac{\varepsilon_2}{\gamma_2 \delta_S}\right)$. Similar proposition 1, the outage probability of D_2 can be obtained by:

$$OP_{D_2} = 1 - \frac{1}{\Gamma(m_2)} \Gamma\left(m_2, \frac{\Omega_2 \psi d_{SD_2}^{\tau}}{\delta_S}\right). \tag{20}$$

3.3. Asymptotic analysis

In this section, we denote $\delta = \delta_S = \delta_U$. Then, in the high SNR regime, we assume $\delta \to \infty$. Based on [36], the series representation of incomplete Gamma function can be expression by:

$$\gamma(a,x) \overset{x\to\infty}{\approx} \frac{x^a}{a}. \tag{21}$$

Using the relations in [36], (8.356.3), the asymptotic outage probability of D_1 is expressed by:

$$OP_{D_1}^{\infty} = 1 - \left(1 - \frac{1}{\Gamma(m_U+1)}\left(\frac{\Omega_U \varepsilon_1 d_{SR}^{\tau}}{(\gamma_1 - \varepsilon_1\gamma_2)\delta_S}\right)^{m_U}\right) \times \left(1 - \frac{1}{\Gamma(m_1+1)}\left(\frac{\Omega_1 \varepsilon_1 d_{UD_1}^{\tau}}{\delta_U}\right)^{m_1}\right) \tag{22}$$

similarly, the asymptotic outage probability of D_2 is expressed by:

$$OP_{D_2}^{\infty} = 1 - \frac{1}{\Gamma(m_2+1)}\left(\frac{\Omega_2 \psi d_{SD_2}^{\tau}}{\delta_S}\right)^{m_2} \tag{23}$$

3.4. Throughput analysis

Based on the outage probability, we can achieve the throughput of the system as [37].

$$\xi = (1 - OP_{D_1})R_1 + (1 - OP_{D_2})R_2 \tag{24}$$

4. NUMERICAL RESULTS

In this section, we set $\gamma_1 = 0.8$, $\gamma_2 = 0.2$, $\tau = 2$, $m_1 = m_2 = m_U = 2$, $\lambda_1 = \lambda_2 = \lambda_U = 1$, $d_1 = 10\ m$, $d_2 = 5\ m$, $h = 20\ m$, $r = 5\ m, R_1 = 0.5, R_1 = 0.5$, and $R_2 = 1$ bit per channel use. Two users experience different outage performance when we compare outage probability with different values of fading parameter $m_1 = m_2 = m_U$, shown in Figure 2. In this case, the best performance corresponds to $m_1 = m_2 = m_U = 2$. As can be seen from the figure, in the high SNR region, a significant reduction of outage probability occurs for two users. The asymptotic curves are matched with exact curves at the high SNR region, which confirms the correction of our derived expressions. We can see the analytical curves match well with Monte-Carlo simulations. At the different heights of UAV, the performance of the first user D_1 will be changed, as shown in Figure 3. As can be seen, when $h = 50$ the outage event occurs. The higher SNR contributes to the outage performance of user D_1.

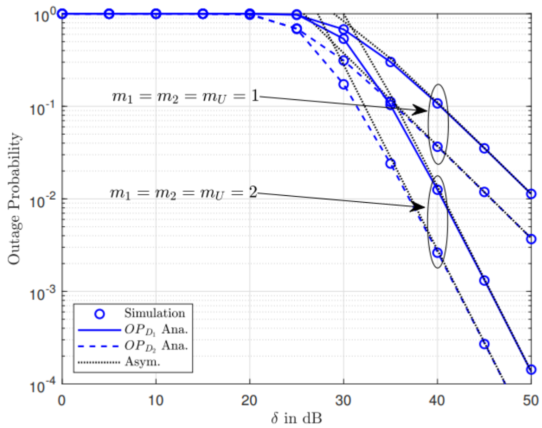

Figure 2. The outage probability of D_1 and D_2 vs δ in dB with varying $m_1 = m_2 = m_U$

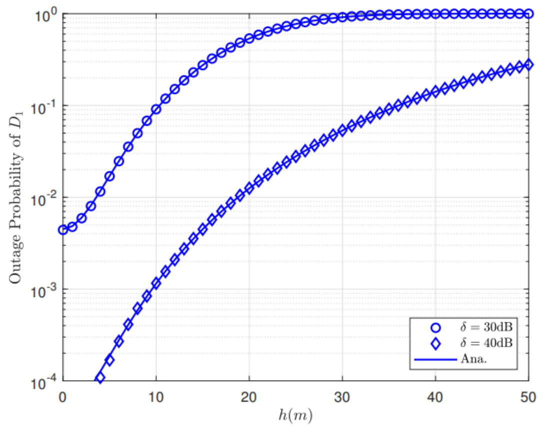

Figure 3. The outage probability of D_1 vs h with varying δ

In Figure 4, when the UAV node locates far from a base station, the outage performance of user D_1 will become worse. In this case, the height of UAV is also a factor affecting outage probability. Figure 5 depicts the trend of throughput when transmit SNR comes from 0 to 50 dB. Depending on outage probability, the throughput meets the ceiling for the case of $\delta = 40\ dB$ fading parameters as $m_1 = m_2 = m_U = 2, 3$.

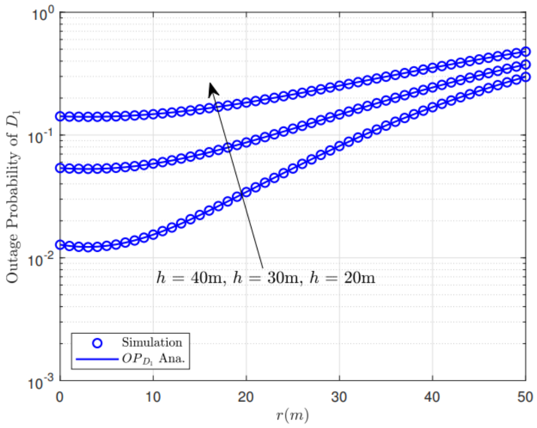

Figure 4. The outage probability of D_1 vs r in m varying h with $\delta = 40\ dB$

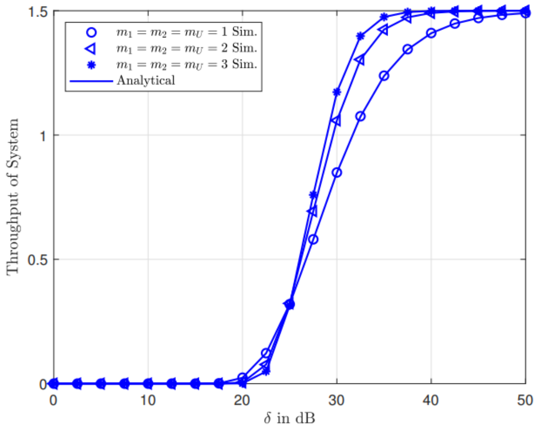

Figure 5. The throughput of system δ with varying $m_1 = m_2 = m_U$

5. CONCLUSION

In this paper, we provided the outage probability analysis of a UAV-aided network with the functionality of NOMA. We derived expressions of outage probability for different users. We focus on the performance of the far user which needs the assistance of UAV. The height and location of the UAV contribute a crucial impact on the outage performance of the far user. The comparison is provided to emphasize the difference between two users which depends on the power allocation factors assigned. In future work, we will consider the system with multiple UAVs.

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