Performance Evaluation of Downlink Multiple Users NOMA-enable UAV-aided Communication Systems over Nakagami-$m$ Fading Environments

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ABSTRACT We evaluate a downlink non-orthogonal multiple access (NOMA)-enable UAV-aided communication system to address the demand of spectrum usage of unmanned aerial vehicles (UAVs). In this paper, multiple NOMA users are served by an UAV to improve the effective spectrum usage. Over Nakagami-$m$ fading model, the performance of the system was investigated based on the analysis of outage probabilities (OPs) of the NOMA users, the ergodic rate, and symbol error rate of the system under two scenarios, i.e., perfect successive interference cancellation (pSIC) and imperfect successive interference cancellation (ipSIC). Additionally, the effects of the system parameters such as the transmit power and altitude of the UAV, the coefficients of channel model on the system performance were studied. The results demonstrate that the performance of the NOMA-based system is better compared with that of the conventional orthogonal multiple access (OMA)-based system in terms of OP, throughput and ergodic rate. Considering outage probabilities at the users, the system in the ipSIC case achieves the same performance as the pSIC case at a low transmit power of the UAV. In addition, an increase in the height of the UAV decreases the ergodic capacity of each user.

INDEX TERMS unmanned aerial vehicle, NOMA, outage probability, ergodic capacity.

I. INTRODUCTION

High data-rate applications and increase in the number of user devices in the future wireless networks demand new solutions. Therefore, innovative architectures were developed for the deployment of a combination of different technologies and wireless communications schemes to solve these requirements. To ensure spectrum usage, non-orthogonal multiple access (NOMA) is a key technique for future wireless networks because it can serve multiple users in the same resource block by multiplexing users in other domains than frequency, time, or coding [1]. Therefore, NOMA schemes have prominent benefits over orthogonal multiple access (OMA) schemes such as enhanced user fairness and spectral efficiency, upper cell-edge throughput, huge connectivity support, and low transmission latency [2,3]. The typical characteristic of power domain NOMA is that multiple users are allowed to use the same time/bandwidth resource by applying a superposition coding scheme. This coding method in NOMA can distribute different powers to the signals, and the nearest user receives a signal with the lowest transmit power and vice versa. At the NOMA users, the successive interference cancellation (SIC) method is adopted to decode the received signals [4, 5, 6]. Additionally, unmanned aerial vehicles (UAVs) have considerable advantages in facilitating on-demand deployment, high flexibility in network configuration, and controllable...
movement in three-dimensional space. Therefore, the applications of UAVs have increased significantly in support of wireless communication for situations such as sports events, traffic in the smart city, Internet of Things systems, or disaster areas [7, 8, 9, 10, 11, 12]. Dedicated UAVs can be set up as flying base stations (BSs) for the leverage of strong point of line-of-sight (LOS) links to increase the coverage and enhance the system throughput [13]. In [14], the UAVs are used as intermediate aerial nodes between the macro and small cell tiers to improve the coverage and increase the capacity of heterogeneous networks. To improve coverage and performance of an UAV system, the authors of [15] proposed a reconfigurable intelligent surface (RIS)-assisted UAV scheme where the UAV operates as a relay to forward the signals from the RIS to the destination.

Recently, NOMA technique has been considered for applications in UAV-enabled communication to improve system performance. In [5], the authors studied the max-min rate optimization problem of a multiuser communication system, in which a single-antenna UAV-BS serves a large number of ground users employing NOMA. In [16], the power allocation for NOMA was optimized by using the optimal location of the UAV to maximize the sum rate of the network. Various solutions to ensure secure transmission in UAV-NOMA networks were researched in [17]. The secure transmission for ground passive receivers and a nonlinear energy harvesting model of an UAV-aided NOMA scheme were studied in [18]. The results in paper [19] were obtained by applying NOMA technique to the uplink communication from a UAV to cellular BS. This study conducted under spectrum sharing with the existing ground users demonstrated that the cooperative NOMA scheme has a higher throughput than that of conventional OMA and non-cooperative NOMA. In [20], the authors investigated the outage probability (OP) of an UAV-BS model with two ground users using NOMA downlink and adopting the Rician fading model for the LOS UAV-to-ground links. In [21], the authors considered the NOMA-UAV’s system’s coverage probability using Nakagami-m fading channel for multiple terrestrial NOMA users. In [22], the authors investigated the capacity region of an UAV-aided NOMA system under Nakagami-\(m\) fading environments.

In [23], the authors considered the NOMA-UAVs system’s coverage probability using Nakagami-\(m\) fading channel for multiple terrestrial NOMA users. In [22], the authors investigated the capacity region of an UAV-enabled system with two users at different fixed locations on the ground. The authors in [23] evaluated the performance of a UAV under Rayleigh fading environments. The performance of a multi-cell setup for UAV communications where two NOMA-assisted UAV cellular strategies, i.e., user-centric strategy and UAV-centric strategy were evaluated in terms of coverage probability [24].

Therefore, we evaluated the performance of a downlink NOMA-enabled UAV-aided communication system with multiple NOMA users. The key contributions are listed as follows:

1) In contrast to previous works conducted on UAV-assisted wireless communication systems that focused on optimization metrics for max-min rate [5], sum-rate maximization [16, 19], and average probability [22], this paper investigates outage performance of a multiple users downlink NOMA-enabled UAV-aided communication system under Nakagami-\(m\) fading environments.

2) We derive the closed-form and asymptotic expressions of OPs, ergodic capacity of the system, and symbol error rate for perfect successive interference cancellation (pSIC) and imperfect successive interference cancellation (ipSIC) cases.

3) We reveal that system parameters such as the UAV’s transmit power, altitude, and the coefficients of channel model significantly impact the outage performance of the proposed NOMA-UAV system.

Organization: The paper is organized as follows. Section II describes the proposed system model. Section III analyzes the exact and asymptotic outage probabilities, system throughput, and diversity order. Section IV and V analyze ergodic capacity and symbol error rate, respectively. Section VI shows the results and respective discussions. Finally, section VII provides the conclusion of this paper.

II. SYSTEM MODEL

![FIGURE 1: An illustration of a downlink NOMA-enable UAV-aided communication system.](image)

In Figure 1, an UAV deploying NOMA technique to serve multiple users is shown. In this paper, we use the probabilistic LoS and non-LoS (NLoS) to model for the large scale fading of the channel the UAV and terrestrial users. Thus, the probability of user \(k\) experiencing a LoS link is expressed as [25]

\[
P_{\text{LoS},k} = \frac{1}{1 + \text{exp}(-q(d_k - p))}, \quad k \in \{1, \ldots, K\},
\]

where \(p\) and \(q\) are constant values depending on the surrounding environment (e.g., sub-urban, urban, dense-urban), and

\[
\theta_k = \arcsin \left( \frac{H}{d_k} \right),
\]

in which \(H\) is the height of UAV, \(d_k = \sqrt{r_k^2 + H_k^2},\) \(r_k\) are the distance between the UAV and the user \(k\), and the distance between the user \(k\) and center of the given area, respectively. Moreover, the probability of NLoS is \(P_{\text{NLoS},k} = 1 - P_{\text{LoS},k}\).
TABLE 1: Notations.

| Symbol | Definition                                                                 | Symbol | Definition                          |
|--------|---------------------------------------------------------------------------|--------|-------------------------------------|
| \( \varphi_k \) | The power allocation coefficient with \( \sum_{k=1}^{K} \varphi_k = 1 \) and \( \varphi_1 < \ldots < \varphi_K \) | \( H \) | The vertical height of the UAV       |
| \( P_R \) | The total transmitted power of UAV                                        | \( r_k \) | The distance between the user \( k \) and the center of the given area |
| \( \tilde{\omega}_k \) | The AWGN noise term followed \( \mathcal{CN}(0, N_0) \) | \( d_k \) | The distance between the user \( k \) and the UAV               |
| \( h_k \) | The channel link from the UAV to the \( k \)-th user                      | \( v \) | The additional attenuation factor of NLoS transmission |
| \( R_k \) | The target rate at the \( k \)-th user                                    | \( \alpha \) | The path loss exponent from the UAV to the users               |
| \( \mathbb{P}(\bullet) \) | The probability operator                                                  | \( \mathbb{E}(\bullet) \) | The expectation operator                                      |
| \( f_X(\bullet) \) | The probability density function of the random variable \( X \)         | \( F_X(\bullet) \) | The cumulative distribution function of the random variable \( X \) |
| \( \mathcal{Q}(\cdot) \) | The Gaussian function: \( \mathcal{Q}(x) = \frac{1}{\sqrt{\pi}} \int_{x}^{\infty} e^{-z^2/2} dz \) | \( \Gamma(a) \) | The Gamma function: \( \Gamma(a) = \int_{0}^{\infty} x^{a-1} \exp(-x) dx \) |

In downlink NOMA, the UAV broadcasts a signal \( s = \sum_{k=1}^{K} \sqrt{P_R} \varphi_k s_k \) to the users, in which \( \varphi_k \in [0, 1] \) is the power allocation coefficient with \( \sum_{k=1}^{K} \varphi_k = 1 \), and \( s_k \) is assumed to be normalised the unity power signal for the \( k \)-th user, i.e., \( \mathbb{E}\{s_k^2\} = 1 \). Hence, the received signal at the user \( k \) can be expressed as

\[
\tilde{y}_k = h_k \sqrt{P_R} \sum_{k=1}^{K} \sqrt{d_k^{-\alpha}} \varphi_k s_k + \tilde{\omega}_k, \tag{3}
\]

where \( P_R \) denotes the transmit power at the UAV, \( \alpha \) is the path loss exponent of the link between the UAV and user \( k \), and \( \tilde{\omega}_k \) denotes the zero mean and variance \( N_0 \) additive white Gaussian noise at the user \( k \), i.e., \( \tilde{\omega}_k \sim \mathcal{CN}(0, N_0) \). Without loss of generality, we assume that the channel power gains of the users are in the order of \( |h_1|^2 < |h_2|^2 < \ldots < |h_K|^2 \). Thus, to ensure user fairness, the power allocation is distributed as \( \varphi_1 > \varphi_2 > \ldots > \varphi_K \) and the distances between the users and the UAV are distributed as \( d_1 > d_2 > \ldots > d_K \).

Based on the principle of successive interference cancellation (SIC), it is assumed that the user \( k \) detects the messages \( s_t \) of other users with \( t = 1 \) till \( t = k-1 \) in prior to detect its own \( s_k \). After correctly detecting \( s_t \), the user then uses SIC for removal it from \( \tilde{y}_k \) and then detects \( s_{t+1} \). Hence, the instantaneous achievable rate at the \( k \)-th user for detecting \( s_t \) is expressed as

\[
\hat{R}_{t \rightarrow k}^{\text{SIC}} = \log_2 \left( 1 + \frac{\hat{\rho}_R \varphi_t P_L d_t^{-\alpha} |h_k|^2}{\hat{\rho}_R P_L |h_k|^2 \sum_{l=t+1}^{K} \varphi_l d_l^{-\alpha} + 1} \right), \tag{4}
\]

where \( \hat{\rho}_R = \frac{P_R}{N_0} \) is the transmit signal-to-noise ratio (SNR) and \( P_L = (P_{\text{LoS},t} + v P_{\text{NLoS},t}) \) in which \( v \) denotes the additional attenuation factor of NLoS transmission [23].

Note that when decoding \( s_t \), the user \( k \) considers \( s_{t+1}, \ldots, s_K \) as interference. It is assumed that perfect SIC (pSIC) is deployed at all users, the achievable rate of the \( k \)-th user for detecting its own \( s_k \) is given by

\[
\hat{R}_{k}^{\text{pSIC}} = \log_2 \left( 1 + \frac{\hat{\rho}_R \varphi_k P_L d_k^{-\alpha} |h_k|^2}{\hat{\rho}_R P_L |h_k|^2 \sum_{l=k+1}^{K} \varphi_l d_l^{-\alpha} + 1} \right). \tag{5}
\]

III. PERFORMANCE EVALUATION

A. OUTAGE PROBABILITY (OP) ANALYSIS

Assume that predefined QoS rate \( R_k \) measured in bit per channel use (BPCU) are distributed at each downlink user, thus the OP at the \( k \)-th user can be calculated via the complementary of the joint events \( \hat{R}_{t \rightarrow k}^{\text{SIC}} > R_t, \forall t \leq k-1 \) and

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\( \tilde{R}_{k}^{pSIC} > R_{k} \). Thus, the OP with pSIC can be expressed as

\[
\begin{align*}
\tilde{\rho}_{k}^{pSIC} & = 1 - \Pr \left( \bigcap_{t=1}^{k-1} \tilde{R}_{t+k}^{pSIC} > R_{t}, \tilde{R}_{k}^{pSIC} > R_{k} \right) \\
& = \begin{cases} \\
F_{|h_{k}|^2} (\theta_{k}^*) & , \forall t \leq k, \forall \gamma_{th_i} \sum_{i=1}^{K} d_{i}^{-1} \varphi_{i} \\
1 & , \text{otherwise}.
\end{cases}
\end{align*}
\]

where \( \theta_{t} = \Delta_{R^{PL}(\varphi_{i} d_{i}^{-1} \gamma_{th_i} \sum_{i=1}^{k} + \gamma_{th_i} \varphi_{i})} \), \( \forall t < K, \theta_{k}^* = \max (\theta_{1}, \ldots, \theta_{k}) \), and \( \gamma_{ht_k} = 2^{R_{k}} - 1 \) in which \( R_{k} \) being the target rate at \( k \)-th user.

In this paper, we use the probability density function (PDF) and cumulative distribution function (CDF) of \(|h_{k}|^2\) expressed as [26]

\[
\begin{align*}
f_{|h_{k}|^2} (x) & = \frac{\mu^{m} e^{-\mu x} x^{m-1}}{\Gamma (m)}, \\
F_{|h_{k}|^2} (x) & = 1 - e^{-\mu x} \sum_{s=0}^{m-1} \frac{\mu^{s} x^{s}}{s!},
\end{align*}
\]

where \( \Gamma (\cdot) \) is the Gamma function [27, Eq. (8.310)] and \( \mu = \frac{m}{\lambda} \) in which \( m \) and \( \lambda \) denote integer fading factor and the mean, respectively.

Moreover, the PDF and CDF of channel gain \(|h_{k}|^2\) of the \( k \)-th user can be expressed as [28]

\[
\begin{align*}
f_{|h_{k}|^2} (x) & = \frac{K!}{(k-1)! (K-k)!} f_{|h|^{2}} (x) \\
& \times \left[ F_{|h|^{2}} (x) \right]^{k-1} \left[ 1 - F_{|h|^{2}} (x) \right]^{K-k}, \\
F_{|h_{k}|^2} (x) & = \frac{K!}{(k-1)! (K-k)!} \sum_{i=0}^{K-k} \binom{K-k}{i} \left( \frac{K-k}{i} \right) \\
& \times (-1)^{i+k+i} \left[ F_{|h|^{2}} (x) \right]^{k+i}.
\end{align*}
\]

Based on (9) and after few steps, the exact OP with pSIC of the user \( k \) is given as

\[
\tilde{\rho}_{k}^{pSIC} = F_{|h_{k}|^2} (\theta_{k}^*)
\]

\[
= \chi_{k} \sum_{i=0}^{K-k} \binom{K-k}{i} (-1)^{i} \left[ 1 - e^{-\mu a \gamma_{k}^{a}} \sum_{s=0}^{m-1} \frac{\mu^{s} \gamma_{k}^{a} \gamma_{k}^{s}}{s!} \right]^{k+i} \\
= \chi_{k} \sum_{i=0}^{K-k} \binom{K-k}{i} (-1)^{i} \binom{k+i}{i} \left( \frac{a}{\gamma_{k}^{a}} \right)^{a} \\
\times e^{-\mu a \gamma_{k}^{a}} \sum_{j_{0}+\ldots+j_{m-1}=a} \binom{a}{j_{0}, \ldots, j_{m-1}} \prod_{b=0}^{m-1} \binom{\mu a \gamma_{k}^{a} \gamma_{k}^{b}}{b!}^{j_{k}},
\]

where \( \chi_{k} = \frac{K!}{(k-1)! (K-k)!} \).

**B. SCENARIO OF IMPERFECT SUCCESSIVE INTERFERENCE CANCELLATION (IPSIIC)**

In the case of imperfect SIC (ipSIC), (4) demonstrates that the instantaneous achievable rate at the \( t \)-th user to detect the information of the \( k \)-th user \((k > t)\) is provided by [29]:

\[
\tilde{\tau}_{k}^{ipSIC} = \log_{2} \left( 1 + \frac{\tilde{\rho}_{R}^{\tau_{k}^{ipSIC}} d_{k-1}^{a} |h_{k}|^{2}}{\tilde{\rho}_{R}^{\tau_{k}^{ipSIC}} \sum_{i=t+1}^{K} d_{i}^{-1} + \tilde{\rho}_{R} |h_{l}|^{2} + 1} \right).
\]

We assume that \( h_{t} \) represents residual interference, which follows a complicated Gaussian distribution with zero mean and variance \( \lambda_{h_{k}}, \) i.e., \( h_{t} \sim CN (0, \xi \lambda_{h_{k}}) \) where \( \xi (0 \leq \xi \leq 1) \) is the level of residual interference caused by ipSIC [30, 31].

Then the instantaneous achievable rate of \( k \)-th user detecting the information by treating \( K-k \) users’ signals as interference is given by

\[
\tilde{R}_{k}^{ipSIC} = \log_{2} \left( 1 + \frac{\tilde{\rho}_{R}^{\tau_{k}^{ipSIC}} d_{k}^{a} |h_{k}|^{2}}{\tilde{\rho}_{R}^{\tau_{k}^{ipSIC}} \sum_{i=t+1}^{K} d_{i}^{-1} + \tilde{\rho}_{R} |h_{l}|^{2} + 1} \right).
\]

On the basis of (11) and (12), the OP of the user \( k \) with ipSIC case can be formulated as follows:

\[
\tilde{\rho}_{k}^{ipSIC} = 1 - \Pr \left( \bigcap_{t=1}^{k-1} \tilde{R}_{t+k}^{ipSIC} > R_{t}, \tilde{R}_{k}^{ipSIC} > R_{k} \right) \\
= 1 - \Pr \left( |h_{k}|^2 > \theta_{k}^{*} \left( \tilde{\rho}_{R} |h_{l}|^2 + 1 \right) \right) \\
= 1 - \int_{0}^{\infty} \int_{\theta_{k}^{*} (\tilde{\rho}_{R} x + 1)}^{\infty} f_{|h|^{2}} (x) f_{|h|^{2}} (y) dy dx \\
= \frac{1}{\xi \lambda_{h_{k}}} \int_{0}^{\infty} e^{-\frac{\xi \lambda_{h_{k}}}{\tilde{\rho}_{R} x + 1}} F_{|h|^{2}} (\theta_{k}^{*} (\tilde{\rho}_{R} x + 1)) dx.
\]

Using the Newton’s binomial, i.e., \( (a + x)^{k} = k\sum_{v=0}^{k} \binom{k}{v} x^{v} a^{k-v} \) and [27, Eq. (3.351.3)], we obtain the closed-form expression of \( \tilde{\rho}_{k}^{ipSIC} \) as

\[
\tilde{\rho}_{k}^{ipSIC} = \chi_{k} \sum_{i=0}^{K-k} \binom{K-k}{i} \left( \frac{K-k}{i} \right) (-1)^{i} \binom{k+i}{i} \sum_{a=0}^{m-1} \binom{\mu a \gamma_{k}^{a} \gamma_{k}^{b}}{b!}^{j_{k}} \\
\times e^{-\mu a \gamma_{k}^{a}} \sum_{j_{0}+\ldots+j_{m-1}=a} \binom{a}{j_{0}, \ldots, j_{m-1}} \prod_{b=0}^{m-1} \binom{\mu a \gamma_{k}^{a} \gamma_{k}^{b}}{b!}^{j_{k}}.
\]

**C. DIVERSITY ANALYSIS**

In this section, to gain more insights, the diversity order achieved by the users for two scenarios can be obtained based
on the above analytical results. The diversity order is defined as [32, Eq. (13)]
\[ d_k^* = - \lim_{\bar{\rho}_R \to \infty} \frac{\log(\bar{P}_k^{-\infty}(\bar{\rho}_R))}{\log(\bar{\rho}_R)}, \quad * \in \{\text{pSIC, ipSIC}\}. \]  
(15)

When \( x \to 0 \), the approximate expressions of CDF for the unsorted channel gain \(|h_k|^2\) and the \( k \)-th user’s sorted channel gain \(|\tilde{h}_k|^2\) are given by [33]
\[ F_{|h|^2}(x) \approx \left(\frac{\mu x}{m!}\right)^m, \]  
(16a)
\[ F_{|\tilde{h}_k|^2}(x) \approx \frac{K!}{k!} \frac{(\mu x)^{mk}}{(K-k)! (m!)^k}. \]  
(16b)

In (16b), the asymptotic OP with pSIC for the user \( k \) can be expression as
\[ \tilde{P}_k^{\infty,\text{pSIC}} = \frac{K!(\mu \theta_k)^{mk}}{(K-k)! (m!)^k}. \]  
(17)

Upon substituting (17) into (15), the diversity order achieved by the \( k \)-th user is \( d_k = \mu k \).

In the high SNR domain, the asymptotic OP of the \( k \)-th terrestrial user with ipSIC is given by
\[ \tilde{P}_k^{\infty,\text{pSIC}} = 1 - \Pr[|\tilde{h}_k|^2 > \nu_k^* |\tilde{h}|^2], \]  
(18)
where \( \nu_k^* = \frac{P_L(k)}{\sum_k \nu_k^*} \) and \( \nu_k^* \) is max \( (\nu_1, \ldots, \nu_K) \).

Similar to (14), the asymptotic OP with ipSIC can be given as
\[ \tilde{P}_k^{\infty,\text{ipSIC}} = \sum_{i=0}^{K-k} \binom{K-i}{k-i} \left( \frac{-1}{k+i} \right) \sum_{a=0}^{k+i} \binom{k+i}{a} \times \left( \frac{1}{\xi \lambda_{\tilde{h}}}, \frac{e^{-\xi \lambda_{\tilde{h}}}}{\xi \lambda_{\tilde{h}}} \right) \]  
(21)

This study of diversity order begins with a description of CDF \( F_{|\tilde{h}_k|^2} \) in the high SNR domain. When \( \bar{\rho}_R \to \infty \), the conditions \( \mu_k = \frac{1}{\lambda_{\tilde{h}}} (\rho_k |\tilde{h}|^2 + 1) \) of \( \tilde{P}_k^{\infty,\text{ipSIC}} \) is equal to \( \nu_k^* |h|^2\). Upon substituting the conditions into (13), we obtain (18). The user \( k \) with ipSIC reaches the zero diversity order by replacing (19) into (15). This is due to the impact of residual ipSIC interference.

D. SYSTEM THROUGHPUT ANALYSIS

Additionally, based on the analytical results for the OP in (10) and (14), the system throughput with the constant rates is expressed as
\[ \tau_{total}^* = \sum_{k=1}^{K} \left( 1 - \tilde{P}_k^* \right) R_k, \quad * \in \{\text{pSIC, ipSIC}\}. \]  
(20)

IV. ERGODIC CAPACITY ANALYSIS

A. ERGODIC RATE WITH pSIC

In this section, link-level performance is analysed via ergodic rate with pSIC defined by
\[ \bar{C}_{k,\text{erg}}^{\text{pSIC}} = \mathbb{E}\{ \bar{P}_k^{\text{pSIC}} \} \]
\[ = \mathbb{E} \left\{ \log_2 \left( 1 + \frac{\tilde{\rho}_R \varphi_k P_L |h_k|^2}{\tilde{\rho}_R P_L |h_k|^2 \sum_{l=k+1}^{K} \varphi_l d_l^{-t} + 1} \right) \right\}. \]  
(21)

By the definition of the expectation operator and after integration-by-part, \( \bar{C}_{k,\text{erg}}^{\text{pSIC}} \) can then be evaluated on the next page, where \( \varphi_{k+1} = \sum_{l=k+1}^{K} d_l^{-t} \).

Proposition 1. The closed-form expression of ergodic rate with pSIC of the user \( k \) is expressed as (23), shown at the top of the next page with \( \delta(t) = \frac{d_k^{-t} \varphi_k}{2 \varphi_k}, \) \( \tilde{g}(t) = \frac{\tilde{\rho}_R P_L |\tilde{h}_k|^2 - \delta - (t+1) \varphi_k}{\tilde{\rho}_R P_L |\tilde{h}_k|^2}, \) \( \tilde{t}(t) = \frac{\tan(\pi(t+1)/4)}{\tilde{\rho}_R P_L |\tilde{h}_k|^2}, \) \( \tilde{t}(x) = \cos \left( \frac{2x}{x^2 + 1} \right) \).

Proof: See Appendix A.

B. ERGODIC RATE WITH ipSIC

From (12), the ergodic capacity with ipSIC can be calculated by
\[ \bar{C}_{k,\text{erg}}^{\text{ipSIC}} = \mathbb{E}\{ \bar{P}_k^{\text{ipSIC}} \} \]
\[ = \mathbb{E} \left\{ \log_2 \left( 1 + \frac{\tilde{\rho}_R \varphi_k P_L |h_k|^2 \sum_{l=k+1}^{K} \varphi_l d_l^{-t} + \tilde{\rho}_R |h_k|^2 + 1} \right) \right\}. \]  
(24)

Similarly, by solving \( \bar{P}_k^{\text{ipSIC}} \) in (23) and after a few mathematical simplifications, the ergodic capacity of \( \bar{C}_{k,\text{erg}}^{\text{ipSIC}} \) can be obtained.

V. SYMBOL ERROR RATE ANALYSIS

The average symbol error rate (SER) with pSIC can be expressed in terms of the form [34]
\[ \bar{S}_{pSIC,\text{SER}}^{\text{pSIC}} = \mathbb{E}\left\{ a Q \sqrt{2 b \bar{P}_k^{\text{pSIC}}} \right\}, \]  
(26)
where \( Q(\cdot) \) is the Gaussian Q-function, \( a \) and \( b \) are modulation-specific constants, e.g., \( a = 1, b = 2 \) for the binary phase-shift keying (BPSK) modulation and \( a = 2, b = 1 \) for quadrature phase shift keying (QPSK) and 4-quadrature amplitude modulation (4-QAM) in [35].
Outage Probability

\[ \bar{C}_{k,\text{erg}}^{\text{pSIC}} = \left\{ \begin{array}{ll}
\frac{1}{\ln 2} \int_0^{1/\ln 2} \left[ 1 - F_{|h_k|^2} \left( \frac{x}{\rho_P P L_k \phi_k \bar{d}_{k+1}} \right) \right] dx, & k < K, \quad k \in [1, \ldots, K] \\
\frac{1}{\ln 2} \int_0^{1/\ln 2} \left[ 1 - F_{|h_k|^2} \left( \frac{x}{\rho_P P L_k \phi_k \bar{d}_{k+1}} \right) \right] dx, & k = K
\end{array} \right. \] (22)

\[ \bar{C}_{k,\text{erg}}^{\text{pSIC}} \approx \left\{ \begin{array}{ll}
\frac{1}{\ln 2} \left[ \log \left( \frac{d_{\text{pSIC}} \bar{d}_{k+1}}{d_{\text{pSIC}} + 1} \right) + \frac{\chi_a \sqrt{\rho_k}}{\sqrt{\rho_k}} \sum_{i=0}^{K-1} \left( K - k \right) \binom{k+i}{k+i} \binom{k+i}{a} \left( -1 \right)^a \right] & k < K \\
\sum_{j_0+j_m+1=1}^{a} \left( j_0, j_m \right) \left( a \right) \left( a \right) \binom{k+i}{a} \left( -1 \right)^a e^{-\mu a \lambda(\phi_k)} \sum_{j_0+j_m+1=1}^{a} \left( j_0, j_m \right) \left( a \right) \left( a \right) \binom{k+i}{a} \left( -1 \right)^a \right] & k = K
\end{array} \right. \] (23)

\[ \bar{C}_{k,\text{erg}}^{\text{pSIC}} \approx \left\{ \begin{array}{ll}
\frac{1}{\ln 2} \left[ \log \left( \frac{d_{\text{pSIC}} \bar{d}_{k+1}}{d_{\text{pSIC}} + 1} \right) + \frac{\chi_a \sqrt{\rho_k}}{\sqrt{\rho_k}} \sum_{i=0}^{K-1} \left( K - k \right) \binom{k+i}{k+i} \binom{k+i}{a} \left( -1 \right)^a \right] & k < K \\
\sum_{j_0+j_m+1=1}^{a} \left( j_0, j_m \right) \left( a \right) \left( a \right) \binom{k+i}{a} \left( -1 \right)^a e^{-\mu a \lambda(\phi_k)} \sum_{j_0+j_m+1=1}^{a} \left( j_0, j_m \right) \left( a \right) \left( a \right) \binom{k+i}{a} \left( -1 \right)^a \right] & k = K
\end{array} \right. \] (25)

We begin by invoking a general result from [36], which allows us to express the SER in (26) directly in terms of the CDF of the output SNR as follows:

\[ \bar{S}_{k,\text{SER}}^{\text{pSIC}} = \bar{a} \sqrt{b} \int_0^{\infty} e^{-\frac{b}{2x}} F_{|h_k|^2}(x) dx. \] (27)

By substituting (10) into (27), we can obtain the SER of the user \( k \) as follows on the next page.

**Proposition 2.** The SER with pSIC of the UAV-NOMA network assuming Nakagami-\( m \) fading model can be analytically obtained as in (29), given the top of the next page with \( \delta \) and \( \bar{g}(t) \) being available in (23), respectively, \( \Theta(r) = \sqrt{\frac{r+1}{r}} \), \( \eta_k = \frac{1}{\rho_P P L_k \phi_k \bar{d}_{k+1}} \) and \( \phi_u = \cos \left( \frac{2m-1}{2m} \pi \right) \).

**Proof:** See Appendix B.

The average SER with ipSIC case can be computed by

\[ \bar{S}_{k,\text{SER}}^{\text{ipSIC}} = \mathbb{E} \left\{ \bar{a} \sqrt{b} \bar{C}_{k,\text{erg}}^{\text{ipSIC}} \right\}. \] (30)

Similar to that of (29), after a few mathematical simplifications, the SER with ipSIC case of the user \( k \) can be given by equation (31).

**VI. NUMERICAL RESULTS**

In this section, we consider that there are three users for analyzing outage performance, and four users for evaluating ergodic capacity and symbol error rate. We assume that the system is deployed in a sub-urban environment and Monte Carlo simulations are used to verify the theoretical expressions. The system parameters used are shown in Table 2. In addition, for obtaining close approximation, the Gauss-Chebyshev parameter is selected as \( T = U = 300, \lambda_b = 1 \) and \( \xi = 0.01 \) in [31]. It’s worth noting that the power allocations are set as follows \( \varphi_k = (2K-k+1)/(2K - 1) \) in [37].

**FIGURE 2:** The outage probability versus transmit SNR \( \hat{\rho}_R \) with \( m = 1 \).

Figure 2 shows the OPs at the users versus transmit SNR \( \hat{\rho}_R \) for both the NOMA and the conventional OMA under Nakagami-\( m \) fading with \( m = 1 \). Obviously, the performance of the NOMA system outperforms the conventional OMA.
Values

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2. It is clearly that the higher system throughput can be achieved in Figure 5. The throughputs which are obtained from (20) is too large. This is because increasing distances between the UAV and the ground users will not be able to perform when the distance between the UAV and ground user is too large. This is because increasing distances between the UAV and the users result in increasing the path loss, and as a consequence, the outage performance of the system is dropped.

The system throughputs versus SNR in delay limited transmission mode for the NOMA and OMA systems are plotted in Figure 5. The throughputs which are obtained from (20) with different values of \( m \) are represented by the solid curves. It is clearly that the higher system throughput can be achieved with the higher values \( m \) at the high SNR. In addition, in the high SNR region, the throughput ceiling exits. This is because the OP is tending to zero, throughput is determined only by the target rate.

The plots between ergodic rates and transmit SNR for NOMA and OMA schemes are presented in Figure 6a (for the perfect SIC case) and Figure 6b (for the imperfect SIC case). In Figure 6a, the simulation and analytical curves for NOMA are obtained from (21) and (23), respectively. It can be observed that the ergodic rate had different trends for NOMA and OMA schemes. The curve of ergodic rate performance increases significantly for OMA case. Therefore, this can be used as a key indicator to determine the performance gain of NOMA scheme. The ergodic capacity of NOMA users

system. Moreover, at the high SNR, the asymptotic curves are well approximated the exact performance curves. In addition, due to multiple decoding stages, the performance of user 3 is worse at the transmit SNR but achieves the best at high SNR regime.

We illustrate the OPs at the users versus the transmit SNR \( \hat{\rho}_R \) for the perfect SIC case (Figure 3a) and the imperfect SIC case (Figure 3b). Figure 3a plots the OPs at the users with \( m = 1 \) and \( m = 3 \). It can be observed that NOMA system has a lower outage performance with the parameter \( m \) increasing. This is because a larger \( m \) leads to a higher diversity order for each user, which in turn results in a lower OP. The effects of imperfect SIC on the outage performance are shown in Figure 3b. A similar trend can be observed for the OPs shown in Figure 3a and Figure 3b when \( \hat{\rho}_R \) is less than 25dB. However, when \( \hat{\rho}_R \) is less than 25 dB. However, when \( \hat{\rho}_R \) is greater than 25 dB, decoding at the users is significantly impacted by SIC imperfection, leading to different OP floors of the users.

In Figure 4, we analyze the OP of the users at different heights of the UAV with the transmit SNR = 35 dB. We can see that the lines of three users with each other for the ideal target rate. As shown in Figure 4, the outage performance of the system is declined as the height of the UAV increases, which means that with the given transmit power, communication between the UAV and the ground users will not be able to perform when the distance between the UAV and ground user is too large. This is because increasing distances between the UAV and the users result in increasing the path loss, and as a consequence, the outage performance of the system is dropped.

\[
\frac{d_{\hat{\rho}_R}}{N} = \sum_{i=0}^{U} \left( \sqrt{1 - \rho_{\hat{\rho}_R}^2} \right) \sum_{k=0}^{K-1} \left( \frac{K-k}{K-k+1} \right) \frac{k+i}{a} \left( -\frac{1}{a} \right) \left( \frac{k+i}{a} \right)
\]

\[
\frac{d_{\hat{\rho}_R}}{N} = \sum_{i=0}^{U} \left( \sqrt{1 - \rho_{\hat{\rho}_R}^2} \right) \sum_{k=0}^{K-1} \left( \frac{K-k}{K-k+1} \right) \frac{k+i}{a} \left( -\frac{1}{a} \right) \left( \frac{k+i}{a} \right)
\]

\[
\frac{d_{\hat{\rho}_R}}{N} = \sum_{i=0}^{U} \left( \sqrt{1 - \rho_{\hat{\rho}_R}^2} \right) \sum_{k=0}^{K-1} \left( \frac{K-k}{K-k+1} \right) \frac{k+i}{a} \left( -\frac{1}{a} \right) \left( \frac{k+i}{a} \right)
\]

\[
\frac{d_{\hat{\rho}_R}}{N} = \sum_{i=0}^{U} \left( \sqrt{1 - \rho_{\hat{\rho}_R}^2} \right) \sum_{k=0}^{K-1} \left( \frac{K-k}{K-k+1} \right) \frac{k+i}{a} \left( -\frac{1}{a} \right) \left( \frac{k+i}{a} \right)
\]

TABLE 2: System parameters

| Parameters | Values |
|------------|--------|
| \( \phi_1, \phi_2, \phi_3 \) | \( (0.6364, 0.2727, 0.0909) \) |
| \( H, v, \alpha \) | \( (35 \text{ m}, 20 \text{ dB}, 2) \) [25] |
| \( r_1, r_2, r_3 \) | \( (10 \text{ m}, 20 \text{ m}, 40 \text{ m}) \) |
| \( p, q \) | \( \{4.886, 0.429\} \) [38, 39] |
| \( K_k \) | \( 0.5 \text{ BPCU} \) |
| \( m, \lambda \) | \( \{2, 1\} \) [40] |
FIGURE 3: The outage probabilities at the users versus the transmit SNR $\tilde{\rho}_R$ with $m = 1$ and $m = 3$.

FIGURE 4: The outage probability with an ideal target rate of different UAV altitude, with $\tilde{\rho}_R = 35$ (dB).

FIGURE 5: System throughput versus transmit SNR $\tilde{\rho}_R$, with $m = 1$ and 3.
From (22), we consider two cases

Case 1: With $k < K$, $\hat{\gamma}_{pSIC}^{\text{erg}}$ can be expressed as

$$\hat{\gamma}_{pSIC}^{\text{erg}} = \frac{1}{m^2} \int_0^{\delta_{m+1}} \frac{1}{1 + x} \left[ 1 - F_{|h_k|^2}(g(x)) \right] dx$$

$$= \frac{1}{m^2} \left[ \int_0^{\delta_{m+1}} \frac{1}{1 + x} dx - \chi_k \sum_{i=0}^{K-k-1} \binom{K-k-1}{i} \chi_k^{k+i} \left( \frac{\chi_k}{\varphi_{k+1}} \right)^i \right]$$

$$\times \sum_{a=0}^{m-1} \binom{k+a}{a} \chi_k^{j_m-1} \sum_{j_0+\ldots+j_{m-1}=a} \binom{a}{j_0, \ldots, j_{m-1}} \left( \frac{1}{1 + x} \right)^{j_0 \ldots j_{m-1}} e^{-\mu a g(x)(g(x)^{b_j}) dx} ,$$

(32)

where $\chi_k = \frac{K!}{(k-1)! (K-k)!}$ and $g(x) = \frac{x}{\hat{\rho}_R P L_k (\varphi_k d_{k+1}^{\alpha} x \varphi_{k+1})}$.

$A_1$ can be obtained as

$$A_1 = \int_0^{\delta_{m+1}} \frac{1}{1 + x} dx$$

$$= \log \left( \frac{d_{m}^{\alpha} \varphi_k}{\varphi_{k+1}^{\alpha}} + 1 \right).$$

(33)

Let $t = \frac{2\varphi_{k+1} x}{d_{k+1}^{\alpha} \varphi_k} - 1 \Rightarrow \frac{d_{m}^{\alpha} \varphi_k (t+1)}{2\varphi_{k+1}} = x \Rightarrow \frac{d_{m}^{\alpha} \varphi_k}{2\varphi_{k+1}} dt = dx$.

$A_2$ is calculated as

$$A_2 = \delta \int_{-1}^{1} \frac{1}{1 + \delta (t+1) e^{-\mu g(t)(g(t)^{b_j})} dt},$$

(34)

where $\delta = \frac{d_{m}^{\alpha} \varphi_k}{2\varphi_{k+1}}$ and $\hat{g}(t) = \frac{\delta (t+1)}{\hat{\rho}_R P L_k (\varphi_k d_{k+1}^{\alpha} \delta (t+1) \varphi_{k+1})}$.
Unfortunately, it is difficult to find closed-form expression for (34). By using Gaussian-Chebyshev quadrature [41, Eq. (25.4.38)], $A_2$ can be obtained by

$$A_2 \approx \frac{\delta \pi}{T} \sum_{t=1}^{T} \frac{1}{1 + \delta (\phi_t + 1)} e^{-\mu a \tilde{g}(t)} (\tilde{g}(\phi_t))^{bj_k}, \quad (35)$$

where $\phi_t = \cos \left(\frac{2t - 1}{2T} \pi\right)$.

Substituting (35) into (33), $\tilde{C}_{pSIC}$ is given by

$$\tilde{C}_{pSIC} \approx \frac{1}{\ln 2} \left[ \log \left(\frac{d_i - \varphi_k}{\varphi_{k+1}} + 1\right) - \chi_k \delta \pi \right] \times \sum_{i=0}^{K-k} \binom{K-k}{i} (-1)^{k+i} \sum_{a=0}^{k+i} \binom{k+i}{a} \left(\frac{k + i}{a}\right) (-1)^a \sum_{j_0+\ldots+j_{m-1}=a} \left(\frac{a}{j_0, \ldots, j_{m-1}}\right) \prod_{b=0}^{m-1} \left(\frac{\mu^b}{b!}\right) \times \sum_{t=0}^{T} \frac{1 - \delta \phi_t}{1 + \delta (\phi_t + 1)} e^{-\mu a \tilde{g}(t)} (\tilde{g}(\phi_t))^{bj_k}. \quad (36)$$

Case 2: With $k = K$, $\tilde{C}_{pSIC}$ is given in (37) shown at the top of the page, in which $\tilde{A}(x) = \frac{x}{\tilde{\rho} R P L_k p_k d_k^{\alpha}}$.

Putting $t = \frac{4}{\pi} \arctan (x) - 1 \Rightarrow \tan \left(\frac{\pi (t+1)}{4}\right) = x \Rightarrow \frac{\pi}{4} \sec^2 \left(\frac{\pi}{4} (t + 1)\right) dt = dx$ then $\tilde{C}_{k,erg}$ has become

$$\tilde{C}_{pSIC} \approx \frac{\pi}{4 \ln 2} \int_{-1}^{1} \sec^2 \left(\frac{\pi}{4} (t + 1)\right) dt = dx \Rightarrow \tilde{C}_{k,erg} \text{ has become}$$

$$\tilde{C}_{pSIC} \approx \frac{\pi}{4 \ln 2} \int_{-1}^{1} \sec^2 \left(\frac{\pi}{4} (t+1)/4\right) 1 + \tan(\pi (t+1)/4) dt \times \sum_{i=0}^{K-k} \binom{K-k}{i} (-1)^{k+i} \sum_{a=0}^{k+i} \binom{k+i}{a} \left(\frac{k + i}{a}\right) (-1)^a \sum_{j_0+\ldots+j_{m-1}=a} \left(\frac{a}{j_0, \ldots, j_{m-1}}\right) \prod_{b=0}^{m-1} \left(\frac{\mu^b}{b!}\right) \times \sum_{t=1}^{T} \frac{1 - \phi_t}{1 + \phi_t} e^{-\mu a \tilde{g}(t)} (\tilde{g}(\phi_t))^{bj_k}. \quad (38)$$

where $\tilde{A}(t) = \frac{\tan(\pi (t+1)/4)}{\tilde{\rho} R P L_k p_k d_k^{\alpha}}$. (38) can be approximated as

$$\tilde{C}_{pSIC} \approx \frac{\pi^2}{4 T \ln 2} \sum_{t=1}^{T} \frac{1 - \phi_t \sec^2(\pi (\phi_t+1)/4)}{1 + \tan(\pi (\phi_t+1)/4)} \times \left[ 1 - \chi_k \sum_{i=0}^{K-k} \binom{K-k}{i} (-1)^{k+i} \sum_{a=0}^{k+i} \binom{k+i}{a} \left(\frac{k + i}{a}\right) (-1)^a \sum_{j_0+\ldots+j_{m-1}=a} \left(\frac{a}{j_0, \ldots, j_{m-1}}\right) \prod_{b=0}^{m-1} \left(\frac{\mu^b}{b!}\right) \right] \times \sum_{t=1}^{T} \frac{1 - \phi_t}{1 + \phi_t} e^{-\mu a \tilde{g}(t)} (\tilde{g}(\phi_t))^{bj_k}, \quad (39)$$

where $\phi_t = \cos \left(\frac{2t - 1}{2T} \pi\right)$ and $\tilde{C}_{k,erg}$ is achieved by applying the Gaussian-Chebyshev quadrature.

Substituting (39) and (33) into (22), we can obtain (23).

The proof is completed.

**APPENDIX B PROOF OF PROPOSITION 2**

Substituting (10) into (28), in $k < K$ case, $S_{k,SER}$ is calculated as

$$S_{k,SER} = \frac{\bar{\rho} R P L_k p_k d_k^{\alpha}}{2 \sqrt{x}} \sum_{i=0}^{K-k} \binom{K-k}{i} (-1)^i \sum_{a=0}^{K-k} \binom{K-k}{a} \left(\frac{K - k}{a}\right) \sum_{j_0+\ldots+j_{m-1}=a} \left(\frac{a}{j_0, \ldots, j_{m-1}}\right) \prod_{b=0}^{m-1} \left(\frac{\mu^b}{b!}\right) \times \int_{0}^{\tilde{A}(x)} e^{-\mu a x} \left(\frac{\tilde{g}(x)}{b!}\right)^{bj_k} dx. \quad (40)$$

By replacing the variable $x = \frac{d_i - \varphi_k (t+1)}{2 P_k}$ in (40) and
\[
\eta_k \approx \frac{\mu_a}{\rho_a} \sum_{a=0}^{K-k} \frac{1}{\pi} \sqrt{1 - \phi_a^2} \sum_{i=0}^{K-k} \left( \frac{K-k}{i} \right) (-1)^i \frac{K-k}{i+1} \frac{1}{a+1} \left( \frac{k+i}{a} \right) (-1)^a e^{-\mu_a \Lambda(x)} \sum_{j_0+\ldots+j_{m-1}=a} \left( \frac{a}{j_0, \ldots, j_{m-1}} \right) \prod_{b=0}^{m-1} \left( \frac{\phi_b}{\theta} \right)^{j_b} \right) dx,
\]

(37)

using Gaussian-Chebyshev quadrature, we have

\[
\begin{align*}
\xi_{\text{SER}}^{pSIC} & \approx \frac{\pi R_{\text{pSIC}} a}{2 h_{\text{pSIC}}^2} \sum_{\kappa=1}^{U} \sqrt{1 - \phi_a^2} \sum_{i=0}^{K-k} \left( \frac{K-k}{i} \right) (-1)^i \frac{K-k}{i+1} \frac{1}{a+1} \left( \frac{k+i}{a} \right) (-1)^a e^{-\mu_a \Lambda(x)} \sum_{j_0+\ldots+j_{m-1}=a} \left( \frac{a}{j_0, \ldots, j_{m-1}} \right) \prod_{b=0}^{m-1} \left( \frac{\phi_b}{\theta} \right)^{j_b} dt,
\end{align*}
\]

(42)

where \( \phi_a = \cos \left( \frac{2\pi a}{a+1} \right) \). Assuming \( r = \frac{1}{2} \arctan(t) - 1 \), and using the Chebyshev–Gauss quadrature, we can approximate (42) as

\[
\begin{align*}
\xi_{\text{SER}}^{pSIC} & \approx \frac{\pi^2 \rho_{\text{pSIC}} a^2}{4 h_{\text{pSIC}}^2} \sum_{\kappa=1}^{U} \sqrt{1 - \phi_a^2} \sec^2 \left( \Theta(\phi_a) \right) \chi_k \sum_{i=0}^{K-k} \left( \frac{K-k}{i} \right) (-1)^i \frac{K-k}{i+1} \frac{1}{a+1} \left( \frac{k+i}{a} \right) (-1)^a e^{-\mu_a \Lambda(x)} \sum_{j_0+\ldots+j_{m-1}=a} \left( \frac{a}{j_0, \ldots, j_{m-1}} \right) \prod_{b=0}^{m-1} \left( \frac{\phi_b}{\theta} \right)^{j_b} \eta_b^{j_b} dt,
\end{align*}
\]

(43)

where \( \Theta(r) = \frac{\pi (r+1)}{4} \) and \( \phi_a = \cos \left( \frac{2\pi a}{a+1} \right) \).

The expression in (29) is obtained by combining (43) and (41). The proof 2 is completed.

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