

UAV-Assisted Hybrid Power-Frequency Multiple Access with Transmit Antenna Selection over Double Nakagami- m Channels

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Abstract. This paper investigates the performance of an unmanned aerial vehicle (UAV)-assisted hybrid power-frequency multiple access (HPMA) system with transmit antenna selection (TAS) over double Nakagami- m fading channels. While existing literature has largely focused on conventional non-orthogonal multiple access (NOMA) or single-antenna setups, the novelty of this work lies in the joint integration of HPMA and TAS within a multi-antenna UAV network to combat the severe cascaded scattering effects modeled by the double Nakagami- m distribution. By avoiding the complexity of successive interference cancellation, this joint framework offers a highly reliable and low-complexity transmission strategy. In the considered model, a multi-antenna UAV employs TAS to serve ground users over these cascaded fading channels. Closed-form expressions for the outage probability (OP) are derived by characterizing the statistical distribution of the equivalent channel gain. To provide further insights, asymptotic OP expressions are also obtained in the high-SNR regime, from which the diversity order of the considered system is determined. In addition, the throughput under delay-limited transmission is evaluated. Monte Carlo simulations are presented to validate the accuracy of the theoretical analysis, and numerical results demonstrate that the proposed HPMA scheme achieves better outage performance than the conventional NOMA scheme under the same system settings.

Keywords

UAV communication, hybrid power-frequency multiple access, transmit antenna selection, double Nakagami- m fading, outage probability, diversity analysis

1. Introduction

Unmanned aerial vehicle (UAV)-assisted wireless communication has recently emerged as a promising technology for future wireless networks due to its flexible deployment, wide coverage capability, and its ability to establish reliable air-to-ground links. Compared with conventional terrestrial base stations, UAV platforms can dynamically adjust their positions to improve channel conditions and extend connectivity in scenarios such as emergency communications, temporary hotspots, and remote areas [1–3]. For instance, in post-disaster scenarios (e.g., floods or earthquakes) where terrestrial cellular infrastructure is incapacitated, an aerial UAV can be swiftly deployed to serve as an aerial base station. In this context, the proposed HPMA framework with TAS allows the UAV to reliably collect telemetry data from low-power ground sensors (IoT nodes) while concurrently broadcasting high-priority emergency instructions to rescue teams under severe cascaded fading channels without requiring complex SIC processing. Owing to these advantages, UAV-assisted communication systems have attracted significant attention in both academia and industry, particularly in the context of next-generation wireless networks [4].

Furthermore, multiple access techniques play a critical role in improving spectral efficiency and supporting massive connectivity. Among them, non-orthogonal multiple access (NOMA) has been widely investigated as a promising solution that allows multiple users to share the same time-frequency resources through power-domain multiplexing and successive interference cancellation (SIC) [5]. By exploiting the differences in channel conditions among users, NOMA can enhance system throughput and fairness compared with conventional orthogonal multiple access (OMA) schemes [6].

Recent research efforts have further examined NOMA-based systems under practical communication constraints, including short-packet transmission, imperfect SIC, and low-complexity relaying protocols, providing deeper insights into system reliability and implementation aspects [7]. Moreover, advanced NOMA frameworks incorporating emerging technologies, such as reconfigurable intelligent surfaces, physical layer security, and covert communication strategies, have also been explored to enhance system robustness, reliability, and security performance [8], [9]. Motivated by these benefits, several studies have investigated the integration of NOMA with UAV-assisted networks to further improve spectral efficiency and coverage performance [10].

Despite these advantages, the performance of NOMA systems can be sensitive to interference and power allocation strategies, particularly in complex wireless environments. To address these challenges, hybrid multiple access techniques have recently been proposed to combine the benefits of different multiple access paradigms. Specifically, hybrid power-frequency multiple access (HPMA) has attracted growing interest as it allows users to share both power and frequency resources in a flexible manner, thereby improving resource utilization and reducing interference in certain transmission scenarios [11]. This hybrid structure can provide additional degrees of freedom in system design and may offer performance improvements over conventional NOMA under appropriate configurations [12].

An additional important factor affecting the performance of UAV-assisted wireless systems is the wireless propagation environment. In many practical scenarios, the communication links between the UAV and ground users may experience cascaded fading effects due to multiple scattering processes, reflections, or relay-type signal propagation. Such conditions are often well characterized by the double Nakagami- m fading model, which provides a flexible framework for capturing various channel fluctuations in composite wireless environments [13–15]. Compared with conventional single-hop fading models, the double Nakagami- m distribution can more accurately describe the behavior of cascaded channels that frequently appear in UAV-assisted or relay-based communication systems [16].

Furthermore, the use of multiple antennas at the UAV can further enhance system performance through spatial diversity techniques. However, employing multiple radio-frequency (RF) chains may increase hardware complexity and energy consumption. Transmit antenna selection (TAS) offers a practical solution to this issue by selecting the best transmit antenna according to channel conditions, thereby achieving diversity gain while maintaining relatively low implementation complexity [17–19]. For this reason, TAS has been widely studied in various wireless systems, including cooperative communications, NOMA networks, and UAV-assisted transmissions [20–22].

Although significant progress has been made in analyzing UAV-enabled communication systems and hybrid multi-

ple access schemes, the performance of HPMA-based UAV networks over cascaded fading environments remains relatively less explored. In particular, conventional UAV-NOMA networks [23], [24] inherently suffer from high receiver complexity due to the requirement of successive interference cancellation (SIC). While HPMA offers a low-complexity alternative, existing literature on HPMA [11], [12] is limited to single-antenna configurations and standard terrestrial fading models. Furthermore, while recent studies have explored transmissive reconfigurable intelligent surface (TRIS) mounted UAV networks [25], they typically assume a single-antenna UAV and require complex joint optimization of beamforming and phase shifts. To the best of our knowledge, the direct exploitation of spatial diversity via transmit antenna selection (TAS) in HPMA-based UAV networks over double Nakagami- m fading channels has not been investigated. The main technical challenge lies in evaluating the coupled statistical properties of the equivalent channel gains under the antenna selection policy over cascaded scattering links. A comprehensive analytical framework is therefore established in this paper to better understand the outage behavior and achievable throughput of such systems.

Motivated by the above observations, this paper investigates the performance of a UAV-assisted HPMA communication system employing transmit antenna selection over double Nakagami- m fading channels. The main contributions of this work can be summarized as follows:

- **Comprehensive Framework Design and Novelty:** We propose a novel multi-antenna UAV-assisted HPMA downlink network operating over composite double Nakagami- m fading channels. By integrating TAS with joint frequency- and power-domain multiplexing, this framework completely bypasses the hardware-intensive SIC at ground receivers while effectively mitigating severe cascaded scattering effects.
- **Rigorous Theoretical and Asymptotic Analysis:** We establish a precise mathematical framework by characterizing the coupled statistical properties of the equivalent channel gains under the antenna selection policy. We derive exact closed-form analytical expressions for the OP of the ground users, along with highly accurate high-SNR asymptotic approximations that explicitly reveal a diversity order of $Km_{i,a}$, demonstrating the linear scaling advantage of the TAS scheme.
- **Throughput Analysis and Benchmark Comparison:** We evaluate the delay-limited throughput performance of the proposed architecture and provide a rigorous comparative analysis against the conventional NOMA scheme. Furthermore, extensive Monte Carlo simulations are presented to validate the theoretical bounds, proving the clear reliability and transmission efficiency advantages of the proposed HPMA framework under various network geometries and resource allocation configurations.

1.1 Organization & Notations

The remainder of this paper is organized as follows. Section 2 introduces the considered UAV-assisted HPMA system model and the associated channel characteristics. Section 3 presents the performance analysis, including the derivation of the OP, the asymptotic OP analysis with the corresponding diversity order, and the throughput evaluation. Section 4 provides numerical results to validate the theoretical analysis and discusses the performance comparison with the conventional NOMA scheme. Finally, Section 5 concludes the paper.

Notations: Throughout this paper, the operator $\mathbb{E}\{\cdot\}$ denotes the expectation; $CN(a, b)$ represents the circularly symmetric complex Gaussian distribution with mean a and variance b ; $\Gamma(\cdot)$ denotes the Gamma function; $G_{p,q}^{m,n}(\cdot)$ denotes the Meijer- G function; and for any random variable X , its probability density function (PDF) and cumulative distribution function (CDF) are denoted by $f_X(\cdot)$ and $F_X(\cdot)$, respectively.

2. System Model and Terrestrial Channel Model

2.1 System Description

Figure 1 illustrates the considered downlink communication scenario where a UAV operates as an aerial base station to serve two ground users, denoted as U_1 and U_2 . Unlike conventional single-antenna deployments, the UAV in this work is equipped with K transmit antennas. This multi-antenna capability provides additional spatial diversity, thereby improving the reliability of the air-to-ground (A2G) links. Instead of relying on conventional NOMA, which typically requires SIC at the receivers, this study adopts an HPMA scheme. The key idea behind HPMA is to combine both frequency-domain and power-domain resource allocation, thereby enabling flexible transmission while avoiding the complexity associated with SIC processing. More specifically, the available bandwidth is divided into multiple sub-carriers. Two of them, denoted by s_1 and s_2 , are allocated to users U_1 and U_2 , respectively. These sub-carriers independently transmit signals x_1 and x_2 , where each signal satisfies the normalized power condition $\mathbb{E}\{|x_1|^2\} = \mathbb{E}\{|x_2|^2\} = 1$. The corresponding bandwidth portions are represented by α_1 and α_2 , which operate in a manner similar to conventional OMA.

In addition to these orthogonal components, a third sub-carrier s_{12} is employed to carry a superposed signal defined as $x_{12} = \sqrt{\delta_1}x_1 + \sqrt{\delta_2}x_2$, where δ_1 and δ_2 represent the power allocation coefficients satisfying $\delta_1 + \delta_2 = 1$ and $0 \leq \delta_i \leq 1$. The bandwidth fraction associated with this shared sub-carrier is denoted by α_{12} . Naturally, the overall bandwidth allocation must satisfy $\alpha_1 + \alpha_2 + \alpha_{12} = 1$. Consequently, at the receiver side, the signal processing procedure becomes relatively straightforward. After the baseband signals are recovered, the components transmitted over different

sub-carriers can be combined appropriately. Due to the joint allocation of power and frequency resources, the desired signal component for each user generally becomes dominant over the residual interference from the other user. As a result, each user can decode its own signal by treating the undesired component as additional noise, which effectively removes the need for SIC operations.

Regarding the system geometry, the two users are assumed to be fixed on the ground. This scenario may represent users located outside the effective coverage of conventional terrestrial base stations. To keep the analysis tractable, we focus on a two-user case in this work. Although extending the framework to multi-user scenarios is possible, such extensions are left for future investigation. The UAV moves along a circular trajectory with radius r at a constant altitude H and velocity v . For convenience, a three-dimensional Cartesian coordinate system is considered, where the ground plane corresponds to $(x, y, 0)$. The two users are located along the x -axis at positions $U_1(-L, 0, 0)$ and $U_2(L, 0, 0)$. Meanwhile, the center of the UAV trajectory is located at $O'(0, 0, H)$. Hence, when the UAV moves along its circular path, its instantaneous position can be expressed as $S(r \cos \theta, r \sin \theta, H)$, where θ denotes the angular position of the UAV. Under such mobility conditions, the A2G links may experience noticeable fading fluctuations. To capture these effects more realistically, the wireless channels are modeled using the double Nakagami- m distribution, which is commonly adopted to represent cascaded fading environments.

Based on the geometry described above, the distances between the UAV and the ground users can be determined using standard Euclidean relations. Let d_1 and d_2 denote the instantaneous distances from the UAV to users U_1 and U_2 , respectively. By substituting the corresponding coordinates, the distance to U_1 can be expressed as

$$\begin{aligned} d_1 &= \sqrt{(r \cos \theta + L)^2 + (r \sin \theta)^2 + H^2} \\ &= \sqrt{r^2 + L^2 + H^2 + 2rL \cos \theta}. \end{aligned} \quad (1)$$

Similarly, the distance between the UAV and user U_2 becomes

$$\begin{aligned} d_2 &= \sqrt{(r \cos \theta - L)^2 + (r \sin \theta)^2 + H^2} \\ &= \sqrt{r^2 + L^2 + H^2 - 2rL \cos \theta}. \end{aligned} \quad (2)$$

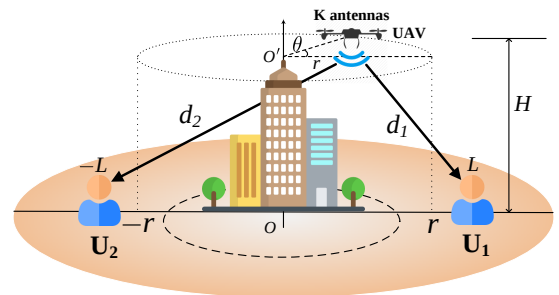


Fig. 1. Illustration of the considered HPMA-based UAV downlink system.

From (1) and (2), it can be observed that the link distances vary with the UAV position along its trajectory. Consequently, the corresponding channel conditions for both users change over time.

2.2 Channel Model and Antenna Selection

To characterize the propagation environment more accurately, the A2G links are modeled using the double Nakagami- m distribution. Compared with simple Rayleigh or Rician models, this distribution is capable of capturing cascaded scattering effects that may occur in UAV-assisted wireless systems. Let $h_{k,i}$ ($\forall i \in \{1, 2\}$) denote the channel coefficient between the k -th transmit antenna of the UAV, where $k \in \{1, \dots, K\}$, and the i -th ground user. The channel coefficient can be expressed as

$$h_{k,i} = \sqrt{L(d_i)} \tilde{h}_{k,i}. \quad (3)$$

Here, $L(d_i) = \eta d_i^{-\zeta}$ represents the large-scale path loss component, where η is the reference path loss constant and ζ denotes the path loss exponent. The term $\tilde{h}_{k,i}$ corresponds to the small-scale fading component, which follows a double Nakagami- m distribution. In other words, $\tilde{h}_{k,i}$ can be viewed as the product of two independent Nakagami- m random variables.

To facilitate a clear understanding of the subsequent mathematical derivations, the core technical assumptions adopted throughout this paper are explicitly stated as follows:

- **Perfect CSI:** The UAV is assumed to possess perfect channel state information (CSI) of the air-to-ground (A2G) links to perform instantaneous transmit antenna selection.
- **Independent Fading:** The small-scale channel coefficients are statistically independent and identically distributed (i.i.d.) across different transmit antennas, and independent across the distinct ground users due to sufficient spatial separation.
- **Fixed User Locations:** The ground users U_1 and U_2 are assumed to remain at fixed spatial coordinates during each transmission block interval, which is a standard assumption for quasi-static hovering UAV deployments.
- **Ideal Receiver Processing:** The radio frequency front-ends at both the UAV and ground nodes are assumed to be ideal, meaning that residual hardware impairments, phase noise, and synchronization errors are negligible.
- **Fading Parameter Condition:** The shape parameters of the cascaded double Nakagami- m fading channels strictly satisfy the condition $|m_{i,1} - m_{i,2}| = 1/2$, which enables a highly tractable power-series expansion for the channel statistics without sacrificing physical modeling accuracy.

To further improve the system reliability, a TAS scheme is employed at the UAV. Specifically, to maximize the transmission performance, the UAV selects the optimal transmit antenna for each ground user independently based on their respective instantaneous small-scale channel gains. This independent operation is highly practical in the proposed HPMA framework since the signals are multiplexed across different sub-carriers in the frequency domain. Thus, the selected antenna index for user U_i can be expressed as [18]

$$k_i^* = \arg \max_{k \in \{1, \dots, K\}} |\tilde{h}_{k,i}|^2, \quad \forall i \in \{1, 2\}. \quad (4)$$

After antenna selection, the effective channel gain for each user becomes $G_i = \max_{k=1, \dots, K} |\tilde{h}_{k,i}|^2$. As a result, both the near and far users can fully exploit the spatial diversity gains provided by the multiple antennas at the UAV, which perfectly matches the subsequent analytical framework and results in a diversity order of $Km_{i,a}$ for both links.

2.3 Statistical Characteristics of the Channels

To analyze the system performance, the statistical properties of the channel gains must first be established. Let $G_{k,i} = |\tilde{h}_{k,i}|^2$ denote the instantaneous small-scale channel power gain between the k -th antenna and user U_i . For double Nakagami- m fading channels, the PDF of $G_{k,i}$ can be expressed using the Meijer-G function as [26, Eq. (9)]

$$f_{G_{k,i}}(x) = \frac{G_{0,2}^{2,0} \left(x \xi_i \left| \begin{matrix} - \\ m_{i,1}, m_{i,2} \end{matrix} \right. \right)}{x \Gamma(m_{i,1}) \Gamma(m_{i,2})} \quad (5)$$

where $\xi_i = \frac{m_{i,1}m_{i,2}}{\Omega_{i,1}\Omega_{i,2}}$ and $\Gamma(\cdot)$ denotes the Gamma function. By integrating the above PDF, the CDF can be obtained as [27, Eq. (4)]

$$F_{G_{k,i}}(x) = \frac{G_{1,3}^{2,1} \left(x \xi_i \left| \begin{matrix} 1 \\ m_{i,1}, m_{i,2}, 0 \end{matrix} \right. \right)}{\Gamma(m_{i,1}) \Gamma(m_{i,2})}. \quad (6)$$

Although the Meijer-G representation is mathematically compact, it is often inconvenient for system-level performance analysis. Therefore, a power-series expansion is commonly adopted to obtain a more tractable form. Under this representation, the CDF of the effective channel gain G_i can be expressed as [27, Eq. (28)]

$$F_{G_i}(x) = [\Gamma(2m_{i,1}) \zeta_i]^K \sum_{k=0}^K \sum_{r=0}^{k(2m_{i,1}-1)} \binom{K}{k} (-1)^k \cdot q_r^k x^{\frac{r}{2}} e^{-2k\sqrt{x}\xi_i}. \quad (7)$$

By differentiating the above CDF, the corresponding PDF can be obtained as [27, Eq. (29)]

$$f_{G_i}(x) = \frac{1}{2} [\Gamma(2m_{i,1})\zeta_i]^K \sum_{k=0}^K \sum_{r=0}^{k(2m_{i,1}-1)} \binom{K}{k} (-1)^k \cdot q_r^k e^{-2k\sqrt{x}\xi_i} \left(r x^{\frac{r}{2}-1} - 2k\sqrt{\xi_i} x^{\frac{r-1}{2}} \right). \quad (8)$$

The parameter ζ_i is defined as $\zeta_i = \frac{2^{1-2m_{i,1}}\sqrt{\pi}}{\Gamma(m_{i,1})\Gamma(m_{i,2})}$, under the condition $|m_{i,1} - m_{i,2}| = 1/2$. The coefficients q_r^k can be recursively computed according to $q_0^k = (p_0)^k$, $q_1^k = k p_1$, $q_r^k = \frac{1}{r p_0} \sum_{\ell=1}^{\min(r, 2m_{i,1}-1)} (\ell k - r + \ell) p_\ell q_{r-\ell}^k$, for $2 \leq r \leq k(2m_{i,1} - 1)$, where $p_r = \frac{1}{r!} (4\xi_i)^{r/2}$.

2.4 Received Signal and SINR Model

Based on the transmit antenna selection scheme described in the previous subsection, the UAV selects the antenna index k_i^* that maximizes the instantaneous channel gain. Therefore, the received signal at user U_i can be expressed as

$$y_{U_i} = h_{k_i^*,i} \left(\sqrt{P\alpha_i} x_i + \sqrt{P\alpha_{12}\delta_i} x_i + \sqrt{P\alpha_{12}\delta_j} x_j \right) + n_{U_i} \quad (9)$$

where $i, j \in \{1, 2\}$ with $i \neq j$, and $n_{U_i} \sim \mathcal{CN}(0, (\alpha_i + \alpha_{12})N_0)$ denotes the additive white Gaussian noise, with N_0 representing the noise power. Accordingly, the instantaneous SINR at user U_i is given by

$$\begin{aligned} \gamma_i &= \frac{P|h_{k_i^*,i}|^2 \beta_i (\alpha_i + \alpha_{12}\delta_i)}{P|h_{k_i^*,i}|^2 \beta_i (\alpha_{12}\delta_j) + N_0} \\ &= \frac{\rho \eta d_i^{-\zeta} G_i \beta_i (\alpha_i + \alpha_{12}\delta_i)}{\rho \eta d_i^{-\zeta} G_i \beta_i (\alpha_{12}\delta_j) + 1} \end{aligned} \quad (10)$$

where $\beta_i \triangleq 1/(\alpha_i + \alpha_{12})$, and $\rho = P/N_0$ denotes the transmit signal-to-noise ratio (SNR). The achievable data rate of user U_i can be expressed as

$$\mathcal{R}_i = \log_2(1 + \gamma_i). \quad (11)$$

3. Performance Evaluation

3.1 Outage Probability Analysis

In this section, the OP performance of the considered UAV-enabled HPMA system is analyzed over double Nakagami- m fading channels with TAS. According to (11), an outage event occurs when the achievable data rate of user U_i falls below the target rate requirement R_i . Hence, the OP of U_i can be defined as

$$P_{\text{out},i} = \Pr(\mathcal{R}_i < R_i). \quad (12)$$

By using (11), the OP can be equivalently expressed as

$$P_{\text{out},i} = \Pr(\gamma_i < \gamma_{\text{th},i}) \quad (13)$$

where $\gamma_{\text{th},i} = 2^{R_i} - 1$ denotes the SINR threshold corresponding to the target rate R_i . Substituting the SINR expression into the outage definition yields

$$P_{\text{out},i} = \Pr \left(\frac{\rho \eta d_i^{-\zeta} G_i \beta_i (\alpha_i + \alpha_{12}\delta_i)}{\rho \eta d_i^{-\zeta} G_i \beta_i (\alpha_{12}\delta_j) + 1} < \gamma_{\text{th},i} \right). \quad (14)$$

To evaluate this probability, we expand the inequality inside the probability operator by multiplying both sides by the positive denominator, which yields

$$\rho \eta d_i^{-\zeta} G_i \beta_i (\alpha_i + \alpha_{12}\delta_i) < \gamma_{\text{th},i} [\rho \eta d_i^{-\zeta} G_i \beta_i (\alpha_{12}\delta_j) + 1]. \quad (15)$$

By collecting all terms involving the small-scale equivalent channel gain G_i onto the left-hand side, we obtain

$$\rho \eta d_i^{-\zeta} G_i \beta_i [(\alpha_i + \alpha_{12}\delta_i) - \gamma_{\text{th},i} \alpha_{12}\delta_j] < \gamma_{\text{th},i}. \quad (16)$$

Let us define $\varphi_i = (\alpha_i + \alpha_{12}\delta_i) - \gamma_{\text{th},i} \alpha_{12}\delta_j$. Here, we explicitly assume that the system parameters satisfy the condition $\varphi_i > 0$ to ensure successful decoding. If this condition is violated (i.e., $\varphi_i \leq 0$), the left-hand side becomes non-positive, meaning that the inequality holds true for any valid channel gain $G_i \geq 0$. Under such a scenario, the system experiences a permanent outage floor ($P_{\text{out},i} = 1$) because the power allocated to the desired signal is insufficient to overcome the co-channel interference. Under the standard operational constraint $\varphi_i > 0$, we can divide both sides by $\rho \eta d_i^{-\zeta} \beta_i \varphi_i$ to isolate G_i , leading to

$$P_{\text{out},i} = \Pr \left(G_i < \frac{\gamma_{\text{th},i}}{\rho \eta d_i^{-\zeta} \beta_i \varphi_i} \right) = F_{G_i}(\Lambda_i) \quad (17)$$

where $F_{G_i}(\cdot)$ denotes the CDF of G_i and $\Lambda_i = \gamma_{\text{th},i} / (\rho \eta d_i^{-\zeta} \beta_i \varphi_i)$.

For the case $K = 1$, the TAS scheme reduces to the conventional transmission scenario without antenna selection. By using the CDF expression in (6), the OP of U_i is obtained as

$$P_{\text{out},i} = \frac{G_{1,3}^{2,1} \left(\Lambda_i \xi_i \middle| m_{i,1}, m_{i,2}, 0 \right)}{\Gamma(m_{i,1})\Gamma(m_{i,2})}. \quad (18)$$

Conversely, for the case $K > 1$, the transmit antenna selection scheme is applied at the UAV. The closed-form expression of the OP of U_i is given by

$$\begin{aligned} P_{\text{out},i} &= [\Gamma(2m_{i,1})\zeta_i]^K \sum_{k=0}^K \sum_{r=0}^{k(2m_{i,1}-1)} \binom{K}{k} (-1)^k \\ &\quad \cdot q_r^k \Lambda_i^{\frac{r}{2}} e^{-2k\sqrt{\Lambda_i}\xi_i}. \end{aligned} \quad (19)$$

3.2 Asymptotic Outage Probability

To gain further insights into the system performance, the asymptotic OP is investigated in the high-SNR region, i.e., $\rho \rightarrow \infty$. By following a similar procedure as in the derivation of the closed-form OP and using the asymptotic expansion of the double Nakagami- m distribution, the high-SNR approximation can be obtained. Specifically, for the case $K = 1$, the TAS scheme reduces to the conventional single-antenna transmission. The asymptotic OP of user U_i can be approximated as [27, Eq. (12)]

$$P_{\text{out},i}^{\text{asy}} \approx \frac{\chi_i}{2m_{i,a}} \left(\frac{4\gamma_{\text{th},i}\xi_i}{\eta d_i^{-\zeta} \beta_i \varphi_i} \right)^{m_{i,a}} \left(\frac{1}{\rho} \right)^{m_{i,a}} \quad (20)$$

where $m_{i,a} = \min(m_{i,1}, m_{i,2})$, $|m_{i,2} - m_{i,1}| = 1/2$, and

$$\chi_i = \frac{2^{1-2m_{i,a}} \sqrt{\pi}}{\Gamma(m_{i,1})\Gamma(m_{i,2})}. \quad (21)$$

Alternatively, for the case $K > 1$, the transmit antenna selection scheme is applied at the UAV. Since $G_i = \max_{k=1,\dots,K} |h_{k,i}|^2$, the asymptotic OP can be expressed as [27, Eq. (35)]

$$P_{\text{out},i}^{\text{asy}} \approx \left[\frac{\chi_i}{2m_{i,a}} \left(\frac{4\gamma_{\text{th},i}\xi_i}{\eta d_i^{-\zeta} \beta_i \varphi_i} \right)^{m_{i,a}} \right]^K \left(\frac{1}{\rho} \right)^{Km_{i,a}}. \quad (22)$$

3.3 Diversity Order

Based on the asymptotic OP expressions, the diversity order of the considered system is defined as [28, Eq. (20)]

$$\mathcal{D}_i = - \lim_{\rho \rightarrow \infty} \frac{\log P_{\text{out},i}}{\log \rho}. \quad (23)$$

Thus, the diversity order of the proposed UAV-enabled HPMA system can be obtained as

$$\mathcal{D}_i = \begin{cases} m_{i,a}, & K = 1, \\ Km_{i,a}, & K > 1. \end{cases} \quad (24)$$

It can be observed that the diversity order increases linearly with the number of transmit antennas, demonstrating the diversity gain achieved by the TAS scheme.

3.4 Throughput Performance

Furthermore, the throughput performance of the considered multiple access schemes is also evaluated. Throughput reflects the effective data transmission rate achieved at the user while accounting for outage events. For user i , the achievable throughput is defined as

$$T_i = R_i (1 - P_{\text{out},i}). \quad (25)$$

In the simulations, the throughput is evaluated by substituting the simulated outage probabilities obtained for both HPMA and NOMA schemes into the above expressions. This metric provides additional insight into the practical transmission efficiency of the considered systems. The numerical results will illustrate how the proposed HPMA scheme improves the achievable throughput compared with the conventional NOMA scheme under different antenna configurations and SNR regimes.

4. Results and Discussions

In this section, numerical results are presented to evaluate the outage performance of the proposed HPMA system and to compare it with the conventional NOMA scheme. To ensure high statistical accuracy, especially in the high-SNR regime, all Monte Carlo simulation results are obtained by averaging over 10^6 independent channel realizations. Given this large sample size, the calculated 95% confidence intervals are strictly within $\pm 0.19\%$ of the estimated outage probability values, rendering the confidence error bounds visually negligible and seamlessly bounded within the simulation markers. The simulations were conducted using MATLAB R2024a on a workstation equipped with an Intel Core Ultra 9 275HX processor and 32 GB of RAM. To support reproducible research, the complete simulation source codes are made publicly available.¹ For clarity and self-containment, the key simulation parameters adopted throughout this evaluation are summarized in Tab. 1.

As summarized in Tab. 1, the bandwidth allocation factors are $\alpha_1 = 0.45$, $\alpha_2 = 0.45$, and $\alpha_{12} = 0.1$, which are chosen to provide symmetric dedicated frequency resources to both users while allocating a minor fraction to the shared sub-carrier for HPMA multiplexing. The power allocation coefficients are $\delta_1^{\text{HPMA}} = 0.5$ and $\delta_2^{\text{HPMA}} = 0.5$ for HPMA, reflecting an equal power splitting strategy on the shared resource. For a fair and rigorous comparison, the conventional NOMA benchmark adopts $\delta_2^{\text{NOMA}} = 0.7$ and $\delta_1^{\text{NOMA}} = 0.3$.

Parameter Description	Symbol	Value
Monte Carlo channel realizations	-	10^6
HPMA bandwidth allocation factors	$\alpha_1, \alpha_2, \alpha_{12}$	0.45, 0.45, 0.1
HPMA power allocation coefficients	$\delta_1^{\text{HPMA}}, \delta_2^{\text{HPMA}}$	0.5, 0.5
Conventional NOMA power coefficients	$\delta_1^{\text{NOMA}}, \delta_2^{\text{NOMA}}$	0.3, 0.7
Target data rates	R_1, R_2	1.5, 1 bps/Hz
Double Nakagami- m fading severity	$m_{1,1}, m_{2,1}$	1
	$m_{1,2}, m_{2,2}$	1.5
Number of UAV transmit antennas	K	3
Path-loss exponent	ζ	2
Channel scaling coefficient	η	1
Geometric network parameters	H, L, r, θ	1, 1, 0.1, 0°

Tab. 1. Simulation parameters configuration.

¹Matlab code is public at <https://github.com/lechibao123/HPMA-Radioengineering>

This setting strictly complies with the fundamental NOMA principle of allocating a larger portion of the transmit power to the far user (U_2 , who experiences stronger path loss) to ensure the successful execution of SIC at the near user. The target rates are $R_1 = 1.5$ bps/Hz and $R_2 = 1$ bps/Hz. The fading parameters follow the double Nakagami- m distribution with $m_{1,1} = m_{2,1} = 1$ and $m_{1,2} = m_{2,2} = 1.5$. Furthermore, the UAV is configured with $K = 3$ transmit antennas. This setup represents a practical and balanced aerial deployment scenario, which yields substantial spatial diversity gains to combat severe cascaded fading while strictly adhering to the limited physical payload, aerodynamic drag, and onboard energy constraints of small UAV platforms. Regarding the propagation environment, the path-loss exponent is set to $\zeta = 2$ and the channel scaling coefficient is $\eta = 1$. The distances between the UAV and the ground users are determined by the geometric parameters [29] $H = 1$, $L = 1$, $r = 0.1$, and $\theta = 0^\circ$. These parameters are used to model the large-scale channel attenuation in the considered UAV-assisted transmission scenario.

Figure 2 illustrates the OP versus the transmit SNR for the considered HPMA and NOMA schemes. As depicted, the exact analytical curves closely follow the Monte Carlo simulation results over the entire SNR region, which confirms the correctness of the derived expressions. Furthermore, the asymptotic results gradually approach the exact analytical curves in the high-SNR regime, validating the accuracy of the developed high-SNR approximation. From the figure, the proposed HPMA scheme generally achieves a lower OP compared with the conventional NOMA approach, especially when the SNR becomes large, mainly because the hybrid power-frequency resource allocation mitigates the inter-user interference more effectively. Additionally, since the UAV employs transmit antenna selection with $K = 3$ antennas, additional spatial diversity can be exploited, which significantly improves the reliability performance of the considered system. The slope of the curves in the high-SNR region also verifies the diversity gain achieved by the TAS scheme.

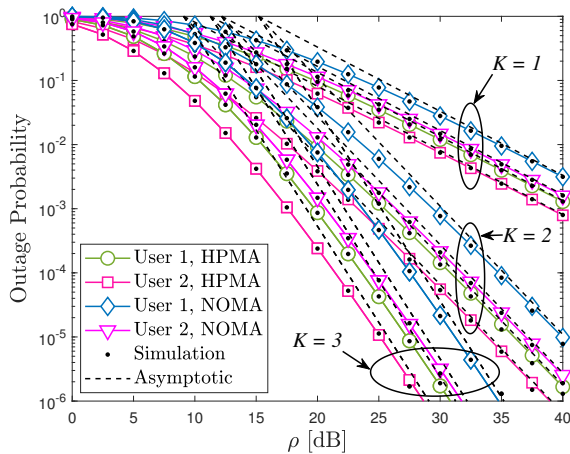


Fig. 2. OP versus the transmit SNR ρ for different numbers of antennas K , with $m_{1,1} = m_{2,1} = 1$ and $m_{1,2} = m_{2,2} = 1.5$.

Figure 3 illustrates the OP versus the power allocation factor δ_1 . It can be observed that the outage probabilities of the two users vary noticeably as δ_1 changes. Specifically, this behavior highlights a fundamental trade-off in the shared sub-carrier allocation: since the total shared power is constrained (i.e., $\delta_1 + \delta_2 = 1$), increasing the power allocated to one user intrinsically reduces the power available to the other user, whilst simultaneously altering the co-channel interference they experience. This emphasizes the critical need for a dynamically optimized power allocation strategy to balance user fairness and individual link reliability in practical HPMA deployments. In particular, the OP of U_1 tends to increase as δ_1 becomes large, while U_2 experiences improved reliability in most regions due to the different interference conditions under the HPMA transmission. In comparison to the baseline, the proposed HPMA scheme generally achieves lower OP compared with the conventional NOMA scheme over most of the considered range of δ_1 . Finally, when the fading parameters increase (i.e., from $m_{i,1} = 1, m_{i,2} = 1.5$ to $m_{i,1} = 2, m_{i,2} = 2.5$), the outage performance further improves due to the less severe channel fading conditions.

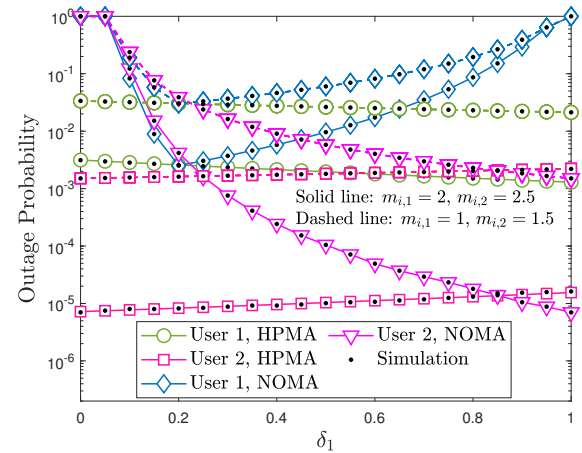


Fig. 3. OP versus power allocation factor δ_1 , with $R_1 = 0.5$ bps/Hz, $R_2 = 0.1$ bps/Hz, $\rho = 10$ dB and $K = 2$.

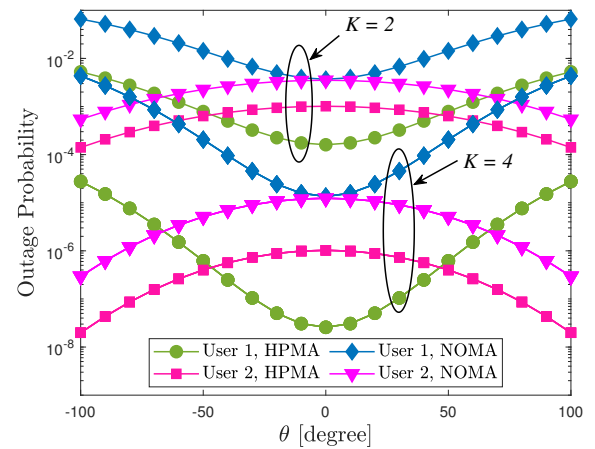


Fig. 4. OP of U_1 and U_2 with HPMA/NOMA transmissions for different user locations characterized by angle θ , with $R_1 = 1$ bps/Hz, $R_2 = 0.5$ bps/Hz, $\rho = 15$ dB, $m_{1,1} = m_{2,1} = 2$, $m_{1,2} = m_{2,2} = 2.5$, and $K \in \{2, 4\}$.

Figure 4 illustrates the OP of U_1 and U_2 under both HPMA and NOMA transmissions for different user locations characterized by the angle θ . Evidently, the OP varies symmetrically with respect to $\theta = 0^\circ$, which is mainly due to the geometric structure of the considered system model. Moreover, increasing the number of transmit antennas from $K = 2$ to $K = 4$ significantly improves the outage performance for both users, as additional spatial diversity is achieved through the TAS scheme. Consistent with previous findings, the proposed HPMA scheme consistently provides a lower OP than the conventional NOMA scheme for both users across most user locations.

Figure 5 illustrates the OP of U_1 and U_2 versus the distance parameter L for both the proposed HPMA and the conventional NOMA schemes. First, it is evident that the HPMA framework consistently outperforms NOMA across the entire evaluated distance range, firmly demonstrating its superior link reliability under identical system configurations. Second, an interesting crossover behavior is observed between the OP curves of U_1 and U_2 within the HPMA scheme. In the shorter distance regime ($L \leq 4$), U_1 achieves a lower OP than U_2 . This implies that the adopted resource allocation policy effectively compensates for the higher target data rate of U_1 ($R_1 = 1$ bps/Hz compared to $R_2 = 0.5$ bps/Hz). However, as the distance L increases to 5 and beyond, severe path loss becomes the overwhelmingly dominant factor affecting the transmission links. Consequently, the stricter target rate requirement of U_1 causes its outage performance to degrade more rapidly, resulting in U_2 exhibiting better reliability than U_1 at larger distances. This finding provides valuable insights into the crucial trade-off between spatial user deployments, target rates, and resource allocation in aerial networks.

Finally, Figure 6 depicts the throughput performance versus the target rates $R_1 = R_2$ for different numbers of transmit antennas K . It can be observed that the throughput initially increases with the target rate, reaches a peak, and then gradually decreases as the OP becomes dominant at higher rates. From a practical perspective, this peak occurs because throughput is essentially the product of the target rate and the successful transmission probability ($1 - P_{\text{out},i}$). At low target rates, the success probability is near 1, allowing the throughput to grow linearly. However, as the target rate continues to increase, the required SINR threshold grows exponentially, causing the OP to rapidly approach 1. This practical implication indicates that simply adopting a higher modulation and coding scheme does not guarantee higher data delivery; instead, the system must employ an adaptive rate control mechanism to operate near this peak, thereby maximizing the effective data transmission efficiency. Additionally, increasing the number of transmit antennas from $K = 1$ to $K = 2$ noticeably improves the throughput due to the diversity gain provided by the TAS scheme. Furthermore, the proposed HPMA scheme consistently achieves higher throughput than the conventional NOMA scheme for both users across most rate regions.

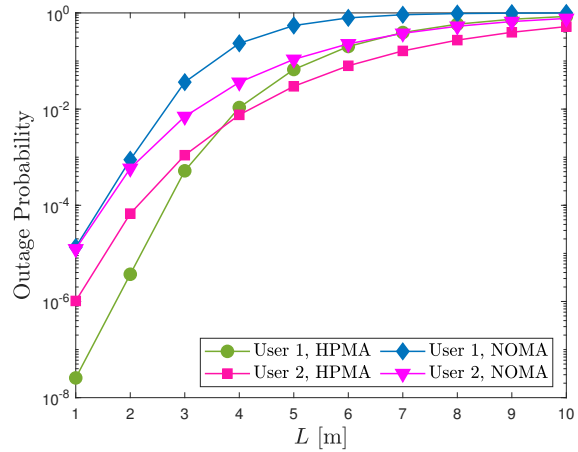


Fig. 5. OP of U_1 and U_2 with HPMA/NOMA transmissions for different locations, with $R_1 = 1$ bps/Hz, $R_2 = 0.5$ bps/Hz, $\rho = 15$ dB, $m_{1,1} = m_{2,1} = 2$, $m_{1,2} = m_{2,2} = 2.5$ and $K = 4$.

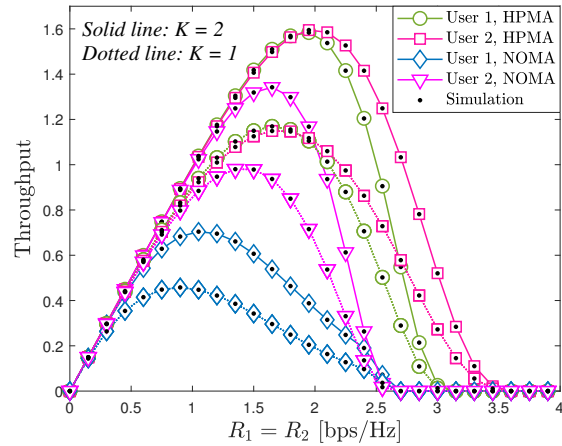


Fig. 6. Throughput versus the R_1 and R_2 for different numbers of antennas K , with $\delta_1 = 0.4$, $\delta_2 = 0.6$, $\rho = 12$ dB, $m_{1,1} = m_{2,1} = 2$ and $m_{1,2} = m_{2,2} = 2.5$.

5. Conclusion

This paper investigated a UAV-assisted HPMA system with TAS over double Nakagami- m fading channels. Closed-form expressions for the OP were derived, followed by asymptotic analysis to reveal the diversity behavior at high SNR. The throughput performance of the considered scheme was also examined to assess its transmission efficiency. Numerical results verified the accuracy of the theoretical analysis and showed that the proposed HPMA scheme achieves noticeable reliability gains compared with conventional NOMA. As a promising direction for future research, this framework could be extended to consider more practical scenarios, such as imperfect channel information, larger multi-user networks, or the integration of emerging technologies to further enhance system performance.

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