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Unmanned Aerial Vehicle Relay System: Performance Evaluation and 3D Location Optimization

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ABSTRACT The deployment of unmanned aerial vehicle (UAV) in wireless communication as a flying base station (BS) or relay is expected to be dominant in the following years to enhance wireless network performance in terms of coverage and capacity owing to their ability to change altitude, easy 3D movement, low cost, and easy deployment in wireless networks. In this paper, we study the performance of a wireless network in which a UAV is employed as a decode-and-forward (DF) relay linking a ground base station (BS) with multiple users in area where direct terrestrial path between the ground BS and the users is assumed to be blocked. The channel between the BS and the UAV is assumed to follow Rician channel model, while the links between the UAV and the end users are assumed to follow Rayleigh fading model with opportunistic scheduling scheme for user selection. Closed-form expressions for the outage probability and average symbol error rate (ASER) are derived. Due to complexity of the derived closed-form expressions and in order to get more insights at the system behavior in terms of system coding gain and diversity order, an asymptotic expression is derived for the outage probability at high signal-to-noise ratio (SNR) values. Furthermore, an optimization of the UAV 3D location that minimizes the asymptotic outage probability is achieved. Our numerical results show that increasing the UAV transmit power much more than the ground BS transmit power does not improve the system performance. The increase in the UAV transmit power is positive only if the ground BS transmit power is higher than the UAV transmit power. We also show that the increase of the Rician K-factor leads to improving the system performance when the ground BS transmit power is less than or close to the UAV transmit power. Furthermore, the proposed optimization scheme shows superior performance gain in minimizing the outage probability compared to the conventional scenarios, where the UAV is located at a fixed altitude over the center of the coverage region.

INDEX TERMS Unmanned aerial vehicle, Rician fading, outage probability, asymptotic outage probability, average symbol error rate, 3D location optimization.

I. INTRODUCTION

Employment of unmanned aerial vehicle (UAV) in wireless communication networks as flying base stations (BSs) or relays represents a promising solution to enhance network performance in terms of reliability and capacity. Mobility and agility represent the main characteristics of UAV that make it superior to ground BSs and relay. This allows for quick network establishment and flexible modification of the network configuration and relay location to improve the network performance. Also, they help in quick establishment of wireless supplementary network to take load off existing networks in crowded hotspots situations, provide communications in emergency where the terrestrial network collapses and communication is required for relief teams activities [1].

Another application for UAV networks is in providing wireless communications for temporarily events like sport and outdoor activities. Also, UAV can be applied to provide wireless communication relaying for missions in areas not served by terrestrial network to establish communication

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TABLE 1. List of acronyms.

Acronym	Description
2D	2 Dimensional
3D	3 Dimensional
A2G	Air-to-ground
ASER	Average symbol error rate
AWGN	Additive white Gaussian noise
BPSK	Binary phase shift keying
BS	Base station
CDF	Cumulative distribution function
D2D	Device-to-device
DF	Decode-and-forward
e2e	End-to-end
EH	Energy harvesting
GPS	Global positioning system
LOS	Line-of-sight
NLOS	Non-line-of-sight
PLOS	Probability of line-of-sight
SNR	Signal-to-noise ratio
UAV	Unmanned aerial vehicle

between main control center and terminal users [1]. UAV can also help in gathering data from ground terminals like sensors or in providing communication between members of teams working outdoor in far areas such as scientific and rescue teams. Another important application is in providing communication and internet in regions and countries where establishing terrestrial network is expensive. UAV network is less expensive than ground BSs in terms of infrastructure due to the dispensing cables and towers required there. For all these potential applications of UAVs in wireless communication, it is important to develop wide understanding of channel performance and system resources of available communication networks like bandwidth and energy.

Many works can be found in literature that concentrate on deriving models for the channel between UAV and ground nodes [2]–[6]. For instance, authors in [2] and [3] derived the probability of line-of-sight (LOS) in terms of elevation angle and urban environmental parameters like building heights and concentration, whereas authors in [4] and [5] paid more attention for developing a path loss model for the UAV network air-to-ground (A2G) channel. They showed that the UAV altitude plays a significant role in determining the A2G channel characteristics. In [6] an experimental work was achieved to build a statistical model for the A2G channel, where the authors did measurement in suburban environment at different operating frequencies in the C-Band and L-Band ranges. They used the collected data to model the free space path loss and the K-factor.

The performance of a wireless network with a flying BS was studied in [7], where authors considered the existence of interference from device-to-device (D2D) communication in their derivations. The channel between the UAV and ground nodes was modeled using the probability of LOS and probability of NLOS models. The average coverage probability and sum-rate were derived in terms of the UAV altitude and number of D2D devices. Also, the scenario of a moving UAV was considered and optimization of number of stop points required by the UAV to maximize the coverage probability was provided using the disc coverage problem. The optimal altitude was derived for the scenario of static single UAV in [8]. The same study was extended to the case of two UAVs in [9].

A study of the terrestrial cooperative network containing several destinations and relay nodes served by a single UAV as a flying BS was conducted in [10]. The authors assumed the A2G channel was following Rician fading model in the derivation of the outage probability of the system and the optimal altitude of the UAV. The findings showed that the optimal altitude of the UAVs with respect to the ground nodes is not affected by the availability of relays on the ground. In [11] authors proposed two UAVs working together on a circular region, where a UAV is assumed to be fixed over the center of the region, while the other UAV is hovering in a circular path close to the edges of the coverage region. The capacity limit of a moving UAV connecting two nodes on the ground was considered in [12].

The authors in [13]–[15] studied the performance of mixed relaying networks for the scenario where the relay is fixed and not necessarily a UAV, where a UAV location optimization scheme can be proposed. In addition, these papers derived expressions for one performance measure, which is the outage probability. In [13] a relay network was studied, where a single source node and multiple destination nodes model was proposed. Rayleigh fading channels were assumed for source-to-relay and relay-to-destinations links and the effects of interference at both the relay and destination nodes were studied, where the outage probability closed-form expression was derived. A mixed Rayleigh and Gamma dual hop relaying network was studied in [14], where in this paper the exact outage probability was derived assuming single source and single destination scenario. The relay network studied in [15] consisted of a single source node, multiple DF relays, and a single destination node with opportunistic relay scheduling. Exact and asymptotic expressions of the outage probability were derived for different mixed Rician/Rayleigh fading environments. The results showed that the same diversity order was achieved for different mixed fading environments and its value was equal to the number of relays.

In [16] a UAV relay was studied, where the authors derived the outage probability and proposed a variable rate protocol for a UAV relay that hovers in a circular trajectory with fixed altitude. Optimization of the data-rate was achieved to improve the system performance in terms of the outage probability and information rate. Authors in [17] studied the application of UAV as a relay with the functionality of energy harvesting (EH). The UAV was used to connect two nodes on the ground, where the channels were assumed to follow Rician and Shadowed Rician distributions. The outage probability was analytically derived and the effects of the UAV altitude on the outage probability was studied.

In [18] optimization of the energy efficiency of a UAV relay was achieved, where the UAV was assumed to fly in a circular path at fixed altitude. Another study was conducted in [19], where both the spectrum efficiency and the energy efficiency optimizations were studied. The tradeoff between these two important measures was studied in this paper for a UAV-based relay network. The work in [20] proposed an optimization scheme for the outage probability of a UAV-based relay network by controlling the trajectory and transmission power of the UAV. In [21] the system throughput was studied for a mobile UAV end-to-end (e2e) system, where authors proposed a framework to jointly optimize the source and relay transmission powers and the UAV trajectory to maximize the system throughput. The work focused on the e2e system performance, while multiple users effect was ignored.

In [22] a study of the optimal altitude to improve a UAV relaying system performance in terms of outage probability, bit error rate, and power loss was presented. In [23] the 3D location of a relay UAV and the source/relay power allocation were jointly optimized to maximize the system sum rate for multiple users. The UAV-to-ground channels were assumed to follow free space path loss model, and the loss exponent elevation angle dependency and environment effects on the system performance were not considered. In [24] authors studied multiple UAV relays with EH for internet-of-things (IoT) applications, where closed-form expressions for the outage probability and bit error rate were derived.

In [25] the power and UAV 2D trajectory were jointly optimized to maximize the e2e throughput for a UAV relay system with two communicating nodes. The same study was conducted in [26], where a UAV was used to link an onshore BS with multiple sensors placed offshore. A study of the UAV 3D location optimization was also addressed in [27], where the system model consisted of multiple users multiple-input-multiple-output (MIMO) with a UAV mounted DF relay. The source to destination links were operating in a half duplex (HD) mode, while time division mutiple access (TDMA) was considered for users scheduling. Assuming Rician and Rayleigh channel models, authors derived the outage probability for different mixed fading channels. A joint optimization of power allocation and UAV location was solved analytically for a simple case where single user, single antenna, and Rayleigh/Rayleigh fading is assumed. For the general case of multiple users, multiple antennas, and mixed Rayleigh/Rician channel they solved the optimization problem numerically.

As can be noticed, none of the previous papers addressed or studied UAV-based relay networks with user selection, where opportunistic scheduling is used. UAV-based relay network with multiple users can be seen in several applications such as in collecting data from ground sensors and in providing communication between members of teams working outdoor in far areas such as scientific and rescue teams.

To the best of our knowledge, UAV relay network with multiple users where opportunistic user scheduling is used over Rician fading channels has not been studied yet. Additionally, the outage behavior, asymptotic [high signal-to-noise ratio (SNR)] outage probability, and ASER of this system have not yet been investigated. Moreover, optimization of the 3D location of the UAV for the considered system has not been addressed in the available papers. The contributions of this paper are summarized in the following points:

- Deriving closed-form expressions for the e2e outage probability and ASER for the UAV relay network with multiple users, where opportunistic user scheduling is used over Rician fading channels;
- Achieving the asymptotic analysis to study the coding gain and diversity order of the system;
- Proposing an optimization scheme for the 3D UAV location to minimize the e2e outage probability of the considered system, where in this proposed scheme the size and the center of the coverage region are made adaptable and determined by the users location; and
- Studying the performance of the proposed scheme in different urban environments.

The rest of this paper is organized as follows. In Section II the system and channel models are presented. Derivation of the outage probability, ASER, asymptotic outage probability, loss exponent, and Rician factor are illustrated in Section III. The UAV location optimization is presented in IV. Simulation and numerical results are discussed in Section V. Finally, the paper conclusion is provided in Section VI.

TABLE 2. List of symbols.

Symbol	Discrioption
α,β	Modulation dependent constants
η	Free space path loss exponent
γ	Instantaneous SNR
γ_{d}	The e2e SNR
$\gamma_{\text{g,u}}$	Ground BS to UAV link SNR
γ_{out}	SNR threshold
$\gamma_{\text{u},n}$	UAV to the n^{th} user link SNR
$\gamma_{\text{u},*}$	UAV to the selected user link SNR
$d_{\text{g,u}}$, $d_{\text{u},n}$	BS to UAV distance, UAV to the n^{th} user distance
$\gamma_{\text{u},*}$	UAV to the selected user link SNR
$F_{\gamma_{\text{g,u}}}(\gamma)$	CDF of the ground BS to UAV link SNR
$F_{\gamma_{\text{g},*}}(\gamma)$	CDF of the UAV to the selected user link SNR
$F_{\gamma_{\text{d}}}(\gamma)$	CDF of the e2e SNR
$h_{\text{g,u}}$	UAV to the n^{th} user channel coefficient
K	Rician factor
h_{min}	Minimum UAV altitude
h_{max}	Maximum UAV altitude
$h_{\text{u},n}$	Ground BS to the UAV channel coefficient
$n_{\text{g,u}}$	Ground BS to UAV AWGN signal
$n_{\text{u},n}$	UAV to the n^{th} user AWGN signal
N	Number of users
N_0	AWGN noise power
p_{g}	Power transmitted by the ground BS
p_{u}	Power transmitted by the UAV
P_{out}	Outage probability
P_{out}^{∞}	Asymptotic outage probability
Q_1	First order Marcum Q-function
$\Re$	The spectral efficiency
ρ	Coverage area radius
v_{max}	UAV maximum speed
x_{g}	Sybmol transmitted at the ground BS
$x_{\text{u},n}$	Symbol transmitted at the UAV to the n^{th} user

II. SYSTEM AND CHANNEL MODELS

The scenario studied in this paper includes a UAV serving as a relay between a ground BS and N users U_n, where

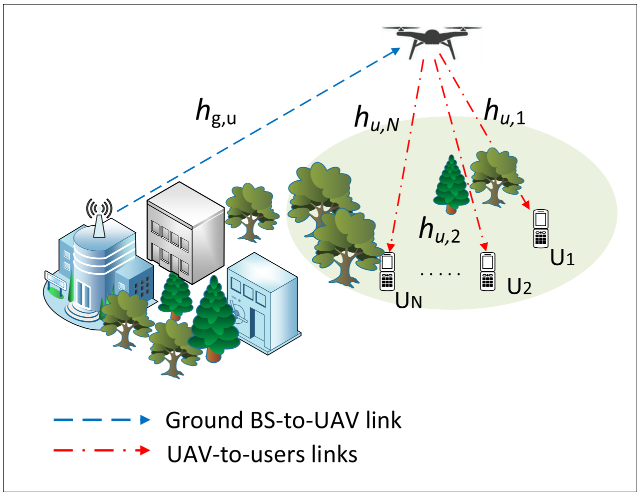

FIGURE 1. UAV relay system model.

$n \in \{1, 2, \ldots N\}$ distributed within a geographical area on the ground plane, as shown in Figure 1. It is assumed that the wireless links between the users and the ground BS are blocked by a man-made or natural obstacle like high building or small mountain. We assume that a LOS exists between the ground BS and the UAV, while in the link between the UAV and the ground users no LOS exists.

According to this assumption, the link between the ground BS and the UAV is modeled using Rician fading model and the links between the UAV and users are modeled using Rayleigh fading channel model. The UAV acts as a DF relaying node. Although the amplify-and-forward (AF) relaying scheme is simple to implement, DF offers better performance [22].

A. GROUND BS-TO-UAV CHANNEL

The received signal at the UAV is given by

$$y_{\mathrm{g,u}} = \sqrt{P_{\mathrm{g}}} h_{\mathrm{g,u}} x_{\mathrm{g}} + n_{\mathrm{g,u}}, \tag{1}$$

where P_{g} is the power transmitted by the ground BS, $h_{\mathrm{g,u}}$ is the channel coefficient of the link between the ground BS and the UAV and it is Rician distributed withe $\mathbb{E}[|h_{\mathrm{g,u}}|^2] = 1$, where $\mathbb{E}[\ .\ ]$ is the average operator, x_{g} is the data symbol transmitted by the ground BS with $\mathbb{E}[x_{\mathrm{g}}^2] = 1$, and $n_{\mathrm{g,u}} \sim \mathcal{N}(0, N_0)$ is the additive white Gaussian noise (AWGN) with zero mean and variance N_0.

The SNR for the Rician channels between the ground BS and the UAV is given by

$$\gamma_{\mathrm{g,u}} = \frac{P_{\mathrm{g}} |h_{\mathrm{g,u}}|^2}{N_0 d_{\mathrm{g,u}}^{\eta}}, \tag{2}$$

where η is the path loss coefficient and $d_{\mathrm{g,u}}$ is the distance between the UAV and the ground BS. The channel coefficient $h_{\mathrm{g,u}}$ is modeled using Rician fading model, and hence, the CDF of $\gamma_{\mathrm{g,u}}$ is chi-square distributed, which can be expressed as [28]

$$F_{\gamma_{\mathrm{g,u}}}(\gamma) = 1 - Q_1\left(\sqrt{2K}, \sqrt{\frac{2(K+1)\gamma}{\bar{\gamma}_{\mathrm{g,u}}}}\right), \tag{3}$$

where Q_1 represents the first order Marcum Q-function and K is the Rician factor, which is the ratio of the LOS power to the NLOS power, and $\bar{\gamma}_{\mathrm{g,u}} = \mathbb{E}[\gamma_{\mathrm{g,u}}] = \frac{P_{\mathrm{g}} d_{\mathrm{g,u}}^{-\eta}}{N_0}$. The Marcum Q-function can be approximated as [29, Eq. (7)]

$$Q_1(x, y) \approx \sum_{r=0}^{M} g_r r! e^{-\frac{y^2}{2}} \sum_{j=0}^{r} \frac{(\frac{y^2}{2})^j}{j!}, \tag{4}$$

where M depends on $\max\{1, x, y\}$, which can be truncated as $50 \max\{1, x, y\}$ [17], and g_r is given by

$$g_r = \frac{\Gamma(1+M) M^{1-2r} x^{2r} 2^{-r}}{\Gamma(r+1)\Gamma(M-r+1)\Gamma(1+r) e^{\frac{x^2}{2}}}, \tag{5}$$

where $\Gamma(\ .\ )$ is the Gamma function.

B. UAV-TO-USERS CHANNEL

The received signal at the n^{th} user is given by

$$y_{\mathrm{u},n} = \sqrt{P_{\mathrm{u}}} h_{\mathrm{u},n} x_{\mathrm{u},n} + n_{\mathrm{u},n}, \tag{6}$$

where P_{u} is the UAV transmit power, $n \in \{1, 2, \ldots, N\}$, $h_{\mathrm{u},n}$ is the UAV to the n^{th} user channel coefficient, which is modeled using Rayleigh distribution with $\mathbb{E}[|h_{\mathrm{u},n}|^2] = 1$, $x_{\mathrm{u},n}$ is the data symbol transmitted by the UAV to the n^{th} user with $\mathbb{E}[x_{\mathrm{u},n}^2] = 1$, and $n_{\mathrm{u},n} \sim \mathcal{N}(0, N_0)$ is the AWGN noise. The SNR of the second hop is given by

$$\gamma_{\mathrm{u},n} = \frac{P_{\mathrm{u}} |h_{\mathrm{u},n}|^2}{N_0 d_{\mathrm{u},n}^{\eta}}, \tag{7}$$

where $d_{\mathrm{u},n}$ represents the UAV to the n^{th} user distance.
We assume i.i.d. wireless paths between the UAV and the users, where the average SNRs for the links between the UAV and the n^{th} user $\bar{\gamma}_{\mathrm{u}} = \mathbb{E}[\gamma_{\mathrm{u},n}] = \frac{P_{\mathrm{u}} d_{\mathrm{u},n}^{-\eta}}{N_0}$, $n \in \{1, 2, \ldots, N\}$ and using opportunistic user scheduling, where the user with the largest instantaneous SNR $\gamma_{\mathrm{u},*}$ is selected among other users to transmit its message to the UAV. $\gamma_{\mathrm{u},*}$ is given by

$$\gamma_{\mathrm{u},*} = \max_{n \in \{1,\ldots,N\}} \{\gamma_{\mathrm{u},n}\}. \tag{8}$$

We assume that the UAV periodically transmits pilot signals so that each user can estimate its instantaneous received SNR from the UAV. During user selection stage, each user estimates its instantaneous SNR and feeds the value back to the UAV. After that, the UAV selects the user with the best instantaneous SNR [30]. An opportunistic user scheduling scheme is found to improve the overall system capacity despite the fact that it ignores the fairness among users. However, fairness among users can be compensated using some hybrid capacity-fairness trade-off techniques [31].

The CDF of the SNR for the link between the UAV to the selected user is given by

$$F_{\gamma_{\mathrm{u},*}}(\gamma) = (1 - e^{-\frac{\gamma}{\bar{\gamma}_{\mathrm{u}}}})^N. \tag{9}$$

Using binomial theorem, (9) can be rewritten as

$$F_{\gamma_{u,*}}(\gamma) = \sum_{i=0}^{N} \binom{N}{i} (-1)^i e^{-\frac{\gamma i}{\bar{\gamma}_u}}. \quad (10)$$

The e2e SNR can be written using the SNR bound as [32]

$$\gamma_d = \frac{\gamma_{g,u}\gamma_{u,*}}{1+\gamma_{g,u}+\gamma_{u,*}}. \quad (11)$$

III. PERFORMANCE ANALYSIS

In this section, we derive the exact outage probability and ASER of the considered system.

A. OUTAGE PROBABILITY

The outage probability of any wireless communication system is given by

$$P_{out} = P(\gamma_d \le \gamma_{out}), \quad (12)$$

where γ_d is the e2e SNR, $P(\,.\,)$ is the probability operation, and γ_{out} is the outage SNR threshold, which is given by $\gamma_{out} = 2^{\mathfrak{R}} - 1$, where $\mathfrak{R}$ is the spectral efficiency. The CDF of the e2e SNR can be written as [32]

$$F_{\gamma_d}(\gamma) = F_{\gamma_{g,u}}(\gamma) + F_{\gamma_{u,*}}(\gamma) - F_{\gamma_{g,u}}(\gamma)F_{\gamma_{u,*}}(\gamma). \quad (13)$$

Upon substituting (3) and (10) in (13) and using (4) then replacing γ by γ_{out}, we get

$$P_{out} = 1 - \sum_{r=0}^{M}\sum_{j=0}^{r} g_r r! e^{-\frac{(K+1)\gamma_{out}}{\bar{\gamma}_{g,u}}} \left[\frac{(K+1)\gamma_{out}}{\bar{\gamma}_{g,u}}\right]^j \times \left(1 - \sum_{i=0}^{N}\binom{N}{i}(-1)^i e^{-\frac{\gamma_{out}}{\bar{\gamma}_u} i}\right). \quad (14)$$

B. AVERAGE SYMPOL ERROR RATE

The ASER can be obtained by substituting the CDF obtained in (14) into [33, Eq. (15)] as follows

$$\text{ASER} = \frac{\alpha\sqrt{\beta}}{2\sqrt{\pi}} \int_0^{\infty} \frac{e^{-\beta\gamma}}{\sqrt{\gamma}} F_{\gamma_d}(\gamma) d\gamma, \quad (15)$$

where α and β are modulation specific parameters. Using [34, Eq. (3.361.2)] and [34, Eq. (3.371.1)] and after doing some mathematical manipulations, we get

$$\begin{aligned}\text{ASER} = \frac{\alpha\sqrt{\beta}}{2}\Bigg[&\sqrt{\frac{1}{\beta}} - e^{-K}\sqrt{\frac{1}{KL_1+L_1+\beta}} - \sum_{r=1}^{M} g_r r! \\ &\times \sqrt{\frac{1}{KL_1+L_1+\beta}} + \sum_{r=1}^{M}\sum_{j=0}^{r} g_r r! \frac{(L_1(K+1))^j}{j!} \\ &\times \frac{(2j-1)!!}{2^j(KL_1+L_1+\beta)^{j+0.5}} + \sum_{i=0}^{N}(-1)^i\binom{N}{i}\Bigg\{e^{-K} \\ &+ \sum_{r=1}^{M} g_r r!\Bigg\}\sqrt{\frac{1}{KL_1+L_1+L_2 i+\beta}} \\ &+ \sum_{i=0}^{N}\sum_{r=1}^{M}\sum_{j=0}^{r} g_r r! (-1)^i \binom{N}{i}\frac{(L_1(K+1))^j}{j!} \\ &\times \frac{(2j-1)!!}{2^j(KL_1+L_1+L_2 i+\beta)^{j+0.5}}\Bigg],\end{aligned} \quad (16)$$

where $L_1 = \frac{1}{\bar{\gamma}_{g,u}}$ and $L_2 = \frac{1}{\bar{\gamma}_u}$.

C. ASYMPTOTIC OUTAGE PROBABILITY

As it can be seen in (14) and (16), the derived expressions are complex and hard to be analyzed to study the system performance for different system parameters. Therefore, we study in this section the system performance at high values of average SNR, $\bar{\gamma} \rightarrow \infty$, where we derive simple asymptotic expression for the outage probability. This will also allow us to know the coding gain and diversity order of the system, where the outage probability at high $\bar{\gamma}$ values can be expressed as $P_{out}^{\infty} \simeq (G_C\bar{\gamma})^{-G_D}$, where G_C denotes the coding gain of the system and G_D is the diversity order of the system [35]. At the high SNR mode, the e2e CDF of the system SNR can be written as [36]

$$F_{\gamma_d}^{\infty}(\gamma) = F_{\gamma_{g,u}}^{\infty}(\gamma) + F_{\gamma_{u,*}}^{\infty}(\gamma), \quad (17)$$

where the product term in (13) can be ignored at high average SNR values. The CDF of the first hop can be written at high values of average SNR as [37, Eq. (17)]

$$F_{\gamma_{g,u}}^{\infty}(\gamma) = e^{-K}(K+1)\left(\frac{\gamma}{\bar{\gamma}_{g,u}}\right). \quad (18)$$

The second hop CDF can be written using Taylor series expansion of the exponential function with ignoring the higher order terms as

$$F_{\gamma_{u,*}}^{\infty}(\gamma) = \left(\frac{\gamma}{\bar{\gamma}_u}\right)^N. \quad (19)$$

Upon substituting (18) and (19) in (17), the e2e asymptotic expression of the outage probability can be written as

$$P_{out}^{\infty} = e^{-K}(K+1)\left(\frac{\gamma_{out}}{\bar{\gamma}_{g,u}}\right) + \left(\frac{\gamma_{out}}{\bar{\gamma}_u}\right)^N. \quad (20)$$

In the following sections, we study both the case where the first hop is dominating the system performance and the case where the performance is dominated by the second hop.

D. GROUND BS TO UAV HOP IS DOMINANT

In this case, the asymptotic expression of the outage probability is given by

$$P_{out}^{\infty} = e^{-K}(K+1)\left(\frac{\gamma_{out}}{\bar{\gamma}_{g,u}}\right), \quad (21)$$

which can be written in the form

$$P_{out}^{\infty} = e^{-K}(K+1)\gamma_{out}(\bar{\gamma}_{g,u})^{-1}. \quad (22)$$

It is clear from (22) that the coding gain of the system in this case equals $[e^{-K}(K+1)\gamma_{out}]^{-1}$ and the diversity order equals 1.

E. UAV TO USERS HOP IS DOMINANT

In this case, the asymptotic expression of the outage probability is given by

$$P_{\text{out}}^{\infty} = \left(\frac{\gamma_{\text{out}}}{\bar{\gamma}_{\text{u}}}\right)^{N}, \tag{23}$$

which can be further simplified as

$$P_{\text{out}}^{\infty} = ({\gamma_{\text{out}}}^{-1}\bar{\gamma}_{\text{u}})^{-N}. \tag{24}$$

It is clear from (25) that the coding gain of the system in this case is ${\gamma_{\text{out}}}^{-1}$ and the diversity order is N.

F. LOSS EXPONENT AND RICIAN FACTOR AS A FUNCTION OF UAV ELEVATION ANGLE

According to [8], the path loss exponent and the probability of LOS are related by

$$\eta(\theta) = a_1 \text{PLOS}(\theta) + b_1, \tag{25}$$

where

$$\text{PLOS}(\eta) = \frac{1}{1 + ce^{-d\theta}}, \tag{26}$$

where a_1, b_1, c, and d are constants determined by the environment characteristics and the transmission frequency, and θ is the UAV elevation angle in radian.

For the Rician K-factor, in consistency with [38], we use the exponential relationship between K and θ as follows

$$K(\theta) = a_2 e^{b_2\theta}, \tag{27}$$

where a_2 and b_2 are environment and frequency dependent constants.

IV. UAV LOCATION OPTIMIZATION

In this section, the UAV 3D location is optimized to improve the relaying system performance by minimizing the asymptotic outage probability in (20). For this purpose, we propose and investigate a new UAV location optimizing scheme. The proposed scheme assumes a circular coverage area whose radius and center are adaptable according to the locations of users within a fixed geographical area. After the coverage area center and radius are determined, the optimal UAV locations are calculated. Referring to Figure 2, without loss of generality, a 3D Cartesian coordinate system is considered where the Ground BS is located at $(0, 0, h_g)$ the users are located within the coverage region at locations $(x_n, y_n, 0)$, where $n = 1, 2 \ldots N$. The center and radius of the coverage region are (ρ_x, ρ_y) and ρ, respectively, where ρ is given by

$$\rho = \sqrt{\{\max(\boldsymbol{x}) - \rho_x\}^2 + \{\max(\boldsymbol{y}) - \rho_y\}^2}, \tag{28}$$

where $\rho_{\boldsymbol{x}} = \frac{\max(\boldsymbol{x})+\min(\boldsymbol{x})}{2}$, $\rho_{\boldsymbol{y}} = \frac{\max(\boldsymbol{y})+\min(\boldsymbol{y})}{2}$, $\boldsymbol{x} = \{x_k : k = 0, 1, 2, \ldots, N\}$, and $\boldsymbol{y} = \{y_p : p = 0, 1, 2, \ldots, N\}$.

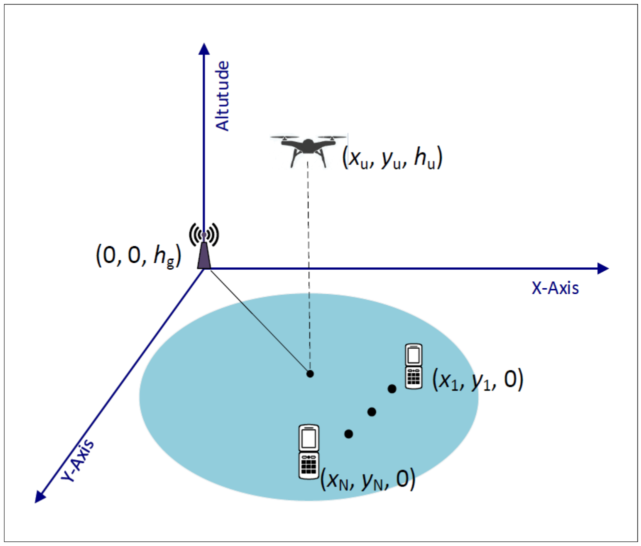

FIGURE 2. UAV network optimization problem description.

The UAV can dynamically move in a 3D space and its location is (x_u, y_u, h_u), where its footprint on ground is not allowed to be outside the coverage circle and altitude $h_{\min} < h_u < h_{\max}$, where $h_{\min}$ and $h_{\max}$ are the minimum and maximum allowed UAV altitude, respectively. Both UAV and users locations are assumed to be known via GPS [39]. The asymptotic outage probability can be rewritten in terms of power and distance as

$$P_{\text{out}}^{\infty} = e^{-K(\theta_g)}(K(\theta_g)) + 1)\left(\frac{N_0 d_{g,u}^{\eta(\theta_g)}\gamma_{\text{out}}}{P_g}\right) + \prod_{i=1}^{N}\left(\frac{N_0 d_{u,i}^{\eta(\theta_i)}\gamma_{\text{out}}}{P_{u,i}}\right), \tag{29}$$

where $\theta_{g,u}$ is the UAV look angle at the ground BS which is given by

$$\theta_g = \sin^{-1}\left(\frac{h_u - h_g}{d_{g,u}}\right), \tag{30}$$

where $d_{g,u}$ is the distance from the ground BS to the UAV which is given

$$d_{g,u} = \sqrt{x_u^2 + y_u^2 + (h_u - h_g)^2}, \tag{31}$$

$\theta_{u,i}$ is the UAV look angle at the i^{th} user location, which is given by

$$\theta_{u,i} = \sin^{-1}\left(\frac{h_u}{d_{u,i}}\right), \tag{32}$$

where $d_{u,i}$ is the distance from the UAV to the i^{th} user at location $(x_i, y_i, 0)$ which is given by

$$d_{u,i} = \sqrt{(x_u - x_i)^2 + (y_u - y_i)^2 + h_u^2}. \tag{33}$$

Upon substituting Equations (30) to (33) in (29), we get the asymptotic outage probability of the UAV relay system in terms of UAV location 3D coordinates as follows

$$\begin{aligned}P_{\text{out}}^{\infty}&(x_{\text{u}}, y_{\text{u}}, h_{\text{u}})\\ &= e^{-K(\theta_{\text{g}})}(K(\theta_{\text{g}}))+1)\\ &\times\left[\frac{N_0\gamma_{\text{out}}(\sqrt{x_{\text{u}}^2+y_{\text{u}}^2+(h_{\text{u}}-h_{\text{g}})^2})^{\eta(\theta_{\text{g}})}}{P_{\text{g}}}\right]\\ &+\prod_{i=1}^{N}\left[\frac{N_0\gamma_{\text{out}}(\sqrt{(x_{\text{u}}-x_i)^2+(y_{\text{u}}-y_i)^2+h_{\text{u}}^2})^{\eta(\theta_i)}}{P_{\text{u},i}}\right].\end{aligned} \tag{34}$$

A. FORMULATION OF THE OPTIMIZATION PROBLEM

The objective of the optimization problem is to minimize the asymptotic outage probability under the constrains imposed by the network structure with considering the users location within the coverage area, and the altitude and mobility limitations of the UAV. We assume the UAV to operate during a finite duration of time T. This period of time is divided into Z equal time slots each with a duration $t_{\text{z}} = \frac{T}{Z}$. The UAV maximum flying distance will be $V = v_{\max} t_{\text{z}}$. We assume that the UAV moves to the optimal location then links the selected user to the ground BS during time duration t_{z}. From the previous discussion, the optimization problem can be formulated as

$$\begin{aligned}&\underset{x_{\text{u}},y_{\text{u}},h_{\text{u}}}{\text{minimize}}\ P_{\text{out}}^{\infty}(x_{\text{u}}, y_{\text{u}}, h_{\text{u}})\\ &\text{subjected to } x_{\text{u}}^2+y_{\text{u}}^2+(h_{\text{u}}-h_{\text{g}})^2 \le \rho^2,\\ &\qquad [x_{\text{u}}(z)-x_{\text{u}}(z+1)]^2+[y_{\text{u}}(z)-y_{\text{u}}(z+1)]^2\\ &\qquad +\ [h_{\text{u}}(z)-h_{\text{u}}(z+1)]^2 \le V^2,\\ &\qquad h_{\min} \le h \le h_{\max}.\end{aligned} \tag{35}$$

In the optimization problem, we study two cases, the first case assuming a single user located at $(x_1, y_1, 0)$ within a circular area with radius ρ and the UAV is located at a fixed altitude, and the second case is the general case in which multiple users and variable UAV altitudes are assumed, where the environment and multiple users scheduling scheme effects are studied.

B. CASE 1: SINGLE USER AND FIXED ALTITUDE UAV

Under the assumption that the UAV is located at fixed altitude and serving a single user located at $(x_1, y_1, 0)$, assuming a loss exponent $\eta = 2$, the asymptotic outage probability in this case can be rewritten as

$$P_{\text{out}}^{\infty}(x_{\text{u}}, y_{\text{u}})=e^{-K}(K+1)\left[\frac{N_0\gamma_{\text{out}}d_{\text{g,u}}^2}{P_{\text{g}}}\right]+\frac{N_0\gamma_{\text{out}}d_{\text{u}}^2}{P_{\text{u}}}, \tag{36}$$

where $d_{\text{u}} = \sqrt{(x_{\text{u}}-x_1)^2+(y_{\text{u}}-y_1)^2+h_{\text{u}}^2}$ is the distance separating the UAV and the user.

Accordingly, the optimization problem in (35) can be rewritten as

$$\begin{aligned}&\underset{x_{\text{u}},y_{\text{u}}}{\text{minimize}}\ P_{\text{out}}^{\infty}(x_{\text{u}}, y_{\text{u}})\\ &\text{subjected to } x_{\text{u}}^2+y_{\text{u}}^2+(h_{\text{u}}-h_{\text{g}})^2 \le \rho^2.\end{aligned} \tag{37}$$

It is easy to prove that the optimization problem in (37) is a convex problem, which can be solved using Lagrange multiplier method. A closed-from expression for the optimal 2D UAV footprint $(x_{\text{opt}}, y_{\text{opt}})$ is given by

$$x_{\text{opt}} = \frac{Bx_1 + C\rho}{A+B-C}, \tag{38}$$

$$y_{\text{opt}} = \frac{By_1 + C\rho}{A+B-C}, \tag{39}$$

where $A = e^{-K}\gamma_{\text{out}}\frac{N_0}{P_{\text{G}}}$, $B = \frac{N_0}{P_{\text{U}}}$, and $C = A+B-\sqrt{D}$, where $D = 2\rho^2(A+B)^2 + B(x_1^2+y_1^2) - 2\rho B(x_1+y_1)(1-A)$. The results in (38) and (39) give the optimal location of a fixed altitude UAV. This optimal location is dependent on the user location coordinates, powers of both the UAV and ground BS, and other network parameters like the Rician K-factor.

C. CASE 2: MULTIUSER AND VARIABLE ALTITUDE UAV

In this case, the UAV is assumed to adjust its location in the 3D coordinate system, and the aim is to find the UAV optimal position to minimize the outage probability. Here, the users are assumed to be included within a virtual circular region whose center and radius are determined by the users locations according to (28). Also, the users and UAV coordinates are assumed to be known by the ground BS. In this case, the optimization problem in (35) is solved numerically using particle swarm algorithm provided in MATLAB optimization toolbox due to its complexity.

V. SIMULATION AND NUMERICAL RESULTS

In this section, some simulation results are presented to validate the derived expressions and the proposed optimization scheme. The analytical results of the outage probability, asymptotic outage probability, and the ASER are presented. Moreover, the effects of different network parameters such as the number of users, Rician K-factor, UAV transmit power, and the ground BS transmit power on the system performance are investigated. All simulation results are generated using 2×10^6 samples/SNR value. Additionally, a binary phase shift keying (BPSK) modulation scheme has been assumed in simulating the ASER.

For the optimization simulations, we assume the mobile users are randomly distributed within a 2D square area of size 1000×1000 m^2 on the ground, and the ground BS is located at one edge of this area at location $(0, 0)$. According to the proposed scheme, a circular area is assumed to include all users with a radius and center that are depending on users locations. The simulation and urban parameters are summarized in Tables 3 and 4, respectively.

A. SYSTEM PERFORMANCE

Figure 3 shows the exact, asymptotic, and simulation outage probabilities for different values of users N in the case where the second hop is dominating the system performance. It can be noticed from this figure that the exact and asymptotic outage probabilities are perfectly matching at high SNR values, as expected. Also, we can see that increasing N enhances

TABLE 3. Table of simulation parameters.

Simulation Parameters	
Parameter	Numerical value
Frequency	2000 KHz
N_0	1×10^{-15}
α, β	1
h_g	20 m
h_{max}	100 m
h_{min}	50 m
v_{max}	60 m/s

TABLE 4. Table of urban parameters.

Urban Parameters			
Urban		Dense Urban	
a_1, a_2	10.39, 3.1623	a_1, a_2	8.96, 3.1623
b_1, b_2	0.05, 3.6172	b_1, b_2	0.04, 3.6172
c, d	0.6, 0.06	c, d	0.36, 0.21

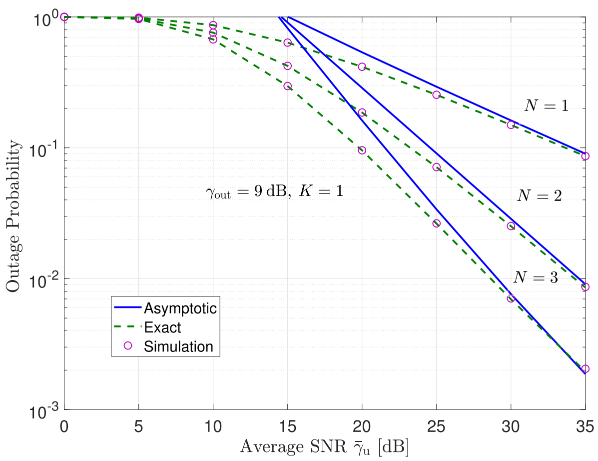

FIGURE 3. Exact, asymptotic, and simulated outage probability versus average SNR for different number of users when the second hop is dominant ($\bar{\gamma}_{g,u} = 2 \times \bar{\gamma}_u$).

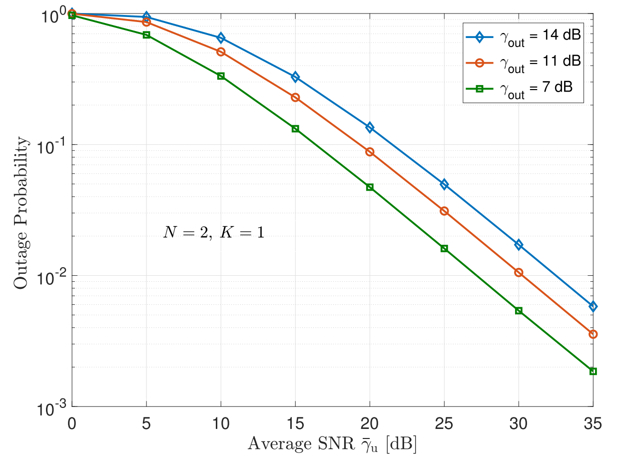

FIGURE 4. Outage probability versus average SNR for different SNR outage thresholds when the second hop is dominant ($\bar{\gamma}_{g,u} = 2 \times \bar{\gamma}_u$).

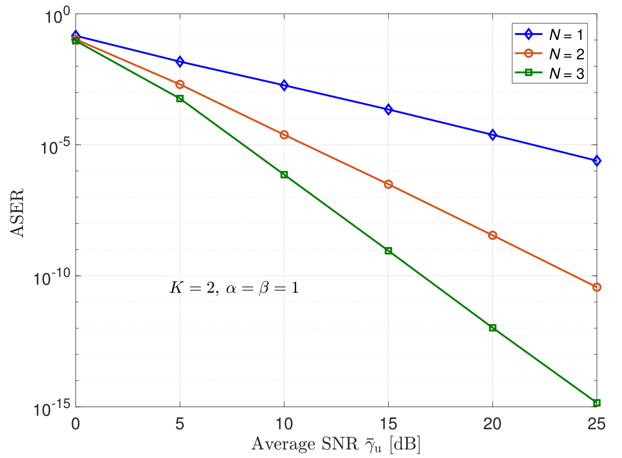

FIGURE 5. ASER versus average SNR for different number of users when the second hop is dominant ($\bar{\gamma}_{g,u} = 2 \times \bar{\gamma}_u$).

the network performance in terms of the coding gain and the diversity order. Approximately 15 dB is achieved when N increases from 1 to 3 at $P_{out} = 10^{-1}$. The SNR threshold effect on the system performance is studied in Figure 4, where it is shown that increasing the SNR threshold results in increasing the system outage probability, as expected. Figure 5 shows the system ASER for different number of users N in the case where the second hop is dominating the system performance. It can be seen from this figure that the system ASER is decreased by increasing the number of users. When N increase from 1 to 3 at ASER $= 10^{-5}$ a diversity gain of approximately 14 dB is acheived.

Figure 6 shows the system outage probability as a function of the UAV relay transmit power P_u for different number of users N and with two different values of ground BS transmit power P_g. Two sets of curves can be seen on this figure, curves of $P_g = 4$ dBm and curves of $P_g = 8$ dBm. Clearly, when P_g has higher values, better performance is achieved, as expected. For both curves an error floor appears at higher values of P_u as at this range of P_u values, the system performance is dominated by the first hop (fixed P_g) and any increase in either P_u or number of users N adds no gain to the system performance. Increasing P_u leads to improving the system performance when P_g is higher than P_u. In this case also, increasing N adds gain to the system performance.

Figure 7 shows the system outage probability as a function of the ground BS transmit power P_g for different number of users N and with two different values of UAV transmit power P_u. Again, two sets of curves can be seen on this figure, curves of $P_u = 1$ dBm and curves of $P_u = 4$ dBm. Clearly, when P_u has higher values, better performance is achieved, as expected. For both curves an error floor appears at higher values of P_g as at this range of P_g values, the system performance is dominated by the second hop (fixed P_u) and any increase in P_g adds no gain to the system performance, while increasing N adds gain to the system performance as a result of dominance of the second hop.

The effect of the Rician K-factor is shown in Figure 8. Again, two sets of curves can be seen on this figure, $P_u = 4$ dBm and curves of $P_u = 8$ dBm. Clearly, increasing

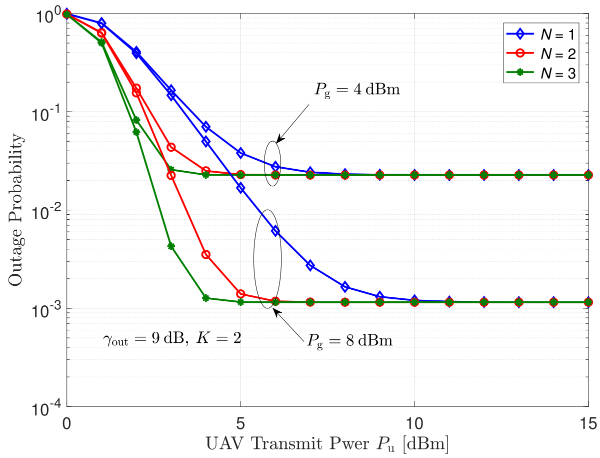

FIGURE 6. **Outage probability versus UAV transmit power for different number of users and ground BS transmit powers.**

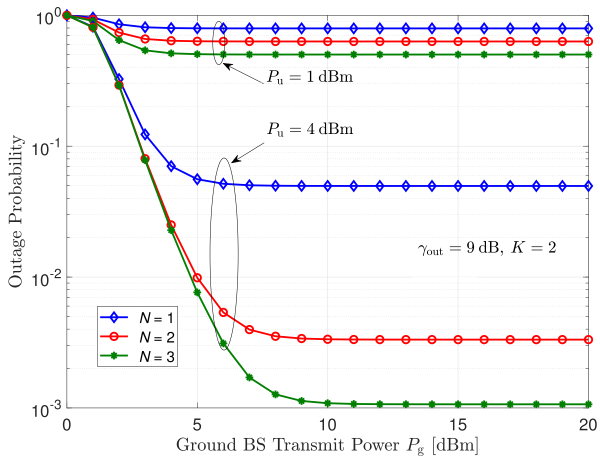

FIGURE 7. **Outage probability versus ground BS transmit power for different number of users and UAV transmit powers.**

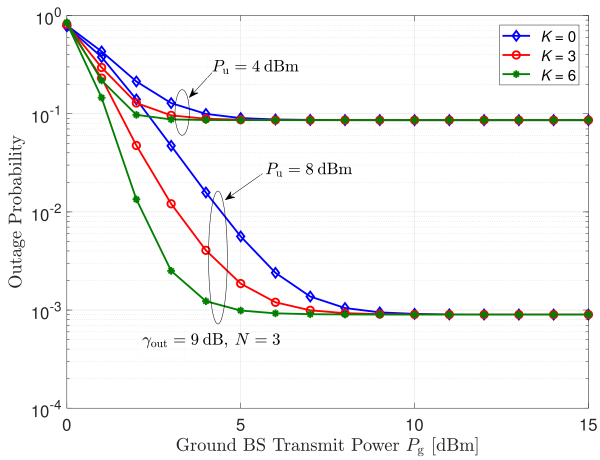

FIGURE 8. **Outage probability versus ground BS transmit power for different *K*-factors and UAV transmit powers.**

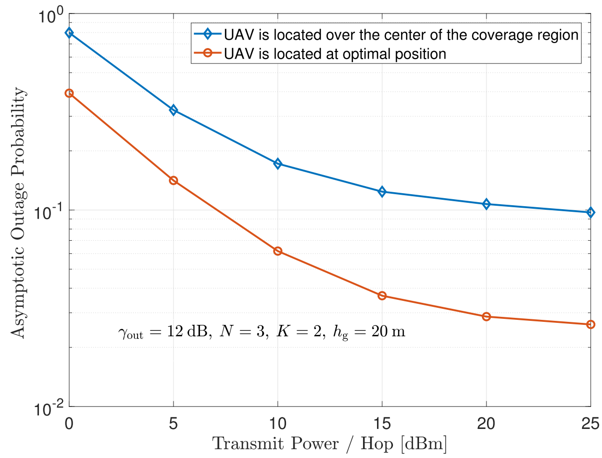

FIGURE 9. **Asymptotic outage probability versus ground BS and UAV transmit powers for single user and constant UAV altitude.**

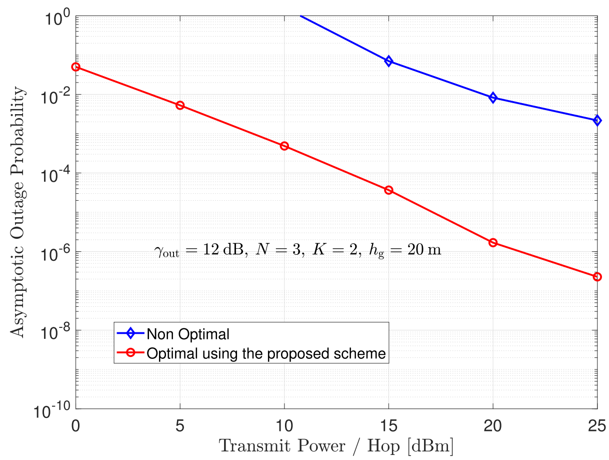

FIGURE 10. **Asymptotic outage probability versus ground BS and UAV transmit powers for the proposed optimization scheme and conventional case.**

P_g and Rician K-factor enhances the system performance until an error floor appears in both cases as P_u becomes dominating the system performance. The higher the value of P_u, the better the achieved performance. For both curves an error floor appears at higher values of P_g as at this range of P_g values, the system performance is dominated by the second hop (fixed P_u) and any increase in either P_g or Rician K-factor adds no gain to the system performance.

B. OPTIMIZATION EVALUATION

For a single user and constant altitude UAV, the minimized asymptotic outage probability is shown in Figure 9, where we compare it with the conventional case, where the UAV is located at a fixed altitude over the center of the coverage region. The asymptotic outage probability is plotted versus the UAV transmit power P_u and the ground BS transmit powers P_g. It can be noted from this figure that the asymptotic outage probability of the proposed scheme is much less than the asymptotic outage probability of the conventional case.

The effectiveness of proposed optimization scheme is shown in Figure 10 for urban region. The asymptotic outage probability is displayed versus the ground BS and UAV transmit powers for two scenarios. The first scenario is for the conventional case, where the UAV is located over the center

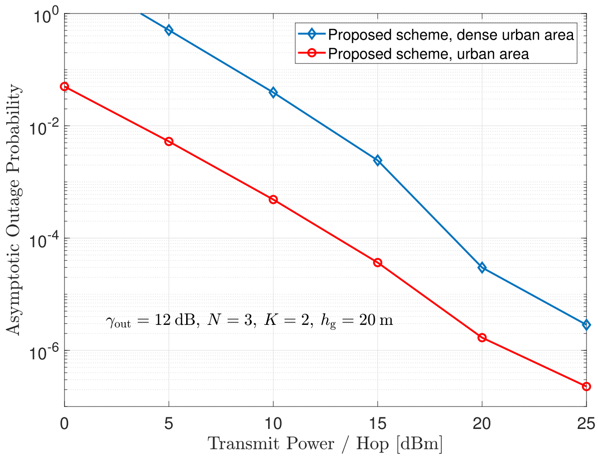

FIGURE 11. Asymptotic outage probability versus ground BS transmit and UAV powers, performance of the proposed scheme in urban and dense urban areas.

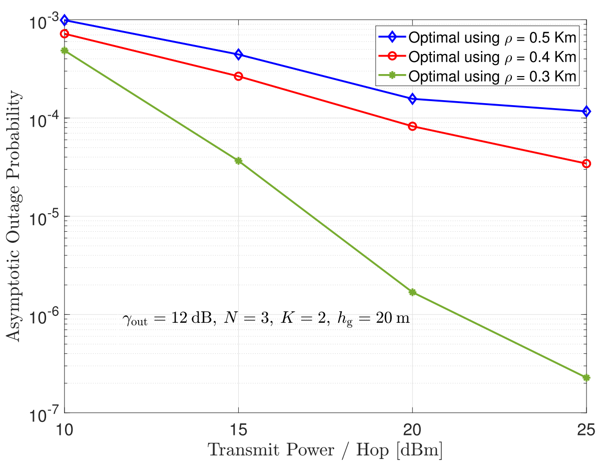

FIGURE 12. Asymptotic outage probability versus ground BS and UAV transmit powers of the proposed optimization scheme with different coverage radius values.

of the coverage area. The second one is for the proposed scheme, where the UAV location is optimized to minimize the asymptotic outage probability. It can be noted from this figure that the asymptotic outage probability of the proposed scheme is much less than the asymptotic outage probability of the conventional case, further verifying the effectiveness of the proposed scheme. Also, by comparing the result shown in this figure with those obtained in Figure 9, we can notice that the performance of multiple users variable altitude UAV relay system outperforms the performance of the single user constant altitude UAV relay system. In Figure 11, we compare the performance of our scheme in urban and dense urban areas. It can be seen from this figure that at urban areas, the system performance is better than the case of employing the UAV relaying system in dense urban areas, as expected.

Finally, the effect of the radius of the coverage region is displayed in Figure 12, It can be seen from this figure that decreasing the coverage area radius adds more gain to the system performances. This is clearly shown when ρ is decreased from 0.5 Km to 0.3 Km.

VI. CONCLUSION

In this paper, we studied the performance of a dual-hop wireless communication system, which employs a UAV as a decode-and-forward relay. The UAV was used to link multiple users to a ground base station where terrestrial communication is blocked due to man-made or natural reasons. The outage and average symbol error probabilities closed-form expressions were derived. Asymptotic outage probability was also derived to get more insights at the system performance. Optimization of the UAV 3D location was achieved to minimize the asymptotic outage probability. Our numerical results showed that increasing the UAV transmit power much more than the ground BS transmit power does not improve the system performance. The increase in the UAV transmit power is positive only if the ground BS transmit power is higher than or close to the UAV transmit power. We also showed that the increase of the Rician K-factor leads to improving the system outage performance when the UAV transmit power is higher than or close to the ground BS transmit power. Also, our proposed location optimization scheme showed superior performance gain in minimizing the outage probability compared to the conventional scenarios, where the UAV is located at a fixed altitude over the center of the coverage region.

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