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On UAV Selection and Position-Based Throughput Maximization in Multi-UAV Relaying Networks

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ABSTRACT Due to flexibility in deployment and high mobility, unmanned aerial vehicles (UAVs) can improve the performance of cellular networks. In this paper, we focus on the UAV-assisted cooperative communication network where multiple UAVs serve as relays between a pair of ground users. Based on signal-to-noise ratio (SNR), we propose two UAV selection strategies namely best harmonic mean (HM) and best downlink SNR (BDS). Then, we derive the closed-form expressions for the outage probability, throughput and coverage probability of both the selection strategies. Furthermore, an optimization problem for maximizing the throughput is formulated, subject to the 3-D coordinates (i.e., x, y, and z coordinates) constraint of the selected UAV. The concavity of the problem is analyzed with respect to the horizontal placement of the selected UAV. Next, we propose algorithms to find optimal and sub-optimal position/coordinates of the selected UAV. Computer simulations validate the accuracy of the derived expressions, and demonstrate that BDS selection strategy has a significant performance gain at low SNR values, whereas both the selection schemes attain a similar performance at high SNRs.

INDEX TERMS Unmanned aerial vehicles (UAVs), UAV selection, harmonic mean, signal-to-noise ratio (SNR), throughput maximization.

I. INTRODUCTION

Due to their fully controllable mobility, flexibility in grouping, low cost, strong line-of-sight (LOS) channels with ground users (GUs) and quick deployment, unmanned aerial vehicle (UAV) has emerged as one of the most popular technologies in recent years [1]–[10] and thus, it has many potential applications such as surveillance in disaster management and other emergency services, cargo delivery, aerial camera, etc. Besides, the low cost and easy implementation make UAVs suitable for wireless communications [3]. However, there are several open issues and challenges that need to be addressed in order to realize the full potential of UAV-aided wireless communications.

Among several applications of UAVs, one of the most popular applications is UAVs based relay networks [9], [11]–[18]. In [9], a mobile relaying technique has been developed by jointly optimizing the source/relay transmit power as well as the relay trajectory for mobile relaying systems, while in [11], the optimal deployment of an UAV has been found in a wireless relay communication system by maximizing the average data rate under a certain threshold on the symbol error rate. Use of UAV based relaying with better secrecy rate has been investigated in [12], whereas the authors in [13] have demonstrated the impact of UAV position between two ground nodes on the communication services. Further, the performance of UAV based relaying has been presented in [14]. In [15], the problem of positioning of UAV as relay and the optimal power allocation in multi-user scenario have been addressed. In [16], the authors have derived an upper

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bound on capacity for a UAV swarm based multiple-input-multiple-output (MIMO) relaying. The optimal position (3D coordinates) of UAV while operating as relay and the effect of physical parameters (such as obstacles height and position) on its position have been discussed in [17]. Furthermore, the authors in [18] have studied the performance of a UAV based automatic relay system. However, the works [9]–[18] have only considered a single UAV as relay between GUs.

When environmental structures are not communication friendly and information transfer between two nodes requires a more reliable link, the use of multiple UAVs as relays becomes essential [19]. The utilization of multiple conventional relays in wireless networks has been widely studied in literature [20]–[23]. However, utilizing multiple UAVs as relays in future generation wireless networks is still required to be explored, and some of the current works [24]–[27] have discussed multiple UAV based relaying. In [24], [25], the performance of multi hop single link and multiple dual hop links between a pair of transmitter and receiver using same number of UAVs have been studied and compared for both amplify-and-forward (AF) and decode-and-forward (DF) relaying protocols. In case of DF relaying, performance analysis has been performed for best-of-worse (BoW) UAV selection strategy considering independent and identically distributed (i.i.d) small scale fading channels. While in [27], placement optimization and resource allocation have been studied (neglecting small scale fading and selection strategy) for a system where multiple UAVs act as relay to serve several GUs pair. To the best of author's knowledge, to date no work has analyzed the performance of multiple UAV based relaying network for independent and non identically distributed (i.n.i.d) small scale fading channels (which is a more practical scenario in terrain conditions).

Influenced by the aforementioned discussion, in this paper we consider UAVs-assisted cooperative communication network wherein multiple UAVs serve as relays between a pair of GUs and focus on investigating the performance of two UAV selection strategies namely best harmonic mean (HM) and best downlink SNR (BDS) along with maximizing the throughput of the network. The key contributions of this paper are summarized as follows:

- We propose the HM and BDS based UAV selection strategies for multiple UAVs-assisted relaying network. Next, we derive the closed-form expressions of the outage probability, throughput and coverage probability for both the selection schemes to analyze the performance of the multiple UAV based relaying network considering i.n.i.d small scale fading channels. We also discuss the computational complexity of HM, BoW, and BDS based selection strategies.
- Further, we formulate an optimization problem in order to maximize the system throughput, subject to the constraint of the 3-D coordinates (i.e., x, y, and z coordinates) of the selected UAV. Since the problem is complex, we propose an algorithm to find the optimal position/coordinates of the selected UAV.
- Moreover, the complex formulated problem is transformed into a simplex form. Then, we prove the concavity of the problem with respect to the horizontal placement of the selected UAV. Next, we propose an algorithm to find a sub-optimal solution.
- By using numerical results, we demonstrate that the BDS based selection scheme ensures a significant gain in the throughput at low SNR values, whereas both selection schemes attain the similar performance in high SNR regimes. Further, important trade-offs and insights about dependency of the optimal position on selection strategies have also been outlined.

Organization: The structure of this paper is as follows. In Section II, we illustrate the UAVs-assisted system model and preliminary. Next, the UAV selection strategies along with their complexity analysis are depicted in Section III, while Section IV presents the performance analysis. In Section V, we describe the throughput maximization problem and the proposed algorithms for solving the optimization problem. Section VI presents the numerical results and discusses about findings. At last, conclusions are drawn in Section VII.

Notation: Cumulative distribution function (CDF) and probability density function (PDF) of any random variable Z are denoted by $F_Z(z)$ and $f_Z(z)$, respectively. $(r)_{ij}$ represents parameter r between device i and device j. Complex Gaussian distribution having mean m and variance σ^2 is represented by $\mathcal{CN}(m, \sigma^2)$. Expectation operator is given by $\mathrm{E}[\cdot]$ and $|z|$ denotes the absolute value of z. $\Gamma(\cdot)$ and $\Gamma(\cdot, \cdot)$ are Gamma and upper incomplete Gamma function, respectively. $K(\cdot)$ represents modified Bessel function of second kind.

II. SYSTEM MODEL

We consider a half duplex (HD) enabled UAV assisted cooperative communication network as shown in Fig. 1. Note that this system model can be considered for the highly terrain environment, where due to some disastrous event (like earthquake, flood etc.) and unavailability of the communication link, exchange of information between GUs is not possible. In such areas, UAVs can be modeled as relays and can be deployed easily and quickly in order to establish the communication between GUs. Further, the use of single UAV under a given scenario in such locations may not provide the desired performance. Therefore, to achieve the better performance, in this work multiple UAVs are considered for relaying operation.

The communication between GU A and GU B is assisted by randomly distributed UAVs $(U_1, U_2, \ldots, U_N)$. The direct link between A and B is unfavourable for communication due to environmental obstructions or extreme physical conditions. It is assumed that GU A and GU B only have a single antenna, Furthermore, each UAV is also equipped with a single antenna for transmission and reception and operates in HD mode. In this communication network, both the uplink and downlink channels are modeled using generalized Nakagami-m distribution.

Let h_{AU_i} and h_{U_iB} denote the channel coefficients between A-U_i and U_i-B, respectively, and can be expressed as

$$h_{AU_i} = g_{AU_i} \times \sqrt{\beta_{AU_i}}, \tag{1}$$

$$h_{U_iB} = g_{U_iB} \times \sqrt{\beta_{U_iB}}, \tag{2}$$

where $i = \{1, 2, \ldots, N\}$, g_{AU_i} and g_{U_iB} are the respective small scale fading coefficients between A-U_i and U_i-B, β_{AU_i} and β_{U_iB} denote the path loss between A-U_i and U_i-B, respectively. Let us consider (x_i, y_i, z_i) as a coordinate of i^{th} device, with $i \in \{\mathrm{A}, \mathrm{B}, U_1, U_2, \ldots, U_N\}$. Now, the path losses β_{AU_i} and β_{U_iB} are computed as

$$\beta_{AU_i} = \frac{(c/4\pi f)^2}{E_{AU_i}}, \tag{3}$$

$$\beta_{U_iB} = \frac{(c/4\pi f)^2}{E_{U_iB}}, \tag{4}$$

where c and f are the speed of light and frequency of operation, respectively. With path loss exponent a, the Euclidean distance between U_i and GU A, U_i and GU B are given by

$$E_{AU_i} = \left((x_A - x_{U_i})^2 + (y_A - y_{U_i})^2 + (z_A - z_{U_i})^2\right)^{a/2},$$

$$E_{U_iB} = \left((x_B - x_{U_i})^2 + (y_B - y_{U_i})^2 + (z_B - z_{U_i})^2\right)^{a/2},$$

respectively. Furthermore, g_{AU_i} and g_{U_iB} are Nakagami-m distributed with PDF given by

$$f_X(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} \exp\left(-\frac{m}{\Omega}x^2\right); \quad x \geq 0, \tag{5}$$

where $X \in \{g_{AU_i}, g_{U_iB}\}$, m and Ω are the shape and spread parameters of Nakagami-m distribution. Let s_{AU_i} ($\mathrm{E}[|s_{AU_i}|^2] = 1$) is the transmit symbol from GU A to U_i. Then, the signal received at U_i can be written as

$$y_{AU_i} = h_{AU_i}\sqrt{P_{AU_i}} s_{AU_i} + w_{AU_i}, \tag{6}$$

where P_{AU_i} denotes the transmit power of A and $w_{AU_i} \sim \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise (AWGN) at U_i. Now, the signal-to-noise ratio (SNR) at U_i is expressed as

$$\gamma_{AU_i} = \frac{|h_{AU_i}|^2 P_{AU_i}}{\sigma^2}. \tag{7}$$

U_i forwards the decoded symbol s_{U_iB} to GU B with power P_{U_iB}. Thus, the SNR at B is given by

$$\gamma_{U_iB} = \frac{|h_{U_iB}|^2 P_{U_iB}}{\sigma^2}. \tag{8}$$

III. UAV SELECTION

This section presents a study of two UAV selection schemes (HM and BDS) that guarantee a certain quality-of-service (QoS). In extreme physical conditions and high terrain areas UAVs can be used as moving relay nodes to relay the information from one location to another location [28]–[31]. In such scenarios, the efficient UAV selection and the position optimization of UAVs are of utmost importance in order to attain a good performance for the data transmission. Various relay selection mechanisms exist in conventional cooperative communication systems. However, the random positioning and continuous movement of UAVs are critical issues in developing an efficient UAV selection strategy. To this end, we investigate the performance of HM and BDS based UAV selection schemes in randomly distributed multiple UAV scenario. A detailed study of HM and BDS based UAV selection strategies is given in subsequent subsections.

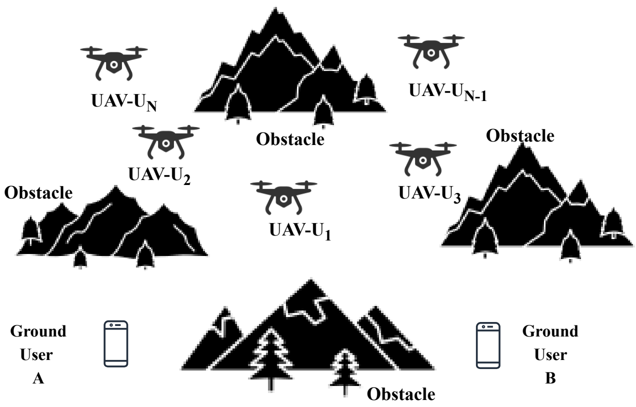

FIGURE 1. Illustration of the UAVs-assisted cooperative communication network.

A. HARMONIC MEAN (HM) BASED UAV SELECTION

HM (γ_i) is calculated by adding the ratio of both uplink and downlink SNRs for each UAV as follows

$$\gamma_i = \frac{1}{\gamma_{AU_i}} + \frac{1}{\gamma_{U_iB}}; \quad \forall i \in Q. \tag{9}$$

Since g_{U_iA} and g_{U_iB} are Nakagami-m distributed, γ_{AU_i} and γ_{U_iB} will be Gamma distributed with PDF and CDF given as follows:

$$f_{\gamma_\kappa}(\gamma) = \frac{(\gamma)^{(m_\kappa - 1)} e^{-\gamma/\hat{\gamma}_\kappa}}{(\hat{\gamma}_\kappa)^{m_\kappa}\Gamma(m_\kappa)}; \quad \gamma \geq 0, \tag{10}$$

$$\mathrm{F}_{\gamma_\kappa}(\gamma) = 1 - \frac{\Gamma(m_\kappa, \gamma/\hat{\gamma}_\kappa)}{\Gamma(m_\kappa)}, \tag{11}$$

where $\kappa \in \{AU_i, U_iB\}$, and $\hat{\gamma}_\kappa$ is given by

$$\hat{\gamma}_\kappa = \frac{\mathbf{E}[\gamma_\kappa]}{m_\kappa} = \frac{\Omega_\kappa \beta_\kappa P_\kappa}{m_\kappa \sigma^2}, \tag{12}$$

where P_κ/σ^2 is non-fading SNR.

Algorithm 1 HM based UAV Selection Strategy

```
1: Initialize Q = {1, 2, ..., N}
2: Calculate γ_{AU_i}, ∀i ∈ Q
3: Calculate γ_{U_iB}, ∀i ∈ Q
4: Measure γ_i = 1/γ_{AU_i} + 1/γ_{U_iB}, ∀i ∈ Q
5: Select k = arg max_{i∈Q}(γ_i)
6: if γ_k > γ_th then
7:     U_k is selected as relay
8: else Repeat step 2 to 5.
9: end if
```

Lemma 1. *CDF of γ_i is given by*

$$F_{\gamma_i}(\gamma) = 1 - 2\exp\left(-\gamma\left(\frac{1}{\hat{\gamma}_{AU_i}} + \frac{1}{\hat{\gamma}_{U_iB}}\right)\right)\sum_{p=0}^{m_{AU_i}-1} \sum_{t=0}^{(p+m_{U_iB}-1)} \binom{p+m_{U_iB}-1}{t} \frac{\gamma^{p+m_{U_iB}}\left(\hat{\gamma}_{U_iB}\right)^{(t-p-2m_{U_iB}+1)/2}}{\Gamma(m_{U_iB})p!\left(\hat{\gamma}_{AU_i}\right)^{(p+t+1)/2}} \times K_{t-p+1}\left(2\sqrt{\frac{\gamma^2}{\hat{\gamma}_{AU_i}\hat{\gamma}_{U_iB}}}\right). \tag{13}$$

Proof. See Appendix A. □

The HM selection criteria is expressed as

$$k = \arg\max_{i\in Q}(\gamma_i). \tag{14}$$

If $\gamma_k > \gamma_{th}$, then U_k is selected for the relaying operation. Algorithm 1 presents pseudo code for HM based UAV selection strategy.

B. BEST DOWNLINK SNR (BDS) BASED UAV SELECTION

Algorithm 2 presents the pseudo code for BDS based UAV selection strategy, in which the criteria for selection of k^{th} UAV U_k as a relay is given by

$$k = \arg\max_{j\in C}(\gamma_{U_jB} > \gamma_{th}). \tag{15}$$

The idea behind formation of C is to ensure that UAV participating in step 7 should be able to successfully decode the incoming signal. As discussed earlier, if $\gamma_{AU_i} > \gamma_{th}$ is true then U_i successfully decodes received signal. Otherwise $i \notin C$ ($\gamma_{AU_i} \leq \gamma_{th}$) and link A-$U_i$ is said to be in outage whose probability is given by

$$\Pr(i \notin C) = P_{out}^{AU_i} = \Pr\left(\gamma_{AU_i} \leq \gamma_{th}\right). \tag{16}$$

If U_k satisfies the condition $\gamma_{U_kB} = \max_{j\in C} \gamma_{U_jB}$, then U_k is selected as relay for end to end communication. The outage probability of link U_k-B is given by

$$P_{out}^{U_kB} = \Pr\left(\gamma_{U_kB} \leq \gamma_{th}\right). \tag{17}$$

Algorithm 2 BDS based UAV Selection Strategy

```
1: Initialize Q = {1, 2, ..., N}
2: Calculate γ_{AU_i} ∀i ∈ Q
3: Form C = {i ∈ Q | γ_{AU_i} > γ_th}
4: if C = φ then
5:     Repeat steps 2 to 3
6: else if C ≠ φ then
7:     Calculate γ_{U_jB} ∀j ∈ C
8: end if
9: Select k = arg max_{j∈C}(γ_{U_jB})
10: if γ_{U_kB} > γ_th then
11:     U_k is selected as relay
12: else Repeat step 2 to 9.
13: end if
```

Lemma 2. *CDF of the SNR using BDS selection scheme is given by*

$$F_{\Theta_i}(\gamma) = 1 - \left(\frac{\Gamma(m_{AU_i}, \gamma/\hat{\gamma}_{AU_i})}{\Gamma(m_{AU_i})} \times \frac{\Gamma(m_{U_iB}, \gamma/\hat{\gamma}_{U_iB})}{\Gamma(m_{U_iB})}\right), \tag{18}$$

where Θ_i is defined as random variable that gives instantaneous SNR at GU B using BDS selection strategy.

Proof. Refer to Appendix C. □

C. COMPUTATIONAL COMPLEXITY ANALYSIS

We use the concept of floating point operations (flops), where each flop unit is equivalent to one arithmetic operation (multiply, divide, add or subtract) [32]. Computational complexity is evaluated in terms of total numbers of flops approximately required for the UAV selection by using HM, BoW and BDS based selection schemes. For example, HM based selection requires three variables (γ_{AU_i}, γ_{U_iB} and γ_i) for UAV selection. Here, we calculate number of flops required to evaluate each one of these variables and sum them up to find the computational complexity of HM based selection scheme in terms of flops. Further, evaluating γ_{AU_i} requires two arithmetic operations (1 multiplication and 1

TABLE 1. Computational complexity of UAV selection schemes

Scheme	Variable	Flops	Total Computations (Flops)
HM	$\gamma_{AU_i}; \forall i \in Q$	$2\|Q\|$	$7\|Q\|$
	$\gamma_{U_iB}; \forall i \in Q$	$2\|Q\|$	
	$\gamma_i; \forall i \in Q$	$3\|Q\|$	
BoW	$\gamma_{AU_i}; \forall i \in Q$	$2\|Q\|$	$4\|Q\|$
	$\gamma_{U_iB}; \forall i \in Q$	$2\|Q\|$	
BDS	$\gamma_{AU_i}; \forall i \in Q$	$2\|Q\|$	$2\|Q\| + 2\|C\|$
	$\gamma_{U_iB}; \forall i \in C$	$2\|C\|$	

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division), hence two flops for each UAV. Thus, evaluating γ_{AU_i} requires $2|Q|$ flops, where $|Q|$ is the cardinality of set Q. Similarly, γ_{U_iB} and γ_i require $2|Q|$ flops and $3|Q|$ flops, respectively. Therefore, HM based selection approximately requires $7|Q|$ flops to select UAV as relay. Similar approach is used to find approximate number of flops for BoW and BDS based selection schemes. Table 1 presents the comparison of computational complexity of all three selection schemes. It can be clearly observed that HM based selection requires the most number of computations as compared to other two and it is noticed that HM based selection criteria requires an additional calculation of γ_i. Further, in downlink, BoW considers all UAVs i.e. set Q for selection whereas BDS uses only UAVs of set C. Thus, in general the BDS selection scheme requires less resources than that of BoW which is evident from the fact that $|C| \leq |Q|$, thus $2|Q|+2|C| \leq 4|Q|$.

D. MODEL EXTENSION

Consider the case of using multiple antennas at GU A, GU B and all UAVs. For uplink transmission, the received signal at UAV U_k (having N_{U_k} antennas) from GU A (having N_A antennas) is given as

$$\mathbf{y}_{U_kA} = \mathbf{H}_{U_kA}\mathbf{s}_{U_kA} + \mathbf{w}_{U_kA}, \tag{19}$$

where $\mathbf{y}_{U_kA}$ is the received signal vector of size $N_{U_k} \times 1$, $\mathbf{H}_{U_kA}$ is the channel vector of size $N_{U_k} \times N_A$, $\mathbf{w}_{U_kA}$ is the received additive white Gaussian noise (AWGN) vector of size $N_{U_k} \times 1$, and $\mathbf{s}_{U_kA}$ is the transmission symbol vector of size $N_A \times 1$, which depends on transmission scheme at A. Considering a simple case where $\mathbf{s}_{U_kA}$ consists of data signal which is transmitted using transmit beamforming vector $\mathbf{b}_{U_kA}$ at A. At U_k, after using receive the beamforming vector $\mathbf{b}_{U_k}$, the SNR at U_k can be expressed as

$$\gamma_{U_kA} = \frac{|\mathbf{b}_{U_k}\mathbf{H}_{U_kA}\mathbf{b}_{U_kA}|^2}{||\mathbf{b}_{U_k}||^2 \times \sigma^2}, \tag{20}$$

where σ^2 is the noise variance.

Similarly for downlink, the received signal at GU B (having N_B antennas) from UAV U_k (having N_{U_k} antennas) is given by

$$\mathbf{y}_{BU_k} = \mathbf{H}_{BU_k}\mathbf{s}_{BU_k} + \mathbf{w}_{BU_k}, \tag{21}$$

where $\mathbf{y}_{BU_k}$ is the revived signal vector of size $N_B \times 1$ and $\mathbf{H}_{BU_k}$ is the channel vector of size $N_B \times N_{U_k}$. Here, $\mathbf{w}_{BU_k}$ denotes the noise vector of size $N_B \times 1$ and $\mathbf{s}_{BU_k}$ indicates the transmission symbol vector of size $N_{U_k} \times 1$, which depends on transmission scheme at U_k. Similar to the uplink case, downlink SNR at B can be expressed as

$$\gamma_{BU_k} = \frac{|\mathbf{b}_B\mathbf{H}_{BU_k}\mathbf{b}_{BU_k}|^2}{||\mathbf{b}_B||^2 \times \sigma^2}, \tag{22}$$

where $\mathbf{b}_{BU_k}$ and $\mathbf{b}_B$ are the beamformer matrix at transmitter U_k and receiver B, respectively. Note that in the case of MIMO, many factors such as number of antennas, beamforming, channel correlation and combining techniques are also considered for the performance evaluation which makes the analysis more complex and some times intractable. Therefore, for analytical simplicity and better understanding of the proposed model, in this work single antenna devices are considered. In future works on UAV, this work will be extended on multiple antenna case along with multiple ground users, where a more efficient strategy for MIMO can be devised to improve the system performance.

IV. END TO END OUTAGE PROBABILITY, COVERAGE PROBABILITY AND THROUGHPUT ANALYSIS

1) Outage Probability

The end-to-end outage probability for the BDS based selection criterion is expressed as

$$\mathrm{P}_{\mathrm{OBDS}} = \Pr\left(\max_{i \in N} \Theta_i \leq \gamma_{th}\right) = \prod_{i=1}^{N} \mathrm{F}_{\Theta_i}(\gamma_{th}). \tag{23}$$

By substituting (18) into (23), the outage probability is computed as

$$\mathrm{P}_{\mathrm{OBDS}} = \prod_{i=1}^{N}\left(1 - \left(\frac{\Gamma\left(m_{AU_i}, \frac{\gamma_{th}}{\hat{\gamma}_{AU_i}}\right)}{\Gamma(m_{AU_i})} \times \frac{\Gamma\left(m_{U_iB}, \frac{\gamma_{th}}{\hat{\gamma}_{U_iB}}\right)}{\Gamma(m_{U_iB})}\right)\right). \tag{24}$$

Similarly, the end-to-end outage probability of HM based UAV selection criterion is written as

$$\mathrm{P}_{\mathrm{OHM}} = \Pr\left(\max_{i \in N} \gamma_i \leq \gamma_{th}\right) = \prod_{i=1}^{N} \mathrm{F}_{\gamma_i}(\gamma_{th}), \tag{25}$$

where $\mathrm{F}_{\gamma_i}(\gamma_{th})$ is given by (13).

2) Coverage Probability

SNR based coverage probability of relaying network is discussed in [33]. For BDS based selection strategy, coverage probability is expressed as

$$\begin{aligned}\mathrm{P}_{\mathrm{CBDS}} &= \Pr\left(\max_{i \in N} \Theta_i > \gamma_{th}\right)\\ &= 1 - \prod_{i=1}^{N} \Pr\left(\max_{i \in N} \Theta_i \leq \gamma_{th}\right)\\ &= 1 - \mathrm{P}_{\mathrm{OBDS}},\end{aligned} \tag{26}$$

where $\mathrm{P}_{\mathrm{OBDS}}$ is given in (24). Similarly, for HM selection strategy the coverage probability can be expressed as

$$\mathrm{P}_{\mathrm{CHM}} = 1 - \mathrm{P}_{\mathrm{OHM}}, \tag{27}$$

where $\mathrm{P}_{\mathrm{OHM}}$ is given by (25).

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3) Throughput Analysis

For a given minimum rate R, the throughput in bits per channel use (bpcu) is given by

$$\tau_{\text{BDS}} = (1 - \mathrm{P}_{\text{OBDS}}) \times \frac{R}{2}. \tag{28}$$

Similarly, for HM based selection scheme the throughput is expressed as

$$\tau_{\text{HM}} = (1 - \mathrm{P}_{\text{OHM}}) \times \frac{R}{2}. \tag{29}$$

In given scenario N UAVs moves randomly and out of these randomly moving UAVs we select one UAV, which act as relay, based on channel and path loss conditions.

V. THROUGHPUT MAXIMIZATION

In this section, the position of the selected UAV in terms of its 3-D coordinates is optimized in order to maximize the network throughput.

A. OPTIMAL POSITION OF SELECTED UAV

Equations (28) and (29) express the throughput of selected UAV using BDS and HM strategies, respectively. In the scenario where the UAVs are randomly distributed, it is essential to find the optimum placement of the selected UAV in order to maximize the throughput. Therefore, for selected UAV (U_k) with coordinate $(x_{U_k}, y_{U_k}, z_{U_k})$, the optimization problem for maximizing the throughput can be formulated as

$$\zeta_{\text{opt}} = \{x_{\text{opt}}, y_{\text{opt}}, z_{\text{opt}}\} = \arg \max_{x_{U_k}, y_{U_k}, z_{U_k}} (\tau_\eta) \tag{30a}$$

$$\text{s.t.} \quad x_{min} \leq x_{U_k} \leq x_{max}, \tag{30b}$$

$$y_{min} \leq y_{U_k} \leq y_{max}, \tag{30c}$$

$$z_{min} \leq z_{U_k} \leq z_{max}, \tag{30d}$$

where $\eta \in \{\text{HM}, \text{BDS}\}$, x_{min} and x_{max}, y_{min} and y_{max}, and z_{min} and z_{max} are the minimum and maximum values of x_{U_i}, y_{U_i} and z_{U_i}, respectively. ζ_{opt} gives the optimal position of the selected UAV corresponding to maximum throughput. With the complex expressions of P_{OBDS} and P_{OHM}, it is quite difficult to find the optimal coordinates analytically [34]. However, we propose a solution in Algorithm 3 to obtain the optimal coordinate values that maximize the network throughput. The idea behind proposed solution is that the selected UAV should give the best throughput of the network among all UAVs, and thus, the average value of coordinates after simulation (ζ_{opt}) gives the best UAV placement.

B. SUB-OPTIMAL POSITION OF SELECTED UAV

With the derived expressions of the outage probabilities in (24) and (25), it is quite difficult to jointly optimize the coordinates of the selected UAV to maximize the system throughput τ_η. Therefore, in this subsection we propose a sub-optimal solution to this problem. Using (24) and (25) into

Algorithm 3 Optimal Position

1: Initialize number of iterations = L
2: **for** $l = 1 : L$ **do**
3: Find U_k using Algorithm 1 or 2
4: Store $x_l = x_{U_k}, y_l = y_{U_k}, z_l = z_{U_k}$
5: **end for**
6: Calculate:
$x_{\text{opt}} = \sum_{l=1}^{L} x_l / L$, $y_{\text{opt}} = \sum_{l=1}^{L} y_l / L$, $z_{\text{opt}} = \sum_{l=1}^{L} z_l / L$
7: Optimal position, $\zeta_{\text{opt}} = \{x_{\text{opt}}, y_{\text{opt}}, z_{\text{opt}}\}$

(28) and (29), the system throughput for BDS and HM based selection schemes can be expressed as

$$\tau_\eta = (1 - \mathrm{P}_{\mathrm{O}\eta}) \times R/2 = \left(1 - \prod_{i=1}^{N} \mathrm{F}_{\phi_i}(\gamma_{th})\right) \times \frac{R}{2}, \tag{31}$$

where $\phi_i \in \{\gamma_i, \Theta_i\}$. Since, the outage probability of the selected UAV is minimum among all UAVs, thus, we can write

$$\mathrm{F}_{\phi_k}(\gamma_{th}) \leq \mathrm{F}_{\phi_i}(\gamma_{th}) \;\; \forall i \in \{1, 2, \ldots, N\}. \tag{32}$$

Using above, we write

$$(\mathrm{F}_{\phi_k}(\gamma_{th}))^N \leq \prod_{i=1}^{N} \mathrm{F}_{\phi_i}(\gamma_{th}) \forall i \in \{1, 2, \ldots, N\}. \tag{33}$$

Now the throughput in (31) can be expressed as

$$\tau_\eta \leq \tau_{0\eta}, \tag{34}$$

where

$$\tau_{0\eta} = \left(1 - (\mathrm{F}_{\phi_k}(\gamma_{th}))^N\right) \times R/2. \tag{35}$$

Clearly, $\tau_{0\eta}$ is an upper bound for τ_η. Further, from (34) and (35) it is evident that maximizing $\tau_{0\eta}$ results in maximization of τ_η. Therefore, a much simpler sub-optimal optimization problem can be formulated as

$$x_{\text{sopt}} = \arg\max_{x_{U_k}} (\tau_{0\eta}) \quad \text{s.t.} \quad x_{min} \leq x_{U_k} \leq x_{max}. \tag{36}$$

To obtain (x_{sopt}), we use $\tau_{0\eta}$ defined by (35). As $\tau_{0\eta}$ is concave w.r.t. (x_{U_k}), an optimum value can be found by solving the problem (36) using standard optimization tools [34].

Lemma 3. *For a given height z_{U_k} and width y_{U_k}, $\tau_{0\eta}$ is concave function of x_{U_k}.*

Proof. Refer to Appendix C. □

As $\tau_{0\eta}$ is concave w.r.t. (x_{U_k}), an optimum value (x_{sopt}) exist which can be derived by solving $\tau'_{0\text{BDS}} = 0$. However, the complexity of the involved expressions make it difficult to find a closed-from solution for (x_{sopt}). To solve the above problem we propose a solution in Algorithm 4.

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Algorithm 4 Sub-Optimal Position

Initialize $y_{U_k}, z_{U_k}, x_A, y_A, z_A, x_B, y_B, z_B, c, f, a$
Initialize $x_{U_k} = x_{min} : 1 : x_{max}$,
for $ii = 1 : \text{length}(x_{U_k})$ **do**
    Calculate
    $E_{AU_k}(ii) = \left((x_A - x(ii))^2 + (y_A - y_{U_k})^2 + (z_A - z_{U_k})^2\right)^{a/2}$,
    $E_{U_k B}(ii) = \left((x_B - x(ii))^2 + (y_B - y_{U_k})^2 + (z_B - z_{U_k})^2\right)^{a/2}$,
    Evaluate $\tau_{0\eta}(ii)$ for $E_{AU_i}(ii)$ and $E_{U_i B}(ii)$
end for
Find $ii_{\text{sopt}} = \arg \max\limits_{ii \in (1:\text{length}(x))} (\tau_{0\eta}(ii))$
Find $x_{\text{sopt}} = x_{U_k}(ii_{\text{sopt}})$
Sub-Optimal position, $\zeta_{\text{sopt}} = \left\{x_{\text{sopt}}, y_{U_k}, z_{U_k}\right\}$

VI. RESULTS AND DISCUSSIONS

In this section we provide the numerical simulations in order to assess the performance of the proposed UAV selection strategies. This will serve to confirm accuracy of the derived analytical expressions, and will assist in drawing the useful insights into the factors influencing the network performance. The main simulation parameters are listed in Table 2. For the simulation, it is assumed that $P_{AU_i}/\sigma^2 = P_{U_iB}/\sigma^2 = \gamma_{\text{NF}}$ dB. We set the value of frequency $f = 2$GHz, while the value of path loss exponent whose value lies between 2 and 4 is $a = 2$ [25], [27], [35]. Furthermore, the distance between GU A to GU B is set as 1200m [25]. The GU A and GU B are fixed with coordinates defined in Table 2, while UAVs $(U_1, U_2, \ldots, U_N)$ are randomly distributed with coordinate values varying in the range of -600m to 600m. Furthermore, it is assumed that no two UAVs have same coordinates at a given point of time in order to avoid collision [25], [27], [36]. As a benchmark, we simulate outage probability (P_{OBoW}) of BoW UAV selection scheme given in Ref. [25] which works as lower bound for the proposed schemes.

TABLE 2. Parameters Value

Parameter	Value	Parameter	Value
f	2 GHz	m_{AU_i}	2
A	(-600m,0,0)	m_{U_iB}	1
B	(600m,0,0)	Ω_{AU_i}	1
a	2	Ω_{U_iB}	2

Fig. 2 depicts the outage probability versus the transmit SNR for BoW, BDS and HM based UAV selection strategies. The accuracy of the analytical expressions for outage probability in (24) and (25) is clearly confirmed by the simulations. We can observe that the performance of BDS is identical to that of the BoW. As can be seen in Table 1, the proposed BDS strategy has advantage over BoW in terms of computation complexity. Moreover, an increase in number of UAVs decreases the outage probability for all the three selection strategies. For N=4, the probability falls below 10^{-6} when $\gamma_{NF} < 20$ dB whereas for N=3 probability falls below 10^{-6} when $\gamma_{NF} > 20$ dB. Also, at lower SNR values BoW and BDS based UAV selection outperforms HM based selection criterion, whereas at higher SNRs all three give similar outage performance.

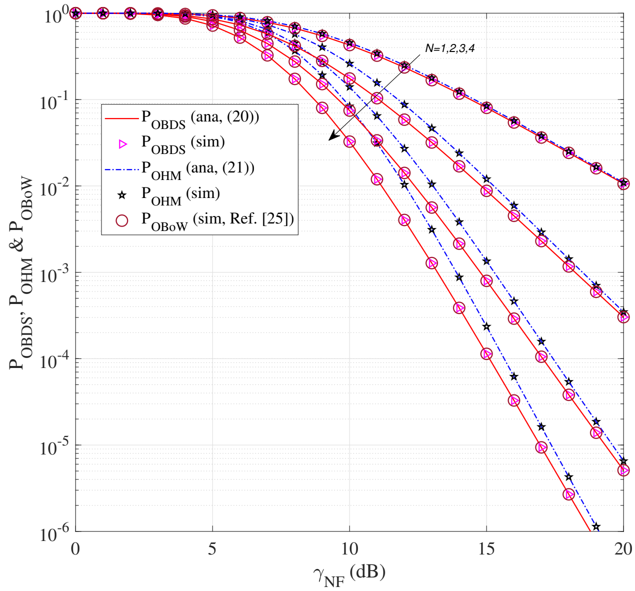

FIGURE 2. P_{OBDS}, P_{OHM} and P_{OBoW} versus γ_{NF} (dB) at $R = 1$.

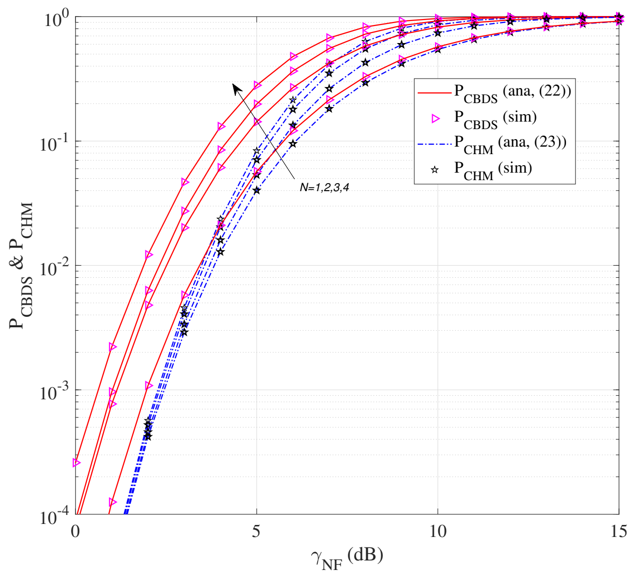

FIGURE 3. P_{CBDS} and P_{CHM} versus γ_{NF} (dB) at $R = 1$.

Fig. 3 shows the variation of the coverage probability versus average SNR for different number of UAVs. The coverage performance of both BDS and HM based selection strategies is compared. As we can observe that for lower values of SNR the coverage performance of BDS based selection strategy is significantly better than HM based selection whereas at high values of SNR both achieve the similar performance.

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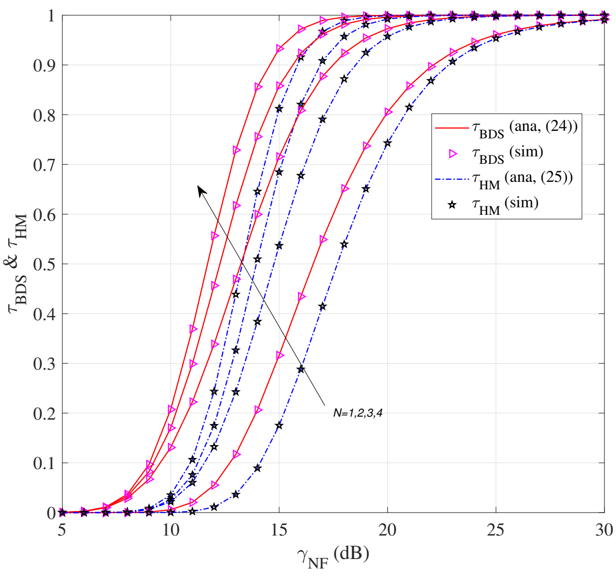

FIGURE 4. τ_{BDS} and τ_{HM} versu γ_{NF} (dB) at $R = 2$.

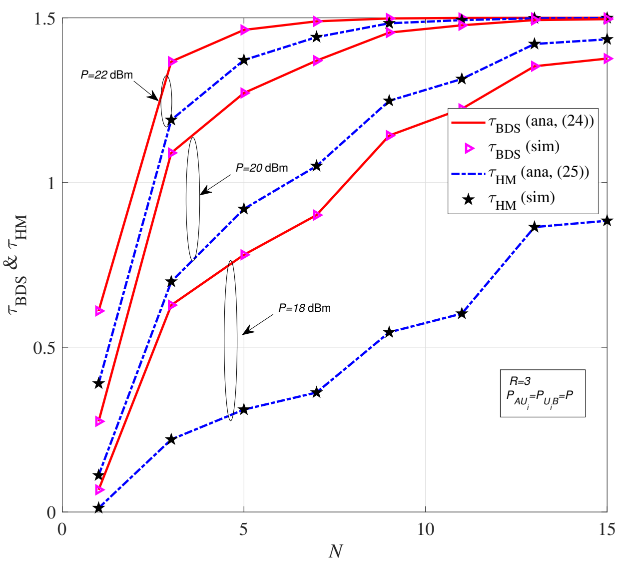

FIGURE 5. τ_{BDS} and τ_{HM} versus N at R=3.

In Fig. 4, we plot the throughput versus average SNR for HM and BDS based UAV selection strategies. With increase in N, throughput performance of both the BDS and HM selection strategies improves. We note that for $N = 4$ at $\gamma_{NF} = 15$ dB, $\tau_{\mathrm{BDS}} = 0.945$ and $\tau_{\mathrm{HM}} = 0.810$, hence, BDS scheme performs better than that of HM scheme.

Fig. 5 represents τ_{BDS} and τ_{HM} versus N at R=3 with equal power transmission from both links i.e. $P_{AU_i} = P_{U_iB} = P$ (dBm). We obtain the result for three different values of transmit power, $P \in \{18, 20, 22\}$ dBm. It is clearly observed that BDS strategy achieves the similar performances with $P = 22$ dBm, N= 7, and with $P = 20$ dBm, N= 13. Thus, there exists a trade off between available power and the number of UAVs to achieve the desired performance.

Fig. 6 illustrate τ_{BDS} and τ_{HM} versus γ_{NF} (dB) at R= 3, N= 3. The effect of $m_{AU_i} = m_{AU_i} = m$ on the throughput performance of the system is observed. Here, $m = 1$ corresponds to worst case (Rayleigh fading). It can be seen that the network performance improve with increasing m for higher values of γ_{NF}. Further, we can also observe that the desired throughput for BDS is achieved at lower γ_{NF} as compared to HM strategy.

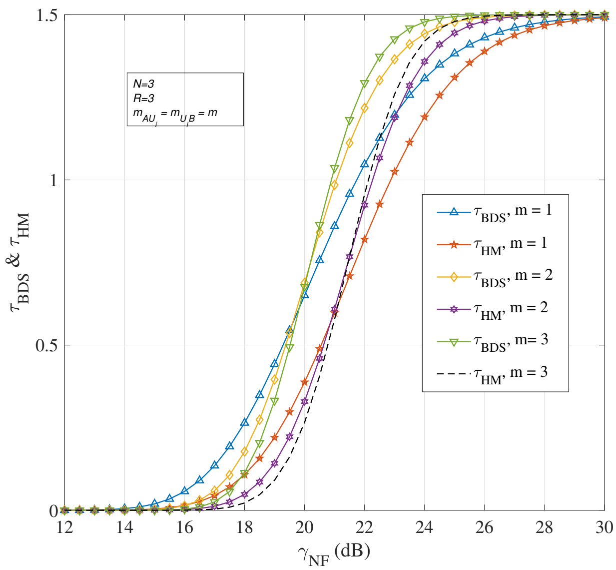

FIGURE 6. τ_{BDS} and τ_{HM} versus γ_{NF} (dB) at R= 3, N= 3.

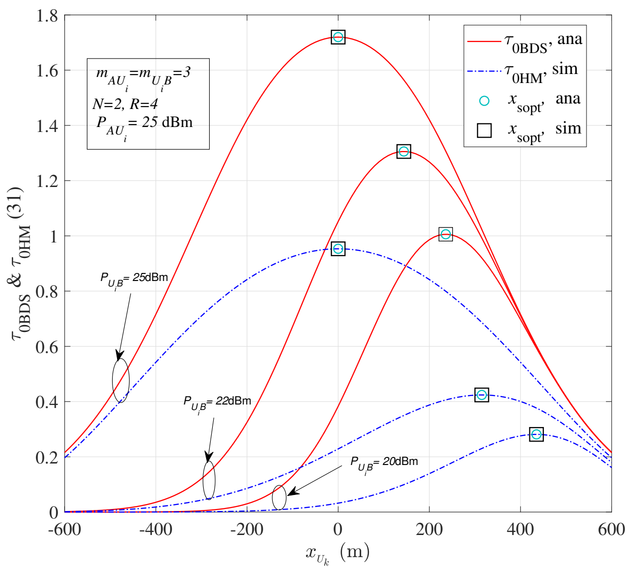

FIGURE 7. τ_{0BDS} and τ_{0HM} versus x_{U_k}.

In Fig. 7, we plot $\tau_{0\eta}$ versus x_{U_k} for both BDS and HM selection strategies at $m_{AU_i} = m_{U_iB} = 3$, N= 2, R= 4, $P_{AU_i} = 25$ dBm, $y = 10$m and $z = 100$m for different

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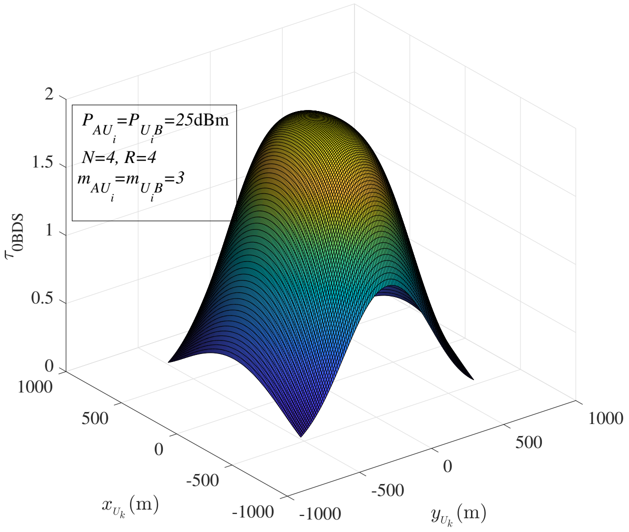

FIGURE 8. $\tau_{0\mathrm{BDS}}$ versus x_{U_k} and y_{U_k}.

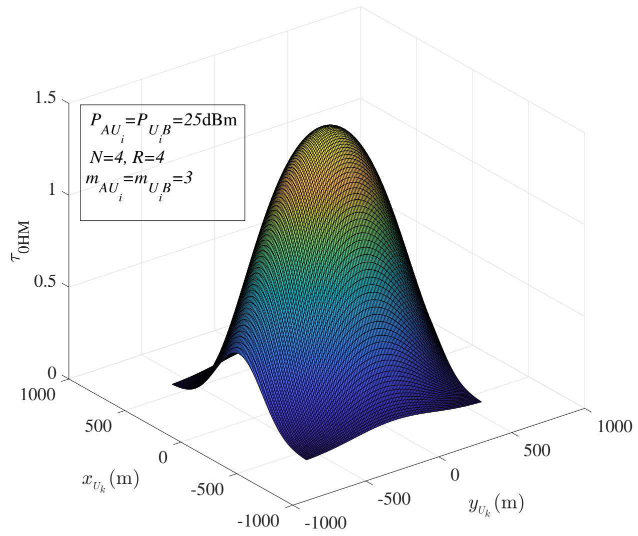

FIGURE 9. $\tau_{0\mathrm{HM}}$ versus x_{U_k} and y_{U_k}.

values of P_{U_iB}. For the case where $P_{AU_i} = P_{U_iB}$ dBm, the optimal position is obtained at the center of both GUs. While for asymmetrical powers the optimal UAV position changes, e.g. when P_{U_iB} decreases, the optimal position moves closer towards GU B and achievable throughput also decreases. Hence, the optimal position of the selected UAV depends on the available power at the transmitting node. Also, it can be clearly seen that throughput is a concave function of x_{U_k} (proved in Lemma 3, Section V), thus, there exists an optimum x_{sopt} that maximizes the throughput. It can also be seen that the derived x_{sopt} values are accurate (the simulated values are also indicated).

For fixed $z_{U_k} = 100$m, Fig. 8 and Fig. 9 show $\tau_{0\eta}$ versus x_{U_k} and y_{U_k} for BDS and HM strategies, respectively. These figures are obtained at $m_{AU_i} = m_{U_iB} = 3$, $N = 4$, $R = 4$, $P_{AU_i} = P_{U_iB} = 25$ dBm. It is clearly observed that the throughput reaches to a maximum value when the coordinates x_{U_k} and y_{U_k} are jointly optimized for fixed z_{U_k} ($z_{U_k} = 100$m into Algorithm 3). Also, the throughput decreases as UAV moves away from the optimal position.

VII. CONCLUSION

In this paper, we investigated two UAV selection strategies $i)$ best HM and $ii)$ BDS for multiple UAV-assisted network. Further, we derived the closed-form expressions of the outage probability, throughput and coverage probability of both the selection strategies. To find the optimal coordinates of the selected UAV, we formulated a throughput maximization problem and proposed an algorithm. In addition, we proposed a sub-optimal solution to the formulated optimization problem by converting it to a much simpler form and hence, proved the concavity of the problem w.r.t. horizontal placement of selected UAV. Furthermore, numerical results demonstrated that BDS based selection strategy performs better at low SNR value, however, both selection strategies achieve the similar performance in high SNR regimes. An important trade-offs and insights about dependency of the optimal position on selection strategies were demonstrated.

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APPENDIX A PROOF OF LEMMA 1

Using (9), the CDF of γ_i can be expressed as

$$\begin{aligned} \mathrm{F}_{\gamma_i}(\gamma) &= \Pr(\gamma_i \le \gamma) = \Pr\left(\frac{\gamma_{AU_i}\gamma_{U_iB}}{\gamma_{AU_i}+\gamma_{U_iB}} \le \gamma\right) \\ &= \int_0^\infty \Pr\left\{\frac{\gamma_{AU_i}\mathfrak{z}}{\gamma_{AU_i}+\mathfrak{z}} \le \gamma | \gamma_{U_iB} = \mathfrak{z}\right\} f_{\gamma_{U_iB}}(\mathfrak{z})d\mathfrak{z} \\ &= \mathrm{F}_{\gamma_{U_iB}}(\gamma) + \int_\gamma^\infty \mathrm{F}_{\gamma_{AU_i}}\left(\frac{\gamma\mathfrak{z}}{\mathfrak{z}-\gamma}\right) f_{\gamma_{U_iB}}(\mathfrak{z})d\mathfrak{z} \\ &= 1 - \int_\gamma^\infty \frac{\Gamma\left(m_{AU_i}, \frac{\mathfrak{z}\gamma}{\hat{\gamma}_{AU_i}(\mathfrak{z}-\gamma)}\right)}{\Gamma(m_{AU_i})} f_{\gamma_{U_iB}}(\mathfrak{z})d\mathfrak{z}. \end{aligned} \quad (37)$$

Using [37, Eq.6.5.32] in above, we obtain

$$\mathrm{F}_{\gamma_i}(\gamma) = 1 - \sum_{p=0}^{m_{AU_i}-1} \int_\gamma^\infty \exp\left(-\frac{\gamma\mathfrak{z}}{\hat{\gamma}_{AU_i}(\mathfrak{z}-\gamma)}\right) \times \left(\frac{(\gamma\mathfrak{z})^p}{p!\left(\hat{\gamma}_{AU_i}(\mathfrak{z}-\gamma)\right)^p}\right) \frac{(\mathfrak{z})^{(m_{U_iB}-1)}\exp\left(\frac{-\mathfrak{z}}{\hat{\gamma}_{U_iB}}\right)}{\left(\hat{\gamma}_{U_iB}\right)^{m_{U_iB}}\Gamma(m_{U_iB})} d\mathfrak{z}. \quad (38)$$

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Substituting $\mathfrak{z} - \gamma = \mathfrak{u}$ and after some mathematical rearrangements, we obtain

$$\mathrm{F}_{\gamma_i}(\gamma) = 1 - \frac{\exp\left(-\gamma\left(\frac{1}{\hat{\gamma}_{AU_i}} + \frac{1}{\hat{\gamma}_{U_iB}}\right)\right)}{\left(\hat{\gamma}_{U_iB}\right)^{m_{U_iB}}\Gamma(m_{U_iB})}\sum_{p=0}^{m_{AU_i}-1} \frac{\gamma^p}{p!\left(\hat{\gamma}_{AU_i}\right)^p}\int_0^\infty \mathfrak{u}^{-p}(\gamma+\mathfrak{u})^{(p+m_{U_iB}-1)}\exp\left(-\frac{\gamma^2}{\gamma_{AU_i}\mathfrak{u}} - \frac{\mathfrak{u}}{\gamma_{U_iB}}\right)d\mathfrak{u}. \tag{39}$$

Using binomial expansion of $(\gamma+\mathfrak{u})^{(p+m_{U_iB}-1)}$, the above equation can be expressed as

$$\mathrm{F}_{\gamma_i}(\gamma) = 1 - \frac{2\exp\left(-\gamma\left(\frac{1}{\hat{\gamma}_{AU_i}} + \frac{1}{\hat{\gamma}_{U_iB}}\right)\right)}{\left(\hat{\gamma}_{U_iB}\right)^{m_{U_iB}}\Gamma(m_{U_iB})}\sum_{p=0}^{m_{AU_i}-1} \frac{\gamma^p}{p!\left(\hat{\gamma}_{AU_i}\right)^p}\sum_{t=0}^{(p+m_{U_iB}-1)}\binom{p+m_{U_iB}-1}{t}\gamma_{th}^{(p+m_{U_iB}-t-1)} \times\int_0^\infty \mathfrak{u}^{t-p}\exp\left(-\frac{\gamma^2}{\gamma_{AU_i}\mathfrak{u}} - \frac{\mathfrak{u}}{\gamma_{U_iB}}\right)d\mathfrak{u}. \tag{40}$$

Solving the integral using [38, Eq. 3.471.9], we obtain

$$\mathrm{F}_{\gamma_i}(\gamma) = 1 - \frac{2\exp\left(-\gamma\left(\frac{1}{\hat{\gamma}_{AU_i}} + \frac{1}{\hat{\gamma}_{U_iB}}\right)\right)}{\left(\hat{\gamma}_{U_iB}\right)^{m_{U_iB}}\Gamma(m_{U_iB})}\sum_{p=0}^{m_{AU_i}-1} \frac{\gamma^p}{p!\left(\hat{\gamma}_{AU_i}\right)^p}\sum_{t=0}^{(p+m_{U_iB}-1)}\binom{p+m_{U_iB}-1}{t}\gamma_{th}^{(p+m_{U_iB}-t-1)} \left(\frac{\gamma^2\hat{\gamma}_{U_iB}}{\hat{\gamma}_{AU_i}}\right)^{(t-p+1)/2} K_{t-p+1}\left(2\sqrt{\frac{\gamma^2}{\hat{\gamma}_{AU_i}\hat{\gamma}_{U_iB}}}\right). \tag{41}$$

After some mathematical rearrangements in (41), we obtain (13).

APPENDIX B PROOF OF LEMMA 2

Let us define the SNR at GU B using BDS UAV selection strategy by a random variable Θ_i. Similar to [39], the PDF of Θ_i can be expressed as

$$f_{\Theta_i}(\gamma) = f_{\Theta_i|i\notin C}(\gamma)\Pr(i \notin C) + f_{\Theta_i|i\in C}(\gamma)\Pr(i \in C), \tag{42}$$

where $\Pr(i \notin C)$ and $\Pr(i \in C)$ are the probabilities when link A-U_i is in outage and in non outage, respectively. $f_{\Theta_i|i\notin C}(\gamma)$ is the conditional PDF of Θ_i with U_i in outage, it will be equal to delta function $\delta(\gamma)$ when link A-U_i is in outage, which in turn results in an end to end outage event. Since (16) gives the probability that U_i does not qualify to be stored in set C, so $1 - P_{out}^{AU_i}$ will be the probability that U_i is in set C. From (16) the outage probability $P_{out}^{AU_i}$ is

$$P_{out}^{AU_i} = 1 - \frac{\Gamma\left(m_{AU_i}, \frac{\gamma_{th}}{\hat{\gamma}_{AU_i}}\right)}{\Gamma(m_{AU_i})} \tag{43}$$

and conditional PDF $f_{\Theta_i|i\in C}(\gamma)$ is given as

$$f_{\Theta_i|i\in C}(\gamma) = \frac{(\gamma)^{(m_{U_iB}-1)}e^{-\gamma/\hat{\gamma}_{U_iB}}}{\left(\hat{\gamma}_{U_iB}\right)^{m_{U_iB}}\Gamma(m_{U_iB})}; \quad x \geq 0. \tag{44}$$

Using (43) and (44) into (42), we obtain

$$f_{\Theta_i}(\gamma) = \left(1 - \frac{\Gamma\left(m_{AU_i}, \frac{\gamma}{\hat{\gamma}_{AU_i}}\right)}{\Gamma(m_{AU_i})}\right)\delta(\gamma) + \left(\frac{\Gamma\left(m_{AU_i}, \frac{\gamma}{\hat{\gamma}_{AU_i}}\right)}{\Gamma(m_{AU_i})}\right)\frac{\left(\hat{\gamma}_{U_iB}\right)^{-m_{U_iB}}x^{m_{U_iB}-1}}{\Gamma(m_{U_iB})} \times \exp\left(-\frac{\gamma}{\hat{\gamma}_{U_iB}}\right); \quad x \geq 0. \tag{45}$$

CDF is given by

$$\mathrm{F}_{\Theta_i}(\gamma) = \int_\gamma^\infty f_{\Theta_i}(\gamma)d\gamma. \tag{46}$$

Solving (46) yields (18).

APPENDIX C PROOF OF LEMMA 3

In order to prove concavity of $\tau_{0\mathrm{BDS}}$ w.r.t. x_{U_k}, taking first order derivative of $\tau_{0\mathrm{BDS}}$ w.r.t. x_{U_k} to obtain

$$\tau'_{0\mathrm{BDS}} = -\frac{aRN(\mathrm{F}_{\Theta_k})^{N-1}}{2\Gamma(m_{AU_k})\Gamma(m_{U_kB})}\times\left[\frac{(x_{U_k} - x_B)e^{-\gamma_{th}/\hat{\gamma}_{U_kB}}\Gamma\left(m_{AU_k}, \frac{\gamma_{th}}{\hat{\gamma}_{AU_k}}\right)}{E_{U_kB}\left(\frac{\hat{\gamma}_{AU_k}}{\gamma_{th}}\right)^{m_{U_kB}}} + \frac{(x_{U_k} - x_A)e^{-\gamma_{th}/\hat{\gamma}_{AU_k}}\Gamma\left(m_{U_kB}, \frac{\gamma_{th}}{\hat{\gamma}_{U_kB}}\right)}{E_{AU_k}\left(\frac{\hat{\gamma}_{AU_k}}{\gamma_{th}}\right)^{m_{AU_k}}}\right]. \tag{47}$$

Keeping all other parameters same for uplink and downlink except x_A and x_B then solving for $\tau'_{0\mathrm{BDS}} = 0$, we obtain

$$x_{U_k} = \frac{(x_A + x_B)}{2}. \tag{48}$$

Furthermore, it is found out that $\tau''_{0\mathrm{BDS}} < 0$ at $x_{U_k} = (x_A + x_B)/2$, hence, $\tau_{0\mathrm{BDS}}$ is concave function of x_{U_k}. Similar can be proved for HM selection strategy.

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