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Opportunistic Cooperative Relaying Protocol for UAV-assisted Flying Adhoc Network

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Abstract - A tremendous rise in the use of Unmanned Aerial Vehicles (UAVs) in wireless communication is recently observed. Due to the useful features of UAVs, a new era of over-the-head wireless communication is finding its space at a rapid pace. A range of civilian and military applications is being tested using such UAV-assisted Flying Ad-hoc Networks. In such networks, the quality of communication is usually affected due to fading on channels and limited resources of the UAVs. In this work, we study the outage performance of dual-hop network over Rayleigh fading air-to-ground channels between source UAV and destination Ground Control Station and a group of intermediate UAV aerial relays. We focus on spatial diversity using cooperative relaying through relaying UAVs working in a cooperative manner to support the communication using maximum ratio combining at the destination. The best relay may be selected based on channel state information in terms of signal-to-noise ratio to make the system resource efficient. UAVs are assumed to work in Amplify and Forward mode in Half Duplexed downlink communication scenarios while deriving the closed-form expression for the outage probability. Numerical results are validated using Monte Carlo Simulations to study the impact of various system parameters on performance. The results of proposed non-buffer aided scheme is compared with compulsory direct-only communication. The impact of number of intermediate relays on dual hop links, symmetric and asymmetric channels is studied. The results are compared by changing the data rate and SNR of the links. The results show that cooperative relaying decreases the outage probability. More relays in cooperation, improve the system performance but at the cost of the network increased resources.

Keywords: Flying Ad-hoc Network, Dual-hop, System Outage Probability, Spatial Diversity, Cooperative Relaying, Relay Selection

INTRODUCTION

The Unmanned Aerial Vehicles (UAVs) assisted Flying Ad-hoc Networks (FANETs) are becoming popular in a range of applications like remote sensing, search and rescue operations, traffic monitoring, disaster management, wildlife surveillance, agriculture and communication network expansions, etc. FANETs can disseminate target area observations through multi-hop relayed communication however; these applications demand quality and reliability in operation. The small UAVs in such networks can provide Line of Sight (LoS) communication up to a range of 75 m. Single cluster FANET has its own limitations while Multi-Cluster FANET provides better efficient network management at a reduced cost of communication. Due to typical issues of UAVs, ensuring the quality of service (QoS) in such networks is challenging. Usually UAVs in FANET move at higher speeds of 30-460 km/hr. (İlker Bekmezci, 2013) due to which the network topology is intermittent having fluctuating channel conditions.

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Due to mobility of the UAVs, topology of FANET is dynamic and it is a challenging task to design an efficient data routing protocol for such networks. The selection of channel fading model depends on environment of deployment. The large-scale channel models capture the channel behaviour in terms of effects like path loss and environment of propagation over larger distances, while small-scale models capture the fast-fading effects due to multipath propagation and variations in received signal due to noise and short distances (Waqas et al., 2017). The small-scale channel models are based on stochastic processes and can be mathematically explained by probability density functions (PDFs) and cumulative distribution functions (CDFs).To improve the performance of such system sound mathematical modelling of the system links and efficient data routing schemes are required.

Various studies on improving the system performance of UAV-assisted FANETs have been reported. The authors (Yanmaz, 2021) studied about a team of UAVs for search and rescue missions and worked on decreasing the number of drones by using static relay positioning techniques. The authors (Bodanese, Araújo, Steup, Raffo, & Becker, 2014) presented a communication scenario using IEEE 802.15.4 UAV transceiver enhancing the protocol by introducing an adaptation layer between network and data link layer. The work (Cetin & Zagli, 2011) used IEEE 802.11 MAC for a FANET performing tasks of data collection and delivery among UAVs. The study (Jawhar, Mohamed, Al-Jaroodi, & Zhang, 2013) presented a communication scheme based on UAV as a node between ground nodes and a sink limiting the range of communication of the ground nodes using IEEE 802.11 MAC.

Authors (Zhan, Yu, & Swindlehurst, 2011) studied a system using UAVs as relays between Ground Control Station (GCS) and mobile units (MUs) and using controlled heading angles to study the system performance. The FANET system outage probability was investigated by (Kim & Lee, 2018) for A2G communication considering the co-channel interferences for both line of sight (LoS) and non-LoS (NLoS) links. The outage probability of the FANET of UAVs with energy harvesting capability was studied by (Yang, Chen, Hasna, & Yang, 2018) by modelling the shadowed rice distribution. Using Rician Shadowed Environment, the outage probability for hybrid duplexed UAVs system is studied by (Ernest, Madhukumar, Sirigina, & Krishna, 2019). The work (Goddemeier & Wietfeld, 2015) evaluated IEEE 802.11 links at 2.4GHz using the Rician faded channels to account for flight altitude multipath effects while the work (Wu, Kumar, & Davari, 2005) analysed BER of 802.11a OFDM signals at 5GHz. The symbol error rate and channel capacity as performance parameters were studied (Chen, Hu, Zhu, Zhong, & Chen, 2018) considering both multipath and the shadowing effects (Malik, 2021).

The performance parameters like throughput, delay, symbol error rate and outage probability needs investigation in such networks considering both direct and indirect communication links. In this work, we consider a dual-hop cooperative relay network of UAVs in Amplify and Forward (AF) mode (Jiang & Schotten, 2021) and study their outage performance over Rayleigh fading channels considering the UAVs exchange their data with each other. Next section II, provides the system model in our considered scenario as a general model. The instantaneous end-to-end Signal to Noise Ratio (SNR) expressions for AF relaying are obtained and closed-form expressions for the system outage probability are derived. An upper bound on the end-to-end SNR is used as a high SNR regime. Section III provides performance analysis by formulating the problem. The results of Monte Carlo Simulations for the system outage probability to study the impact of various system parameters on performance are discussed in Section IV while Section V concludes the discussion.

SYSTEM MODEL

Assume a scenario where low altitude single antenna type UAVs are communicating in an urban environment to observe the target area. The shadowing is causing fading between nodes due to the high-rise obstacles of the urban environment assuming the shadowing or large-scale fading is present along with double scattered propagation. Assume that direct and indirect paths are available among source UAV and destination GCS in presence of possible K, UAV relays in this UAV-assisted FANET as depicted in figure 1.

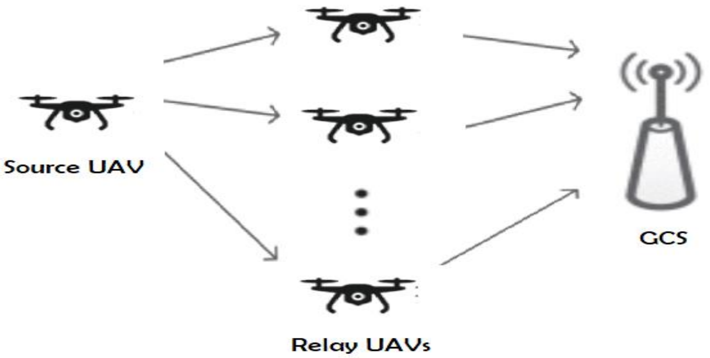

Figure 1: Dual Hop Relay Network of UAVs

The cooperative UAV relay nodes between source and destination provide a means of spatial diversity and pass on the signals over Rayleigh fading channels on dual-hop links assuming UAVs fly at lower altitudes in urban environment. The UAVs are assumed to work in HD fashion and AF mode. The source transmits data that is received by destination and the available relays while relays amplify it and send it to the destination. The source UAV and destination GCS are assumed to calculate transfer probabilities among the available nodes on regular intervals. They use physically distributed opportunistic approach considering their inter-node distance, load, information rate and channel conditions in a non-buffer aiding fashion. The Channel State Information (CSI) is subject to channel variations, however to simplify the analysis, we assume that the CSI remains stationary during a specific time step.

PROBLEM FORMULATION AND PERFORMANCE ANALYSIS

We assume that UAV relays, available between source UAV and destination GCS for the UAVs-assisted FANET communication system, are working in two phases. During first time-slot, source sends a symbol to destination and relays. The destination GCS receives the signal in first time-slot, analyses the signal on direct link from source to destination and if link's SNR is above the threshold value ($\gamma_{th} = 2^{r_o} - 1 \; where \; r_o$ is the data rate on links), it continues with direct transmissions. Once the γ_{SD} falls below γ_{th}, the destination node takes help of the available relays to take part in communication and performs cooperative relaying while destination GCS performs MRC to sum up all signals as per Incremental Relaying (IR) approach. The direct signal received by relay nodes and destination node can be expressed mathematically as

$$y_{N_{SRk}} = E_s x_s h_{SRk} + n_{SRk} \tag{1}$$

$$y_{N_{SD}} = E_s x_s h_{SD} + n_{SD} \tag{2}$$

Here x_s represents the symbol transmitted on first-hop by source and E_s is the average energy of the transmitted signal. Here h_{SD} and h_{SRk} are the direct channel gains from source to destination and relays which are affected by AWGN as $n_{SD} \sim CN(0, N_o)$ with zero mean and N_o variance on source to destination link and $n_{SRk} \sim CN(0, N_o)$ with zero mean and N_o variance on source to relay links respectively. In the second time-slot, the relays amplify and forward the data to the destination as

$$y_{N_{RkD}} = G_{SRk} h_{RkD} y_{N_{SRk}} + n_{RkD} = G_{SRk} h_{RkD} (E_s x_s h_{SRk} + n_{SRk}) + n_{RkD} \tag{3}$$

Here the term G_{SRk} is the gain capability of a k^th^ relay working in AF mode and is defined as $G_{SRk} = \frac{E_s}{E_s |h_{SRk}|^2 + N_o}$. In this expression, E_s is the average energy per symbol, h_{RkD} are the direct channel gains from relays to destination, which are affected by AWGN as $n_{RkD} \sim CN(0, N_o)$ with zero mean and N_o variance. After performing maximum ratio combining (MRC) at the destination node, the signal can be expressed as

$$y_D = y_{N_{SD}} + y_{N_{RkD}} \tag{4}$$

Assuming that all available relays do contribute in cooperative relaying, the instantaneous SNR can be expressed as

$$\gamma_D = \gamma_{SD} + \gamma_{SRkD} = \gamma_{SD} + \sum_{i=1}^{K} \frac{\gamma_{SRk} \cdot \gamma_{RkD}}{1 + \gamma_{SRk} + \gamma_{RkD}} \tag{5}$$

In this expression, the indicated instantaneous SNRs of various links may be defined as $\gamma_{SD} = \frac{E_s|h_{SD}|^2}{N_o}$, $\gamma_{SRk} = \frac{E_s|h_{SRk}|^2}{N_o}$, and $\gamma_{RkD} = \frac{E_s|h_{RkD}|^2}{N_o}$. As per our considered application scenario, Rayleigh fading is selected on the links for whom, the PDF and CDF of the SNR are defined as $f_{\gamma v}(\gamma) = \frac{1}{\overline{\gamma v}} e^{\frac{-\gamma}{\overline{\gamma v}}}$ and $F_{\gamma v}(\gamma) = 1 - e^{\frac{-\gamma}{\overline{\gamma v}}}$. Now assuming upper bound on the total end-to-end SNR to simplify the analysis as

$$\gamma_k \geq \frac{\gamma_{SRk} \cdot \gamma_{RkD}}{1 + \gamma_{SRk} + \gamma_{RkD}} \tag{6}$$

Now the end-to-end SNR after MRC can be expressed as

$$\gamma_D = \gamma_{SD} + \gamma_k \tag{7}$$

In our considered scenario, a best link with a best available relay may be selected to optimize the network resources. This selection can be based on CSI in terms of SNR. Let R_k is a set of available relays and γ_k is the associated SNR of the kth relay, then SNR of the best selected relay in this set will be

$$\gamma_{sRk} = \overset{max}{_{k \in R_k}} \{\gamma_k\} \tag{8}$$

The PDF and CDF of the link SNR in this case can be expressed as $f_{\gamma sr}(\gamma) = K f_k(\gamma) \left[F_{\gamma k}(\gamma)\right]^{K-1}$and $F_{\gamma sk}(\gamma) = \left[F_{\gamma k}(\gamma)\right]^K$ respectively. Now if $\gamma_D < \gamma_{th}$, this situation leads to an event that the communication is not happening. This situation is termed as outage and the probability of outage may be defined in terms of channel capacity. Let c is the channel capacity and if data rate (R) is more than the capacity, situation is termed as outage, as

$$P_{out} = P_r(c < R) \tag{9}$$

That means the total SNR has fallen below γ_{th}. For single relay, outage probability can be expressed as

$$P_{out} = \int_0^{\gamma_{th}} f_\gamma(\gamma) d\gamma = \int_0^{\gamma_{th}} \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}} d\gamma \tag{10}$$

and for the case that if K relays are available and all relays do contribute in the cooperative relaying, the outage probability can be expressed as

$$P_{out} = \int_0^{\gamma_{th}} K f_k(\gamma) \left[F_{\gamma k}(\gamma)\right]^{K-1} d\gamma \tag{11}$$

$$=1 + \sum_{n=1}^{K} \binom{K}{n} \frac{n(-1)^{n-1}}{\bar{\gamma}_c - n\gamma_{SD}} \left[\bar{\gamma}_{SD} e^{-\frac{\gamma_{th}}{\bar{\gamma}_{SD}}} - \frac{\gamma_c}{n} e^{-\frac{n\gamma_{th}}{\bar{\gamma}_c}}\right]$$

Let $\rho_i = \bar{\gamma}_{SRk} = \bar{\gamma}_{RkD}$ is the average channel's SNR on either hop of the relay link, then c is inverse of ρ_i by taking m=1 in expression of Nakagami-m fading for Rayleigh fading case. All available relays can support the communication, however this model is using more resources that makes it resource inefficient. The destination node can select one best relay looking at the channel conditions to make the system more resource efficient as

$$S_{Rk} = arg\overset{max}{_{k \in R_k}} \{\gamma_k\} \tag{12}$$

This selection of a best relay is the case to better utilize the resources as only one relay with best conditions is to be used to relay the signal from source UAV to destination GCS.

RESULTS DISCUSSION

The system performance is studied in terms of outage probability in various settings of the considered system model. Monte Carlo Simulations are used to study the impact of various system parameters and to validate the analytical results of the previous section. Figure 2 demonstrates the impact of Cooperative Relaying (CR) on system performance. The performance of CR using intermediate relays shown by dash graphs is much better compared to direct transmission only between source UAV and the destination GCS ignoring relays shown by solid graph. The relays if considered reduce the outage probability considerably. For this study, the relays count is considered 1 and 2 with the option of relays to cooperate with. For analysis purposes, the data rate is fixed at r = 2 b/s/h. Figure 3 shows a study of the system outage probability for the two data rates as r = 1 corresponding to SNR threshold of 3 and r = 3 corresponding to SNR threshold of 61. Solid graphs show lower data rates and dashed graphs show high data rates with various numbers of intermediate relays as K=1,2, and 3. Results demonstrate that system performance drops at high data rates that confirm the theoretical concepts. On increasing the number of intermediate relays and assuming all relays contribute to the CR, it is observed the outage probability drops and system performance improves. This is due to the fact that there is more chance of successful transmissions.

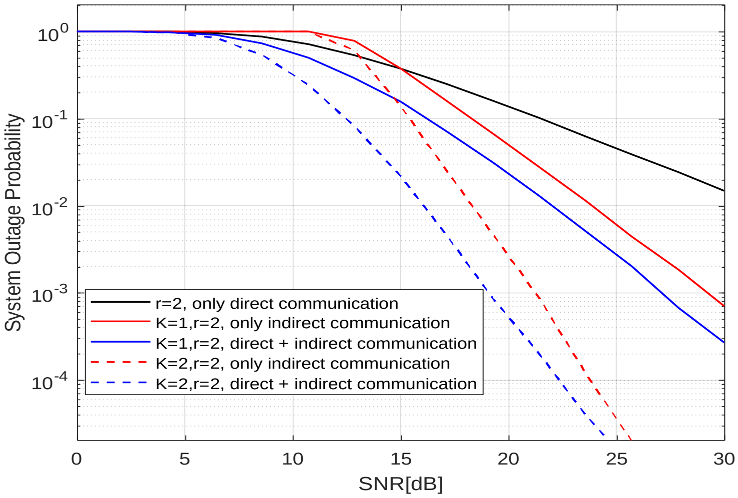

Figure 2: Outage comparison of the direct communication with CR System

Figure 4 compares the same setting but considering that a best relay is selected out of available ones and only the selected relay contributes to CR. The data rate is varied to have the study.

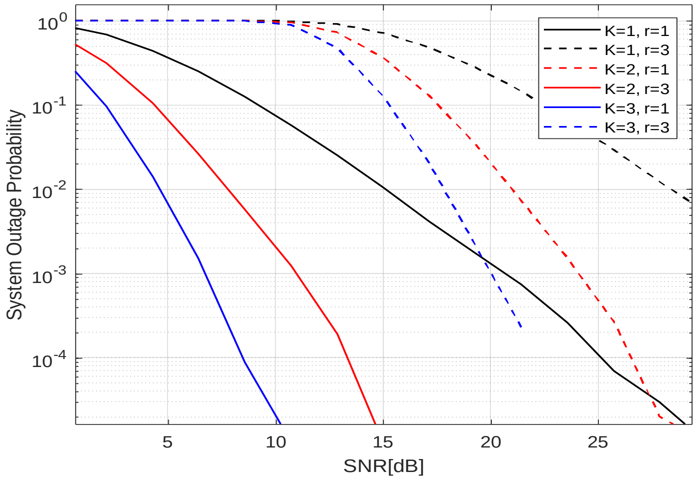

Figure 3: Outage comparison of the CR System with all relays contributing

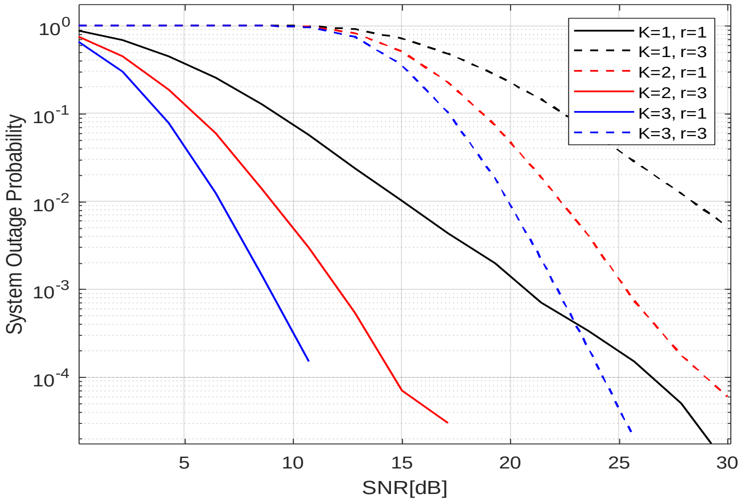

Figure 4: Outage comparison of the CR System with best relay contributing

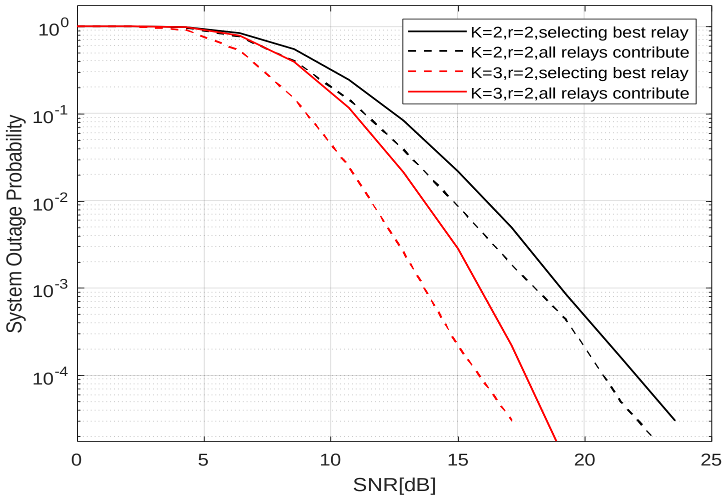

Figure 5: Outage comparison of the CR System with best selected relay and as all relays are contributing

Figure 5 demonstrates a comparison of system performance in conditions that all available relays contribute to CR and when only selected relay contributes providing exact difference. The results are in conformance with previous results that if all relays contribute the outage probability falls improving the system performance. For this study, available relays are considered two, and the data rate is fixed at two. Figure 6 demonstrates the impact of symmetric and asymmetric channels on indirect dual-hop communication. For this study direct link is assumed absent due to heavy shadowing and fading considering the source and destination are far apart. Number of intermediated relays and data rate for this study is considered 2. Results show that a slight improvement is observed in asymmetric cases. This is due to the fact that, asymmetric channels provide relays an option to select suitable packets from the buffer and to take few decisions regarding transmitting to improve the system performance.

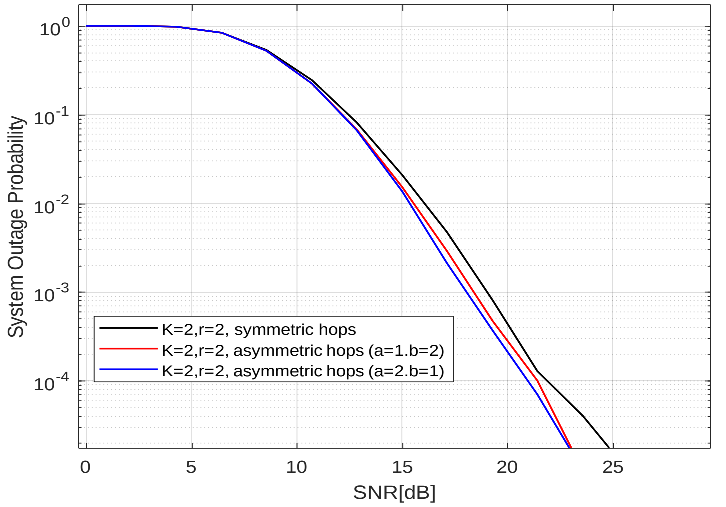

Figure 6: Outage comparison of the dual-hop System with symmetric and asymmetric channels

CONCLUSIONS

In this paper, the performance of the cooperative multi-relay dual-hop UAV-assisted FANET working in AF mode in a downlink scenario is studied over the Rayleigh fading channel affected by AWGN. UAVs have limited powers and limited flight duration that makes the FANET intermittent. General analytical expressions for the end-to-end SNR and the outage probability are derived as a measure of system reliability considering the system taking the opportunity of neighbourhood relays. Opportunistic network formation using available UAVs with sufficient energy can ensure continuous operation of the network. The numerical results are validated using Monte Carlo Simulations that demonstrate that channels working at lower data rates and using cooperative relaying through intermediate relays perform better. Selecting a relay with the best channel conditions improves the system performance and saves the resources. In our study best relay selection is done using the CSI in a non-buffer aided communication scenarios. The asymmetric dual-hop links improve the system performance and provide the option to handle the relay buffer in a better way. In the future, we intend to select the best relay using buffer status conditions in buffer aided network and compare the results with CSI based relay selection scheme for both SISO and MIMO based dual-hop links and with DF type of relays.

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