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UAV Communication Strategies in the Next Generation of Mobile Networks

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***Abstract*— The Next Generation of Mobile Networks (NGMN) alliance advocates the use of different means to support vehicular communications. This aims to cope with the massive data generated by these devices which could affect the Quality of Service (QoS) of the associated applications, but also the overall operation carried out by the vehicles. However, efficient communication strategies must be considered in order to select, for each vehicle, the communication mean ensuring the best QoS. In this paper, we tackle this issue and we propose efficient communication strategies for Unmanned Aerial Vehicles (UAVs). In addition to direct UAV-to-Infrastructure communications (U2I), we also consider UAV-to-UAV scheme (U2U) to transmit data via relay UAVs. The goal is to select for each UAV the best communication strategy and the relay node to maximize the spectral efficiency. The expressions of the effective rate are derived for the different strategies and the problem is formulated using linear programming. Performance evaluations are conducted and the obtained results demonstrate the effectiveness of the proposed solution.**

***Index Terms*— Unmanned Aerial Vehicles (UAVs), Mobile Networks, UAV-to-UAV (U2U), UAV-to-Infrastructure (U2I).**

I. Introduction

Unmanned Aerial Vehicles (UAVs) have initiated a vast range of applications in different fields (cargo delivery, rescue management, surveillance, etc.). Recent forecast studies have shown a wide consensus on the significant expansion that UAVs will achieve in the coming years. The projection from different sources predicts a 300% global growth for the commercial UAV market between 2018 and 2022 [1]. This will put a high pressure on the network infrastructure used for UAVs communication. Indeed, the huge number of connected UAVs will be translated into massive data generated by these devices (e.g., video streaming on the uplink) to be transported by the communication network. Moreover, the latter must also cope with the signaling messages transmitted by the drones. UAV-enabled applications are of critical nature and require signaling messages that are sent with high data rate. This burden could result in decreased Quality of Service (QoS) for the associated applications, and could also affect the overall operations of the flying UAVs.

In order to enable their adoption, it is highly important to ensure an efficient communication infrastructure to accommodate the huge number of UAVs, along with their massive generated data. In this regard, both industrial and scientific communities are heading towards using mobile networks as a key enabler for UAV communications. This enables UAVs to benefit from the advances achieved by these networks (LTE, 5G and beyond). Moreover, in order to boost the efficiency, the Next Generation of Mobile Network (NGMN) alliance advocates the use of different communication means to support vehicular communications. The concept of *cellular vehicle to everything* (V2X) is advanced to refer to the different communication patterns that vehicles can rely on [2]. The consideration of such an approach for UAVs will provide huge opportunity which can be exploited to cope with the burden associated with the UAVs' massive data, and to enhance the spectral efficiency. This must be associated with efficient strategies to select the optimal communication mean for each UAV in a way to maximize the QoS.

The interest in mobile network enabled-UAVs has been translated into different works from both industrial and academic communities. For instance, the 3rd Generation Partnership Project (3GPP) have performed real field trials to evaluate the use of LTE networks to support drones' communications [3]. In another work [4], the authors have carried out real field evaluations on the use of an LTE network to realize uplink data and downlink control of a flying airborne. Beside these field evaluations, different works have studied challenges related the use of cellular networks as a communication infrastructure for UAVs. In [5] the authors have investigated the degradation of the network performance caused by cellular UAVs in the uplink scenario, while enhancing UAVs connectivity in the downlink scenario has been studied in [6]. The problem of connection steering for UAVs has been addressed in [7] and [8]. The authors consider the eventual availability of several mobile network operators within the communication range of the flying UAVs to steer the connection to the mobile network ensuring the best QoS.

However, the issue of communication strategies is not considered by these works dealing with mobile network-enabled UAVs. Such strategies would exploit the different communication means for the UAVs to boost the QoS for the associated applications and also the overall operations. This underpins the focus of this article, where efficient communication strategies are proposed for cellular UAVs. In addition to UAV-to-Infrastructure (U2I) communication, we also consider UAV-to-UAV (U2U) scheme to send data via a relay node. The aim is to select for each UAV the communication strategy ensuring the best QoS. The main contributions of the paper are the following

- Unlike existing works on cellular UAVs, we tackle the issue of efficient selection of communication strategies. We consider in the proposed model most of propagation phenomena experienced by wireless signals, such as fast fading, path loss, and interference. We derive the expression of the effective rate for the different communication strategies (Section II).

- Based on the proposed model, we provide a method to select the optimal communication strategy for each UAV. The problem is formulated using linear programming and and the optimal communication strategy is obtained (Section III).
- We demonstrate through numerical evaluations the benefit of the proposed solutions in enhancing the effective rate of UAVs (Section IV).

II. System model and problem formulation

This section describes the proposed communication model. We consider an *uplink* scenario in which flying UAVs send data to their serving base stations (BSs) using one of the following strategies. In strategy 1, the UAV sends its packet using a direct communication with its serving BS, while in strategy 2, the UAV uses dual-hop communication to transmit its data to the BS via a relay node. The latter is a UAV that operates in a decode-and-forward mode as illustrated in Fig. 1.

Let $\mathbb{U}$ be the set of UAVs and $\mathbb{V}$ the set of BSs (notations are provided in Table I). The source UAV node is denoted by $u \in \mathbb{U}$, while the relay UAV node is referred to as u' and the destination BS node is denoted by v. The fading coefficients for the links uu', $u'v$, and uv are denoted by $h_{uu'}$, $h_{u'v}$, and h_{uv}, respectively, and follow Nakagami-m distributions. Both the relay u' and the destination BS v are affected by several interferers as shown in Fig. 1. This interference originates from other UAVs in neighboring cells that use the same subcarriers as the source UAV u and the relay UAV u'. We assume that each interference term follows a Nakagami-m

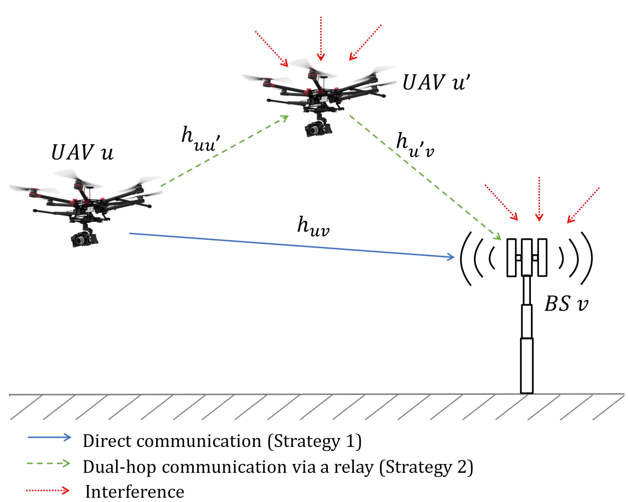

Fig. 1: System model (uplink scenario): The UAV u sends its data to its serving BS v either directly (strategy 1) or via a relay UAV u' (strategy 2).

TABLE I: Summary of Notations.

Notation	Description
$\mathbb{U}$	Set of UAVs.
$\mathbb{V}$	Set of BSs.
uv	Link between a UAV $u \in \mathbb{U}$ and its serving BS $v \in \mathbb{V}$.
uu'	Link between a UAV $u \in \mathbb{U}$ and its relaying UAV $u' \in \mathbb{U}$.
$\eta(u)$	The neighbors of the UAV u in the graph G.
$X_{u,y}$	A boolean variable that indicates whether the UAV $u \in \mathbb{U}$ selects $y \in \eta(u)$ as the next hop.
ε	A variable that represents the minimum effective rate in the network.

distribution. Note that by adjusting the parameters of the Nakagami-m distribution, we can model both LOS (line of sight) and non-LOS conditions. Let $u \in \mathbb{U}$ denotes the transmitting UAV and $y \in \mathbb{U} \cup \mathbb{V}$ the receiving node. Then, the received signal r_y can be expressed as

$$r_y = h_{uy}\sqrt{P_u}x_u + \sum_{t=1}^{N} h_{ty}\sqrt{P_t}x_t + n_y \quad (1)$$

where h_{uy} refers to the channel gain between the transmitter u and the receiver y. The second term in the right hand side of (1) accounts for the interference impact from node t $(t = 1, \ldots, N)$ and h_{ty} refers to the fading coefficient from the interfering node t to the receiver node y. The nodes u and t transmit the symbols x_u and x_t with the powers P_u and P_t, respectively. The third term in (1), n_y, is a zero-mean additive white Gaussian noise with variance N_0. The instantaneous received signal-to-noise ratio (SNR), γ_{uy}, can be expressed as

$$\gamma_{uy} = P_u h_{uy}^2 / N_0. \quad (2)$$

The mean value of γ_{uy} is denoted by $\bar{\gamma}_{uy}$ and can be determined as

$$\bar{\gamma}_{uy} = P_u \mathbb{E}[h_{uy}^2]/N_0 = P_u \times 10^{-\frac{PL_{uy}}{10}}/N_0. \quad (3)$$

where $\mathbb{E}[h_{uy}^2]$ represents the channel variance $\mathbb{E}[\cdot]$ denotes the expectation operator. The channel variance can be computed as $\mathbb{E}[h_{uy}^2] = 10^{-\frac{PL_{uy}}{10}}$, where PL_{uy} represents the path loss in dB scale. We consider in our study the path loss model adopted by 3GPP [3], i.e.,

$$PL_{uy} = 28.0 + 22\,\log_{10}(d_{uy}^{3D}) + 20\,\log_{10}(f_c) \quad (4)$$

where f_c stands for the carrier frequency, and d_{uy}^{3D} is the Euclidean distance between the transmitter and the receiver.

Henceforth, we use the shorthand notation $X \sim \mathscr{G}(\alpha, \beta)$ to denote that X follows a Gamma distribution with parameters α and β. The SNR γ_{uv} is Gamma distributed with parameters α_{uv} and $\beta_{uv} = \bar{\gamma}_{uv}/\alpha_{uv}$, i.e., $\gamma_{uv} \sim \mathscr{G}(\alpha_{uv}, \beta_{uv})$. The BS v is affected by N interfering nodes t $(t = 1, \ldots, N)$. The total interference at the BS $\gamma_{Iv} = \sum_{t=1}^{N} P_t h_{tv}^2 = \sum_{t=1}^{N} \gamma_{Itv}$ is the sum of N independent non-identically distributed Gamma RV, with $\gamma_{Itv} \sim \mathscr{G}(\alpha_{tv}, \beta_{tv})$. The probability density function (PDF) of the total interference γ_{I_v} can be approximated by a Gamma distribution with parameters α_s and β_s, i.e., $\gamma_{I_v} \sim \mathscr{G}(\alpha_s, \beta_s)$. The parameters α_s and β_s can be expressed as

$$\alpha_s = \frac{(\sum_{t=1}^{N_v} \alpha_{tv}\beta_{tv})^2}{\sum_{t=1}^{N_v} \alpha_{tv}\beta_{tv}^2} \quad (5) \qquad \beta_s = \frac{\sum_{t=1}^{N_v} \alpha_{tv}\beta_{tv}^2}{\sum_{t=1}^{N_v} \alpha_{tv}\beta_{tv}} \quad (6)$$

where $\beta_{tv} = \bar{\gamma}_{tv}/\alpha_{tv}$.

In order to evaluate the link quality between a flying UAV and the receiving BS, we derive the expressions of the effective rate in the two strategies (direct communication and dual-hop communication).

Theorem 1: ***Effective Rate for Direct Communication***

For a UAV $u \in \mathbb{U}$ transmitting with a rate R via a direct communication to its serving BS $v \in \mathbb{V}$. The BS is affected by N interfering nodes t ($t = 1, \ldots, N$). The effective rate at the receiving BS can be expressed as

$$R_{\text{eff}}^{uv}(R) = R \times I(2^R - 1, \alpha_{uv}, \beta_{uv}, \alpha_s, \beta_s). \tag{7}$$

The function $I(\cdot)$ is expressed as

$$I(x, \alpha, \beta, \alpha_s, \beta_s) = \left(\frac{x\beta_s}{\beta}\right)^{-\alpha_s} \frac{\Gamma(\alpha + \alpha_s)}{\Gamma(\alpha)\Gamma(1+\alpha_s)} \, {}_2F_1\left(\alpha_s, \alpha + \alpha_s, 1 + \alpha_s, \frac{-\beta}{x\beta_s}\right) \tag{8}$$

where ${}_2F_1(a, b, c, z)$ is the Gauss hypergeometric function.

Proof: See Appendix I. ■

For the second strategy, where dual-hop relaying is used to communicate between a UAV and the BS. The effective rate can be characterized using the following theorem.

Theorem 2: ***Effective Rate for Dual-Hop Communication***

For a UAV $u \in \mathbb{U}$ transmitting with a rate R via a relay UAV u', the effective rate at the receiving BS $v \in \mathbb{V}$ can be expressed as

$$\begin{aligned} R_{\text{eff}}^{u}(R) = R &\times I(2^R - 1, \alpha_{uu'}, \beta_{uu'}, \alpha_{s_{u'}}, \beta_{s_{u'}}) \\ &\times I(2^R - 1, \alpha_{u'v}, \beta_{u'v}, \alpha_s, \beta_s) \end{aligned} \tag{9}$$

The total interference at the relay u' and the BS v are approximated by the Gamma distributions $\mathscr{G}(\alpha_{s_{u'}}, \beta_{s_{u'}})$ and $\mathscr{G}(\alpha_s, \beta_s)$, respectively.

Proof: See Appendix I. ■

The above theorems provide the effective rates for both direct communication (Theorem 1) and dual-hop communication via a relay UAV (Theorem 2). This reflects two different strategies that can be exploited by each UAV to transmit data in the uplink scenario. In order to enhance the effective rate, an optimal selection of the communication strategy and the next hop should be achieved for each UAV in the network. The next section deals with this issue and proposes a solution for optimal strategy selection in the context of cellular-enabled UAVs.

III. UAV COMMUNICATION OPTIMAL STRATEGIES

This section introduces the proposed solution for optimal communication strategies in cellular UAVs. Each UAV can choose transmitting its data either directly (direct communication) to its serving BS, or via a relay UAV (dual-hop communication). In order to lightweight the complexity of the problem, we propose to reduce the search space of the next hop of a UAV u to a feasible set $\eta(u)$. Indeed, if two nodes, $u \in \mathbb{U}$ and $y \in \mathbb{U} \cup \mathbb{V}$, are not able to communicate in interference-free conditions, the communication process would fail in the presence of interference. In the light of this, we define a communication range $\bar{d}_u$ for each UAV u and we introduce the following lemma.

Lemma 1: *A UAV $u \in \mathbb{U}$ can transmit its packets to a next node $y \in \mathbb{U} \cup \mathbb{V}$ iff the Euclidean distance between the two nodes is within a range $\bar{d}_u$ defined as*

$$\bar{d}_u = 10^{-[10log_{10}(\gamma_{th}N_0/P_u)+28.0+20\log_{10}(f_c)]/22}, \tag{10}$$

where γ_{th} is the threshed SNR which reflects the sensitivity of the receiver.

Proof:

Starting from equations (4) and (3), we can write $\bar{\gamma}_{uy}$ as

$$\bar{\gamma}_{uy} = P_u/N_0 \times 10^{-\frac{28.0+22\log_{10}(d_{uy}^{3D})+20\log_{10}(f_c)}{10}}. \tag{11}$$

In general, a packet is successfully received if the mean SNR at y, $\bar{\gamma}_{uy}$, exceeds the threshold γ_{th}. Thus, we can derive $\bar{d}_u$ from (11) as follows

$$\bar{d}_u = 10^{-[10log_{10}(\gamma_{th}N_0/P_u)+28.0+20\log_{10}(f_c)]/22}. \tag{12}$$

Note that the result of (12) is the same as that of equation (10) of Lemma 1.

■

Based on the communication range $\bar{d}_u$ of each UAV u, we formally define the set $\eta(u)$ of u's neighbors as depicted in equation (13). This set gathers the UAVs having an euclidean distance less than $\bar{d}_u$ to the UAV u. In addition, we also assume that, v, the serving BS of u is among the neighbors.

$$\eta(u) = \{u' \in \mathbb{U}; d_{uu'}^{3D} \leq \bar{d}_u\} \cup \{v\}. \tag{13}$$

In order to find the optimal strategy to be selected by each UAV, we model the problem as an integer program. We define a boolean variable, $X_{u,y}$, to indicate whether the UAV $u \in \mathbb{U}$ selects the node $y \in \eta(u)$ as the next hop or not. This variable is also used to ensure that each UAV is connected to a BS with at most two hops. The formulation of the problem is as follows:

$$\max \min_{u \in \mathbb{U}} \left(\sum_{y \in \eta(u)} X_{u,y} R_{\text{eff}}^{u}(R) \right) \tag{14}$$

s.t.

$$\forall u \in \mathbb{U}, \forall y \in \eta(u); \quad X_{u,y} \in \{0, 1\} \tag{15}$$

$$\forall u \in \mathbb{U}; \quad \sum_{y \in \eta(u)} X_{u,y} = 1 \tag{16}$$

$$\forall u \in \mathbb{U}; \quad \left(\sum_{y \in \eta(u) \cap \mathbb{U}} X_{u,y} \right) \times \left(\sum_{z \in \eta(y) \cap \mathbb{U}} X_{y,z} \right) = 0 \tag{17}$$

The objective function (14) of the above optimization problem aims to maximize the minimum effective rate for the set U of UAVs, while ensuring constraints (15) - (17). Constraint (15) limits the value of the decision variable $X_{u,y}$ to $\{0,1\}$. Constraint (16) ensures that each UAV u will select only one neighbor as successor. Constraint (17) ensures that the communication between a UAV to a BS will go at most through two hops. If a UAV y is selected as a relay node for another UAV u, the former should not choose another UAV. Consequently, $\forall u \in \mathbb{U}; \left(\sum_{y \in \eta(u) \cap \mathbb{U}} X_{u,y}\right) = 1 \implies \left(\sum_{z \in \eta(y) \cap \mathbb{U}} X_{y,z}\right) = 0$. This constraint also ensures that there will be no cycle when relaying UAVs' packets.

However, the above optimization problem is not convex, which is due to the constraint (17). The latter limits the communication between a UAV and a BS to two hops, at most. Therefore, to simplify this constraint and make the related optimization problem linear, we propose the following transformation:

$$\forall u \in \mathbb{U}; \quad \sum_{y \in \eta(u) \cap \mathbb{U}} X_{y,u} \leq \left(1 - \sum_{z \in \eta(u) \cap \mathbb{U}} X_{u,z} \right) (|\eta(u)| - 1) \tag{18}$$

The above equation ensures the following. If a UAV u selects another UAV z as a relay node, the former should not be selected by any other UAV y for relaying packets. The second term of equation (18), $(1 - \sum_{z \in \eta(u) \cap \mathbb{U}} X_{u,z})(|\eta(u)| - 1)$, will be equal to zero if u selects another UAV z as a relay node. In this case, no other UAV y in u's neighbors ($y \in \eta(u) \cap \mathbb{U}$) should select u as a relay node. In the other hand, if u uses direct communication and does not select a relaying UAV, the second term of equation (18) will be equal to $|\eta(u)| - 1$. This would allow u to be the relaying node of this number of UAVs, which represents the number of its UAVs neighbors. In addition, in order to implement the *max-min* problem, we introduce a variable ε which represents the minimum effective rate in the network. The following condition is therefore considered

$$\forall u \in \mathbb{U}; \quad \varepsilon \leq \sum_{y \in \eta(u)} X_{u,y} R^{u}_{\text{eff}}(R) \tag{19}$$

Consequently, the objective function becomes maximizing the variable ε and the previous model can be updated as follows:

$$\max \ \varepsilon \tag{20}$$

s.t.

$$\forall u \in \mathbb{U}; \quad \varepsilon \leq \sum_{y \in \eta(u)} X_{u,y} R^{u}_{\text{eff}}(R) \tag{21}$$

$$\forall u \in \mathbb{U}, \forall y \in \eta(u); \quad X_{u,y} \in \{0,1\} \tag{22}$$

$$\forall u \in \mathbb{U}; \quad \sum_{y \in \eta(u)} X_{u,y} = 1 \tag{23}$$

$$\forall u \in \mathbb{U}; \quad \sum_{y \in \eta(u) \cap \mathbb{U}} X_{y,u} \leq \left(1 - \sum_{z \in \eta(u) \cap \mathbb{U}} X_{u,z} \right) (|\eta(u)| - 1) \tag{24}$$

IV. PERFORMANCE EVALUATION

Performance evaluations are performed in order to assess the proposed method. The evaluations are performed throughout simulations, while the Gurobi optimization tool [9] is used to solve the optimization problem. The communication model is implemented using a carrier frequency f_c of 2 GHz and a noise variance N_0 of $-130dBm$ [10]. We consider a square area of size $1000m \times 1000m$ with 12 BSs and different number of deployed UAVs depending on the performed test. The illustrated results are obtained by averaging over 10 trials.

We have evaluated the effect of the receiver sensitivity (γ_{th}) on the achieved effective rate at the BSs, considering 100 UAVs and different transmission rates (i.e. 0.01, 0.05 and 0.1 bit/s/Hz). This parameter affects the communication range $\bar{d_u}$ which is used to define the set of neighbors for the UAV u, as specified in equation (13). As can be seen from Fig. 2, decreasing the value of the parameter γ_{th} allows enhancing the effective rate at the BSs. This is due to the fact that the smaller γ_{th} is the better the receiver can detect weaker signals. Consequently, the communication range $\bar{d_u}$ becomes higher allowing to have bigger size of the neighboring set $\eta(u)$. This provides more choices for selecting the next hop in a way to enhance the effective rate. In the other hand, big values of the parameter γ_{th} could be translated into having only the serving BS in the neighboring list. This limits the strategies to the direct communication. Moreover, decreasing the parameter γ_{th} bellow a certain value does not enhance more the effective rate. This is because that the included neighbors are not used as next hops, as they do not ensure enhanced effective rate. The value 10^6 is used for the receiver sensitivity parameter (γ_{th}) in the next evaluations. We can also see from Fig. 2 that the parameter γ_{th} does not affect much the effective rate when employing lower value for R. This is because direct communication was selected as the best strategy when using lower rate. The value 0.1 is for R in the next evaluations.

Fig. 3 shows the benefit of the proposed solution compared to the use of direct communication. The latter reflects the baseline situation as UAVs, by default, rely on direct communication (U2I) for transmitting data. As it can be seen, the proposed solution achieves better effective rate even when considering different number of deployed UAVs. Indeed, while UAVs can use direct link to communicate with the serving BS, the proposed solution introduces more choices through the use of relay nodes. The efficient exploitation of the different choices allows providing enhanced effective rate

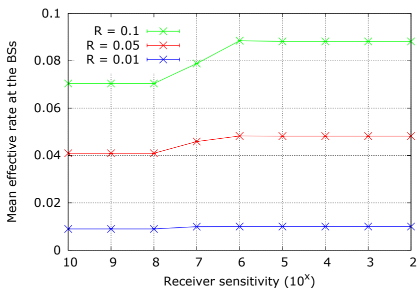

Fig. 2: Effect of the receiver sensitivity

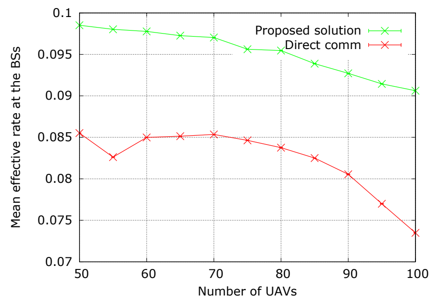

Fig. 3: Evaluation of the effective rate at the BSs

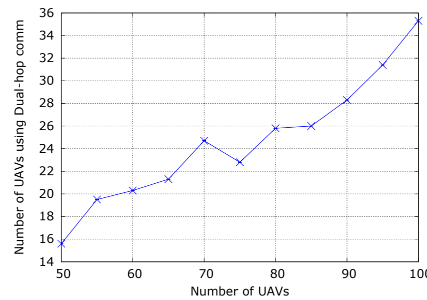

Fig. 4: Evaluation of the umber of UAVs using Dual-hop communication

at the receiving BS. This also proves the effectiveness of the proposed solution in selecting the strategy and the next hop for each UAV in a way to increase the spectral efficiency. We can also see from Fig. 3 that the effective rate at the BSs decreases as the number of deployed UAVs increases. This results from the increased amount of interference in the network. However, the obtained results demonstrate that the proposed solution achieves better QoS even when considering big number of UAVs.

We have also evaluated the number of UAVs using dual-hop communication (strategy 2) in the network considering different deployments. This reflects the strategy which is not used in the default situation by the UAVs. The obtained results are shown in Fig. 4. In the different evaluations the number of UAVs relying on dual-hop communication is almost 30% of the total number of deployed UAVs. This shows that an important portion of the deployed UAVs are using dual-hop communication to achieve enhanced QoS, whereas this strategy is not considered in default situation. This goes in the same direction as the results obtained in the previous evaluations and confirms the relevance of such strategies in maximizing the spectral efficiency.

V. Conclusion

One challenging problem in cellular UAVs is to cope with the massive data generated by these vehicles which could lead to decreased QoS. In this paper, we addressed the issue of selecting the efficient communication strategy for UAVs. For this purpose, we considered a communication model that accounts for most of propagation phenomena experienced by wireless signals, and we derived the expression of the effective rate for the two strategies i.e., direct communication and via a relay. Thereafter, we proposed a solution for selecting for each UAV the communication strategy providing better effective rate. We have also shown through simulations the efficiency of the proposed solution in achieving optimized QoS for the cellular UAVs.

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Appendix I
Appendix: Proof of Theorems 1 and 2

This section provides the proof of theorems 1 and 2. We derive the effective rate for both direct communication and dual-hop communication via a relay UAV, respectively. We start by providing the general expression of the effective rate which is given as

$$R^u_{\text{eff}}(R) = R \times (1 - P_{out}(R)), \tag{I.1}$$

where R is the transmission rate of the source UAV u. $P_{out}(R)$ is the probability of a packet transmission failure if the source UAV uses a transmission rate R which can be expressed as

$$P_{out}(R) = P[\log_2(1 + SINR) < R] = P[SINR < 2^R - 1] \tag{I.2}$$

where the $SINR$ stands for the Signal-to-interference-plus-noise ratio computed as follows

$$SINR_{uv} = \frac{\gamma_{uv}}{1+\sum \gamma_{tv}} \approx \frac{\gamma_{uv}}{\sum \gamma_{tv}}. \tag{I.3}$$

The approximation in (I.3) is valid if the noise power can be neglected compared to the interference power. This is generally a well accepted assumption in the literature and is known as an interference-limited regime.

Strategy 1: Direct Communication

In this scenario, the source UAV u transmits its packets to its serving BS v. We can therefore define the outage probability for the link uv as follows

$$\begin{aligned} P_{out}(x) &= P(SINR_{uv} < x) && \text{(I.4)} \\ &= P\left(\frac{\gamma_{uv}}{\gamma_{Iv}} < x\right) = E_{\gamma_{Iv}}\left(P[\gamma_{uv} < x\gamma_{Iv}]\right) && \text{(I.5)} \\ &= \int_0^\infty F_{\gamma uv}(xy) f_{\gamma_{Iv}}(y)dy && \text{(I.6)} \end{aligned}$$

where $F_{\gamma uv}(\cdot)$ is the Cumulative Distribution Function (CDF) of γ_{uv} and $f_{\gamma_{Iv}}(\cdot)$ is the PDF of γ_{Iv}. The channel coefficient h_{uv} for link uv is assumed to be Nakagami distribution, and thus γ_{uv} is Gamma distributed, i.e., $\gamma_{uv} \sim \mathscr{G}(\alpha_{uv}, \beta_{uv})$, with the corresponding PDF given as

$$f_{\gamma_{uv}}(x) = \frac{x^{\alpha_{uv}-1}}{\beta_{uv}^{\alpha_{uv}}\Gamma(\alpha_{uv})} exp\left(-\frac{x}{\beta_{uv}}\right), \tag{I.7}$$

where α_{uv} is the Nakgami fading parameter for the link uv, and $\beta_{uv} = \frac{\bar{\gamma}_{uv}}{\alpha_{uv}}$. The CDF of γ_{uv} can be computed as

$$F_{\gamma_{uv}}(x) = 1 - \frac{\Gamma(\alpha_{uv}, x/\beta_{uv})}{\Gamma(\alpha_{uv})}, \tag{I.8}$$

where $\Gamma(\alpha_{uv}, x/\beta_{uv})$ is the upper incomplete gamma function defined as $\Gamma(s,x) = \int_x^\infty t^{s-1}e^{-t}dt$. As for the PDF of $f_{\gamma_{Iv}}(y)$, it represents the PDF of the interference which is the sum of independent and non-identical Gamma distributions, where $\gamma_{tv} \sim \mathscr{G}(\alpha_{tv}, \beta_{tv})$ and $\beta_{tv} = \frac{\bar{\gamma}_{tv}}{\alpha_{tv}}$. The PDF of the total interference γ_{Iv} can be approximated by a Gamma distribution with parameters α_s and β_s which are given as

$$\alpha_s = \frac{(\mathbb{E}[\gamma_{Iv}])^2}{Var(\gamma_{Iv})} \quad \text{(I.9)} \qquad \beta_s = \frac{Var(\gamma_{Iv})}{\mathbb{E}[\gamma_{Iv}]} \quad \text{(I.10)}$$

As for $\mathbb{E}[\gamma_{Iv}]$ and $Var(\gamma_{Iv})$, they are computed as

$$\mathbb{E}[\gamma_{Iv}] = \sum_{t=1}^{N_v} \mathbb{E}[\gamma_{tv}] = \sum_{t=1}^{N_v} \alpha_t \beta_t \tag{I.11}$$

$$Var(\gamma_{Iv}) = \sum_{t=1}^{N_v} Var(\gamma_{tv}) = \sum_{t=1}^{N_v} (\mathbb{E}[(\gamma_{tv})^2] - (\mathbb{E}[\gamma_{tv}])^2) \tag{I.12}$$

Consequently, α_s and β_s will be

$$\alpha_s = \frac{(\sum_{t=1}^{N_v} \alpha_{tv}\beta_{tv})^2}{\sum_{t=1}^{N_v} \alpha_{tv}\beta_{tv}^2} \quad \text{(I.13)} \qquad \beta_s = \frac{\sum_{t=1}^{N_v} \alpha_{tv}\beta_{tv}^2}{\sum_{t=1}^{N_v} \alpha_{tv}\beta_{tv}} \quad \text{(I.14)}$$

Thereafter, the outage probability can be expressed as

$$\begin{aligned} P_{out}(x) &= 1 - \int_0^\infty \frac{\Gamma(\alpha_{uv}, xy/\beta_{uv})}{\Gamma(\alpha_{uv})} f_{\gamma_{Iv}}(y)dy && \text{(I.15)} \\ &= 1 - \underbrace{\int_0^\infty \frac{\Gamma(\alpha_{uv}, xy/\beta_{uv})}{\Gamma(\alpha_{uv})} \frac{y^{\alpha_s-1}}{\beta_s^{\alpha_s}\Gamma(\alpha_s)} exp\left(-\frac{y}{\beta_s}\right) dy}_{I_u} \\ &= 1 - I_u && \text{(I.16)} \end{aligned}$$

The integral I_u can be computed as

$$\begin{aligned} I_u = \left(\frac{x\beta_s}{\beta_{uv}}\right)^{-\alpha_s} & \frac{\Gamma(\alpha_{uv}+\alpha_s)}{\Gamma(\alpha_{uv})\Gamma(1+\alpha_s)} \\ & {}_2F_1\left(\alpha_s, \alpha_{uv}+\alpha_s, 1+\alpha_s, \frac{-\beta_{uv}}{x\beta_s}\right), && \text{(I.17)} \end{aligned}$$

where ${}_2F_1(.)$ is the Gauss hypergeometric. Thus the outage probability for the direct link uv can be written as

$$P_{out}(x) = 1 - I(x, \alpha_{uv}, \beta_{uv}, \alpha_s, \beta_s), \tag{I.18}$$

where the function $I(\cdot)$ is the same provided in equation (I.17). With the help of equations (I.1) and (I.2), the effective rate expression for the direct link can be expressed as

$$R^u_{\text{eff}}(R) = R \times I(2^R - 1, \alpha_{uv}, \beta_{uv}, \alpha_s, \beta_s) \tag{I.19}$$

The result in (I.19) is the same as the effective rate provided in Theorem 1. ■

Strategy 2: Dual-Hop Communication

In this strategy, the UAV u transmits its data to the BS v using dual-hop communication via a relay UAV u'. This relay UAV forward the packets from the source UAV u to its serving BS v. Thus, the outage probability can be computed as

$$\begin{aligned} P_{out}(x) &= P\big(\min(SINR_{uu'}, SINR_{u'v}) \leq x\big) && \text{(I.20)} \\ &= F_{\gamma_{uu'}}(x) + F_{\gamma_{u'v}}(x) - F_{\gamma_{uu'}}(x)F_{\gamma_{u'v}}(x) && \text{(I.21)} \end{aligned}$$

Similar to the direct communication case, the CDF $F_{\gamma_{uu'}}$ can be obtained by assuming that the relay u' is subject to $N_{u'}$ interferers. The link uu' is assumed to be Nakagami distributed their corresponding SNR are Gamma distributed. We can express the CDFs $F_{\gamma_{uu'}}(x)$ and $F_{\gamma_{u'v}}(x)$ as

$$\begin{cases} F_{\gamma_{uu'}}(x) = 1 - I(x, \alpha_{uu'}, \beta_{uu'}, \alpha_{s_{u'}}, \beta_{s_{u'}}) \\ F_{\gamma_{u'v}}(x) = 1 - I(x, \alpha_{u'v}, \beta_{u'v}, \alpha_s, \beta_s). \end{cases} \tag{I.22}$$

With the help of (I.20) and (I.22), we can determine the outage probability as

$$\begin{aligned} P_{out}(x) = 1 - I(x, \alpha_{uu'}, \beta_{uu'}, \alpha_{s_{u'}}, \beta_{s_{u'}}) \times \\ I(x, I(x, \alpha_{u'v}, \beta_{u'v}, \alpha_s, \beta_s). && \text{(I.23)} \end{aligned}$$

Using (I.23) and (I.1), the effective rate can be obtained as

$$\begin{aligned} R^u_{\text{eff}}(R) = R \times I(2^R - 1, \alpha_{uu'}, \beta_{uu'}, \alpha_{s_{u'}}, \beta_{s_{u'}}) \\ \times I(2^R - 1, \alpha_{u'v}, \beta_{u'v}, \alpha_s, \beta_s), && \text{(I.24)} \end{aligned}$$

which is the same as (9) given in Theorem 2. This concludes the proof of the two theorems. ■