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Published in:
2022 20th Mediterranean Communication and Computer Networking Conference (MedComNet)

DOI (link to publication from Publisher):
10.1109/MedComNet55087.2022.9810453

Publication date:
2022

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Deshpande, A. A., Vaca-Rubio, C. J., Mohebi, S., Salami, D., Carvalho, E. D., Popovski, P., Sigg, S., Zorzi, M., & Zanella, A. (2022). Energy-Efficient Design for RIS-assisted UAV communications in beyond-5G Networks. In *2022 20th Mediterranean Communication and Computer Networking Conference (MedComNet)* (pp. 158-165). Article 9810453 IEEE Communications Society. https://doi.org/10.1109/MedComNet55087.2022.9810453

Energy-Efficient Design for RIS-assisted UAV communications in beyond-5G Networks

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***Abstract*—The usage of Reconfigurable Intelligent Surfaces (RIS) in conjunction with Unmanned Ariel Vehicles (UAVs) is being investigated as a way to provide energy-efficient communication to ground users in dense urban areas. In this paper, we devise an optimization scenario to reduce overall energy consumption in the network while guaranteeing certain Quality of Service (QoS) to the ground users in the area. Due to the complex nature of the optimization problem, we provide a joint UAV trajectory and RIS phase decision to minimize transmission power of the UAV and Base Station (BS) that yields good performance with lower complexity. So, the proposed method uses a Successive Convex Approximation (SCA) to iteratively determine a joint optimal solution for UAV Trajectory, RIS phase and BS and UAV Transmission Power. The simulation results show the algorithm provides a minimum guaranteed rate while minimising transmission power of UAV and BS.**

***Index Terms*—Energy Efficient Network, Unmanned Aerial Vehicles, Reconfigurable Intelligent Surfaces**

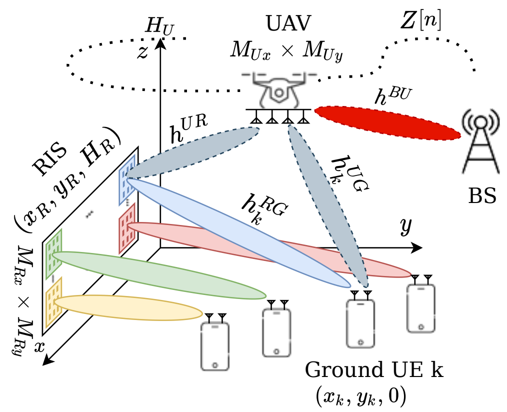

Fig. 1. The problem scenario

I. Introduction

Increasing demand for sustainable and flexible connectivity specifically for either semi-urban/rural areas [1], [2] or disaster scenarios for monitoring and surveillance [3], [4], has led to focus on the usage of Unmanned Aerial Vehicles (UAVs) and Reconfigurable Intelligent Surfaces (RIS) for enhancing the network coverage and, thereby, the service availability of cellular networks. The conceptual design of RIS consists of several reflective elements which can be configured so as to reflect and, in particular, beamform a signal towards a particular direction. Recently, there have been certain works that have provided definitions and optimization scenarios to tackle the direct links between UAVs and User Equipments (UEs) as well as links between UAV and UE with the aid of RIS [5]–[8]. However, the issues of the existence and capacity limitation of the link from Base Stations (BSs) to UAVs have not been considered so far in conjunction with the issue of optimizing the UAV movement and RIS configuration. This should not be overlooked as the performance of the system clearly depends on the whole path from BS to the UEs. Indeed, UAVs and RIS can be used to create mobile micro cells to serve temporary hotspots, i.e., areas with very high service requirement at a certain time.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant agreement No. 813999.

One of the major hurdles while using both these technologies is the energy consumption of the system as a whole. UAVs, especially quadcopters, generally run on small batteries and the energy consumption is very high when the UAV is in flight. Therefore, to provide sustained coverage to the UEs with high Quality of Service (QoS) requirements, the trajectory of the UAV has to be optimized. The use of RIS, which can improve the coverage in certain areas, may help reducing the need for UAVs to travel further, with a small trade-off on the energy consumed for RIS operation [5], [9], [10]. To summarize, in this paper we explore the possibility of the combined usage of UAVs and RISs to reduce the energy consumption of the entire system, while providing a certain level of QoS to the UEs in the area. Fig. 1 denotes the overall scenario in question. The UAV acts as a mobile BS relay that can establish Line-of-Sight (LoS) links with the UEs and the RIS, something that might not be always possible for the fixed BS. This can potentially extend the area of coverage (i.e., of

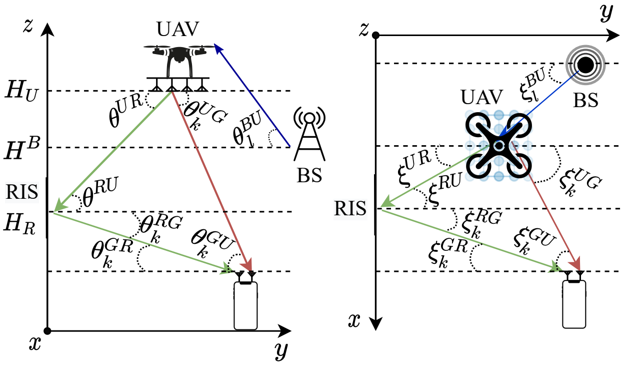

Fig. 2. The vertical (left) and horizontal (right) AoDs/AoAs between the UAV, RIS, and k^{th} UE in the downlink communication system respectively.

the area of satisfactory QoS), also in situations where a BS could not be relied upon for service, such as emergency or disaster scenarios [4].

II. Scenario Definition and Problem Formulation

Consider a network environment with K UEs randomly spread in the area with a RIS in fixed and known position. We assume that the user association and additional control information needed for data transfer are exchanged between BS and UEs by means of a dedicated long range control channel. We also assume that the UEs are aware of their own position (e.g., calculated through triangulation with respect to the BSs in the area) and UAVs as well as the UEs periodically communication this information to the BS. We also assume BSs, UAVs and UEs are equipped with Uniform Planar Square Array (UPA) antennas so as to perform concurrent beamforming in different directions. Additionally, for RIS, an extra large scale massive MIMO (XL-MIMO) RIS deployment is considered in which every UE is served by a specific region of the surface. This holds when the RIS dimensions is large and the UEs are sufficiently spaced apart to have partial observability of the surface [11].

1) Channel Models: As visible from Fig. 1, there are four channels in the scenario: BS to UAV, UAV to UE, UAV to RIS and RIS to UE. We adopt them from [5]. Hence, the Signal-to-Noise Ratio (SNR) is given by

$$\gamma^{\mathrm{U}}[n] = \frac{P_U^T |\mathrm{h}^{\mathrm{U}}[n]|^2}{\sigma_n^2}, \tag{1}$$

$$\gamma^{\mathrm{i,k}}[n] = \frac{P_{i,k}^T |\mathrm{h}^{\mathrm{i}}[n]|^2}{\sigma_n^2}, \tag{2}$$

where, P_U^T is the transmit power for BS towards the UAV, $\mathrm{P}_{i,k}^T$ is the transmit power for the UAV towards the k^{th} UE, $\mathrm{h}^{\mathrm{U}}[n]$ refers to the channel between the BS and the UAV. Similarly, $\mathrm{h}^{\mathrm{i}}[n]\ \forall\ i \in \{1,2\}$ where $i = 1$ is the LoS link between UAV and k^{th} UE and $i = 2$ is the link between UAV and k^{th} UE through RIS, and σ_n^2 is the white noise power. Communication using (1) and assuming a Gaussian channel, the maximum achievable rate for the channel between BS to UAV, UAV to UE with and without RIS is given by the Shannon bound

$$R^U[n] = \log_2(1 + \gamma^U[n]) \qquad \text{[bits/s/Hz]}, \tag{3}$$

$$R_k^i[n] = \log_2(1 + \gamma^{i,k}[n]) \qquad \text{[bits/s/Hz]}. \tag{4}$$

Note that, to use the above formula, we must assume that BS, UAV and UE know the channel between them and can determine the rate based on the available SNR. Also, we assume that the UEs are sufficiently spread apart to avoid mutual interference when communicating with the UAV.

2) Energy Consumption for UAV: The power consumption for UAV is critical due to its limited battery capacity. In the paper, we use the distance-based energy consumption model from [12] given by

$$\mathrm{P}^U[n] = \underbrace{P_o\left(1 + \frac{3\|\mathbf{v}[n]\|^2}{\Omega^2 r^2}\right)}_{\text{Bladeprofile}} + \underbrace{\frac{P_i v_0}{\|\mathbf{v}[n]\|}}_{\text{Induced}} + \underbrace{\frac{1}{2} d_0 \rho s A_{\mathrm{r}} \|\mathbf{v}[n]\|^3}_{\text{Parasite}}, \tag{5}$$

where $\mathbf{v}[n]$ is the velocity vector, and the other terms of the equation are explained in TABLE I. We only considered the energy consumption for the in-flight movement of the UAV for now and keep the impact of take off and landing on energy consumption for further research.

TABLE I
Notation for Energy Consumption Model[5]

Symbol	Meaning	Simulation Values
Ω	Blade Angular Velocity	300 rad/s
r	Rotor radius	0.4 m
ρ	Air Density	1.225 kg/m^3
s	Rotor Solidity	0.05 m^3
A_r	Rotor Disc Area	0.503 m^3
v_0	Forward Flight Rotor Induced velocity	4.03 m^3
d_0	Fuselage drag ratio	0.3
P_0	Blade profile power in hovering status	79.86 W
P_p	Induced power in hovering status	88.63 W

3) Optimization Problem: Considering the assumptions, the objective is to find an energy efficient UAV path and corresponding RIS phase shift in order to minimize the overall transmission power consumption of UAV and BS under minimum QoS constraints and maximum UAV energy budget which is defined as

$$\min_{\mathbf{P},\mathbf{Z},\mathbf{V},\mathbf{\Phi}} \sum_{n=1}^{N} \mathrm{P}_U^T[n] + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{2} \mathrm{P}_{i,k}^T[n] \tag{6}$$

$$s.t.$$

$$C1: \sum_{i=1}^{2} R_k^i[n] \geq R_{min}, \forall\ k, n;$$

$$C2: R^U[n] \geq \sum_{k=1}^{K}\sum_{i=1}^{2} R_k^i[n],\ \forall\ n;$$

$$C3: 0 \leq \mathbf{\Phi}[n] \leq 2\pi;$$

$$C4: \sum_{n=1}^{N} \mathrm{P}^U[n] \leq \mathrm{E}_{max}^{UAV};$$
$$C5: \mathbf{Z}[n+1] = \mathbf{Z}[n] + \mathbf{v}[n]\tau,\ n = 1, \ldots, N-1;$$
$$C6: \|\mathbf{v}[n]\| \leq V_{max},\ \forall n;$$
$$C7: \|\mathbf{v}[n+1] - \mathbf{v}[n]\| \leq V_{acc}\tau,\ n = 1, \ldots, N-1;$$
$$C8: \|\mathbf{v}[n]\| \geq 0\ \forall n;$$
$$C9: \mathbf{Z}[1] = \mathbf{Z}_0;$$
$$C10: \mathbf{Z}[N] = \mathbf{Z}_F.$$

We remark that, as shown in Fig. 1 the UAV has two parallel links to each UE: one directional and the other with the RIS sector associated to the UE. The multipath approach offers a greater chance to satisfy the service requirement by jointly optimizing the UAV trajectory $\mathbf{Z}[n]$ and RIS phase configuration $\mathbf{\Phi}$, while minimizing the transmission power of the entire system. To facilitate the UEs to determine the multipath connections, the BS has to continuously communicate the beams to be used to the UE taking into account the mobility information of the UEs and the trajectory of the UAV. As mentioned before, the BS may communicate this information over long-range low-rate technologies such as LoRa [13].

III. Analytical Solution

The optimization problem discussed in the previous section is clearly non-convex and, hence, quite difficult to solve in itself. But we can determine a feasible solution by considering the initial transmission powers for the UAV and BS so as to jointly optimize the UAV trajectory and RIS phase and, then, minimize the transmission powers for the given trajectory and phase configuration within the constraints in (6). This method is explained in detail in the following subsections.

A. Joint UAV Trajectory and RIS phase optimization

Joint UAV Trajectory and RIS phase optimization can be facilitated considering a particular $\mathbf{P}$ over different links [14]. As shown in the Fig. 2, the BS to UAV, UAV to UE, UAV to RIS and RIS to UE links are assumed to be deterministic LoS channels. For ease of notation, in the following we indicate the nodes involved in a link using the subscript U, B, R and G for UAV, BS, RIS and (ground) UE, respectively. The channel information is supposed to be available at the UAV and the UEs. Hence, to maximise the transmission efficiency, a Maximum Ratio Transmission (MRT) is applied, i.e., the transmission beamformer for any k^{th} UE as well as for the UAV can be defined as $\mathrm{w}^{\mathrm{BU}} = \frac{1}{\sqrt{M_B}}\mathrm{h}^{\mathrm{BU}}, \mathrm{w}_{\mathrm{k}}^{\mathrm{UG}} = \frac{1}{\sqrt{M_U}}\mathrm{h}^{\mathrm{UG}}$ and $\mathrm{w}^{\mathrm{UR}} = \frac{1}{\sqrt{M_U}}\mathrm{h}^{\mathrm{UR}}$. The overall channel gains can hence be obtained as

$$\mathrm{H}^{\mathrm{BU}}[n] = (\mathrm{h}^{\mathrm{BU}}[n])^{\mathrm{H}}[n]\mathrm{w}^{\mathrm{BU}}[n] = \frac{\sqrt{M_{\mathrm{B}}}\alpha_0}{d^{\mathrm{BU}}[n]}; \quad (7)$$

$$\mathrm{H}_{\mathrm{k}}^{\mathrm{UG}}[n] = (\mathrm{h}_{\mathrm{k}}^{\mathrm{UG}}[n])^{\mathrm{H}}[n]\mathrm{w}_{\mathrm{k}}^{\mathrm{UG}}[n] = \frac{\sqrt{M_{\mathrm{U}}}\alpha_0}{d_k^{\mathrm{UG}}[n]}; \quad (8)$$

$$\begin{aligned}\mathrm{H}_{\mathrm{k}}^{\mathrm{URG}}[n] &= (\mathrm{h}_{\mathrm{k}}^{\mathrm{RG}}[n])^{\mathrm{H}}\mathbf{\Phi}_k[n]\mathrm{H}^{\mathrm{UR}}[n]\mathrm{w}^{\mathrm{UR}}[n] \\ &= \sqrt{M_{\mathrm{U}}}(\mathrm{h}_{\mathrm{k}}^{\mathrm{RG}}[n])^{\mathrm{H}}\mathbf{\Phi}_k[n]\mathrm{h}^{\mathrm{RU}}[n] \\ &= \frac{\sqrt{M_{\mathrm{U}}}M_{\mathrm{R}}\alpha_0}{d_k^{\mathrm{RG}}d^{\mathrm{UR}}[n]}. \end{aligned} \quad (9)$$

To determine the $\mathrm{H}_{\mathrm{k}}^{\mathrm{URG}}[n]$ coefficients correctly, the optimal phase control policy for the phase shift in every timestep (which maximizes the reflection-mode channel gain by aligning the phase of the RIS to match those of the channel) is given by

$$\begin{aligned}\mathbf{\Phi}_{m_{\mathrm{R}x},m_{\mathrm{R}y},k} = \frac{2\pi\Delta_{\mathrm{R}}}{\lambda_{\mathrm{c}}}[(m_{\mathrm{R}x}-1)(\sin\theta^{\mathrm{RU}}\cos\xi^{\mathrm{RU}} \\ + \sin\theta_k^{\mathrm{RG}}\cos\xi_k^{\mathrm{RG}}) + (m_{\mathrm{R}y}-1)(\sin\theta^{\mathrm{RU}}\sin\xi^{\mathrm{RU}} \\ + \sin\theta_k^{\mathrm{RG}}\sin\xi_k^{\mathrm{RG}})],\end{aligned} \quad (10)$$

where θ^{RU} and ξ^{RU} are the Angle of Arrivals (AoAs) and θ^{RG} and ξ^{RG} are the Angle of Departures (AoDs) as defined in Fig. 2. The assumption for RIS phase configuration is that there is a wired direct link to the RIS controller and that, delay and imperfect phase configuration are negligible.

Note that, the problem is still non-convex due to C1 and C2 w.r.t. $\mathbf{Z}$. In order to overcome this issue, we add three slack variables $\lambda_{k,i}[n]$ and $\pi[n]$. In this way, we keep the constraints C1-9, and the problem can be reformulated as follows

$$\min_{\mathbf{Z},\mathbf{V},\mathbf{\Lambda},\mathbf{M},\mathbf{\Pi}} \sum_{n=1}^{N} \mathrm{P}_U^T[n] + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{2} \mathrm{P}_{i,k}^T[n] \quad (11)$$
$$s.t.$$
$$C1 - C10;$$
$$C11: \|\mathbf{Z}_k^{UE} - \mathbf{Z}[n]\|^2 \leq \lambda_{k,1}[n], k \in \{1, ..., K\};$$
$$C12: \|\hat{\mathbf{Z}}_k^{RIS} - \mathbf{Z}[n]\|^2 \leq \lambda_{k,2}[n], k \in \{1, ..., K\};$$
$$C13: \|\mathbf{Z}^{BS} - \mathbf{Z}[n]\|^2 \leq \mu[n];$$
$$C14: \|\mathbf{v}[n]\|^2 \geq \pi^2[n];$$
$$C15: \pi[n] \geq 0;$$

where $\mathbf{\Lambda} = \{\lambda_{k,i}[n], \forall\ n, k, i\}$, $\mathbf{M} = \{\mu[n], \forall\ n\}$ and $\mathbf{\Pi} = \{\pi[n], \forall\ n\}$. Similarly to what proposed in [5], we overcome the non-convex constraints C1 and C2 via Successive Convex Approximation (SCA) in an iterative way. We can compute a lower bound of the instant achievable rate for each user by modifying $\lambda_{k,i}[n]$, $\mu[n]$ and $\pi[n]$ and calculating the first-order Taylor expansion which is a global under-estimator of the rate convex function [15]. Hence, omitting the argument $[n]$ for notation clarity, we redefine the SNR expression as

$$\gamma^U = \frac{\hat{\gamma}^U}{\mu}; \quad (12)$$

$$\gamma^{k,i} = \frac{\hat{\gamma}^{k,i}}{\lambda_{k,i}},\ \forall\ i = \{1, 2\}, \quad (13)$$

where,

$$\hat{\gamma}^U = \frac{\mathrm{P}_U^T \mathrm{M}_{\mathrm{B}}\alpha_0^2}{\sigma_n^2}; \quad (14)$$

$$\hat{\gamma}^{k,1} = \frac{\mathrm{P}_{1,k}^T \mathrm{M}_{\mathrm{U}}\alpha_0^2}{\sigma_n^2}; \quad (15)$$

$$\hat{\gamma}^{k,2} = \frac{\mathrm{P}_{2,k}^{T}\mathrm{M_U M_R^2}\alpha_0^2}{(d_k^{\mathrm{RG}})^2\sigma_n^2}. \quad (16)$$

Using (12) and (13) in (3) and (4) respectively and applying the first-order Taylor expansions in the j-th iteration for a particular value of $\lambda_{k,i}^{j}[n]$, $\mu^{j}[n]$ and $\mathbf{v}^{j}[n]$, the lower bound for the rates is given by

$$\begin{aligned}
&\hat{R}_k^i[n] \geq \\
&(\hat{R}_k^i[n])^j = \log_2\left(1+\frac{\gamma^{i,k}[n]}{\lambda_{k,i}^{j}[n]}\right) \\
&\quad - \frac{\gamma^{i,k}[n](\lambda_{k,i}[n]-\lambda_{k,i}^{j}[n])}{\lambda_{k,i}^{j}[n](\lambda_{k,i}^{j}[n]+\gamma^{i,k}[n])\ln 2}, \quad (17)\\
&\hat{R}^U[n] \geq \\
&(\hat{R}^U[n])^j = \log_2\left(1+\frac{\gamma^{U}[n]}{\mu^{j}[n]}\right) \\
&\quad -\frac{\gamma^{U}[n](\mu[n]-\mu^{j}[n])}{\mu^{j}[n](\mu^{j}[n]+\gamma^{U}[n])\ln 2}, \quad (18)\\
&\|\mathbf{v}[n]\|^2 \geq \|\mathbf{v}^j[n]\|^2 + 2[\mathbf{v}^j[n]]^{\mathrm{T}}(\mathbf{v}[n]-\mathbf{v}^j[n]). \quad (19)
\end{aligned}$$

where $(\hat{R}_k^i[n])^j$ and $(\hat{R}_U[n])^j$ are the lower bound achievable rates for the k^{th} UE and UAV respectively, in the j^{th} iteration of SCA. The in-flight power consumption for UAV can be written as

$$\mathrm{P}^U[n] = P_o\left(1+\frac{3\|\mathbf{v}[n]\|^2}{\Omega^2 r^2}\right) + \frac{P_p v_0}{\pi[n]} + \frac{1}{2}d_0\rho_s A_{\mathrm{r}}\|\mathbf{v}[n]\|^3. \quad (20)$$

Applying the lower bounds in (17), (18) and (19) in (11) we obtain a convex problem defined as

$$\begin{aligned}
\min_{\mathbf{Z},\mathbf{V},\mathbf{\Lambda},\mathbf{M},\mathbf{\Pi}} \quad & \sum_{n=1}^{N}\mathrm{P}_U^T[n] + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{2}\mathrm{P}_{i,k}^T[n] \quad (21)\\
s.t. \quad & \\
\hat{C}1: \ & \sum_{i=1}^{2}(\hat{R}_k^i[n])^j \geq R_{min}, \forall\, k;\\
\hat{C}2: \ & (\hat{R}^U[n])^j \geq \sum_{k=1}^{K}\sum_{i=1}^{2}(\hat{R}_{k,i})^j[n];\\
\hat{C}14: \ & \|\mathbf{v}^j[n]\|^2 + 2[\mathbf{v}^j[n]]^{\mathrm{T}}(\mathbf{v}[n]-\mathbf{v}^j[n]) \geq \pi^2[n];\\
& C3 - C15,
\end{aligned}$$

which solving it provides an upper bound of the problem in (11). We iteratively update the feasible solution $\mathbf{Z}^j[n]$, $\lambda_{k,i}^{j}[n]$, $\mu^j[n], \mathbf{v}^j[n]$ and $\pi^j[n]$ by solving the convex problem in (21) using the CVX standard optimization solver [16] in the j-th iteration.

B. Transmission Power Control

For a determined UAV trajectory and RIS phase, the UAV and BS transmission power can be minimized. To define the transmission power minimization with a predefined trajectory $\mathbf{Z}$, the optimization problem in (6) can be rewritten with constraints $C3-C10$ already satisfied for the pre-defined trajectory $\mathbf{Z}$. So the optimization problem can be written as

$$\begin{aligned}
\min_{\mathbf{P}} \quad & \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{i=1}^{3}\mathrm{P}_i^T[n] \quad (22)\\
s.t. \quad & \\
C1: \ & \sum_{i=1}^{2}R_k^i[n] \geq R_{min}, \forall\, k, n;\\
C2: \ & C[n] \geq \sum_{k=1}^{K}\sum_{i=1}^{2}R_k^i[n],\ \forall\, n.
\end{aligned}$$

The constraints $C1$ and $C2$ are concave with respect to the $\mathbf{P}$. Hence it can be easily solved by employing SCA using the Taylor's expansions, which are global over-estimators of the concave functions [15]. To do so, the SNR expressions are rewritten as

$$\gamma^U[n] = \mathrm{P}_U^T[n]\kappa_U[n]; \quad (23)$$
$$\gamma^{i,k}[n] = \mathrm{P}_{i,k}^T[n]\kappa_{k,i}[n], \forall\, i\in\{1,2\},\ k; \quad (24)$$

where,

$$\kappa_U[n] = \left\{\frac{\sqrt{M_{\mathrm{B}}}\alpha_0}{d^{\mathrm{BU}}[n]\sigma}\right\}^2, \quad (25)$$
$$\kappa_{k,1}[n] = \left\{\frac{\sqrt{M_{\mathrm{U}}}\alpha_0}{d^{\mathrm{UG}}[n]\sigma}\right\}^2, \quad (26)$$
$$\kappa_{k,2}[n] = \left\{\frac{\sqrt{M_{\mathrm{U}}}\alpha_0}{d^{\mathrm{URG}}[n]\sigma}\right\}^2. \quad (27)$$

Using (23) and (24) in (3) and (4) respectively and applying the first-order Taylor expansions, we get

$$\begin{aligned}
&\hat{R}^U[n] \leq \\
&(\hat{R}^U[n])^j = \log_2\left(1+(\mathrm{P}_U^T)^j|\kappa_U[n]|^2\right) \\
&\quad + \frac{|\kappa_U[n]|^2(\mathrm{P}_U^T-(\mathrm{P}_U^T)^j)}{(1+(\mathrm{P}_U^T)^j|\kappa_U[n]|^2)\ln(2)}, \quad (28)\\
&\hat{R}_k^i[n] \leq \\
&(\hat{R}_k^i[n])^j = \log_2\left(1+(\mathrm{P}_{i,k}^T)^j|\kappa_{k,i}[n]|^2\right) \\
&\quad + \frac{|\kappa_{k,i}[n]|^2(\mathrm{P}_{i,k}^T-(\mathrm{P}_{i,k}^T)^j)}{(1+(\mathrm{P}_{i,k}^T)^j|\kappa_{k,i}[n]|^2)\ln(2)},\ \forall\, i\in\{1,2\}. \quad (29)
\end{aligned}$$

Hence, the optimization problem (22) can be rewritten as

$$\begin{aligned}
\min_{\mathbf{P}} \quad & \sum_{n=1}^{N}\mathrm{P}_U^T[n] + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{2}\mathrm{P}_{i,k}^T[n] \quad (30)\\
s.t. \quad &
\end{aligned}$$

Algorithm 1: Joint Trajectory, RIS Phase Configuration and Transmission Power Control algorithm

Result: UAV Trajectory $\mathbf{Z}$, UAV Velocity $\mathbf{V}$, P^{Total}

Initialize trajectory $\mathbf{Z}$, $\mathbf{V}$, maximum number of iteration J_{max}, initial iteration index $j = 0$, Particular UAV and BS transmission power $\mathbf{P}$, Initial trajectory $\mathbf{Z}$, Initial velocity $\mathbf{V}$ and Convergence tolerance ϵ;

while $j \leq J_{max}$ *or* $\frac{\mathrm{P}^{j}_{Total} - \mathrm{P}^{j-1}_{Total}}{\mathrm{P}^{j}_{Total}} \leq \epsilon$ **do**

  Set $j = j + 1$ and $\{\mathbf{P}^j, \mathbf{V}^j, \mathbf{\Lambda}^j, \mathbf{M}^j, \mathbf{\Pi}^j\} = \{\mathbf{P}, \mathbf{V}, \mathbf{\Lambda}, \mathbf{M}, \mathbf{\Pi}\}$;

  Solving optimization problem (21) to obtain $\mathbf{Z}, \mathbf{V}, \mathbf{\Lambda}, \mathbf{M}$ and $\mathbf{\Pi}$ for a Particular $\mathbf{P}$;

  Solving optimization problem (30) to obtain $\mathbf{P}$ and P_{Total} for a Particular $\mathbf{Z}, \mathbf{V}, \mathbf{\Lambda}, \mathbf{M}, \mathbf{\Pi}$

  Update $\mathrm{P}^{j}_{Total} = \mathrm{P}_{Total}$;

end

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Area	500m × 500m
Number of Users (K)	3
Position of Users	[20, 450; 250, 0; 500, 200]
Position of Base Station	[0, 0]
Position of RIS	[200, 500]
Number of RIS Elements per user	64
Number of UAVs	1
Initial/Final Position of UAV ($\mathrm{Z}_0/\mathrm{Z}_F$)	[0, 0; 500, 500]
Maximum Velocity	20 m/s
Maximum Acceleration	4 m/s^2
Height of the [UAV, BS, RIS]	[20,15,10] m
Path Loss (α_0)	61 dBm
Noise Power Spectral Density (σ^2)	-174 dBm

$$C1: \sum_{i=1}^{2} (\hat{R}^i_k[n])^j[n] \geq R_{min}, \forall\, k, n;$$

$$C2: (\hat{R}^U[n])^j[n] \geq \sum_{k=1}^{K}\sum_{i=1}^{2} (\hat{R}^i_k)^j[n], \;\forall\, n.$$

Similar to the UAV trajectory and RIS phase optimization problem, this optimization can be solved using the CVX standard optimization solver. Algorithm 1 provides the pseudocode to solve the optimization problem.

IV. RESULTS AND DISCUSSION

The solution discussed in the previous section is implemented in MATLAB simulation environment. The base simulation parameters are defined by TABLE II. The simulation environment is shown in the Fig. 3. As visible from the figure, over the SCA iterations, the UAV trajectory and transmission power is optimized using Algorithm 1 until it converges, i.e., UAV trajectory and transmission power are no longer improved. Different configurations in terms of static number of UEs in the network have been simulated. Looking at the

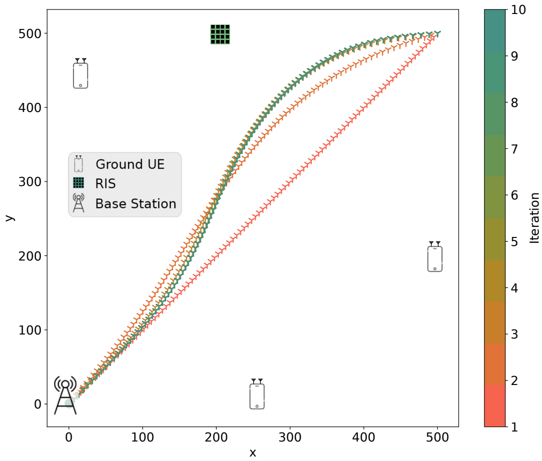

Fig. 3. Optimization of the UAV trajectory and transmission power over SCA iterations. The marked lines represent the UAV trajectories obtained during the execution of the iterative algorithm. The straight line is the initial solution, while the darkest one is the final solution.

total transmission power used along the optimized trajectory, that is, the summation of the power from the BS and the transmission power for the UAV, Fig. 4 shows now that the power increases with the number of users in the network for different values of R_{min}. To be noted that the curve bends when the number of users increases, since their distance to the BS, UAV and RIS reduces. Also, the total power increases with the minimum rate requirement. Another significant observation is the change in average power consumption per set of users for different rates. The change in principle should be exponential, i.e., linear increase in rate should require exponential increase in power. But, to follow this criteria, the distance has to be constant, i.e., the trajectory of the UAV has to be constant for all the different rates. But, as visible in Fig. 5, which shows the optimal trajectories for different values of R_{min}, the optimal trajectory for $R_{min} = 0.057$ is able to deviate more from the straight line trajectory as it can still satisfy the low required minimum rate for the UEs. On the contrary, the optimal trajectory for $R_{min} = 0.757$ is able to deviate less from the straight line trajectory than that for $R_{min} = 0.057$ as the required minimum rate is higher. Note that, we only show optimal trajectories for $R_{min} = \{0.057, 0.257, 0.557, 0.757\}$ to be able to visually distinguish between the optimal trajectories for the different values of R_{min}. The optimal trajectories for the remaining values of R_{min} are between the optimal trajectory for $R_{min} = 0.057$ and $R_{min} = 0.757$. This trend for optimal trajectories is also true for the scenarios involving one, two, four and five UEs. Hence, the average power consumption for UEs, as shown in Fig. 4, does not follow an exponential criteria due to change in optimal trajectory for different values of R_{min}. Additionally, the system is very sensitive to the network configuration, i.e., it is inherently limited with respect to number of UEs that can be served simultaneously in a single flight. To improve the scalability of the system, the usage of reinforcement learning can be explored, which has been left

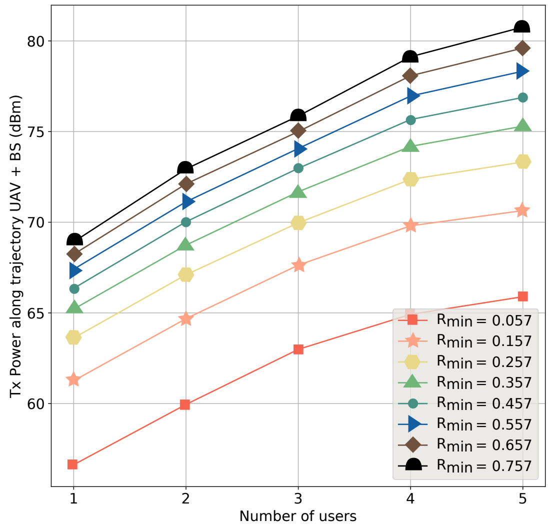

Fig. 4. Total Transmission Power (UAV and BS) when increasing the number K of static UEs for different values of R_{min}.

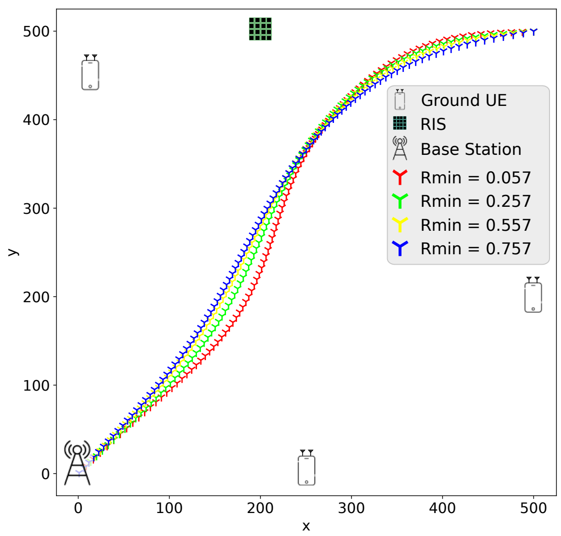

Fig. 5. Different Optimal Trajectories for the UAV for three UEs and for different values of R_{min}.

for future work.

V. Conclusion

Beyond 5G and 6G Networks are expected to provide a certain service level while reducing the power consumption of the system. To this end, we discussed the usage of UAVs and RIS as a way to guarantee certain service requirements while trying to minimise the power consumption of the system.

In this work, we devised jointly, a method to roughly optimize UAV trajectory, RIS phase and UAV transmission power consumption to provide a certain guaranteed service rate to the UEs on the ground. We showed the usage of convex approximation techniques can provide a feasible solution. Moving forward, the usage of reinforcement learning seems very attractive especially due to the sensitive nature of convex approximation schemes to different network configurations.

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