Energy Efficient Multi-User Communications Aided by Reconfigurable Intelligent Surfaces and UAVs

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***Abstract*—To support the provisioning of modern services in a smart city environment, future communication networks need to be intelligently designed with respect to the city infrastructure and energy efficient utilization of resources. Unmanned Aerial Vehicles (UAVs) are already being utilized as part of a smart city wireless network infrastructure to provide on-demand connectivity and eliminate the network's coverage holes, especially when communication conditions are unfavorable. Complementary to this, the adoption of Reconfigurable Intelligent Surface (RIS) technology allows for the creation of a more controllable smart wireless communications environment. In this article, a multi-user Non-Orthogonal Multiple Access (NOMA) communications system aided by a RIS and a UAV is studied. Based on a single-leader multiple-followers Stackelberg Game, we aim to jointly optimize the overall received signal strength at the UAV and maximize the users' achieved energy efficiency. The UAV – acting as a leader - intelligently steers the RIS-reflected signals in order to enhance the corresponding received signal quality, by determining the RIS elements' effective phase shifts. This, in turn, is exploited by the users (i.e., followers), which through the formulation of a non-cooperative game, where each user aims at maximizing its achieved energy efficiency, they determine their optimal uplink transmission power. The proposed optimization framework is evaluated via modeling and simulation, demonstrating the significant power savings and the ultimate users' satisfaction occurring by the introduction of the RIS.**

***Index Terms*—Unmanned Aerial Vehicles, Reconfigurable Intelligent Surfaces, Power Control, Game Theory.**

I. Introduction

The rapid development of 5G technology and Internet of Things (IoT) has motivated the evolution of a wide spectrum of diverse mobile applications, while the number of connected IoT nodes/users is ever increasing. Towards supporting the energy-efficient communication of the users with the Next-Generation Node Bases (gNBs), the Unmanned Aerial Vehicles (UAVs) have been introduced as a cost-efficient solution, acting as mobile relays and flying gNBs. The UAVs' salient characteristics of maneuverability, fast deployment and Line-of-Sight (LoS) communication links, have resulted to their adoption as an integral part of the next-generation wireless networks, providing important and diverse contributions to smart cities' evolution and offering cost-efficient services [1].

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Another technology that has also been recently introduced as a promising solution to improve the energy efficiency of the communications in the next-generation networks, is the commonly named Reconfigurable Intelligent Surface (RIS). The RIS comprises of multiple reflecting elements, constructed by engineered metamaterials, which can be controlled in a software-based manner to optimize the electromagnetic properties of the wireless links. The latter revolutionary attribute of RIS has the potential to contribute to transmission power savings for the users, the extension of the communications' range and the improvement of the signal strength [2]. This is of high importance especially for the support and provisioning of demanding communications and computing applications in cities' environments, where the communication channels between the users and the gNBs may become rather poor in several cases due to the existence of various obstacles [3].

In this paper, a multi-user communications system aided by a RIS and a UAV is studied, aiming at jointly optimizing the overall received signal strength at the UAV-mounted gNB, and maximizing the users' achieved energy efficiency, based on a single-leader multiple-followers Stackelberg game.

A. Related Work & Motivation

The improvement of energy efficiency and the power saving in wireless networks, assisted by the technology of RIS, has recently attracted the interest of the research community. In [4], the downlink communication is examined by formulating a transmission power minimization problem subject to the constraints of the RIS's reflecting elements. The optimization problem is studied under different multiple access schemes, e.g., Non-Orthogonal (NOMA) and Orthogonal Multiple Access (OMA), to quantify the power savings under each scenario and highlight the drawbacks and benefits of each multiple access approach. In [5], the authors introduce a novel method to group the RIS elements, through which each group of reflecting elements has the same reflection coefficient. Subsequently, the joint transmission power and RIS elements' reflection coefficients control problem is formulated as a non-convex optimization problem and a low-complexity heuristic mechanism is proposed, towards maximizing the users' achievable data rate. Focusing on the uplink, a maximization problem of the users' sum rate is formulated as a non-convex optimization problem by the authors in [6], considering the users'

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personal power constraints in a NOMA-enabled RIS-assisted wireless network. A near-optimal solution is determined via a semidefinite relaxation of the original optimization problem. In [7], a joint optimization problem of the users' transmission power and the RIS elements' reflection coefficients is introduced to maximize the overall system's energy efficiency, while considering the users' personal data rate constraints. In this work, the successive convex approximation method is adopted to address the corresponding optimization problem.

Complementary to the standalone RIS technology, the combination of the RIS and UAV-enabled communications has been studied in the recent literature to further corroborate the energy-efficient operation of the future wireless networks [8]. In [9], a reinforcement learning algorithm is designed to obtain the optimal location and reflection coefficients of a UAV-carried RIS to maximize the overall downlink transmission capacity in the examined network. In [10], the problem of jointly determining the UAV's trajectory, the RIS scheduling, and the communication resource allocation is considered, under a RIS-enhanced and UAV-enabled OMA wireless network, to maximize the overall system's sum rate. On the contrary, targeting at the minimization of the overall system's average power consumption, the joint optimization of the UAV's trajectory and velocity, the resource allocation, and the RIS elements' reflecting coefficients is addressed in [11], while considering the users' individual data rate constraints and the RIS's limited energy availability. Given the inherent complexity and non-convexity of the original optimization problem, a heuristic algorithm is devised to produce a near-optimal solution.

B. Contributions & Outline

Despite the research efforts made so far, regarding the joint exploitation of the RIS and UAV technologies to ameliorate the networks' energy efficiency, limited works have been devoted to thoroughly studying and quantifying their benefits in the uplink direction of the communications. Moreover, the problem of distributed and autonomous organization and operation of both the gNB and the users, while targeting to optimize their competing goals under a RIS-assisted network topology, still remains an open research challenge. In this paper, we strive to tackle these issues. The main contributions of our work are summarized below.

1) A RIS-assisted and UAV-enabled communications system is considered, serving a set of mobile users. We study the uplink communication between the users and the UAV, aiming at jointly maximizing the overall received signal strength at the UAV and the achieved energy efficiency of each user in a distributed and autonomous manner.
2) To achieve the latter goal, a joint optimization problem is formulated as a single-leader multiple-followers Stackelberg game, where the UAV (i.e., the leader) maximizes the overall received signal strength and the users (i.e., the followers), in turn, autonomously maximize their achieved energy efficiency. The leader's maximization problem is solved via a linear combination of the RIS elements' phase shifts that enhance each distinct user's signal strength. The followers' optimization problem is formulated as a non-cooperative game, in which each user aims at maximizing its achieved energy efficiency by determining its optimal uplink transmission power.
3) Indicative numerical results are presented to demonstrate the benefits in terms of power savings and users' satisfaction, by jointly exploiting the RIS and UAV technologies in wireless communications systems.

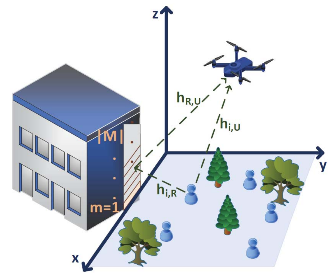


Fig. 1: RIS-assisted UAV communications system.

The remainder of this paper is organized as follows. In Section II, the system model is presented. The Stackelberg game formulation is provided in Section III-A, while its solution is derived in Section III-B. The numerical results are discussed in Section IV, while Section V concludes the paper.

II. System Model

A RIS-assisted and UAV-enabled wireless communications system is considered, as presented in Fig. 1, consisting of a UAV, a building facade composed by a RIS, and a set of mobile users $I = \{1, \dots, i, \dots, |I|\}$. The users communicate directly with the UAV, which plays the role of the gNB. The RIS is equipped with $|M|$ reflecting elements, and their set is denoted as $M = \{1, \dots, m, \dots, |M|\}$. Each RIS element's phase shift is $\theta_m \in [0, 2\pi]$, $\forall m \in M$, and the corresponding diagonal phase-shift matrix is defined as $\mathbf{\Theta} = diag(e^{j\theta_1}, \dots, e^{j\theta_m}, \dots, e^{j\theta_{|M|}})$. It is noted that the first RIS element (i.e., $m = 1$) is used as a reference point for the following calculations and its corresponding coordinates are $(x_R, y_R = 0, z_R)$ [m]. The UAV's coordinates in the three-dimensional space are indicated by (x_U, y_U, z_U) [m]. Both the users and the UAV bear single-antenna transmitters and receiver, respectively, while the users are assumed to remain stationary during the joint RIS elements' phase shifts and uplink transmission power control optimization procedure.

Each user's i signal received by the UAV is the outcome of the coherent addition of the direct signal and the reflected signal from the RIS to the UAV. The channel gain of the direct wireless link between a user i and the UAV is denoted as h_{iU}, the channel gain between a user i and the RIS is defined as $\mathbf{h}_{iR}$, while the channel gain of the wireless link created by reflection from the RIS to the UAV is $\mathbf{h}_{RU}$. The communication between a user i and the UAV is assumed to be Non Line-of-Sight (NLoS) and thus, the Rayleigh fading channel model is adopted to define the respective channel gain as $h_{iU} = \sqrt{\rho d_{iU}^{-\kappa_1}}\widetilde{h} \in \mathbb{C}$, where ρ represents the path loss at the reference distance of 1m, κ_1 is the path loss exponent, d_{iU} [m] is the euclidean distance between the user i and the UAV, and the parameter $\widetilde{h} \sim CN(0,1)$ captures the extensive signal's scattering by a zero-mean and unit-variance complex Gaussian random variable. Focusing on the channel gain of the link between the RIS and the UAV, we consider that these two network entities are in close proximity, thus, a LoS communication link exists between them. The corresponding channel gain of their in-between wireless link is $\mathbf{h}_{RU} = \sqrt{\rho(d_{RU})^{-2}}[1, e^{-j\frac{2\pi}{\lambda}d\phi_{RU}}, \dots, e^{-j\frac{2\pi}{\lambda}(|M|-1)d\phi_{RU}}]^T \in \mathbb{C}^{|M|\times 1}$, where λ [m] is the carrier wavelength, d_{RU} [m] is the distance between the RIS's reference element and the UAV, d [m] is the antenna separation and ϕ_{RU} is the cosine of the signal's angle of departure from the RIS to the UAV.

With reference to the definition of the channel gain between each user i and the RIS, it is assumed that their in-between wireless communication link is exposed to Rician fading due to the existence of at least one strong LoS propagation path and of multiple other NLoS paths, within a full-of-obstacles wireless environment. Thus, the corresponding channel gain is defined as $\mathbf{h}_{iR} = \sqrt{\rho d_{iR}^{-\kappa_2}}(\sqrt{\frac{\beta}{1+\beta}}\mathbf{h}_{iR}^{LoS} + \sqrt{\frac{1}{1+\beta}}\mathbf{h}_{iR}^{NLoS}) \in \mathbb{C}^{|M|\times 1}$, where κ_2 is the path loss exponent of the specific communication link, d_{iR} [m] is the distance between the user and the reference RIS element and β is the Rician factor. Also, $\mathbf{h}_{iR}^{LoS} = [1, e^{-j\frac{2\pi}{\lambda}d\phi_{iR}}, \dots, e^{-j\frac{2\pi}{\lambda}(|M|-1)d\phi_{iR}}]^T$ is the LoS component, with ϕ_{iR} being the cosine of the angle of arrival of the signal from the user to the RIS, and $\mathbf{h}_{iR}^{NLoS} \sim CN(0,1)$ is the NLoS component. For ease of presentation, we rewrite the channel gain between each user and the RIS as $\mathbf{h}_{iR} = [|h_{iR,1}|e^{j\omega_1}, \dots, |h_{iR,m}|e^{j\omega_m}, \dots, |h_{iR,|M|}|e^{j\omega_{|M|}}]^T$. Based on the above, the overall channel power gain between each user i and the UAV is given by $G_i = |h_{iU} + \mathbf{h}_{RU}^H \mathbf{\Theta} \mathbf{h}_{iR}|^2$.

The Non-Orthogonal Multiple Access (NOMA) technique is adopted in the examined communications system to facilitate the concurrent users' communication with the UAV. Without loss of generality, we consider that the users' received signal strengths at the UAV are sorted in ascending order as $G_1P_1 \leq \cdots \leq G_iP_i \leq \cdots \leq G_{|I|}P_{|I|}$ and decoding starts from the highest signal strength user. Subsequently, the Successive Interference Cancellation (SIC) is implemented at the UAV's receiver to decode the received superposed signal and thus, the experienced interference by each user is defined as follows:

$$I_i = \sum_{j<i} G_jP_j + I_0, \tag{1}$$

where P_j [W] is the uplink transmission power of the user j and I_0 denotes the power of the zero-mean Additive White Gaussian Noise (AWGN). Thus, each user's achieved Signal-to-Interference-plus-Noise Ratio (SINR) is defined as follows:

$$\gamma_i = \frac{P_iG_i}{I_i}. \tag{2}$$

III. Power Control: A Game-theoretic Approach

In this section, the joint optimization problem of the overall received signal strength at the UAV and the achieved energy

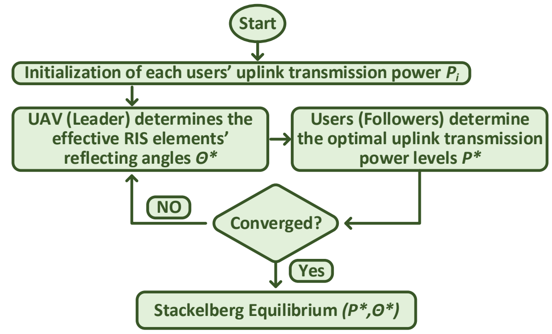


Fig. 2: Energy-efficient power control: A Stackelberg game-theoretic approach.

efficiency of each user is studied based on a game-theoretic approach. Through the game taking place among the users and the UAV, the RIS elements' effective phase shifts and the users' optimal uplink transmission power levels are ultimately determined. Initially, the utility function of each user is defined based on a network economics approach [12], and is given by:

$$U_i(P_i, \mathbf{P}_{-i}) = \frac{W \cdot (1 - e^{-\alpha\gamma_i})^M}{P_i}, \tag{3}$$

where $\mathbf{P}_{-i}$ is the transmission power vector of all the users except for user i, W [Hz] is the system's bandwidth, and $\alpha, M \in \mathbb{R}^+$ constitute appropriate control parameters of the user's utility function's slope. The numerator of Eq. (3) captures the user's satisfaction with respect to the achieved SINR, which has an one-to-one relationship with the user's uplink transmission power P_i. It is noted that the numerator of Eq. (3) is a sigmoidal function with respect to the user's achieved Quality of Service (QoS), i.e., SINR, which is mapped to its inflection point. Thus, the user's utility function, as defined in Eq. (3), inherently represents its experienced energy efficiency, i.e., the trade-off between the achieved QoS satisfaction and the invested uplink transmission power.

A. Problem Formulation

In this research work, our main goal is to jointly maximize the received signal strength at the UAV and the achieved energy efficiency of each user. The joint optimization problem is formulated as a single-leader multiple-followers Stackelberg game. The UAV acts as the leader seeking to maximize the overall received signal strength via determining the effective phase shifts of the RIS elements. The corresponding problem solved at the UAV is written as:

$$\max_{\boldsymbol{\theta}} \sum_{\forall i \in I} P_i |h_{iU} + \mathbf{h}_{RU}^H \mathbf{\Theta} \mathbf{h}_{iR}|^2 \tag{4a}$$

$$\text{s.t.} \quad 0 \leq \theta_m \leq 2\pi, \forall m \in M. \tag{4b}$$

The users, acting as followers, aim to maximize their experienced utility in a distributed and autonomous manner via determining their optimal uplink transmission power levels.

The interactions among the users are captured via a non-cooperative game $G = [I, \{A_i\}_{\forall i \in I}, \{U_i\}_{\forall i \in I}]$, where I is the set of players, i.e., users, $A_i = [P_i^{min}, P_i^{max}]$ is each user's strategy set, with P_i^{min} [W] and P_i^{max} [W] corresponding to the minimum and maximum uplink transmission power levels of each user, respectively, and U_i is the user's payoff (i.e., utility function). Each user's minimum uplink transmission power level P_i^{min} derives from the SIC prerequisite of the UAV's receiver, which is defined as follows:

$$G_i P_i - I_i \geq P_{tol}, \forall i \in \{2, \dots, i, \dots, |I|\}, \tag{5}$$

such that each user's signal is successfully decoded. Specifically, Eq. (5) implies that each user's signal strength $G_i P_i$ should be greater than or equal to the specific user's i sensed interference I_i, plus a minimum acceptable power level $P_{tol} \in \mathbb{R}^+$, which accounts for the SIC receiver's tolerance/sensitivity. On the other hand, the user's maximum uplink transmission power level P_i^{max} is imposed by the mobile user's device maximum power budget.

During the execution of the non-cooperative game G, each user aims at maximizing its experienced utility, i.e., energy efficiency, and the corresponding maximization problem is defined as follows:

$$\max_{P_i \in A_i} U_i\left(P_i, \mathbf{P}_{-i}\right) = \frac{W \cdot \left(1 - e^{-\alpha \gamma_i}\right)^M}{P_i}, \forall i \in I \tag{6a}$$

$$\text{s.t.} \quad G_i P_i - I_i \geq P_{tol}, \forall i \in \{2, \dots, i, \dots, |I|\} \tag{6b}$$

$$P_i \leq P_i^{max}, \forall i \in I. \tag{6c}$$

The outcome of the non-cooperative game G is a Nash equilibrium, which determines the users' optimal transmission power vector $\mathbf{P}^* = [P_1^*, \dots, P_i^*, \dots, P_{|I|}^*]$.

B. Problem Solution

The solution of the optimization problem, as presented in Eq. (4a)-(4b), will result in obtaining the RIS elements' effective phase shifts' vector $\boldsymbol{\theta^*}$, while the outcome of the non-cooperative game G will allow the derivation of the users' optimal uplink transmission power vector $\mathbf{P}^*$. The Stackelberg equilibrium, concluding this mathematical analysis is $(\boldsymbol{\theta^*}, \mathbf{P}^*)$. The information and control flow in order to jointly maximize the UAV's total received signals' strength and the users' utility functions via deriving the Stackelberg equilibrium is presented in Fig. 2.

As described before, the goal of the UAV is to maximize the overall received signal strength (Eq. (4a)-(4b)) via determining the RIS elements' effective phase shifts. It is noted that the corresponding optimization problem, presented in Eq. (4a)-(4b), is non-convex and hence, a globally optimal solution is hard to be found. In the ideal case, where a single user i exists in the system, the RIS elements' optimal phase shifts are given by the following closed form solution:

$$\theta_m^* = \angle h_{iU} + \omega_m + \frac{2\pi}{\lambda} d(m-1)\phi_{RU}, \forall m \in\ M, \tag{7}$$

whereas in the multi-user case, Eq. (7) gives only an upper bound for each user's potentially achievable signal strength. For practical purposes and in order to conclude to a single vector of phase shifts $\boldsymbol{\theta}^*$, the linear combination and approximation approach proposed in [4] is adopted, according to which a set of appropriate weights is found for each user i, such that the linear combination of the phase shifts derived from Eq. (7) for each user separately yields the maximum overall users' signal strength, as defined in Eq. (4a).

Given the RIS elements' effective phase shifts, each user determines its optimal uplink transmission power P_i^* via interacting with the rest of the users in the field in a non-cooperative manner. The solution of the non-cooperative game G is the users' optimal uplink transmission power vector $\mathbf{P}^*$, i.e., Nash equilibrium point. The formal definition of the Nash equilibrium point is provided below.

Definition** 1: **(Nash Equilibrium) An uplink transmission power vector $\mathbf{P}^* = [P_1^*, \dots, P_i^*, \dots, P_I^*]$ constitutes a Nash equilibrium of the non-cooperative game $G = [I, \{A_i\}_{\forall i \in I}, \{U_i\}_{\forall i \in I}]$ if for every user $i \in I$, it holds that $U_i(P_i^*, \mathbf{P_{-i}}) \geq U_i(P_i, \mathbf{P_{-i}}), \forall P_i \in A_i$.

The physical meaning of the above definition is that at the Nash equilibrium point, no user has any incentive to improve its achieved utility by unilaterally changing its uplink transmission power strategy, given the strategies of the rest of the users.

Theorem** 1: **(Existence and Uniqueness of a Nash Equilibrium) A unique Nash equilibrium point exists for the non-cooperative game $G = [I, \{A_i\}_{\forall i \in I}, \{U_i\}_{\forall i \in I}]$, which is given as follows:

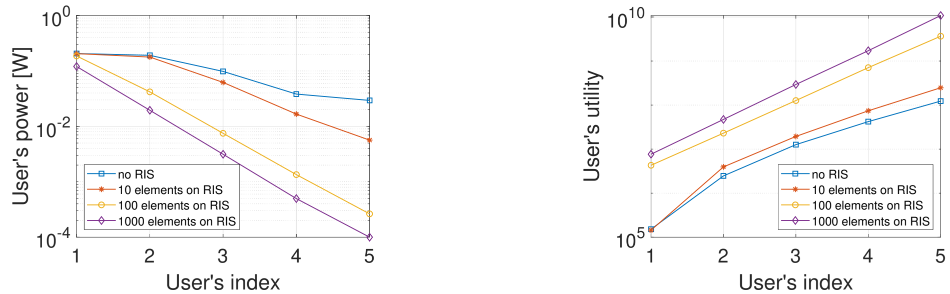
$$P_i^* = \max\{P_i^{min}, \min\{\frac{\gamma_i^* \cdot I_i}{W G_i}, P_i^{max}\}\}, \forall i \in I, \tag{8}$$

where γ_i^* is the unique positive solution of the equation $\frac{\partial f(\gamma_i)}{\partial \gamma_i}\gamma_i - f(\gamma_i) = 0, f(\gamma_i) = (1 - e^{-a\gamma_i})^M$.

The proof of the above theorem is based on the quasi-concavity property of the utility function $U_i(P_i, \mathbf{P}_{-i})$ with respect to the uplink transmission power P_i and is omitted here due to space limitation. The interested reader may consult [13] for a reference guide regarding the detailed steps of the proof. It is noted that the optimal uplink transmission power P_i^*, as presented in Eq. (8), needs as input the sensed interference I_i. This information is broadcasted by the UAV to the users in order the latter ones to make an autonomous decision regarding their optimal uplink transmission power. Given the RIS elements' effective phase shifts $\theta_m^*, \forall m \in M$, and the optimal uplink transmission power $P_i^*, \forall i \in I$, the Stackelberg equilibrium is determined in an iterative manner as presented in Fig. 2.

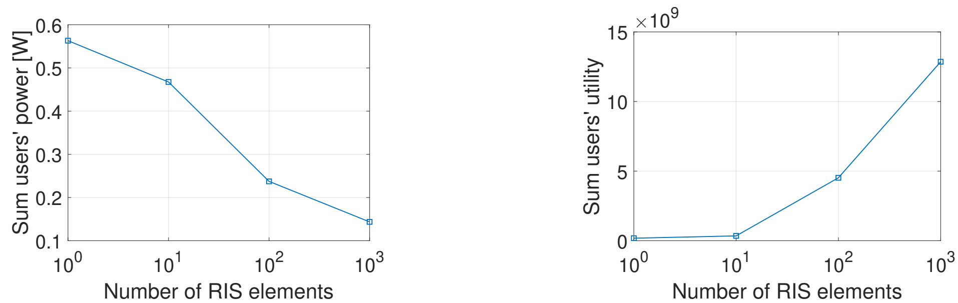
IV. Evaluation & Results

To assess the performance of the proposed framework, and in particular the gain provided by the RIS to the UAV-enabled communications in terms of power savings and user satisfaction, we consider the following network topology. A UAV hovers above the assumed topology at the point $(x_U = 25, y_U = 50, z_U = 120)$ [m] of the three-dimensional space and $(x_R = 49, y_R = 0, z_R = 55)$ [m] is the reference point of



(a) (b)

Fig. 3: Evaluation of the game-theoretic power control per user, under different number of RIS elements.



(a) (b)

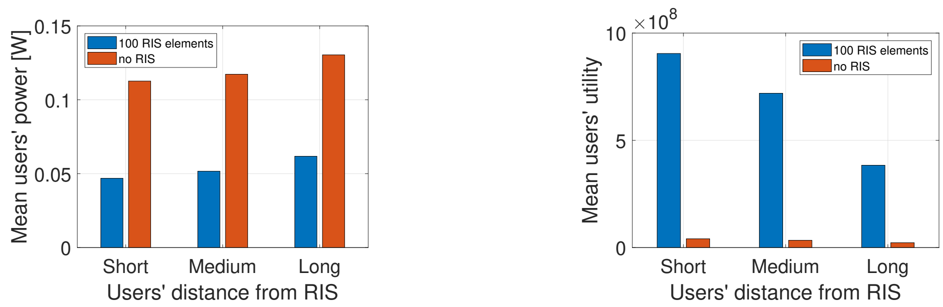
Fig. 4: Evaluation of the game-theoretic power control on the entire system, under different number of RIS elements.

the RIS, for which a different number of reflecting elements is considered and evaluated in the following. For demonstration purposes, we assume that the UAV serves a single NOMA cluster of $|I| = 5$ users in total, where the distance of each user from the RIS varies around the value of $d_{i,R} = 55$m. The overall system's bandwidth is set equal to $W = 1.08$MHz, the power of the AWGN is $I_0 = -130$dBm, while the appropriate control parameters of the users' utility function's slope are set as $a = 1.15$ and $M = 80$. Other required parameters, related to the wireless links' channel modeling, are defined as follows: $\kappa_1 = 3.5$, $\kappa_2 = 2.8$, $\rho = 0.01$, $d = \frac{\lambda}{2}$, $\beta = 2$. Concerning the optimization problem, the mobile users' maximum power budget is $P_i^{max} = 23$dBm and the tolerance/sensitivity of the UAV's receiver is considered to be equal to $P_{tol} = -150$dBm. The results presented in the current section have been averaged over 100 different channel model realizations.

First, we evaluate the performance of the proposed game-theoretic power control approach, by examining the allocated uplink transmission power level and achieved utility of each user, in both an independent manner and as a whole. Specifically, Fig. 3, illustrates each user's allocated uplink transmission power (Fig. 3a) and achieved utility (Fig. 3b), versus the respective user's index (in the horizontal axis), under a different number of RIS's reflecting elements. The users are sorted in descending order with respect to their channel gains and thus, the lowest user index corresponds to the user with the highest channel gain, whereas the highest user index represents the user with the lowest channel gain. It is noted that the proposed game-theoretic power control results in a power allocation among the users of the considered NOMA cluster, such that a low channel gain user is allowed to transmit with a lower power level and achieve a higher personal utility, accordingly. This is due to the devised user's utility function in Eq. 3, which is directly affected by the specific user's channel-gain-to-interference ratio $\frac{G_i}{I_i}$ at the exponent of the utility's numerator. Indeed, the low channel gain users usually exhibit low channel-gain-to-interference ratio $\frac{G_i}{I_i}$, which in turn forces the maximum point of the devised utility function to take a low power P_i value. Additionally, it can be easily deduced by the graphs in Fig. 3a and Fig. 3b that as the number of RIS's reflecting elements increases, then the users' allocated uplink transmission powers decrease and consequently, their achieved utilities increase.

The overall performance gain provided to the considered NOMA cluster is more comprehensively depicted in Fig. 4. In particular, in Fig. 4a and Fig. 4b, the sum users' allocated power levels and sum users' utilities are presented, respectively, as a function of the different number of RIS elements. It can be easily seen that when the number of RIS elements is quite small (e.g., 10^1 RIS elements) the system's performance is comparable to the case when no RIS exists within the network topology (i.e., 10^0 RIS elements). On the contrary, the increased number of RIS elements has as a consequence the reduced sum users' powers and their increased sum utility/satisfaction.

Continuing, we enclose a comparative analysis between dif-



(a) (b)

Fig. 5: Evaluation of the performance gain provided by RIS, under different user distances.

ferent users' distances from the RIS and the UAV, advocating the enhanced overall system's performance in terms of both users' allocated power levels and achieved utilities. Along this analysis, a fixed number of 100 RIS elements is assumed, while three different distance scenarios are examined, in which each user's distance from the RIS varies around the values $d_{i,R} = [55, 60, 80]$ [m], respectively. In Fig. 5, the three distance scenarios are accordingly represented by the terms "Short", "Medium" and "Long" distance from the RIS (in the horizontal axis). Specifically, Fig. 5a depicts the mean NOMA cluster's allocated powers under the three scenarios, considering the existence and non existence of the RIS, while in a similar manner, Fig. 5b presents the mean users' achieved utilities. Obviously, the existence of the RIS results to significantly decreased mean users' powers and hence, remarkably increased mean users' utility values of about one order of magnitude. Thus, the introduction of the RIS can eliminate potential coverage holes within the wireless network and at the same time, ameliorate the users' energy efficiency.

V. Conclusion & Future Work

In this paper, an energy-efficient resource management framework based on a game-theoretic approach is introduced to support the operation of RIS-assisted and UAV-enabled communications systems. Such a setting facilitates the realization of energy-efficient communications within a smart city environment, while promoting Internet of Things. Our goal is to maximize the overall received signal strength at the UAV, while jointly maximizing the experienced energy efficiency by each user. Towards this direction, a single-leader multiple-followers Stackelberg game is formulated where the UAV (leader) determines the RIS elements' effective phase shifts to maximize the overall received signal strength. The users (followers) participate in a non-cooperative game among them, aiming at maximizing their achieved utility, via deriving their optimal uplink transmission power in an autonomous and distributed manner. Indicative numerical results demonstrate the significant power savings and the overall users' satisfaction improvements, that can be achieved based on the proposed framework.

Part of our current and future work focuses on examining the problem of optimal position deployment of the RIS in a wireless network of a smart city. Moreover the performance of the proposed modeling and approach, under scenarios where the users' mobility patterns are stochastic and the network provider has limited information about them and the users' QoS prerequisites, is of high importance.

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