On the Prospect of UAV-assisted Communications Paradigm in Public Safety Networks

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***Abstract*—Modern models for Public Safety Networks (PSNs) utilize Unmanned Aerial Vehicles (UAVs) acting as ad-hoc base stations and complementing the Macro Base Station (MBS) to support the ground users' efficient and undisturbed communication. In this paper, we introduce a holistic and realistic framework that dynamically enables the ground users to invest their transmission power in an autonomous manner either in the UAV-based and/or MBS-based communication, while accounting for their Quality of Service (QoS) prerequisites and risk preferences. The UAV-based communication is characterized by limited available bandwidth, but close distance among the users and the UAV, thus resulting in users' low transmission powers and high achievable data rate, if properly utilized. In our work, the UAV's bandwidth is treated as a Common Pool of Resources (CPR), which can be exploited by all the users residing in the disaster area. However, the latter comes at the expense of resource fragility and potential failure from over-exploitation, due to its fully shared nature and excessive competition among the users. In contrast, the MBS due to its inherent characteristics acts as a safe resource, providing a guaranteed perceived satisfaction to the users based on their transmission power investment. Considering ground users' diverse behavioral patterns, when probabilistic uncertainty of the UAV's shared bandwidth is introduced, we model the ground users' power control problem under the principles of Prospect Theory. The formulated resource orchestration problem is solved as a Fragile CPR game and its convergence to a unique Pure Nash Equilibrium (PNE) point is proven. A distributed low-complexity algorithm that converges to the unique PNE is devised, while the performance of the proposed approach is evaluated through modeling and simulation.**

***Index Terms*—Extreme Communication, Public Safety Networks, Resource Fragility, Prospect Theory, Game Theory.**

I. Introduction

Public Safety Networks (PSNs) are utilized to ensure resilient and reliable exchange of data in disaster-stuck areas (e.g., natural disasters, terrorist attacks). PSNs are expected to be deployed in extreme communication environments and are characterized by their fast deployment, adaptive operation, coverage guarantee, low latency, and extended energy availability for their users. Unmanned Aerial Vehicles (UAVs) support PSNs towards improving system adaptivity and resilience by providing coverage extension, reduced transmission power requirements and enhanced bandwidth availability.

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A. Related Work

Among the key challenges related to the deployment and operation of the UAVs to support the communication demands in PSNs, that have attracted significant interest in the literature, are: (a) the intelligent resource management to support the PSNs' energy-efficient operation, and (b) the efficient bandwidth allocation to improve users' achievable data rate. In [1], the authors use the UAV as a relay to enable the communication of ground users, who are either far away from a base station or simply obstructed. A non-convex joint optimization problem is formulated and solved towards optimizing users' transmission power, achievable data rate, bandwidth usage and UAV's position. Furthermore, a centralized resource allocation problem is studied in [2] towards maximizing the overall users' throughput in a UAV relay system, while considering that the users adopt the Non-Orthogonal Multiple Access (NOMA) technique for their communication. In [3], the problem of maximizing the uplink minimum throughput of all the ground users during a specific period of the UAV's flight is studied, while considering the UAV's maximum speed constraint and the users' energy availability. The problem of joint aerial-terrestrial resource management in mobile radio networks supported by a UAV is studied in [4] and the authors show that significant improvement in users' achievable data rate and energy-efficiency can be obtained, by properly optimizing the system's parameters related to the UAV flight.

The uplink resource allocation regarding the power and transmission timeslots allocation among the ground users is investigated in [5] to optimize the users' uplink sum rate. The authors decompose the joint sum rate optimization problem into the individual problems of energy allocation and transmission timeslots allocation, which subsequently are solved separately. Furthermore, in [6], the authors propose a game-theoretic mechanism for load balancing between WiFi access points and LTE unlicensed base stations mounted on a UAV, utilizing a no-regret learning algorithm. The optimal location of a UAV when device-to-device underlay links are present is studied in [7].

B. Contributions and Outline

The previous examined research works, have demonstrated that the UAV provides additional bandwidth and communication flexibility to the users. The majority of the literature has assumed that the users in PSNs act as neutral expected utility maximizers, thus the Expected Utility Theory (EUT) has been used to solve the emerging resource management problems [8]. However, this does not hold true in real PSNs, where users make decisions: a) under risks introduced by the extreme and uncertain communication environment, the limited information availability and bandwidth limitations, and b) based on their personal characteristics and reactions under risks.

Despite the extensive existing literature with respect to the resource allocation problem in UAV-assisted PSNs, to the best of our knowledge the resource orchestration considering users' risk-aware behavior in terms of communicating either over the UAV and/or the MBS has not been studied so far. In this paper, we aim at exactly filling this gap, by designing a novel flexible users' power control framework, where the users exploit both the MBS and UAV connectivity, while exhibiting risk-based behavior. This is based on the use of Prospect Theory (PT) [9] which presents a realistic model to capture users' risk-aware characteristics within the UAV-assisted PSN, thus introducing a more pragmatic approach compared to the conventional EUT, that treats the humans as risk-neutral utility maximizers.

Specific prospect-theoretic utility functions are defined representing the ground users' satisfaction from the UAV and MBS-based communication and corresponding bandwidth usage. The bandwidth's fragility in the UAV-based communication is examined regarding its exploitation by the users (Section II-B). Based on the above, a user-centric power control problem is formulated as a maximization problem of each user's expected prospect-theoretic utility, and it is confronted as a non-cooperative game among the users [10]. The specific decision at stake refers to the users' investment of their transmission power in the two available communication alternatives. The existence and uniqueness of a Pure Nash Equilibrium (PNE) is shown and the convergence of the users' power strategies to the unique PNE is proven (Section III). A distributed low-complexity algorithm that converges to the unique PNE is also devised (Section IV). A series of experiments are performed to evaluate the performance of the proposed user-centric risk-aware power control framework in the UAV-assisted PSNs, in terms of users' transmission power investment, achievable data rate, fragility of the UAV's available bandwidth and impact of users' risk-aware behavior on the system's operation. Moreover, the concept of the freshness of information is adopted and numerically evaluated, in order to capture the need and criticality of fast data exchange that can be achieved through the UAV-based communication, and thus contribute to the greater rate of return and corresponding satisfaction for the users in some scenarios (Section V). Finally, Section VI concludes the paper.

II. Prospect-theoretic UAV-assisted Public Safety Systems: Operation Overview and Modeling

A. The Tragedy of the Commons

In the UAV-assisted PSN, each ground user $i, i \in N$, where N denotes the set of users, can communicate over the UAV and/or the MBS. The UAV-based communication is characterized by limited available bandwidth (as the UAV acts as an ad-hoc communication solution in the disaster area) compared to the MBS-based communication. However, due to the UAV's proximity to the users and respectively improved channel gain, the UAV-based communication becomes more attractive to them as they can achieve higher data rates with lower transmission power. Similarly, the close distance between the users and the UAV contributes to the fast exchange of data, thus, improving the *freshness of information*, which is critical in many requested services especially during a catastrophic event. Thus, the available bandwidth in the UAV-based communication is considered as a *Common Pool of Resources (CPR)*, since it is non-excludable (i.e that is accessible by all users), rivalrous, and subtractable. However, the potential over-exploitation of the CPR would conclude to the failure of the UAV's bandwidth, as due to the increased interference at the receiver, i.e., UAV, none of the ground users will be eventually satisfied . This observation is motivated by the well-known concept of the Tragedy of the Commons [11].

In contrast, the MBS usually resides far away from the majority of the users and higher transmission power levels are required by the ground users to achieve their QoS satisfaction. Thus, the MBS-based communication becomes less attractive as it results to lower energy-efficiency transmissions. On the other hand, assuming that usually a greater portion of bandwidth is available by the MBS to support the ground users' communication and considering that more processing capabilities are offered by the MBS, in our system model the MBS's available bandwidth is treated as a safe resource alternative, due to the fact that each user can obtain a guaranteed level of QoS given its personal characteristics (e.g. channel gain, transmission power).

Within the considered UAV-assisted PSN, each user $i, i \in N$ has a maximum transmission power P_i^{Max}, which is invested to the UAV and MBS-based communication towards fulfilling its QoS demands. Each user's goal is to determine in an autonomous manner its transmission power investment to the UAV-based communication P_i^{UAV} and to the MBS-based communication P_i^{MBS}. The percentage of user's i power investment to its transmission to the UAV is $x_i, x_i \in [0, 1]$, thus, $P_i^{UAV} = x_i P_i^{Max}$, thus, $P_i^{MBS} = (1 - x_i) P_i^{Max}$.

B. Prospect-theoretic Utility Functions

The ground users are assumed to exhibit risk-aware behavior towards determining their transmission power levels P_i^{UAV}. This behavior stems from the uncertainty of the outcome and the enjoyed QoS, due to the UAV's limited available bandwidth, communication traffic congestion, and the increased interference. To capture users' risk-aware behavior, we follow the Prospect Theory principles, and the users' prospect-theoretic utility is accordingly defined as follows [9].

$$\mathscr{U}_i(y_i) = \begin{cases} (y_i - y_{0,i})^{\lambda_i} & when\ y_i > y_{0,i} \\ -k_i(y_{0,i} - y_i)^{\mu_i} & otherwise \end{cases} \quad (1)$$

where $y_i(x_i, x_T)$ is the user's i actual utility, $x_T = \sum_{i=1}^{N} x_i$ the total power investment to the UAV-based communication, and $y_{0,i}$ the reference point. The users' satisfaction is determined with respect to a reference point $y_{0,i}$ [9], which is considered as the ground truth of the users' actual utility $y_i(x_i, x_T)$. We define $y_{0,i} \triangleq \frac{B_{MBS}/N_{MBS}}{P_i^{MBS}} ln(1 + \gamma_i^{MBS}), \forall i \in N$, as the achieved energy-efficiency, if the users were exploiting only the safe resource (transmission only to the MBS), where B_{MBS} is the MBS's bandwidth, N_{MBS} the number of users transmitting to the MBS, $\gamma_i^{MBS} = \frac{B_{MBS}}{R_i^{MBS}} \frac{h_i^{MBS} P_i^{MBS}}{\sum_{j>i} h_j^{MBS/UAV} P_j^{MBS/UAV} + \sigma^2}$ represents the user's i Signal to Interference plus Noise Ratio (SINR), R_i^{MBS} is the users' requested service data rate, h_i^{MBS} reflects the user's channel gain to the MBS, $\sum_{j>i} h_j^{MBS/UAV} P_j^{MBS/UAV}$ is the interference considering the NOMA technique, and σ^2 is the variance of the noise power.

The parameters $\lambda_i, \mu_i \in (0, 1]$ express the user's sensitivity to the gains and losses of its actual utility $y_i(x_i, x_T)$, respectively. The risk seeking behavior of a user in losses and its risk averse behavior in gains is reflected by small values of the parameter λ_i. Small values of parameter μ_i imply higher decrease of user's prospect-theoretic utility for small values of y_i and close to the reference point $y_{0,i}$. Without loss of generality, we assume $\lambda_i = \mu_i$. The loss aversion parameter $k_i, k_i \in [0, +\infty)$ reflects the impact of losses compared to gains on user's prospect-theoretic utility. If $k_i > 1$, the user i weighs the losses more than the gains, while if $0 \leq k_i \leq 1$, the user weighs more or equal the gains than the losses, thus presenting an aggressive gain seeking behavior.

If the UAV's bandwidth is not over-exploited (CPR survives), the user enjoys the utility (measured in energy-efficiency units) of transmitting data to the MBS (first term of Eq. 2) and the UAV (second term of Eq. 2) as follows.

$$y_i(x_i, x_T) = y_{0,i}(1 - x_i) + E_i x_i \mathfrak{R}(x_T) \tag{2}$$

where $E_i = \frac{B_{UAV}/N_{UAV}}{P_i^{UAV}} ln(1 + \gamma_i^{UAV})$, B_{UAV} is the UAV's bandwidth, N_{UAV} is the number of users transmitting to the UAV, and $\gamma_i^{UAV} = \frac{B_{UAV}}{R_i^{UAV}} \frac{h_i^{UAV} P_i^{UAV}}{\sigma^2 + \sum_{j>i} h_j^{MBS/UAV} P_k^{MBS/UAV}}$ reflects the user's i SINR measured at the UAV. The function $\mathfrak{R}(x_T)$ represents the rate of return of the UAV-based communication to the users, which is a decreasing concave function with respect to $x_T = \sum_{i=1}^{N} x_i$. For demonstration purposes, the rate of return $\mathfrak{R}(x_T)$ of the CPR is formulated as follows:

$$\mathfrak{R}(x_T) = 2 - e^{x_T - 1} \tag{3}$$

The CPR has a probability of failure $Pr(x_T)$ (CPR's fragility) to serve the users who transmit to the UAV, which is increasing with respect to users' aggregate power investment x_T. In the following, we consider $Pr(x_T) = x_T^2$ and x_T is considered normalized. If the CPR survives, then each user perceives an actual utility (Eq. 2) greater than the reference point ($y_i > y_{0,i}$). Via subtracting the reference point $y_{0,i}$ from the actual utility (Eq. 2), and shaping the result according to the first branch of Eq. 1, we have $\mathscr{U}_i(x_i) = x_i^{\lambda_i}[E_i \mathfrak{R}(x_T) - y_{0,i}]^{\lambda_i}$. For the simplicity of the notation, we normalize the rate of return function, so that $y_{0,i} = 1$, and denote $\overline{\mathfrak{R}_i}(x_T) \triangleq (E_i \mathfrak{R}(x_T) - 1)^{\lambda_i}$, where $\overline{\mathfrak{R}_i}(x_T)$ is concave, decreasing, twice continuously differentiable and positive. Thus, $\mathscr{U}_i(x_i) = x_i^{\lambda_i} \overline{\mathfrak{R}_i}(x_T)$. On the other hand, if the UAV's bandwidth is over-exploited by the users' transmissions, then no user receives any satisfaction from its transmission to the UAV. Thus, the second term of Eq. 2 becomes zero and the users enjoy the transmission only to the MBS. In this case, the actual utility is $y_i \leq y_{0,i}$, thus, by subtracting the actual utility from the reference point and reshaping the result based on the second branch of Eq. 1, we have $\mathscr{U}_i(x_i) = -k_i x_i^{\lambda_i}$.

Based on the previous analysis, the ground users' prospect-theoretic utility function (Eq. 1) can be rewritten as follows.

$$\mathscr{U}_i(x_i) = \begin{cases} {x_i}^{\lambda_i} \overline{\mathfrak{R}_i}(x_T) & if\ y_i > y_{0,i} \\ -k_i x_i^{\lambda_i} & otherwise \end{cases} \tag{4}$$

Given the CPR's probability of failure $Pr(x_T)$, the probability that the UAV's bandwidth serves the users is $(1 - Pr(x_T))$. As a result, Eq. 4 can be written equivalently as:

$$\mathscr{U}_i(x_i) = \begin{cases} {x_i}^{\lambda_i} \overline{\mathfrak{R}_i}(x_T) & with\ prob.\ (1 - Pr(x_T)) \\ -k_i x_i^{\lambda_i} & with\ prob.\ Pr(x_T) \end{cases} \tag{5}$$

III. Solution via Fragile CPR Games

The sophisticated design of the prospect-theoretic utility functions sufficiently represents real-life outcomes of ground users' operation in the UAV-assisted PSNs. In view of this realization, user behavioral modeling and actions become the key element for the self-optimization of the PSN. The users incorporate multiple parameters in shaping their strategic decision-making (e.g., QoS, transmission power, probability of CPR failure, heterogeneous risk and gain perceptions etc.) and define their expected prospect-theoretic utilities, under a probabilistic perspective, as follows.

$$\mathbf{E}(\mathscr{U}_i) = {x_i}^{\lambda_i} \overline{\mathfrak{R}_i}(x_T)(1 - Pr(x_T)) - k_i x_i^{\lambda_i} Pr(x_T) \tag{6}$$

Subsequently, the optimization of the operation of the PSN via the resource allocation and simultaneous risk management is formulated as a distributed maximization problem:

$$\begin{gathered} max\mathbf{E}(\mathscr{U}_i) = max\{x_i^{\lambda_i} f_i(x_T)\},\ \forall i \in N \\ s.t.\ x_i \in [0, 1] \end{gathered} \tag{7}$$

where $f_i(x_T) = \overline{\mathfrak{R}_i}(x_T)(1 - Pr(x_T)) - k_i Pr(x_T)$ corresponds to the user's effective rate of return. The above problem can be treated and solved as a *Fragile CPR game* which captures not only the rising opportunity of supporting the performance of the PSN via the commonly shared bandwidth of the UAV, but also the potential implications of resource fragility.

The commonly shared nature of the UAV's bandwidth is well aligned with the fundamental principles of CPR games, since the latter refer to rivalrous and non excludable resources, meaning that the competitive stance of each user aiming to claim a substantial fraction of the provided bandwidth in order to reach satisfactory QoS levels, limits the ability of other users to optimize their own operation and transmission by condensing the returns obtained from the remaining bandwidth. A Fragile CPR game is defined as $\Gamma = [N, \{\mathscr{X}_i\}_{i \in N}, \{\mathscr{U}_i\}_{i \in N}]$, where each user's strategy is $\mathscr{X}_i \in [0,1]$. In Fragile CPR games, the probability of resource failure $Pr(x_T)$ is considered convex, increasing and twice continuously differentiable with respect to x_T.

Pure Nash Equilibrium: The notion of Pure Nash Equilibrium *(PNE)* provides a stable and predictable solution for the non-cooperative game, under which no user has the incentive to deviate from the concluded strategy, since its utility cannot be improved by a unilateral strategy change, given that the strategies of all other users remain unmodified. For game Γ, the PNE is the optimal investment vector $\mathbf{x}^* = \{x_i^*\}$ such that $\mathscr{U}_i(x_i{}^*, \mathbf{x}^*_{-i}) \geq \mathscr{U}_i(x_i, \mathbf{x}^*_{-i})$, $\forall x_i \in \mathscr{X}_i$ [12], under which the UAV's bandwidth does not collapse and the users enjoy sufficient returns through their transmission to the UAV.

Best Response: b_i is considered as the strategy of each user providing the most favorable outcome given the actions of the other users, and is defined as, $b_i(\mathbf{x_{-i}}) = argmax\mathbf{E}(\mathscr{U}_i(x_i, \mathbf{x_{-i}}))$, $b_i : \overline{\mathscr{X}}_{-i} \rightrightarrows \mathscr{X}_i$, where $\overline{\mathscr{X}}_{-i}$ represents aggregate investment space excluding user i. For the game Γ, $0 < b_i < 1$ reflects a joint transmission scheme to the MBS and the UAV, whereas $b_i = 1$ indicates a failure state of the UAV's bandwidth, since all users transmitted their data directly to the UAV.

Theorem 1: (Existence of PNE) There exists at least one point $\varrho \in \mathscr{X}_i$ which is a maximum point $\mathbf{E}(\mathscr{U}_i)$.

Proof: An extremal point for $\mathbf{E}(\mathscr{U}_i)$ can be identified by applying the first order derivative criterion:

$$\frac{\partial \mathbf{E}(\mathscr{U}_i)}{\partial x_i} = x_i{}^{\lambda_i - 1}\phi(x_i) = 0 \tag{8}$$

where $\phi(x_i) = (x_i f_i'(x_T) + \lambda_i f_i(x_T))$. Towards facilitating the study of the above equation, we first study $f_i(x_T)$ and its behavior. Since $\overline{\mathfrak{R}}_i(x_T)$ is decreasing and concave, then $f_i(x_T) = \overline{\mathfrak{R}}_i(x_T)(1 - Pr(x_T)) - k_i Pr(x_T)$ is proven to be decreasing and concave for $E_i > 1$, $\lambda_i < 0.5$, i.e., $\frac{\partial f_i(x_T)}{\partial (x_T)} < 0$, $\frac{\partial^2 f_i(x_T)}{\partial x_T^2} < 0$. By examining the monotonicity of $f_i(x_T)$, we observe that it changes its sign from positive to negative within $(0,1)$, hence there exists a unique value $\xi \in (0,1)$ such that $f_i(\xi) = 0$. By considering the above, from (8), $\phi(x_i)|_{x_i=0} > 0$ and $\phi(x_i)|_{x_i=\xi} < 0$, since $f_i' < 0, \forall x_i \in \mathscr{X}_i$ and $f_i(\xi) = 0$. As a result, by applying and extending Bolzano's theorem for $\frac{\partial \mathbf{E}(\mathscr{U}_i)}{\partial x_i}$, there exists at least one extremal point $\varrho \in (0,\xi)$ for $\mathbf{E}(\mathscr{U}_i)$ such that $\frac{\partial \mathbf{E}(\mathscr{U}_i)}{\partial x_i} = 0$. ■

Lemma 1: The extremal point ϱ in the reduced strategy space $\mathscr{X}_i' = (0,\xi)$ is a local maximum point for $\mathbf{E}(\mathscr{U}_i)$ and is identified as a PNE of game Γ.

Proof: We apply the second order derivative criterion for $\mathbf{E}(\mathscr{U}_i)$, that is, $\frac{\partial^2 \mathbf{E}(\mathscr{U}_i)}{\partial x_i^2} = \lambda_i(\lambda_i - 1)x_i{}^{\lambda_i - 2} f_i(x_T)$ $+ 2\lambda_i x_i{}^{\lambda_i - 1} f_i'(x_T) + x_i{}^{\lambda_i} f_i''(x_T)$. By tracking the sign of all terms of the above equation, we observe that in the reduced space $\mathscr{X}_i'$ are negative, and hence $\mathbf{E}(\mathscr{U}_i)$ is concave, that is $\frac{\partial^2 \mathbf{E}(\mathscr{U}_i)}{\partial x_i^2} < 0$ and ϱ is a local maximum of $\mathbf{E}(\mathscr{U}_i)$. ■

Theorem 2: (Uniqueness of PNE) The point $\varrho \in \mathscr{X}_i'$ is a unique PNE for the game Γ.

Proof: Since $\mathbf{E}(\mathscr{U}_i)$ is concave, $\frac{\partial \mathbf{E}(\mathscr{U}_i)}{\partial x_i}$ is decreasing in $\mathscr{X}_i{}'$. Hence, the point ϱ, $(\frac{\partial \mathbf{E}(\mathscr{U}_i)}{\partial x_i}|_{x_i=\varrho} = 0)$ is unique due to the monotonicity of $\frac{\partial \mathbf{E}(\mathscr{U}_i)}{\partial x_i}$ and ϱ is a unique global maximum point for $\mathbf{E}(\mathscr{U}_i)$ and Γ admits a unique PNE. ■

Theorem 3: (Convergence to PNE) Convergence of game Γ to its unique PNE is established if b_i is decreasing in x_T [13].

Proof: We determine optimal nonzero investment of a player as $\mathscr{I}(x_T) = -\lambda_i f_i(x_T)/f_i'(x_T)$ for which $\mathscr{I}(b_i(\mathbf{x_{-i}}) + \mathbf{x_{-i}}) = b_i(\mathbf{x_{-i}})$, when $b_i(\mathbf{x_{-i}}) > 0$. It is proven that $\mathscr{I}'(x_T) < 0$, thus, $\mathscr{I}$ is decreasing. We assume $x_1 = b_i(\mathbf{x_{-1}})$, $x_2 = b_i(\mathbf{x_{-2}})$, with $\mathbf{x_{-1}}, \mathbf{x_{-2}} \in \overline{\mathscr{X}'}_{-i}$. If b_i is increasing, then for $x_2 > x_1$, then $b_i(x_{-2}) > b_i(x_{-1})$. However, due to $\mathscr{I}$ being decreasing, for $x_2 > x_1$, $\mathscr{I}(b_i(\mathbf{x_{-2}}) + \mathbf{x_{-2}}) = b_i(x_{-2}) < b_i(x_{-1}) = \mathscr{I}(b_i(\mathbf{x_{-1}}) + \mathbf{x_{-1}})$, which is a contradiction. Hence, b_i is decreasing in x_T. ■

IV. Distributed Algorithm

In this section, we introduce a low complexity and iterative **P**rospect-theoretic **A**utonomous **R**esource **I**nvestment algorithm for public **S**afety (*PARIS*) which determines the PNE of the game Γ. The primary novelty of the algorithm lies in the multifaceted execution of different actions of distinct network stakeholders during the investment and resource allocation phases, allowing for decision decentralization which enables the self-optimization dynamics of the network. Each user interacts with the UAV and independently defines its investment to the UAV's bandwidth, stemming from its prospect-theoretic modeling, as decribed above. As the system evolves, PARIS confirms the convergence of the UAV-assisted PSN to a stable operational point, or announces the collapse of UAV's bandwidth due to excessive user resource demand.

V. Numerical Results

A. Experiment Setup and User Behavior Analysis

In this section, we provide an extensive numerical evaluation of the operating features and the performance of the presented prospect-theoretic framework in the UAV-assisted PSNs via modeling and simulation. We consider a UAV-assisted PSN topology with 20 ground users. The MBS-based network covers an area of approximately $6km$, whereas the UAV hovers close to the users (from 0.2 to $1.5km$) ensuring more reliable connections and superior channel gain conditions, both operating under the NOMA transmission technique. The total available bandwidth is $4MHz$, 70% of which is offered by the MBS and the remaining fraction becomes available from the UAV. We set $P_i^{Max} = 0.2Watts$ and the users request emergency services, e.g., $R_i^{UAV} = 64Kbps$.

We examine the case where the UAV is located above a homogeneous population with respect to the users' risk preferences and behaviors ($\lambda_i = 0.1$ and $k_i = 20$). Specifically, Fig. 1-a shows the users' achieved data rate from the UAV and MBS-based communication versus their distance from the MBS. It is shown that only the users closer to the MBS manage to achieve high data rates from the MBS, due to their good channel gain conditions, taking advantage of the highly MBS's

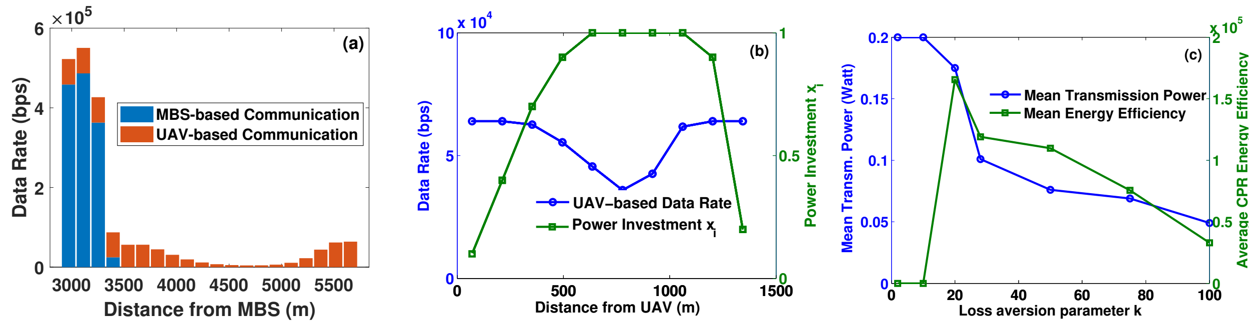

Fig. 1: (a) Users' data Rate vs Distance from the MBS, (b) Users' Data rate and Power Investment vs Distance from the UAV, and (c) Mean Transmission Power and Average CPR Energy-Efficiency vs Loss Aversion Parameter k.

Algorithm 1 PARIS: Prospect-theoretic Autonomous Resource Investment for public Safety

Require:
UAV, MBS, user coordinates & $B_{MBS/UAV}, k_i, \lambda_i$
$step \leftarrow 1$; $UAV_{fails}^{(step)} \leftarrow 0$; $UAV_{active}^{(step)} \leftarrow 0$
Calculate $h_i^{MBS/UAV}$, apply SIC, set random $x_i^{(step=1)}$
while $UAV_{fails}^{(step)} = 0$ **and** $UAV_{active}^{(step)} = 0$ **do**
  Calculate $P_i^{MBS/UAV}$; $\mathbf{E}(\mathscr{U}_i)^{(step)}$;
  for all $x_i \in [0, 1]$ **do**
    x_i^*=$argmax_{x_i}\mathbf{E}(\mathscr{U}_i)$
    if $\mathbf{E}(\mathscr{U}_i) > \mathbf{E}(\mathscr{U}_i)^{(step)}$ **then**
      $x_i^{(step+1)} \leftarrow x_i^*$ **and** $\mathbf{E}(\mathscr{U}_i)^{(step+1)} \leftarrow \mathbf{E}(\mathscr{U}_i)$
    end if
  end for
  if $\sum R_i^{UAV} > B_{UAV}$ **then**
    $UAV_{fails}^{(step+1)} \leftarrow 1$
  end if
  if $x_i^{(step+1)} - x_i^{(step)} < \epsilon$ **then**
    $UAV_{active}^{(step+1)} \leftarrow 1$
  end if
  $step \leftarrow step + 1$
end while
return
User investment x_i and UAV_{fails} if PSN has failed

under-exploited bandwidth, while the more distant ones do not manage to transmit via the MBS at all. On the contrary, all the users exchange data with the UAV, due to its close proximity and superior communication channel gains. The impact from the application of the Successive Interference Cancellation technique in the NOMA communication environment is evident, with the users farthest away (deteriorated communication channel conditions) to successfully operate due to the absence of interference. Regarding the users' investment to the UAV-based communication, in Fig. 1-b it is shown that users closer and farthest away from the UAV do not need to invest heavily in the CPR since they achieve to obtain their target data rates by taking advantage of the NOMA communication environment. On the other hand, middle distant users from the UAV, select to fully invest their transmission power in the UAV-based communication, however they still do not reach their target data rate since they are simultaneously impacted by the high interference levels and the limited UAV's bandwidth.

Following, we modify users' behavior regarding their risk aversion perception, reflected via $k_i = k$. Fig. 1-c presents users mean transmission power and energy-efficiency for increasing values of k. For low values of k, users underestimate the CPR's probability to fail and transmit with maximum power to communicate with the UAV, leading to the inevitable collapse of the UAV's bandwidth due to its over-exploitation, thus, energy-efficiency is zero since users are practically unable to communicate. With the gradual increase of k, users become more conservative, thus, their transmission power decreases and the CPR does not fail with energy-efficiency reaching its highest average value, since the UAV bandwidth is fully utilized. For even higher values of k, users further reduce their investment to the CPR as they become more risk averse and subsequently their energy-efficiency decreases.

B. UAV Positioning

In this subsection we examine impact of UAV's positioning on the overall system performance, by allowing UAV to reposition itself above the users towards improving the communication efficiency of the PSN. Specifically, in Fig. 2-a, we study users' average power investment and average data rates for increasing average distance of the UAV from the users. We conclude that when the UAV has greater proximity to the examined population, the users invest less power to their UAV-based communication, since their favorable channel conditions ensure that they can sufficiently communicate with the UAV. However, as the UAV moves away (especially when the average distance surpasses $1km$), the users' power investment x_i increases rapidly, while the average attainable data rates significantly decrease. The same hold true in Fig. 2-b as well, where we observe that the average energy-efficiency of all users to significantly deteriorates with the increase of the distance of the UAV from the users, since the average energy-efficiency decreases by 67.27% at $1.5km$ when compared to an average distance of $0.7km$.

C. Freshness of Information

When considering special multimedia services during the public safety events, e.g., geolocation data collection, evac-

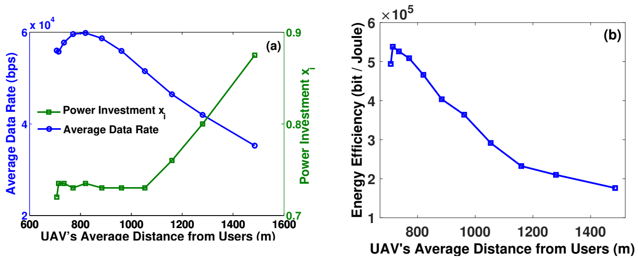

Fig. 2: (a) Average Data Rate and Power Investment, and (b) Energy-efficiency, vs UAV's Average Distance from the Users.

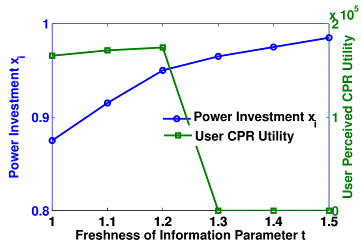

Fig. 3: Users' Power Investment and Perceived CPR Utility as a function of the Freshness of Information Parameter t.

uee coordinates report, etc., the freshness of the transmitted information to the UAV or the MBS becomes of high criticality. Given that the UAV is located close to the users, the latter are attracted to transmit their data to the UAV, since in addition to the significantly better channel conditions, the information may arrive to the UAV much faster, when compared to the MBS that is located far away from the ground users, resulting in high transmission and propagation delays. To capture the impact of the information freshness, we introduce the parameter $t_i, t_i \in [0, +\infty)$, in the CPR's rate of return (Eq. 3), which is reformulated accordingly as follows: $\Re(x_T) = t_i(2 - e^{x_T - 1})$. If $t_i = 1$, this means that the freshness of information is not critical for the ground user i, while if $t_i > 1$, the user enjoys superior satisfaction from sending its data to the UAV in a fast manner. Fig. 3 shows that when the parameter $t_i = t, \forall i \in N$ representing that the PSN importance of information freshness increases, the average user perceived utility from the UAV-based communication (first term of Eq. 6) as well as the users' power investment to the UAV increase. As a result, users have the incentive to invest more in the UAV-based communication not only due to the more favorable channel conditions, but also due to the importance of the data from this transmission. However, as the value of the parameter t further increases, this can lead to the imminent collapse of the UAV's bandwidth, since users' aggregate investment surpasses the capacity of the UAV to meet total demand.

VI. Conclusion

In this paper, a risk-aware transmission power control framework is proposed, considering an UAV-assisted PSN, where the ground users can invest their transmission power towards transmitting data to either the UAV and/or the MBS. Due to its inherent characteristice, the UAV-based communication is considered as a Common Pool of Resources, where the users compete with each other for the UAV's limited bandwidth, while the MBS-based communication acts as the safe resource. The users' risk-aware behavior in the created competitive communication environment is captured in representative utility functions adopting the concepts of Prospect Theory and the Tragedy of the Commons. A non-cooperative power control game is formulated among the users, who aim to maximize their prospect-theoretic utility in an autonomous manner. The existence and uniqueness of a Pure Nash Equilibrium point is shown and a distributed algorithm is introduced to converge to the PNE point. Finally, the performance of our proposed framework in terms of several metrics is examined via modeling and simulation, while accounting for users' realistic behavioral scenarios. Our current and future work contains the extension of the introduced framework and users' realistic behavior modeling, in several other emerging communication systems within the 5G and Internet of Things (IoT) era, including mobile edge computing (MEC), where the users decide their optimal data offloading to the MEC server and/or processing the data locally.

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