Sumer Journal for Pure Science (ISSN: 2790-7031)
2nd International Scientific Conference on Pure and Medical Sciences/University of Sumer 2024

Jamming a Multi-Hop UAV Relay Network

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Abstract

In this paper, we formulate as a game, the dynamic interaction between a pair of transmitter and receiver (or ground stations) through a multi-hop relaying Unmanned Air Vehicles (UAVs) in a hostile environment. We assume that the ground stations can concentrate their transmissions to the relaying UAVs. The UAVs relay their data to their ground stations destinations. Furthermore, we assume limited UAVs capabilities, i.e., without the ability of controlling the power level. This limited UAV capability leads to UAVs transmission to interfere with each other. The jammer is assumed to be a smart jammer that targets the downlink transmission from the UAVs to the ground stations. The ground stations strategically allocate the UAVs' power level such that it is optimal to countermeasure the jamming attack and to limit the interference between the UAVs at the same time. We formulate the problem as a Zero-Sum game and the corresponding optimization problem as a linear program. We solve the game and find the Nash equilibrium (NE) through the use of Fictitious Play (FP) algorithm. Our results show that under linear jammer cost function, the jammer can severely disturb the UAV-ground stations transmission even with using low power levels.

Keywords: Jamming, Multi-hop, NE, Relay network, UAV.

التشويش لشبكة متعدد القفزات باستخدام مركبة غير مأهولة

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الخلاصة

أدى التقدم الحديث في مجال تقنيات الاجسام الطائرة الى تحديات كبيرة للباحثين في هذا المجال. في هذا البحث، تم التوصل الى صيغة رياضية بين زوج من منظومات الاتصال تمر الاشارة من خلال أقلدة متعددة القفز مع افتراض السيطرة على العملية من خلال قاعدة الارسال. بالاضافة الى ذلك، فانه تم افتراض قابليات محددة لمثل هذه الاجسام الطائرة من حيث اتخاذ القرار الذي يسيطر على عتبة القدرة والتي قد تؤدي الى تداخل بين اشارات هذه الاجسام. تم افتراض منظومة تشويش ذكية للتاثير على المسار النازل بين الجسم الطائر والمحطة الارضية. المحطة الارضية تحدد مستوى القدرة ومن ثم قابلية المنظومة للتعامل مع التداخل والتشويش في الوقت نفسه. تم التوصل الى مقاربة علمية للمشكلة مع اقتراح حلول مثلى ومن ثم حل المشكلة من خلال البرمجة الخطية. أثبتت نتائج المحاكاة قابلية المنظومة بالعمل بكفاءة عالية في ظروف التداخل والتشويش دون التأثير الكبير على طاقة الارسال.

1. Introduction

Unmanned Aerial Vehicles (UAVs), or sometimes called drones, attract increasing attention and appeared in many applications in the last decades [1]. Security and defence [2], industrial Internet of Things (IoT) platforms [3], smart agriculture [4], express transportation [5], disaster relief and aerial photography [6] represent the main fields of UAVs applications. As a result, the global drone market is anticipated to grow at a compound annual growth rate to reach USD 96.000 billion by 2027 [7]. UAVs also play a role in various applications of the cellular networks. Such role is either cellular connected UAVs or UAV-assisted wireless communication. The first paradigm realizes the UAV as an aerial user, while the second utilizes the UAV as a flying base station or relay to provide data access from the cellular network [8], [9]. On the other hand, Relaying operation is considered as a promising solution to enhance the communication coverage and the capacity of the transmission channel [10], [11]. In this scenario, a flying UAV is located between the transmitter and the receiver of the conventional communication system. Such network is sometimes called single-hop UAV relay network [12]. Further enhancements in the channel capacity can be achieved with the aid of a multi-hop UAV relay network as have been described in [13], [14]. However, the interference between the data links at each hop is considered a significant factor impacting the performance of the UAV network [15], [16]. In spite of useful applications, malicious UAVs pose serious security threats to the public privacy. The threats are either in the form of restricted harmful payloads or collection of data from restricted private geographic territory [17], [18]. Hence, it is important to develop techniques to avoid the catastrophic harm of these UAVs. Jamming is the most effective attack used frequently against the malicious UAVs [19]. The issue of jamming the data transmission of UAV networks is a vibrant research venue. For example, the work presented in [20] uses deep reinforcement learning algorithm and adaptive intrusion detection system to identify the intruders. The authors in [21] propose an anti-intelligent UAV jamming strategy, in which the ground users can learn the optimal trajectory to avoid jamming. The authors in [22] try to optimize the UAV trajectory and relay power to resist jamming attacks and save the energy consumption. In [23], the interaction between the UAV and a smart jammer are formulated as anti-jamming UAV relay game, which can efficiently reduce the bit error rate of the jammed message. In [24], an optimization problem is formulated to balance the trade-off between the trajectory path and the selection of the classical communication modes (either full duplex or half duplex). The work of [25] investigates a jammer-aided UAV covert communication, which aims to maximize the user's covert rate with optimized transmit and jamming power. A nice and recent survey on using game theoretical models in UAV systems is done in [28] where in addition to provide a literature survey on the state of the art work on game theoretical models in the UAV field, potential research directions and challenges are proposed.

In this work we study the relay-UAV jamming interaction from a different perspective. We summarize our contributions as:

- We formulate for the first time (to our best knowledge) a relay-UAV jamming problem and solve it using a game theoretic model.
- We assume that there is no cost for the transmission power at the ground stations and assume a linear cost function for the jammer. This is an assumption that has not been

used before and it affects the NE of the game. As a result, this gives new insights and understanding to the problem.

- We assume that the UAV units do not have the ability to control their power levels and they can create self-interference to each other. This is different from the assumption used in most literature. Furthermore, we model this interference in the utility function and take its effect on the game results and simulations.
- We formulate the game as $max\,min$ optimization problem and poses it as a linear programming optimization problem.
- We extend the game to a continuous space strategy space and obtain closed form expressions.
- We use a learning algorithm to solve this problem that is FP learning.

2. Multi-hop relaying UAV system

2.1 System Model

We envision a scenario where there is an interaction between the TX-RX pairs and the multi-hop relaying UAVs in the presence of a jammer as shown in Figure 1.In particular, we assume that the ground stations that are represented by the TX-RX pairs can focus (beam-form) their transmissions to the relaying UAVs. The UAVs relay the received-transmitted signal to their ground stations destinations. However, the UAVs are not sophisticated enough to use beam-forming to focus their transmission. As a result, the UAVs transmission is in all direction which makes them cause interference to each other. We also assume that there is a sophisticated jammer (or more) that can jam the downlink transmission from the UAVs to the ground stations. The jammer degrades the received signal to interference plus noise ratio (SINR) at the ground stations. The Relay-UAVs respond to the jammer by increasing their transmission power. However, increasing the UAVs transmission powers leads to interference between the UAVs themselves which degrades the SINR at the ground stations. Specifically, the jammer can choose to jam with low power levels to force the UAVs to increase their transmission power levels and hence the jammer can use the UAVs themselves to degrade the SINR because of the undesired interference We model this type of conflicting goals from a game theoretic point of view. To define a particular game $\mathcal{G}$, there must be a set of players $\mathbb{P}$, where each player has a set of strategies. Let the set of the players' strategies be $\mathbb{S}$. Each strategy has its consequences, formally rewards or cost, that are captured by the set $\mathbb{U}$. We use a zero-sum game model to design players' utilities and study their behaviour. We assume that the jammer is Player $\mathbb{P}1$ and the TX-RX pairs and the multi-hop relaying UAVs as Player $\mathbb{P}2$. The jammer can choose on of M power levels $\{J_1, J_2, ..., J_M\}$ with $J_i - J_{i-1} = \Delta J$. Similarly, we assume that the ground base stations can control the transmit power of the relaying UAVs. Ideally, in the absence of a jammer, this should be sufficient to control their mutual interference. Let the i^{th} UAV transmission power levels be discretized as N power levels $\{P_1, P_2, ..., P_N\}$ with $P_i - P_{i-1} = \Delta P$. The jammer chooses each power level with probability $\{x_i\}_{i=1}^{N}$, whereas $\mathbb{P}2$ chooses her power levels with probability $\{y_i\}_{j=1}^{M}$. WLOG and to clarify the analysis, we assume that there are two available power levels for each player.

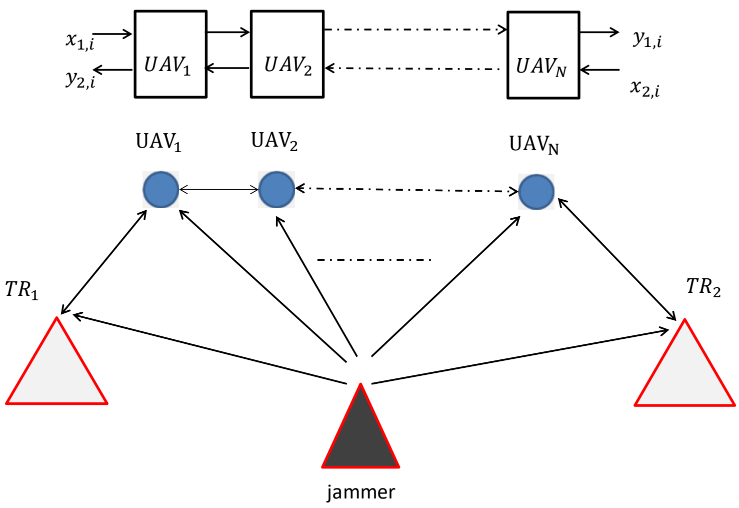

Figure -1: Multi-hop relaying UAVs in the presence of a jammer

For the first player (the jammer), the set of strategies is $\{J_L, J_H\}$ $J_L < J_H$. Similarly, for the k^{th} UAV, the available power levels are $\{P_{Lk}, P_{Hk}\}$ $P_{Lk} < P_{Hk}$. As a result, the second player, TX-UAVs- RX, set of strategies given that there are two relaying UAVs is all combinations of the available power level per a UAV, i.e., $\{(P_{L1}, P_{L2}), (P_{L1}, P_{H2}), (P_{H1}, P_{L2}), (P_{H1}, P_{H2})\}$ Furthermore, we assume identical UAVs such that they have the same power levels and rewrite $\mathbb{P}2$ set of strategies as $\{s_1, s_2, s_3, s_4\}$ with $s_1 = (P_L, P_L)$, $s_2 = (P_L, P_H)$, $s_3 = (P_H, P_L)$ and $s_4 = (P_H, P_H)$. Games can be expressed in the normal form as shown in Table I.

Table -1 Normal Form for the jamming game

	s_1 with y_1	s_2 with y_2	s_3 with y_3	s_4 with y_4
J_L with x_1	a_{11}	a_{12}	a_{13}	a_{14}
J_H with x_2	a_{21}	a_{22}	a_{23}	a_{24}

The $\{a_{ij}\}$ entry of Table I represents the payoff of the jammer if she plays the i^{th} strategy against $\mathbb{P}2$ playing j^{th} strategy. Since we assume a zero-sum game, the payoff of $\mathbb{P}2$ for the same entry is $-\{a_{ij}\}$. A common solution to non-cooperative games is Nash equilibrium (NE) [26] that is defined the NE for a two-player game as $\{s_1^*, s_2^*\}$, where

$$u_1(s_1^*, s_2^*) \geq u_1(s_1, s_2^*) \quad (1)$$

$$u_2(s_1^*, s_2^*) \geq u_2(s_1^*, s_2) \quad (2)$$

Where u_i is the i^{th} player payoff that each player tries to maximize by choosing the NE strategy s_k^* from Eqs. (1) and (2), if any player deviates from its NE, their payoff will be reduced. The NE strategies in Eqs. (1) and (2) are called pure NE (PNE) because they are chosen with probability 1. PNEs do not exist in all games. A more general view of a

PNE is the mixed NE where each equilibrium is chosen with a certain probability. Mixed NEs are guaranteed to exist in all games [26].

2.2 Formulating the Players' Payoffs Functions

Commonly used payoff functions for this scenario are the rate functions or the SINR function. We choose the SINR function since we assume a relatively high power levels although choosing the rate function is better from a convex optimization perspective. The utility function for the TX-UAVs-RX ($\mathbb{P}2$) can be written as,

$$u(P_1, P_2, J_k) = \frac{h_1 P_1}{a h_2 P_2 + g_1 J_k + \sigma^2} + \frac{h_2 P_2}{b h_1 P_1 + g_2 J_k + \sigma^2} + c_J J_k \quad (3)$$

$$\forall \{P_i\}_{i=1,2} \in \{P_L, P_H\} \quad and \quad \forall J_k \in \{P_L, P_H\}$$

where h_1 (h_2) is the channel coefficient between the first (second) UAV and the first (second) TX-RX ground station, respectively. g_1 (g_2)is the channel coefficient between the jammer UAV and the first (second) TX-RX ground station, respectively. ah_1 (bh_2) is the channel coefficient between the first (second) UAV and the second (first) UAV, respectively. σ^2 is the additive white Gaussian noise which is assumed to exists and has the same value at the receivers. The last term, c_J is the jamming power cost which is assumed to be linearly proportional with the jamming power. In literature, this cost can take any non- increasing function shape. Intuitively the payoff (utility) function given in Eq.(3) is built based on maximizing the TX-RX pair rate function that is directly proportional to the SINR given. At the same time, there is an interference cost and a power cost. The interference cost is modeled in the denominator of Eq.(3) by the terms ah_2P_2 , bh_1P_1 which is can also be seen as an indirect power cost. We did not include an explicit power cost for ($\mathbb{P}2$) because we assume that there are many UAVs available to relay the transmission and hence this is not an issue. On the other hand, there is a power cost on the jamming power captured by the term $c_J J_k$. Based on the discussion above, the jammer ($\mathbb{P}1$) objective is to minimize the utility (objective) function given in Eq.(3) by choosing a power level that degrades the SINR and to minimize her jamming cost. On the other hand, $\mathbb{P}2$ would like to maximize the information transmission rate by increasing the received SINR at the ground stations without increasing the interference between the relaying UAVs but at the same time must overcome the jamming power. $\mathbb{P}2$ does this by choosing the power level parameters, i.e, $\{P_i\}_{i=1,2} \in \{P_L, P_H\}$. This is a zero-sum game with $\mathbb{P}1$ as the minimizer and $\mathbb{P}2$ as the maximizer. This can be expressed as the following $\min - \max$ optimization problem. For the jammer this problem is given in Eq. (5).

$$\min_{x_i \in x} \max_{y_i \in y} u(P_1, P_2, J_k)$$

$$\text{subject to} \quad 0 \le \sum_{i=1}^{2} x_i \le 1 \quad 0 \le \sum_{i=1}^{2} y_i \le 1 \quad (4)$$

$$0 \le \{x_i\}_{i=1}^{2} \le 1 \qquad 0 \le \{y_i\}_{i=1}^{4} \le 1$$

Similarly, $\mathbb{P}2$ optimization problem can be written as in Eq.(5) below.

$$\max_{x_i \in x} \min_{y_i \in y} u(P_1, P_2, J_k)$$

$$\text{subject to} \quad 0 \le \sum_{i=1}^{2} x_i \le 1 \quad 0 \le \sum_{i=1}^{2} y_i \le 1 \tag{5}$$

$$0 \le \{x_i\}_{i=1}^{2} \le 1 \qquad 0 \le \{y_i\}_{i=1}^{4} \le 1$$

where $x = \{x_1, x_2\}$ is the jammer probability vector for choosing the power levels. Similarly, $\{y_i\}_{i=1}^{4}$ the TX-UAVs-RX probability vector for choosing the power levels. For security games, it is more interesting to focus on the players' uncertainty to confuse their rivals that is captured by x and y. In addition to this, NE always exists in the mixed strategies [26]. We solve the optimization problems given in Eq.(4) and Eq.(5) using Fictitious Play (FP) learning algorithm that is proved to converge to NE in zero-sum games [27].

2.3 Extending to Continuous Strategies

Our analysis so far is for the problem description in discrete strategies, i.e, the power levels are chosen on discrete steps which are the practical case. However, for the sake of theoretical insight, we extend our analysis to the case where strategies can take any value or take values on a continuous strategy space. We show this through the following claims.

Claim 1: *The game $\mathcal{G}$ with players $\mathcal{P}1$ and $\mathcal{P}2$* and strategies *J and P={P_1, P_2}, respectively with utility function $u(P_1, P_2, J)$ where P_1, P_2, J are defined for all values that are nonnegative has the following NE $\{P_1^*, P_2^*, J^*\}$:*

$$P_1^* = \frac{\sqrt{bh_2\, P_2(ah_2P_2 + g_1J + \sigma^2)}}{bh_1} - \frac{g_2J + \sigma^2}{bh_1}$$

$$P_2^* = \frac{\sqrt{ah_1\, P_1(bh_1P_1 + g_2J + \sigma^2)}}{ah_2} - \frac{g_1J + \sigma^2}{ah_2}$$

$$C_J = \frac{h_1g_1P_1}{(ah_2P_2 + g_1J^* + \sigma^2)^2} + \frac{h_2g_2P_2}{(bh_1P_1 + g_2J^* + \sigma^2)^2}$$

Proof: The proof is straightforward by taking the partial derivative of Eq. (3) (where we assumed it to be defined for all values) and setting it equal to zero.

$\frac{\partial u(P_1,P_2,J)}{\partial P_i} = 0$ *where* $i \in \{1,2\}$ *and* $\frac{\partial(-u(P_1,P_2,J))}{\partial J} = 0$, which completes the proof. □

It can be seen that the expressions for the optimal transmission and jamming powers given in Claim 1 are not easy to evaluate or to interpret. Furthermore, they require a lot of information to be evaluated. As a result, in the next claim we make some assumptions and approximations to get simpler expressions that can provide us with more insight. Of particular interest are the cases where one of the UAVs interference does not affect the other one, or when either $a = 0$ or $b = 0$ but not both. Furthermore, we assume that there are identical channel gains, i.e, $h = h_1 = h_2$ and $g = g_1 = g_2$. Additionally, we assume that the amount of the AWGN at the receiver that is σ^2 is negligible compared to the transmitting and the jamming powers, i.e, $\sigma^2 = 0$.

Claim 2: *The game* $\mathcal{G}$ under the assumption of identical channel gains, zero interference from UAV1 to UAV2 ($a = 0, b \neq 0$), and negligible AWGN with players $\mathcal{P}1$ *and* $\mathcal{P}2$ and strategies *J and P={P_1, P_2}, respectively with utility function $u(P_1, P_2, J)$ where P_1, P_2, J are defined for all values that are nonnegative has the following NE {P_1^*, P_2^*, J^*}:*

$$P_1^* = \sqrt{\frac{g}{bh}J\,P_2} - \frac{g}{bh}J$$

$$P_2^* = \alpha\frac{g}{bh}J, \qquad \alpha > 1, \qquad J \neq 0$$

$$J^* = \frac{\sqrt{\alpha}}{bhg\,C_J}$$

Proof: *By setting* $a = 0,\ h = h_1 = h_2$ and $g = g_1 = g_2$ in P_1^* equation in Claim 1, we get $P_1^* = \sqrt{\frac{g}{bh}J\,P_2} - \frac{g}{bh}J$.

From Claim 1, the $P_2^* = \infty$. However, there is no such power available in any practical systems. As a result, we can assume that $P_2^* = P^{max}$ maximum power available to the second transmitter. However, using the maximum power can hurt the first UAV since the mutual interference term $,b \neq 0$. To solve this, we choose the value of P_2^* such that it causes minimum mutual interference and this value can be obtained from P_1^* equation as follows. Since $P_1^* \geq 0$ this means $\sqrt{\frac{g}{bh}J\,P_2} > \frac{g}{bh}J$ or $P_2^* = \alpha\frac{g}{bh}J, \quad \alpha > 1, \quad J \neq 0$.

Next we find the optimal jamming power where we use the partial derivative of the utility function with respect to the jamming power, or directly the jamming power equation from Claim 1 which we will repeat for convenience: $C_J = \frac{h_1 g_1 P_1}{(ah_2P_2+g_1J^*+\sigma^2)^2} + \frac{h_2 g_2 P_2}{(bh_1P_1+g_2J^*+\sigma^2)^2}$. Substituting $a = 0,\ h = h_1 = h_2$ and $g = g_1 = g_2$, we get: $C_J = \frac{hgP_1}{(gJ^*)^2} + \frac{hgP_2}{(bhP_1+gJ^*)^2}$. Substituting the values of P_1^* *and* P_2^* and after some mathematical manipulation we get the final expression which completes the proof. □

The final claim below considers the opposite case of Claim 2 or the case where the first UAV induces interference to the second UAV, but not the other way, i.e., $a \neq 0, b = 0$.

Claim 3: *The game* $\mathcal{G}$ under the assumption of identical channel gains, zero interference from UAV2 to UAV1 ($a \neq 0, b = 0$), and negligible AWGN with players $\mathcal{P}1$ *and* $\mathcal{P}2$ and strategies

J and P={P_1, P_2}, respectively with utility function $u(P_1, P_2, J)$ where P_1, P_2, J are defined for all values that are nonnegative has the following NE {P_1^*, P_2^*, J^*}:

$$P_1^* = \beta \frac{g}{ah} J$$

$$P_2^* = \sqrt{\frac{g}{ah} J \, P_1} - \frac{g}{ah} J, \qquad \beta > 1, \qquad J \neq 0$$

$$J^* = \frac{\sqrt{\beta}}{ahg \, C_J}$$

Proof: The proof is similar to Claim 2's proof and we will not repeat it due to space limitation.

□

3. Simulation Results

In this section we run our simulations for the following randomly selected parameters to get more insight. $h_1 = h_2 = 0.7, g_1 = 0.7, g_2 = 0.4, a = 0.5, b = 0.75 * a, c_1 = 0.1, \sigma^2 = 0.1$, $\{P_i\}_{i=1,2} \in \{5,10\}$, $\{J_i\}_{i=1,2} \in 0.75 * \{5,10\}$. Our simulation results coincide with our analytical solution for the optimization problems given in Eqs. (4) and (5). Also this set of values gives a pure NE. However, the FP converges to the NE for any set of parameters taking in consideration that they satisfy the physical constraints of the specified problem. Fig. 2 shows the strategy evolution in choosing the transmission power level. It is clear that the jammer chooses this power level with certainty as shown in the bold curve.

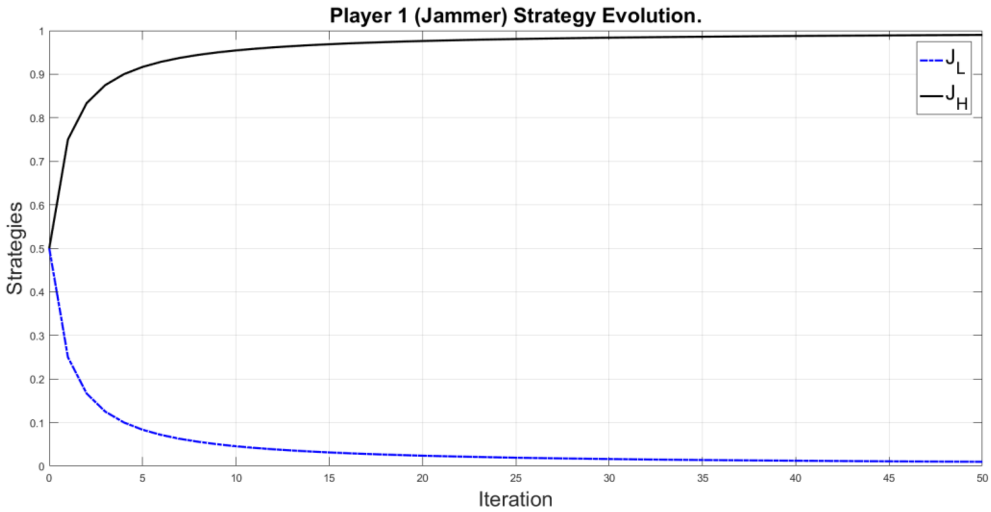

Figure -2 Strategy evolution to a pure NE for the jammer, P1

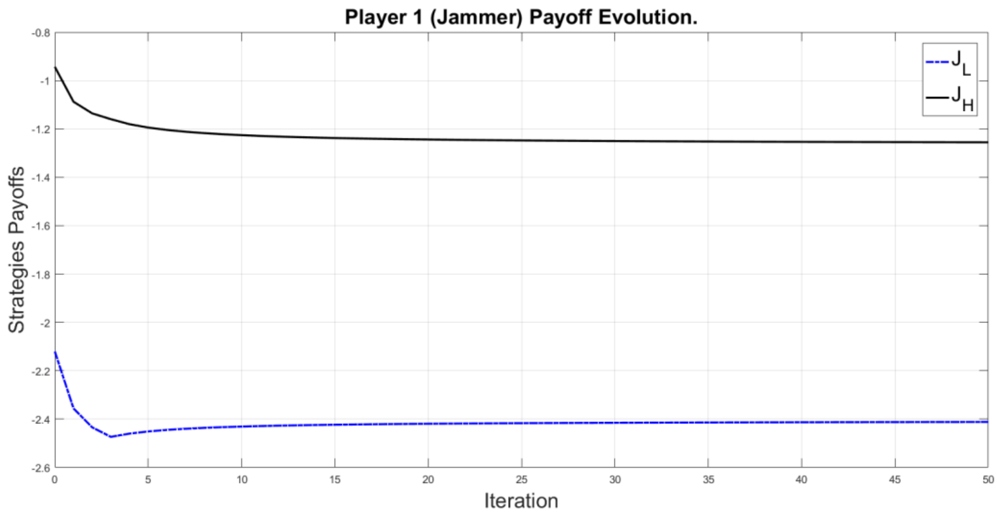

Figure -3 Payoff evolution for the jammer P1

This is also confirmed from Fig.3 since this strategy has the higher payoff. For the second player, TX-UAVs-RX, the strategy evolution is given in Fig.4 that is $s_4 = \{P_H, P_H\}$. This is interesting since this is the most aggressive that creates the highest amount of interference. Another reason for choosing this strategy beyond the game parameters P2, is the removing of the transmission cost from in this problem. However, many possibilities can emerge by changing the game parameter values which depend on the UAVs locations. The UAV locations are functions of the channels' parameters. Also the assumption of a linear cost can be relaxed. However, this can be tackled in a future work. Fig.5 shows the payoff associated with each strategy for the second player. Clearly this figure shows that s_4 strategy gains the highest payoff.

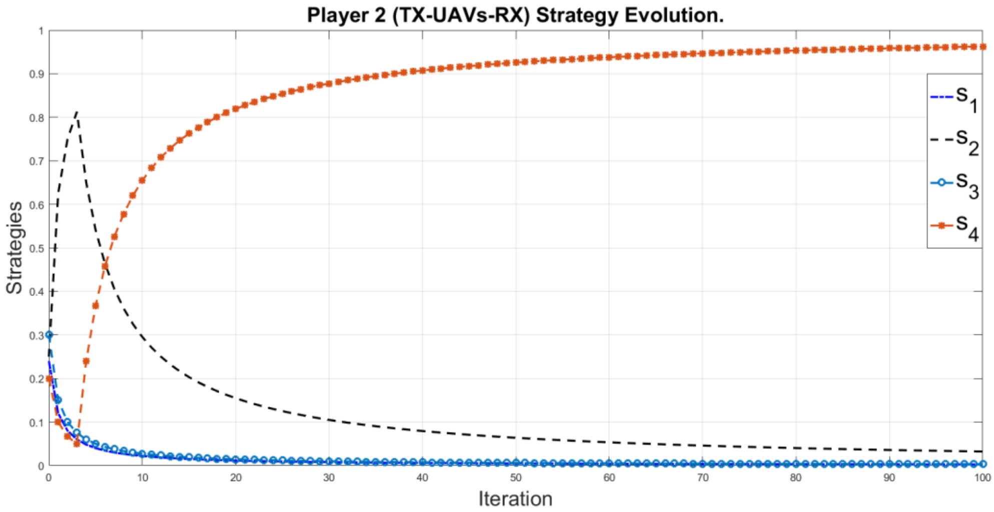

Figure- 4 Strategy evolution to a pure NE for the TX-UAVs-RX,

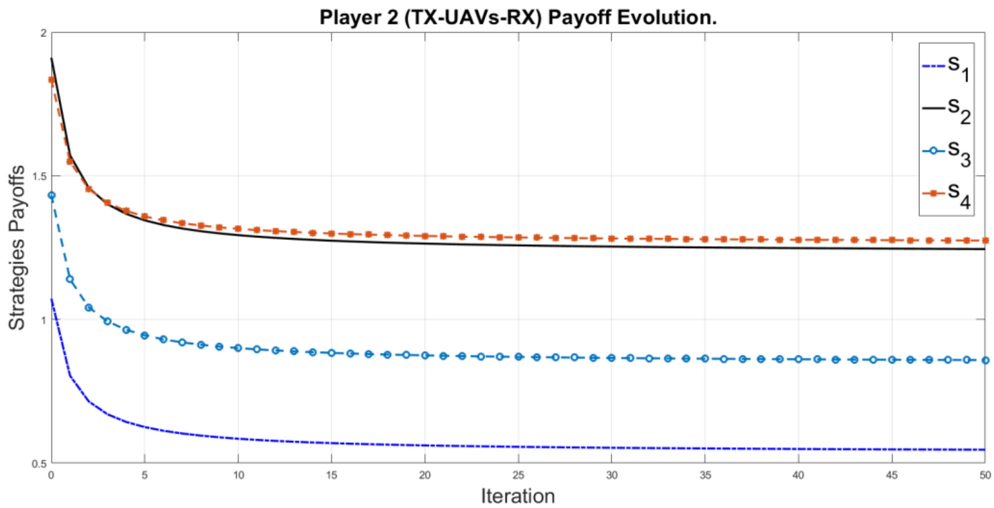

Figure-5 Payoff evolution to a pure NE for the TX-UAVs-RX, P2

4. Conclusion

UAVs are currently being developed for a wide-range of applications, but the malicious purposes represent a challenge for the national security. This work suggests a distributed optimization approach using a game theoretic model to study the interaction of UAVs controlled by ground stations versus a smart jammer that intents to degrade the performance of the UAV communication link due to interference. We solved this problem by formulating it as a LP and found the corresponding NE. We employed the FP algorithm where the players can learn their NE. We found that the a jammer, whose jamming power constrained by a simple linear cost function, can deal damage to the communications link even without imposing power cost on the UAV transmission power. The reason behind this lies in the assumption of the jammer smartness. Meaning that even with low jamming power levels the UAVs can increase their transmission power levels. Increasing the UAVs power level makes their downlinks transmission satisfy the quality constraints but at the same time they hurt each other because of the interference, which is surprising. However, this motivates the need to allocate more smartness in the UAVs, if possible, or to aid them with more strategies that can enable them to avoid undesired interference.

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