Solving Coordination Problems in UAV-Aided Networks Using Game Theory: A Survey

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Abstract

With the increase in demand for low-latency communication in 5G networks and the prevalence of the Internet of Things (IoT), Unmanned Aerial Vehicles (UAVs) are being proposed as an answer to fulfil the high demands of such networks. There has been a significant need to evaluate the advantages and disadvantages of deploying UAVs to assist in network communication. This study focuses on reviewing Cooperative Game Theory solutions implemented to solve the specific problem of coordination and collision avoidance between drones in UAV-aided networks, and providing a state-of-the-art on the subject. Lastly, a comparison is drawn between Game Theory and Machine Learning, as both solutions are often proposed together in this context.

1 Introduction

A UAV, or Unmanned Aerial Vehicle, is a remotely piloted drone or aircraft without passengers. According to Zhang *et. al.*, UAVs can be classified as fixed-wing or rotary-wing. Rotary-wing UAVs are commonly used as base stations, as they are capable of hovering in a fixed place, whereas Fixed-wing UAVs are capable of gliding and carrying a heavier load, and thus are more efficient at providing cellular coverage. [11]

Given the complex nature of networks, by deploying UAVs to aid in network communication, we add an extra layer of complexity. In this context, Game Theory can be used to solve a myriad of problems such as power consumption, navigation, or performance issues. [6]

This work focuses on Cooperative Game Theory solutions to solve the particular problem of coordination and mobility between UAVs in UAV-aided networks. The purpose is to review of possible cooperative solutions that employ game theory and provide a state-of-the-art view of the subject.

2 Context

In this section, the main concepts explored for this review are presented according to the literature on the subject.

Game Theory

Mkiramweni *et. al* and Zhang *et. al.* describe Game Theory as a branch of mathematics and science, used to analyze strategies a player can use to achieve a desired outcome in a decision-making scenario. Those scenarios are referred to, in this context, as a game [6, 11]. In the context of game theory the entities that take part in the decision-making are referred to as players of the game. The players may or may not be aware of the decisions taken by other players. Game Theory is used to solve coordination problems in UAV-aided networks by modelling the interactions between the nodes of the network as a game.

According to Mkiramweni *et. al* , there are three main components of a game: the players, the strategies, and the payoff [6]. In the context of UAV-aided network communication, the players are the UAVs deployed and the other nodes within the network. The strategies are a description of the actions that players will take to achieve a determined payoff. In this case, it defines how UAVs can relocate and plan paths to solve the coordination problem. Finally, the payoff represents the objective of the players within the game.

Cooperative Game

In game theory, a cooperative game allows players to form groups and agree on strategies to achieve a common goal. These games are analysed by predicting the formation of these groups - called coalitions -, what actions will be performed and the payoff.[5]

UAV Aided Communication

UAVs, sometimes referred to as drones, can assist communication networks by acting as Aerial Base Stations to provide wider network coverage, or by acting as relays to facilitate communication between a data transmission source and other nodes in the network. These UAV-aided networks are of advantage when servicing users in exceptional conditions of high network traffic [4, 6].

Coordination in UAVs

To use UAVs to support network communication, it is necessary to deploy many units at once. Due to the high complexity of networks, deploying UAVs to facilitate this communication adds even more complexity to the network. One complication faced in this case is avoiding the collision of drones while trying to find the best position and path to maximize throughput. To do this, an appropriate solution for coordination and motion control must be implemented.

3 Literature Review

To conduct this review, only cooperative games used to solve specific problems in collision avoidance and path planning were considered. Each subsection describes a proposed solution for the reviewed articles.

Distributed Formation Control with Population Games

Barreiro-Gomez *et. al.*, uses a multi-agent approach to create a leader-follower system for UAV coordination. This system is based on a subset of game theory called population games. They present a distributed formation solution for multi-agent systems with time-varying communication networks. The authors assumed that each drone in the network has only partial information about the other nodes in the network due to the limited communication range of the UAVs and that only the closest drones can communicate with the leader.

The presented formation is dynamic and allows for nodes to be added or removed from the network without having to change the formation. The authors conclude that the scenario allows for dynamic control of the position of the UAVs within the network, and the connection remains stable throughout the simulations conducted. It is proposed to extend the simulations to scenarios that include obstacles placed randomly throughout the line-of-sight of the UAVs.[1]

Coordination of Autonomous Communications UAVs

In [3] the authors compare two approaches to solve coordination problems in UAVs, designed to optimize network coverage: a non-cooperative game and an evolutionary Algorithm to collaboratively evolve flight paths. In this work, only the latter is described since the review focuses exclusively on cooperative solutions.

Evolutionary algorithms solutions to population-based problems inspired by natural selection and evolution[6]. The authors deploy a group of UAVs to provide network coverage in a high-traffic scenario. The UAVs were set up to move in a hexagonal grid and an evolutionary algorithm is used to evolve a flight path. A ”master” UAV is chosen and will provide the other drones with flying instructions. The master flies at higher altitudes, whereas the others fly at lower altitudes, closer to the users. This allows the remaining UAVs to spend less power and provide more coverage to users.

Path Planning with Mean-Field Game

Shiri *et. al.* authors propose the use of Mean-Field Game (MFG) to control the acceleration and solve three issues: obtain the fastest route between source and destination; optimize energy efficiency and avoid collision between UAVs. As identified by the authors, despite being a suitable solution for this problem, Mean-Field Game involves solving highly complex equations that require excessive computational power and time.

To bypass this problem, Machine Learning is applied to approximate the values of the equations using neural networks. According to the simulations performed by the authors, the proposed solution achieves paths without collision and is able to increase communication between UAVs with minimal computational and energy costs [8].

Collision Avoidance with the *Homicidal Chaffeur*

The *Homicidal Chaffeur* is a type of pursuit and evasion game where a player - the pursuer - tries to run down another player - the evader - who must try to avoid being run down. Snyder *et. al.* use this game to calculate trajectories to avoid collision in a four-player version of the game. This approach is applied when UAVs are in close proximity, and once the collision between them has been avoided, the UAVs resume an optimal path previously calculated. According to the simulations, the strategy proposed is able to ensure collision avoidance [9].

4 Discussion

The articles discussed in the previous section offer solutions to a very specific problem encountered when using UAVs to assist in network communication. Not much work was found in terms of studies to solve the specific problem of coordination and collision avoidance in UAV-aided networks. This may be due to the problem of collision avoidance being dealt with as a byproduct of a solution to other problems such as Network Coverage [7], Energy Saving[8], Power Optimization, Task Allocation and Network Security [5].

Since the inception of 5G networks, users are increasingly demanding lower latency communication with higher data rates and availability. UAVs are being proposed as an answer to fulfil these demands, and there is an extended need to evaluate the advantages and drawbacks of their deployment to aid network communication.

Another method to solve difficulties faced when deploying UAVs in network communication, often proposed alongside Game Theory, is Machine Learning. Depending on the specific circumstances and requirements, either method or a combination of both may be implemented. A survey [12] was conducted on the use of both approaches in UAV-aided networks. In this survey, the authors identified three scenarios where the application of Game Theory combined with Machine Learning may be of advantage:

- Using machine learning to collect users' data and behaviours, then applying game theory to optimize the network accordingly;
- Applying machine learning to recognize obstacles in UAV line-of-sight and applying game theory for high-level decisions;
- Using Multi-Agent Reinforcement Learning, where neural networks are combined with Game Theory to allow multiple players to make decisions concurrently with the same objective in sight.

The authors of this survey concluded that both Game Theory and Machine Learning are good solutions and may be scaled for large-scale networks[12].

5 Conclusion

Despite the lack of studies found on the specific problem of coordination and collision avoidance, many publications can be found on the use of Game Theory in UAV-aided networks. As evidenced by the literature reviewed in the surveys by Mkiramweni *et. al.* and Zhou *et. al.*, the problem of coordination is far from the only one encountered when dealing with the deployment of UAVs to assist with network communications, and Game Theory has been studied as a useful instrument to model decision strategies and interactions between UAVs in network communication.

Besides Game Theory, Machine Learning has also been the subject of many studies in this context and both approaches can be leveraged in conjunction to achieve solutions that can solve multiple problems in UAV-aided networks.

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