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ANTONIO ARLIS SANTOS DA SILVA

A joint approach to ensuring the stationary location and persistent UAV network service

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Advisor: Prof. Dr. Flávio Rech Wagner
Coadvisor: Prof. Dr. Edison Pignaton de Freitas

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"Try not. Do or do not, there is no try."

— Master Yoda

in "Star Wars - Episode V", 1980

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ABSTRACT

Unmanned Aerial Vehicles (UAVs) are being used in monitoring, transportation, security and disaster management, and other domains. The applications executed in the different missions involve multiple robotic systems connected through a wireless network to perform tasks that are - usually - autonomous. With more software applications being executed on UAVs, existing solutions for stationary location coordination and UAVs' network management fail to provide efficient results due to computational resource limitations. To cover this gap, this thesis presents a joint approach for autonomous coordination and intelligent management of a UAV network. Algorithmic Game Theory (AGT) and Software Defined Network (SDN) techniques are used. Compared to previous work, the approach presented here is different in two aspects: (i) A distributed system with a joint solution to the problems of the stationary location of multiple UAVs and a desired coverage rate; and (ii) A strategy to encourage agent cooperation with a rigorous analysis of network quality data within certain performance bounds. The proposal was evaluated by means of simulation using OMNeT++, Robot Operating System (ROS), and Gazebo. The approach was evaluated in terms of efficiency for area coverage and data flow in the network. Its behavior was analyzed in managing the UAV network in comparison to the Ad-hoc On-Demand Distance Vector (AODV) protocol, considering the post-disaster scenario. The evaluation provides evidence of considerable performance gains when compared to the main related works, mainly in area coverage rate and in service to network users over the operation period.

Keywords: Unmanned Aerial Vehicle (UAV). Autonomous UAV. Algorithmic Game Theory (AGT). Software Defined Network (SDN).

Uma abordagem conjunta para garantir a localização estacionária e o serviço de rede de VANTs persistente

RESUMO

Os Veículos Aéreos Não Tripulados (VANTs) estão sendo usados no monitoramento, transporte, segurança e gerenciamento de desastres, dentre outros domínios. As aplicações executadas nas várias missões envolvem múltiplos sistemas robóticos conectados por meio de uma rede sem fio para realizar tarefas - geralmente - autônomas. Com mais elementos de software sendo executados nos VANTs, as soluções existentes para coordenação de localização estacionária e gerenciamento de rede de VANTs falham em fornecer resultados eficientes devido às limitações de recursos computacionais. Para preencher essa lacuna, essa dissertação apresenta uma proposta conjunta para coordenação autônoma e gerenciamento inteligente de uma rede de VANTs. São utilizadas técnicas de Teoria Algorítmica de Jogos (AGT do Inglês *Algorithmic Game Theory*) e Rede Definida por Software (SDN do Inglês *Software Define Network*). Em comparação com trabalhos anteriores, a abordagem aqui apresentada é diferente em dois aspectos: (i) Um sistema distribuído com uma solução conjunta para o problema da localização estacionária de múltiplos VANTs e a taxa de cobertura desejada; e (ii) Uma estratégia para encorajar a cooperação do agente com uma análise rigorosa dos dados de qualidade da rede dentro de certos limites de desempenho. Experimentamos a proposta em simulação usando OMNeT ++, *Robot Operating System* (ROS) e Gazebo. A proposta teve avaliada sua eficiência para cobertura de área e fluxo de dados na rede. Foi realizada ainda uma avaliação do comportamento no gerenciamento da rede de VANTs em comparação ao protocolo *Ad-hoc On-Demand Distance Vector* (AODV), considerando o cenário pós-desastre. Essa avaliação fornece evidências de ganhos de desempenho consideráveis em relação aos principais trabalhos relacionadas, principalmente na taxa de cobertura de área e no atendimento aos usuários da rede ao longo do período de operação.

Palavras-chave: Veículo Aéreo Não Tripulado (VANT), VANT Autônomo, Rede Definida por Software (SDN), Teoria Algorítmica dos Jogos (AGT).

LIST OF ABBREVIATIONS AND ACRONYMS

ACO	Ant Colony Optimization
AGT	Algorithmic Game Theory
API	Application Programming Interface
BSP	Broadcast Storm Problem
CPU	Central Process Unit
CN	Controller Node
EC	Evolutionary Computing
FANET	Flying Ad hoc Network
IP	Internet Protocol
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network
MPC	Model Predictive Control
OLSR	Optimized Link State Routing Protocol
PSO	Particle Swarm Optimization
QoE	Quality of Experience
RN	Relay Node
SDN	Software-Defined Network
SNT	Sequential Niche Technique
UAV	Unmanned Aerial Vehicle
UN	User Node
VANETs	Vehicular Ad hoc Networks
WSN	Wireless Sensor Network
3D	Three-Dimensional

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1 INTRODUCTION

Over the past decade, the use of Unmanned Aerial Vehicles (UAVs) has been increasingly considered in a wide range of civil and military applications, mainly in those considered inappropriate or potentially hazardous to humans - e.g., surveillance and search and rescue. Moreover, a single UAV may not meet the demanded requirements of a complex mission. In this context, the use of multiple UAVs is a promising approach. In particular, the UAVs can play a central role in providing network recovery services in a disaster-stricken region, in improving public safety nets or in other emergencies.

For Ochoa and Santos (2015), the first 72 hours after a disaster occurs is the most critical period. In this scenario, one of the main concerns is the lack of communication infrastructure and knowledge of the situation, as improvised solutions degrade the mission response's effectiveness. As such, the UAVs can be deployed quickly as flying base stations in Three-Dimensional (3D) space. Aerial deployment is considered a promising way to provide ubiquitous access from the sky to ground users during disaster events (Mozaffari et al., 2019).

Research indicates that, over the last 30 years, there has been an increase in lives and material losses caused by disasters - e.g., geophysical, hydrological, climatological, and meteorological -, in the order of 100–150 percent (Erdelj et al., 2017). Thus, many efforts have been made to act in the post-disaster scenario so that the affected regions can react in a timely manner and quickly and efficiently assess the damage, resolve interruptions, restore normality, and most importantly, save lives. Figure 1.1 illustrates the use of UAVs in providing wireless communication solutions in a real-world scenario.

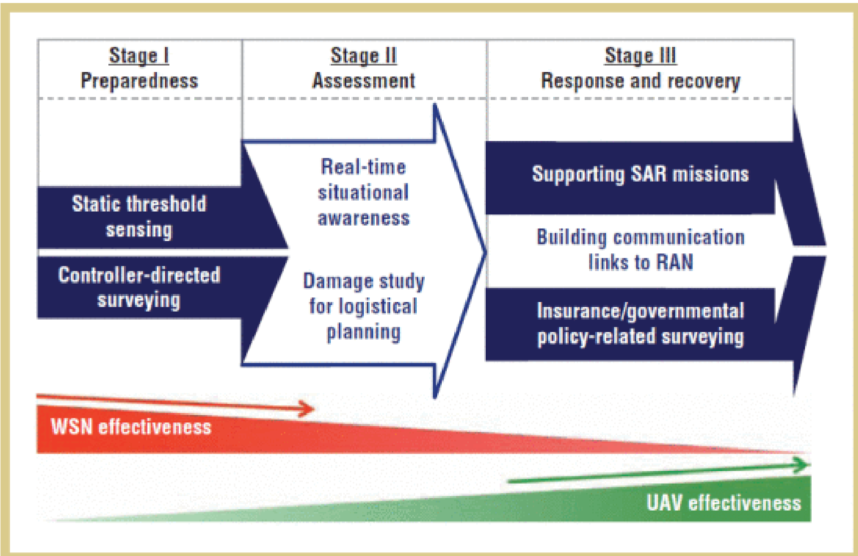
Figure 1.1: Use of UAVs as flying base stations to provide communication service

Source: (Kott, 2018)

The trend towards miniaturizing micro-electromechanical systems and the development of embedded systems have given rise to various technological devices to support rescue teams (Bekmezci; Sahingoz; Temel, 2013). The growing technological advance demands more and more human-robot, robot-robot, and human-human interaction (Murphy, 2012). In this context, the main advantages of using UAVs are their exceptional features, including mobility, dynamism, effortless deployment, adaptive attitude, agility, adjustability, and effective evaluation of real-world functions at any time and anywhere (Shakeri et al., 2019).

The operational life cycle for the performance of UAVs in natural disaster management comprises three stages (Erdelj et al., 2017). As the disaster progresses, and as is evident from the functions involved, as presented in Figure 1.2, the UAVs become more effective. In contrast, static Wireless Sensor Network (WSN) deployments become less effective. In this dissertation, a new approach is proposed to manage and coordinate a network of multiple UAVs in Stage III (Response and recovery).

Figure 1.2: Disaster stages and UAV assisted operations. As the disaster progresses, the use of UAVs becomes more effective



Source: (Erdelj et al., 2017)

Even though recent technological advances have improved UAVs' capabilities, such as internal memory, processing power, and battery capacity, they still present operational constraints due to the limitations of their resources. As a consequence, their use should require lighter use of computational resources, aiming at as few resources as possible (Mahmoud et al., 2016). Like this, the development of efficient algorithms for the cooperative work of UAVs becomes an essential field of research (Saadaoui; Bouanani, 2017).

1.1 Problems in Coordinating Multiple UAVs and Managing Network Topology

The problem of coordinating multiple UAVs is described as a control algorithm that ensures that multiple autonomous vehicles can sustain a specific formation while traversing a generalized trajectory - i.e., not necessarily linear -, and simultaneously avoid collisions. Also, UAVs must remain connected throughout the entire period of operation (Shakeri et al., 2019). In other words, the coordination of multiple UAVs with service persistence is a solution that seeks to optimize mobility, minimize mechanical power consumption, maximize flight time and avoid collisions between UAVs, without losing the connection.

In the literature, the UAV programming problem is recognized as a complex problem, and, with the additional consideration of ensuring coverage, the complexity of the problem only increases (Trotta et al., 2018). Achieving a maximum stationary coverage of a target scenario while preserving connectivity between UAVs is still a problem with several open challenges (Wang et al., 2017). The central concern in multi-objective location is how to define the static location of each UAV so that both the sensing needs of the application and the aerial mesh connectivity requirements are met.

The use of UAVs to provide a communication network in a 3D space presents a major change in the current design of network topologies and consequently reveals new challenges, in particular in the management of a highly dynamic and very fault-sensitive topology. Recent research suggests the use of the Software-Defined Network (SDN) approach, which facilitates the flexible deployment and management of new services and helps to reduce costs (Gupta; Jain; Vaszkun, 2015). The main objectives of these works are to allow the exploration of the dynamic reconfiguration made available by the SDN approach and, in some cases, to benefit from the division between the data plane and the control plane (see Section 2.1).

However, most of these works assume previously known missions - i.e., the set of topology users, the area to be covered, the number of UAVs, and the time of the mission, are presented as parameters for the solution of the problem. It is practically impossible to adopt the current models in a real scenario. Thus, there is a growing need for flexible architectural approaches capable of meeting the objectives of a mission with little context information. This lack of more generic approaches may limit exploring new solutions for post-disaster responses.

Many studies were based on biological models, also known as Evolutionary Computing (EC), for the coordination of UAVs in 3D space (e Silva et al., 2019; Kim; Lee, 2018; Magán-Carrión et al., 2016; Zhang et al., 2010). Coordination models based on EC demonstrate efficiency in topology formation. However, they require high computational power, almost total knowledge of the operation, and the use of a centralized approach. Although this may be useful for a proof of concept, it may also be limiting for adequate exploration of the new topology paradigm formed by UAVs.

On the other hand, some of the more recent works have used distributed strategies (Zheng; Chen, 2019; Trotta et al., 2018), which produce greater flexibility. Although this approach can also provide efficiency in the formation of topology, the distributed models present low effectiveness in obtaining the objectives defined for a mission due to the lack of contextual knowledge of the operation.

1.2 Proposed Research and Contributions

Despite all the advances related to UAV networks, some problems are still significant concerns to enable the adoption of UAV networks to provide communication in a post-disaster scenario. Problems associated with creating the network for relaying information, package delivery, automation of network maintenance, increased security, and the robustness of the UAV network are just some of them (Erdelj; Król; Natalizio, 2017). The growing interest in using UAVs for post-disaster recovery is essential not only to assist rescue teams but also to enable a return to normal routine in the region.

Dynamic and unknown environments, physical extension, which in some cases is huge, and lack of situational awareness are situations commonly encountered after a disaster occurs. As few previous studies have focused on this line of research, there are open questions not only in assessing the benefits of more generic models for network management but also in investigating distributed and intelligent approaches to a stationary location for UAVs.

The main objective of this dissertation is the development of a fully autonomous solution for the coordination of a UAV mesh for stationary positions, as well as an efficient mechanism for managing the UAV network infrastructure formed. In addition, here follows a list of specific objectives that guided the development of this work:

- Review in the literature on the adoption of the SDN paradigm in mobile networks, with emphasis on UAV networking and on the evaluation of the most used protocol for the context under study, namely UAV mesh to provide communication in a post-disaster scenario;

- Review of literature on methods and techniques for coordinating a UAV mesh for stationary positions;
- Analysis of techniques and methods for efficient management of network resources for a UAV network;
- Mapping of the main management problems in a dynamic mobile network, particularly a UAV network.

Thus, this dissertation proposes a solution to coordinate multiple UAVs for stationary position location using a distributed model and centralized UAV network management. The proposed approach uses two algorithms for coordinating the multiple UAVs. The first algorithm computes the positions using a concept of virtual springs, and the second algorithm uses Algorithmic Game Theory (AGT) techniques for intelligent decision making. The UAV network management is based on SDN principles, and an application that uses Decision Tree techniques is used as robust mechanisms to ensure service persistence. The management model divides the network into clusters to not overload the Controller Nodes (CNs) and avoid bottlenecks in the UAV network.

As far as we know, no solution addresses the problem of stationary coverage of UAVs in a model that ensures (i) compliance with the coverage metrics defined for the mission and (ii) the connectivity of the formed network topology, maximizing the required persistent service. Thus, in addition to addressing issues (i) and (ii), our model provides distributed coordination and cooperative intelligence for decision making. The approach is comprised of n UAVs, called Relay Nodes (RNs), to meet n User Nodes (UNs), providing the following major research contributions:

1. An approach with a joint solution to the problem of the stationary location of multiple UAVs for a desired coverage rate;
2. A strategy to encourage the cooperation of agents with a rigorous analysis within given performance limits;
3. Robust and strategic UAV-network management using the principles of SDN.

1.3 Overview

This dissertation is structured as follows. Chapter 2 reviews the main premises for managing a network topology, recaps some network management key notions and related concepts, presents a review of the main works in recent years, and makes a discussion on UAV network management. In Chapter 3, we present the main approaches to the coordination of multiple UAVs so far, summarize some key notions of coordination for stationary location and the main related concepts, and present the main work developed in recent years.

The proposed approach is presented in the next three following chapters. In Chapter 4 a centralized approach is presented, which is a modification of the Particle Swarm Optimization (PSO) algorithm, and a solution for UAV network management is proposed using the concepts of Decision Tree and SDN techniques. Also, an experimental comparison between the proposed management solution and the Ad-hoc On-Demand Distance Vector (AODV) protocol is performed, and the evaluations and discussions of the simulation results are presented. In Chapter 5 a distributed coordination approach for the stationary location of multiple UAVs using AGT techniques is presented, along with an experimental evaluation and discussion of the simulation results. A joint approach for distributed coordination and intelligent, centralized management is presented in Chapter 6. Finally, in Chapter 7, the dissertation is concluded, and some future directions are discussed.

2 NETWORK MANAGEMENT

Wireless networks are particularly challenging and present additional problems not found in traditional wired computer networks. Due to the unreliable nature of the transmission medium, we must deal with greater control traffic (Moura, 2018). The dynamics of the post-disaster environment and the mobility characteristics of the UAVs, maintaining a communication link to ensure the delivery of packages, build an additional challenging scenario. As mentioned before (see Chapter 1), the SDN approach has become an important research line for this scenario.

Initially, SDN is proposed to flexibly and intelligently control the wired network's flows. Recently, many researchers have shown a growing interest in applying SDN to mobile wireless scenarios. Several problems are currently encountered in managing UAVs networks. Erdelj, Król and Natalizio (2017) conduct a literature review and present the main open issues for a UAV network to operate in a disaster scenario. Problems associated with creating the network to relay information, package delivery, automation of network maintenance, increased security, and the robustness of the UAV network will be discussed in more detail in the next sections.

However, this chapter will first present the main concepts of the SDN approach. Next, the main challenges identified by Erdelj, Król and Natalizio (2017) and a compilation of the main work addressing these challenges related to our proposal will be presented.

2.1 Software-Defined Network (SDN)

The SDN approach arose to promote the evolution of traditional computer network equipment. It is considered an innovative approach to designing, implementing, and managing networks that separate the network control and forwarding processes (Benzekki; El Fergougui; Elbelrhiti Elalaoui, 2016). This network segmentation offers several benefits in terms of network flexibility and controllability. Designed to allow networks to be controlled simply and efficiently, using control algorithms designed for demands of the network (Shin; Nam; Kim, 2012), the SDN approach has four main pillars - described below - upon which its architecture is defined (Kreutz et al., 2014).

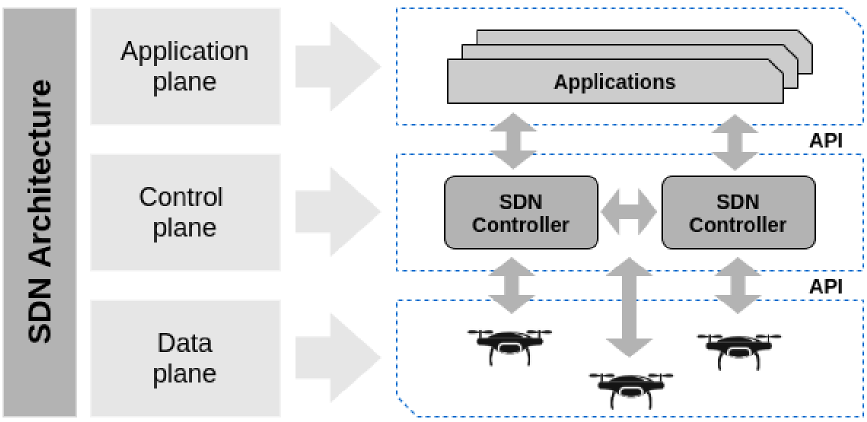
1. The control and data planes are separated. The control plane's assigned responsi-

bilities are removed from the network devices, making the traffic routing devices simpler;

2. Routing decisions are flow-based. A stream is defined as a set of packet field values acting as a filter and a set of instructions. In a packet flow between source and destination, everyone receives equal service policies at network equipment, such as routers, switches, and firewalls;
3. The network programming is given using software running on the controller interacting with the devices' data planes. This is the main feature and value proposal of the SDN;
4. The control logic becomes the responsibility of one or more SDN controllers, in which it is an external entity.

The overall architecture of the SDN divides the entire network into three planes, namely, data plane, control plane, and application plane (Sharma et al., 2017). Figure 2.1 presents an overview of the SDN architecture. The data plane comprises network devices and simply routes traffic, while the control plane forms the policies for this routing and controls each component's activity. The top layer of business applications is used to offer specialized applications that leverage the underlying planes to form a controllable and manageable network.

Figure 2.1: Software-Defined Network (SDN) architecture overview presented in three planes

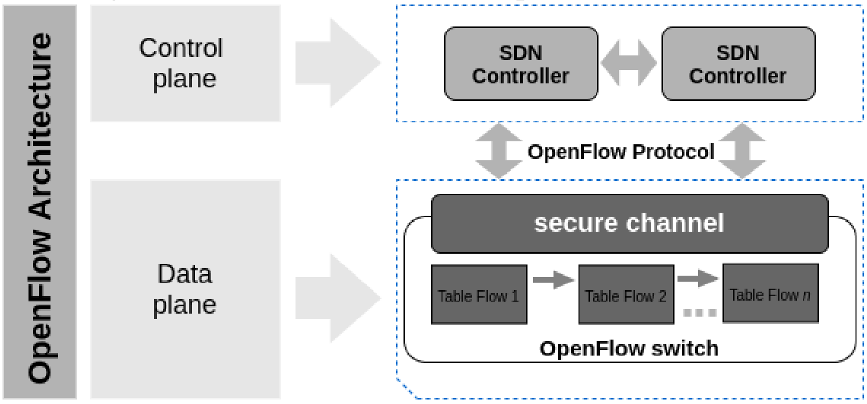


Source: Adapted from (Sharma et al., 2017; Kreutz et al., 2014; McKeown et al., 2008)

The communication between the planes takes place through an Application Programming Interface (API). The best known API is OpenFlow (McKeown et al., 2008). OpenFlow is a flow-oriented protocol with abstractions for the switches and their ports, used to control the data flow. In the OpenFlow protocol, programmability is possible by updating the flow table of the network switches.

Moura (2018) defines three main features of the OpenFlow protocol. Figure 2.2 gives an overview of OpenFlow: (i) flow table - where an action can be associated with each flow input, determining how to process each flow; (ii) secure channel - that links the equipment to the remote controller, allowing network commands and packets to be communicated securely; and (iii) the OpenFlow protocol - provides an open and standardized way for communications between controller and OpenFlow switch.

Figure 2.2: Overview of a basic OpenFlow architecture



Source: Adapted from (Moura, 2018)

Thus, the SDN architecture with the OpenFlow protocol concepts provides tooling capable of facilitating traffic control with the benefits of decoupling planes of control and routing (Landmark; Larsen; Kure, 2018). The introduction of SDN can help in path selection and channel allocation, with good performance in reducing interference, improving the use of wireless resources, including channels and routing in multi-hop mesh networks (Zhang; Wang; Zhao, 2018). Furthermore, due to the approach proposed by the SDN, such as using a controller as a network manager, any decision is based on a complete view of the network state, leading to optimized solutions as a consequence.

2.2 Problems in UAVs Networks Management and Related Work

Starting the research conducted by Erdelj et al. (2017), we identify the four main problems that most affect UAV network management to act in a post-disaster scenario, namely (i) creating and maintaining a network to relay information in response to disasters, (ii) automating network maintenance, (iii) package delivery problems, and (iv) increasing the security and robustness of the UAV network.

Management involves command and control over UAVs. Therefore, a common control interface is required to manage the air nodes efficiently. Management also refers to policy formation and record-keeping of aerial nodes during sessions between nodes in the network (Sharma et al., 2017). In the following, we detail each of the categories of problems identified and their key concepts. The related works on UAV network management are classified into one of the four identified categories and presented according to this classification.

2.2.1 Creating and maintaining a network for relaying information in response to disasters

UAV networks for relaying information are entirely aerial and must have a high level of resilience to link interruptions (Erdelj et al., 2017). The proper functioning of the network requires robust mechanisms (Gupta; Jain; Vaszkun, 2015). First, coordinating the multiple UAVs to avoid collisions with the environment and collisions with other UAVs during their displacement requires unplanned maneuvers in advance, and maintaining a communication link in a highly dynamic environment is already a very complex problem in itself. Second, due to power limitations, UAVs' stationary positions are usually kept for a short period, so maintenance occurs continuously.

Managing the topology efficiently requires models that need to be robust and, at the same time, flexible for operation. In the literature, the approaches used for the creation and maintenance of a UAV network are mostly tied to algorithms for building and coordinating UAVs. As a consequence, we have models with unnecessary complexity and little flexibility for traffic management in topology. To ensure the persistence of network service during the operation, it is necessary to continuously monitor the communication link and react to changes without impacting the services running on the infrastructure (Riestock et al., 2017). In this context, more flexible and autonomous approaches - i.e., which do not depend on other mechanisms, such as coordination or construction algorithms - are more suitable.

Kim and Lee (2018) propose a model for building and maintaining Flying Ad hoc Networks (FANETs) to provide ad hoc end-to-end routing paths for users connected to infrastructure. Although the authors have focused on proposing a solution to create and sustain network communication between terrestrial nodes through relay nodes, their proposal does not address an approach to managing network topology more efficiently, considering network performance and the routing protocol in use. Other works - such as (Cai et al., 2016; Roh; Lee, 2010; Zhang et al., 2010) - have also assumed that a set of wireless network links is provided, and no model for topology management is proposed. However, they are closely related to network performance in practice.

SD-UAVNet (Zhao et al., 2019) use the concept of SDN in its control protocol. The work considered allocating relay UAVs to establish a connection between a source and a destination for video transmission supporting Quality of Experience (QoE). The UAV control protocol manages the inter-UAV communication - and routing protocols - as well as the UAVs movement path. STFANET (e Silva et al., 2019) makes the SD-UAVNet architecture flexible considering that users (sources and origin) do not have a movement path defined by the network controller, i.e., users have an independent movement path. However, the STFANET approach links the topology management to its construction. Consequently, all network users' prior knowledge is required, making the solution extremely complex and not very flexible for traffic management.

To provide a separation between UAV coordination and topology management, Kirichek et al. (2017) formulate a scenario where users would be static WSNs terrestrial and retransmission UAVs are simply switched to establish communication between terrestrial segments, performing routing functions, network traffic service according to the routing rules established by the controller. SD-UAV (Secinti et al., 2018) performs a study on UAV network management using SDN concepts. During operation, the controller acquires the channel location and availability information, generates the routing table with the routing algorithm's help, and forwards the routing table to the relay UAVs. The two proposals mentioned above have important limitations. The first one does neither address the change in the environment nor the mobility of the UAVs. The second one does not evaluate the proposed algorithm under various mobility and traffic patterns; furthermore, the solution was not implemented at the system level in a 3D environment.

2.2.2 Automating network maintenance

Automating the management of a UAV network is of fundamental importance to ensure the success of a mission. Erdelj et al. (2017) point out the need to load UAVs and fluctuations in communication links as one of the main bottlenecks in maintaining a topology formed by UAVs. This, in turn, affects the network layer, usually invalidating Internet Protocol (IP) routes. Repeated searching of network paths after each packet delivery becomes exhaustive and can lead to Broadcast Storm Problem (BSP). Therefore, this type of search is also not ideal for keeping a routing table on this type of intermittent network (Pires; Pinto; Branco, 2019).

Essential differences that distinguish UAV networks from other networks are: speed of movement, differences in altitude, network density, the distance between nodes, and three-dimensional movement pattern that may require - and generally do require - different data exchange strategies (Pires; Pinto; Branco, 2019). The performance of the UAV network depends on the reliability of the communication scheme (Yuan et al., 2016). However, traditional management protocols are designed for terrestrial mobile nodes and do not consider the specific characteristics of UAVs - e.g., dynamic altitude, fast variable routing topology, etc.

Bashir and Yusof (2019) investigated energy conservation techniques. This research shows that, with intelligent network topology management, it is possible to achieve energy efficiency to improve flight time duration. Silva et al. (2017) conduct an assessment of signal quality and network performance to define the formation of UAVs during the mission. The work presented by Silva et al. (2017) and the results presented by Bashir and Yusof (2019) reinforce the importance of network management.

Abolhasan et al. (2015) use a hybrid strategy of SDN, where several nodes send link status information to the central controller. The central SDN controller pre-analyses the data and sends it back to distributed mobile nodes to make optimal routing decisions. E-Mesh (Chen; Yuan; Muntean, 2015) is a proposed power-conscious wireless routing algorithm that balances the need for power savings with maintaining the quality of the transmitted content. E-Mesh is implemented at the network layer and operates in conjunction with the task cycle management of the Medium Access Control (MAC) layer. In the two network management proposals above, retransmission nodes execute algorithms with complex logic to define package routes. However, a UAV has limited data computing capabilities, as most of the Central Process Unit (CPU) and memory resources need to be reserved for the flight control system.

The increasing scale of the network and the constant maintenance of the UAVs increase the management difficulty (Sharma et al., 2017). In this context, Yuan et al. (2016) propose an architecture using techniques of SDN to release the computing load of the relay nodes. In this architecture, the relay nodes would be responsible only for monitoring topology changes and data forwarding. Messous, Senouci and Sedjelmaci (2016) assume energy as a scarce resource and propose a coordination model based on information shared among neighboring UAVs.

In summary, some literature already addresses the potential of UAV-assisted mobile radio networks. Most of them consider UAVs' ideal positioning over the area to be served and a management model inherited from ad hoc networks. However, current communication trends are to have a green network using energy-efficient communication devices and protocols whenever possible (Bashir; Yusof, 2019). In this context, autonomous management of network resources based on mission state data can achieve power optimization involving strategies and algorithms to control transmission power, user allocations, data rates, transfer mechanisms, and modulation schemes (Bashir; Yusof, 2019).

2.2.3 Package delivery problems

The topology of a UAV network changes very often (Pires; Pinto; Branco, 2019). For this reason, problems with package delivery are constant. Also, UAV radio signals are propagated omnidirectionally. Therefore, the same region can be covered by messages from several UAVs, which causes problems such as redundant - therefore unnecessary - retransmission, wireless media containment, and packet collisions. Thus, when the exchange of messages is done arbitrarily, it can cause a transmission storm problem, taking the wireless medium to an inoperable state.

Magán-Carrión et al. (2016) have proposed a three-stage relay node positioning strategy designed to maximize connectivity by measuring performance and accessibility between nodes. In the solution, a set of potential locations is first identified. Then, the LOO (Leave-Out-Out) method is used to select the best locations. Finally, it uses the PSO algorithm to optimize the solution in terms of throughput. Soon after, Magán-Carrión et al. (2017) proposed an approach for multipurpose optimization, where, after the two-goal optimization procedure, network connectivity and performance are maximized together. For this, having included such a feature, they proposed a multi-stage dynamical RN placement solution, based on PSO algorithms and Model Predictive Control (MPC) techniques.

Burdakov et al. (2010) focused their work on presenting a solution by maximizing transmission quality given a known target position and minimizing the number of relay nodes required. They presented two new algorithms: the first one uses label-correcting graph search to efficiently generate a set of optimal relay chains solutions - revealing a trade-off between the number of UAVs and the quality of the chain -, allowing ground operators to choose among them. The second one uses a dual ascent technique to generate a high-quality relay chain given a limited number of UAVs.

Pires, Pinto and Branco (2019) propose a dynamic neighbor-based algorithm for broadcasting message problems. The proposed algorithm addresses broadcast messages for the coordination of UAVs in space. The results reinforce that intelligent models for exchanging networked messages of UAVs increase confidence in package delivery. However, the model presented does not include scenarios where UAVs form a relay network of messages by routes. Ku et al. (2014) applied SDN in Vehicular Ad-hoc Networks (VANETs) and compared the routing protocol with other traditional Mobile Ad-hoc Network (MANET) and VANETs routing protocols. The results show that SDN-based routing outperforms other traditional ad hoc routing protocols in terms of packet delivery rates at various speeds.

Although in some works (Magán-Carrión et al., 2016; Magán-Carrión et al., 2017; Burdakov et al., 2010; Pires; Pinto; Branco, 2019; Ku et al., 2014), the authors have focused on proposing novel solutions to sustain a network communication among ground nodes through the use of relay nodes, their proposals left room for further improvements, especially in maintaining reliability and connectivity (Wang et al., 2017). In this context, unreliability in package delivery becomes a critical factor in executing disaster response operations. For Riestock et al. (2017) a stable and reliable communication link is required to work with mobile nodes. However, few works address package delivery problems. Therefore, proposing a robust model aiming at maximizing package delivery is desirable.

2.2.4 Increasing the security and robustness of the UAV network

To provide robust control of the UAV network and information acquisition, communication security must be emphasized. Malicious attacks are closely related to the UAV network's operation, so robust communication protocols play a critical role (Erdelj et al., 2017). In particular, a network formed by UAVs presents particular properties that lead to new vulnerabilities to unknown attacks in wired or infrastructure-based networks (Buchegger; Boudec, 2002).

Bruce (2000) highlights that a prevention strategy only works if the prevention mechanisms are perfect; otherwise, someone will figure out how to bypass them. In this survey, it was verified that most attacks and vulnerabilities resulted from ignoring the prevention mechanisms. Faced with this reality, detection and response are essential to secure communication between ground agents and UAVs and among the UAVs themselves. On the one hand, terrestrial UAV communications are more prone than terrestrial communications to interception attacks and interference from malicious nodes on the ground.

Compared to malicious ground nodes, malicious UAVs can launch more effective interception attacks and interference of ground communications (Wu; Mei; Zhang, 2019).

Buchegger and Boudec (2002) propose an extension to the Dynamic Source Routing (DSR) protocol to detect and isolate nodes with inappropriate behavior, thus making the denial of cooperation undesirable. In the presented scheme, the trust relationships and routing decisions are made based on the experienced routing and routing behavior observed or reported from other nodes. However, in the scheme presented by Buchegger and Boudec (2002), the nodes must have linear behavior during the whole operation cycle. As previously highlighted, one of the main characteristics of a UAV network is its non-linear behavior, making it unfeasible to apply the solution to this type of application.

Mitchell and Chen (2013) proposed an intrusion detection scheme to protect UAV nodes from malicious threats. This security scheme relies on a set of attack signatures to detect whether the monitored device is an intruder or not. According to the simulation results, the scheme detects near cyber threats that attack UAV networks. However, a high number of false alarms can be triggered by agents. In the work of Sedjelmaci, Senouci and Messous (2016) a model was proposed to solve the problems of false positives and false negatives generated by agents in a UAV network. In this security scheme, they model the behavior of a suspicious device by a threat level function. A belief approach is used to define a set of rule specifications to accurately classify the monitored device into the following categories: Normal, Suspicious, or Malicious. According to the simulation, they prove that a belief approach helps decrease false positive and false negative rates. However, an update of rules is required.

Casals, Owezarski and Descargues (2013) have developed a bio-inspired detection scheme to detect cyber attacks targeting air networks. The bio-inspired technique is based on a machine-learning algorithm. The authors do not provide simulated or experimental results to analyze the performance of their detection scheme. Rani et al. (2016) have proposed an anomaly detection scheme based on a learning algorithm to protect UAV nodes against network attacks such as DDoS (Distributed Denial-of-Service) attacks. The authors used the Nearest neighbor algorithm and fuzzy learning to detect these cyber threats accurately. However, they did not detail the monitoring and detection process performed by agents. In addition, the authors did not evaluate the detection efficiency of their security scheme.

2.3 Discussion

The main characteristics of existing works related to UAV network management problem are presented in Table 2.1. Based on the state-of-the-art analysis, it is possible to conclude that there is a lack of literature approaches that address the main problems encountered in a wireless network. In part, this is explained by the lack of flexibility of network management approaches. The lack of flexibility in network management is a historical problem that can be seen most often in traditional wired computer network management. Traditional wired computer network management methods are essentially to blame for the lack of technological development and until recently were considered ossified by experts and researchers. The ossification of traditional wired computer networks can only be overcome with the development of SDN network management approaches that make traditional networks more flexible.

Considering the recent literature, we are faced with two scenarios. In the first scenario, authors use traditional sensor network management protocols not suitable for UAV network management. In the second scenario, authors develop approaches based on other more modern techniques, such as SDN and AI, to the UAV network. However, they tie their solutions to algorithms for building or coordinating UAVs. Also, few studies show robustness in their solutions, considering the UAVs' constraints and the network management capabilities. Although these papers have, for the most part, evaluated the main problems of management identified and discussed in this chapter, to the best of our knowledge no work addresses or directs research toward solving them.

The premise of decoupling the data plane from the control plane proposed by the SDN approach has been minor - or not - used in UAV network management works. In traditional wired computer network management, the SDN approach has allowed a rapid technological evolution by enabling management applications to centrally execute specific algorithms in specific contexts, in addition to the virtualization of switches. UAV networks can benefit from using different and distributed management applications that uniquely address each mission in this context. Moreover, the possibility of *n* management applications running on a single network enables the distribution of tasks. It balances the limited resource consumption of a single UAV by allowing significant gains in developing technologies for the area.

Table 2.1 presents the related papers, as well as the problems they aim to solve. So far, none of the works consider the four issues mapped by (Erdelj; Król; Natalizio,

Table 2.1: Summary of UAV network management proposals

Reference	Creating / Maintaining	Automatic maintenance	Package delivery	Security / Robustness
Kim and Lee (2018)	Yes	No	Yes	No
Cai et al. (2016)	Yes	No	No	No
Roh and Lee (2010)	Yes	No	No	No
Zhang et al. (2010)	Yes	No	No	No
Zhao et al. (2019)	Yes	No	No	No
e Silva et al. (2019)	Yes	No	Yes	No
Kirichek et al. (2017)	Yes	No	No	No
Secinti et al. (2018)	Yes	Yes	No	No
Bashir and Yusof (2019)	No	Yes	No	No
Silva et al. (2017)	No	Yes	No	No
Abolhasan et al. (2015)	No	Yes	No	No
Chen, Yuan and Mauntean (2015)	No	Yes	No	No
Yuan et al. (2016)	No	Yes	No	No
Messous, Senouci and Sedjelmaci (2016)	No	Yes	No	No
Magán-Carrión et al. (2016)	No	Yes	Yes	No
Magán-Carrión et al. (2017)	No	No	Yes	No
Burdakov et al. (2010)	No	No	Yes	No
Pires, Pinto and Branco (2019)	No	No	Yes	No
Ku et al. (2014)	No	No	Yes	No
Buchegger and Boudec (2002)	No	No	No	Yes
Mitchell and Chen (2013)	No	No	No	Yes
Sedjelmaci, Senouci and Messous (2016)	No	No	No	Yes
Casals, Owezaski and Descargues (2013)	No	No	No	Yes
Rani et al. (2016)	No	No	No	Yes
This proposal	Yes	Yes	Yes	Yes

Source: The author

2017) and try to tackle them. In this work, we present an SDN-based management model that demonstrates efficiency for solving all the mapped problems. The use of SDN allows the solution of the issues at the application level, which increases the flexibility of the proposed solution to adapt to the specific requirements of each mission and application. This work focused mainly on three issues: (i) creating and maintaining a network for relaying information in response to disasters, (ii) automating network maintenance, and (iii) package delivery problems. Still, initial paths are presented for the solution of issue (iv), namely increasing the security and robustness of the UAV network, demonstrating a promising possibility for its resolution at the application level.

3 COORDINATING MULTIPLE UAVS

UAVs flights can be conducted with different degrees of autonomy, e.g., remotely by a human operator or autonomously guided by on-board sensors and computers (Nonami et al., 2013). Several control strategies for the coordination of multiple UAVs have been investigated. In these works, the coordination problem has been more usually related to the trajectory planning than to the flight control (Watanabe; Amiez; Chavent, 2013).

In any case, the coordination process for a stationary or non-stationary location consists of three steps executed sequentially: (i) determine the UAV position as accurately as possible; (ii) relate its current position to the destination, milestones, and possible hazards; and (iii) define the new UAV course based on this information (Franz; Mallot, 2000). The possibility of developing autonomous or semi-autonomous air systems capable of completing missions independently of human interaction, or with very little human intervention (Al-Kaff et al., 2018; Kanellakis; Nikolakopoulos, 2017), has been driving research focused on this field in recent years.

As far as literature is concerned, two models for coordinating multiple UAVs have been widely explored, namely centralized coordination and distributed coordination. EC algorithms have supported the centralized model, while the distributed model has used spring theories or iso-probability mathematical models widely used mainly in Civil Engineering. In the next sections, details of each of the two models and the corresponding related works are presented.

3.1 Centralized Coordination and Related Work

The centralized model for coordination and stationary location of a UAV network is a model that usually runs all the processing in a single UAV (e Silva et al., 2019; Zhao et al., 2019; Kim; Lee, 2018; Magán-Carrión et al., 2016; Zhang et al., 2010). To control a fleet of UAVs in a centralized manner, several routing protocols were proposed in the literature, such as dynamic source routing, pre-computed routing, on-demand routing flooding, cluster-based routing, and others (e Silva et al., 2019).

The vast majority of papers presented in the literature that adopt the centralized model for coordination and stationary location are supported by EC algorithms. However, the coordination problem is recognized as NP-complete, and, with the additional consideration of ensuring coverage, the complexity of the problem only increases (Trotta et al., 2018). One of the significant limitations of the proposed solutions based on EC that make their application in the real world impossible is closely linked to the low processing capacity of UAVs (Bekmezci; Sahingoz; Temel, 2013) and the high execution time complexity of algorithms (e Silva et al., 2019; Trotta et al., 2018).

The EC is an optimization process. It works as a stock search for optimal solutions to a given problem, which focus is on biological evolution (Kennedy; Eberhart, 1995a). Algorithm 1 presents in a general way the EC algorithms. Be $t = 0$ the generation counter; P the population to be optimized; D_m the dimensional space, and P^* the final position of the generation. In line 1, the algorithm creates and initializes a D_m population P. In line 4, the aptitude of the particle pi is evaluated. In line 5, the reproduction generating the descendants is performed. In line 7, the algorithm selects the population according to the utility function. And finally, in line 8, the algorithm proceeds to the new generation.

Input: P and D_m.
Output: P^*.
1 C(0);
2 **while** *stop condition(s) is (are) false* **do**
3   **for** $\forall p_i \in P(t)$ **do**
4         $f(p_i(t))$;
5         $r(p_i(t))$;
6   **end**
7     $C(P^{t+1})$;
8     $t = t + 1$;
9 **end**

Algorithm 1: Generic Evolutionary Algorithm.

One of the most studied algorithms in the literature for the coordination of multiple UAVs is the PSO algorithm, which is a non-deterministic population-based optimization method proposed by Kennedy and Eberhart (Kennedy; Eberhart, 1995b; Roberge; Tarbouchi; Labonte, 2013). The algorithm simulates the movement of a swarm of particles in a multidimensional search space, progressing towards an optimal solution. In the PSO algorithm, each particle is assigned a position and velocity vector in a multidimensional space, where each position coordinate represents a design value. The algorithm calculates the suitability of each particle according to its objective function. At each stage of the iterative process, each particle's position is updated based on the speed of each particle, and the speed is updated based on the previous speed of the particle.

Kim and Lee (2018) proposed a topology management approach to sustain a FANET topology and thus establish a communication media between mobile units (MU) and their ground station by using a set of relay units (RU). Through the execution of two algorithms - construction and adjustment -, they presented their approach's efficacy in terms of maximum and minimum distances among nodes. The strategy begins with the construction algorithm to determine a starting point for each node, computed based on a PSO approach. Consequently, this procedure is computationally intense, and the result may differ significantly from the current nodes' location. To keep the connectivity of the network after its construction, a Gradient function algorithm is used to adjust the current formation - algorithm of adjustment.

To decrease the computational process presented in the Kim and Lee (2018) approach, the authors of STFANET (e Silva et al., 2019) added an integration algorithm. With the integration algorithm, the controller monitors the network and executes the adjustment algorithm, which is much lighter in terms of computational effort; however, the controller must detect the lack of efficiency at some point. In this case, the formation is totally redesigned by applying the construction algorithm and can be completely different from the current one. Finally, the authors proposed a new cost function based on a multi-objective approach to increase network efficiency and consequently decrease the construction algorithm's execution.

Shakhatreh et al. (2017) proposed a PSO-based algorithm for efficient UAV positioning, thus minimizing total transmission power. In the solution proposed by the authors, only one UAV was considered, and two different cases for utility function analysis were considered. In the first case, only the minimum transmission power was taken into account. In the second case, the asymmetry of each floor's dimensions was considered, and a gradient algorithm was used to determine the efficient positioning of the UAV. In this solution, the authors concluded that the PSO-based algorithm would converge to the efficient positioning of the 3D UAV when the maximum number of iterations is equal to 50. On the other hand, the gradient descent algorithm will also converge to the efficient positioning when the maximum number of iterations is equal to 100.

Cai et al. (2016) use the sequential niche technique (SNT) to modify the utility function value. Thus, the utility function's value is modified adaptively to reject the particles of the niche in the subsequent iterations. The results obtained in this study through simulation showed that the method could solve the problem of multiple paths. This study showed that the utility function of the PSO algorithm plays an important role in reaching the final objective of the mission, thus reinforcing the importance of the study of multiple utility functions for the optimization of the PSO algorithm. Zhang et al. (2010) presented a UAV path planning method based on Ant Colony Optimization (ACO). First, the UAV flight area is divided into grids, and the shortest distance between the radar and the flight path segment is considered as the threat intensity. The ACO algorithm is then used to optimize the path between the starting point and the target point. The weighted sum of flight path length, threat cost, and maximum yaw angle restriction is taken as the ACO algorithm's evaluation function.

Na and Yoo (2019) proposed a PSO algorithm with a multi-objective utility function incorporating UAV connectivity, the value of sensory information, and the quality of the communication path. In the proposed solution, the PSO algorithm optimized the communication of sensors woth a base station. In the study, the topology of the sensor implementation and the 3D geographic map were obtained in advance. Shao et al. (2019) proposed a 3D trajectory planning algorithm based on the PSO. In the solution, the authors use a mutation strategy in which the desired ones replace unwanted particles, and the speed of convergence of the algorithm is accelerated.

3.2 Distributed Coordination and Related Work

The distributed coordination model of multiple UAVs aims to converge towards a common strategy. The "theory of coordination variables and coordination functions" states that a typical cooperative behavior can be achieved in a distributed way using a limited set of variables (McLain; Beard, 2005). Thus, if all UAVs share these coordination variables and apply their coordination function, the entire system will converge to a standard solution.

Kingston, Beard and Holt (2008) apply a coordination variables approach to a set of UAVs to adopt a path partitioning strategy for perimeter monitoring missions, assuming communication constraints. In this study, some questions remain open, more specifically synchronization to share information among neighboring UAVs. Previous work using this same approach has proposed simplified versions that divide the whole problem into subproblems that can be more easily solved based on the coordination variables approach.

Kashino, Nejat and Benhabib (2019) use iso-probability target curves, which represent probabilistic information of the target location in a research region, to perform the optimal allocation of tasks among UAVs' team members, as well as the planning of individual flight paths. Schiano et al. (2016) take a decentralized approach for the coordination of multiple UAVs. In their approach, the authors propose a coordination model based on an extension of the theory of rigidity to the case of bearing structures.

The "one-to-one coordination" is a technique that considers an independent and straightforward coordination problem for each UAV pair. Acevedo et al. (2014) propose this technique to solve distributed area allocation among a set of UAVs and converge the solution to the ideal area partitioning strategy. Caraballo et al. (2014) use the "block sharing technique" to accelerate the convergence of the "one-to-one coordination" approach and manage to extend the agent pair coordination problem to larger groups. Each UAV expects to receive individual information from the rest of the UAVs belonging to the same block and then resolves the area division.

Zheng and Chen (2019) use a positive-sum game for path location. This strategy is used to achieve a global optimum and to avoid collisions in teams of UAVs. The mathematical model of environmental and flight restrictions is established for its operation. Thus, the UAV is considered as the participant of the game, while the trajectory planning of the UAV is considered as the ideal strategy of the participants. Falomir, Chaumette and Guerrini (2018), in turn, propose a mobility model based on the principle of Artificial Potential Fields (APF). The model uses communication between UAVs to share information about obstacles so that the UAV that is not close to the obstacles can plan its way, considering these reported obstacles.

Kim et al. (2014) propose a predictive trajectory strategy planning approach of a decentralized nonlinear model for a dynamic environment. For this, the concept of Minimum Spanning Tree (MST) (Diestel, 2000) of the graph theory is used to obtain successful transmission. The collision between UAVs is also included in the cost function of the optimization process. Waharte, Trigoni and Julier (2009) present a probabilistic environmental model based on the distributed grid. The proposal presents a Bayesian technique to follow the probability density function of the target state. Each UAV maintains a grid-based probabilistic map. The search problem begins with assuming a previous probability distribution function that describes the target location's initial belief. Each UAV, therefore, maintains a local belief map that may often differ from other UAVs. Each UAV progressively updates its belief map based on the (time-stamped) measurement lists it receives from other UAVs.

3.3 Discussion

Table 3.1 presents the main works on coordination of multiple UAVs. These works are divided into two approaches, namely, centralized coordination and distributed coordination. The centralized approach performs the entire coordination process in a single device (UAV or computer), defining all UAVs' stationary positions that are part of the mission. In the distributed approach, the coordination process is performed by n UAVs, which define their stationary locations from a set of rules - all UAVs run the same algorithm.

Table 3.1: Summary of UAV coordination proposals

Reference	Centralized coordination	Distributed coordination
Kim and Lee (2018)	Yes	No
e Silva et al. (2019)	Yes	No
Shakhatreh et al. (2017)	Yes	No
Cai et al. (2016)	Yes	No
Zhang et al. (2010)	Yes	No
Na and Yoo (2019)	Yes	No
Shao et al. (2019)	Yes	No
McLain and Beard (2005)	No	Yes
Kingston, Beard and Holt (2008)	No	Yes
Kashino, Nejat and Benhabib (2019)	No	Yes
Schiano et al. (2016)	No	Yes
Acevedo et al. (2014)	No	Yes
Caraballo et al. (2014)	No	Yes
Zheng and Chen (2019)	No	Yes
Falomir, Chaumette and Guerrini (2018)	No	Yes
Kim et al. (2014)	No	Yes
Waharte, Trigoni and Julier (2009)	No	Yes
This proposal	No	Yes

Source: The author

Both approaches (centralized and distributed) have their advantages and disadvantages. The centralized approach, almost always, uses EC algorithms or mathematical optimization models, which always guarantee optimization of the problem. However, these algorithms need to know the location of the network users in advance. The cost function (responsible for optimization) is formed by rules that do not reflect the state of the network at the moment of execution, and it is not possible to insert real-time network metrics for the coordination of UAVs. Distributed approaches use models that maximize area coverage, which is usually good, beyond the use of real-time network metrics. However, distributed algorithms almost always require many message exchanges to coordinate the UAVs to meet the mission requirements. Another impacting factor is the robustness of the algorithms that have to be synchronous, fault-tolerant, and sensitive to packet loss.

What is desired in a proposal to coordinate multiple UAVs for stationary localization is an algorithm that can unite the advantages of both approaches (centralized and distributed). However, there are no works in the literature that fill this gap as far as we know. Considering the works we know of, distributed approaches present better results if we analyze the coordination for stationary coverage with network service persistence. This is possible because the distributed approach allows distributing the processing among the UAVs in the network. Also, new techniques allow distributed algorithms to infer some data from other UAVs, considerably reducing message exchanges.

4 CENTRALIZED APPROACH TO COORDINATE AND TO MANAGE A UAV NETWORK

This chapter presents a centralized PSO approach to coordinating multiple UAVs and an intelligent management model based on SDN techniques to manage the UAV network. Thus, the proposed approach uses SDN techniques to maintain strategic management throughout the operation, consequently increasing network availability and meeting quality requirements. To do this, the division between the data plane and the control plane is used to implement centralized management. Through the centralized network management model, a Decision Trees algorithm to define traffic routes is proposed. Finally, the dynamic reconfiguration of the SDN architecture is explored to keep routes updated according to the current network context.

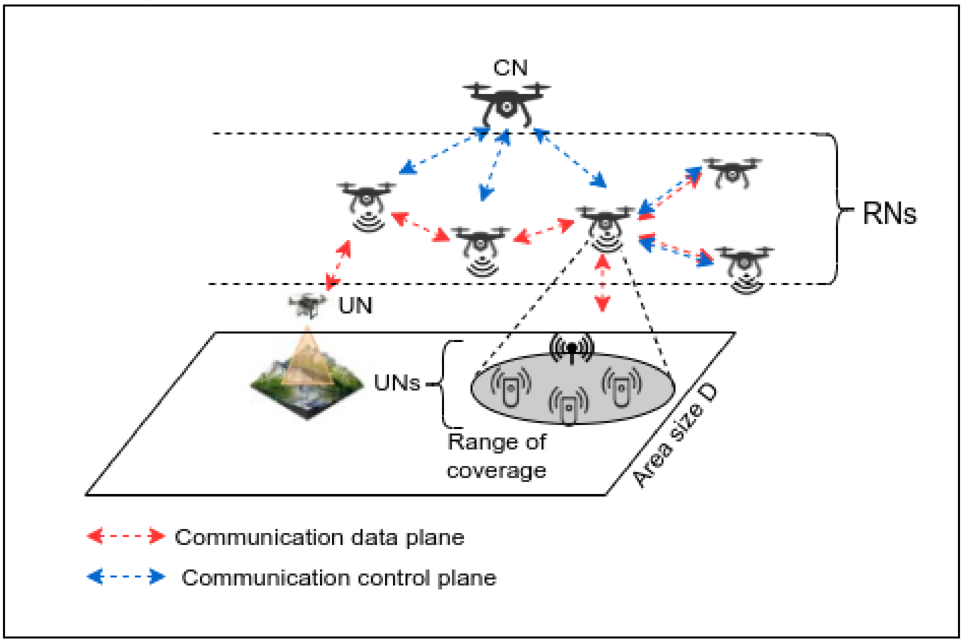
To support the proposed management model, the PSO algorithm is used in building the UAV network. To maintain the built network's manageability, a utility function and three constraints are defined to solve the Coverage and Persistence Aerial Network Deployment Problem (CCPANP). Thus, while the utility function seeks to increase the coverage area and number of degrees (neighbors) of the RNs, the constraints limit the distances to ensure network availability and reduce signal interference.

The remaining of this chapter is structured as follows. The system model and problem formulation are described in Section 4.1. The proposed approach is presented in Section 4.2, and a performance evaluation is presented in Section 4.3.

4.1 System Model

This section introduces the system model and the assumptions adopted in the rest of the chapter, followed by a definition of the research problem. Figure 4.1 presents the architecture overview. The UNs perform an arbitrary mission, such as the search for points of interest (De Moraes; De Freitas, 2018), and, therefore, their positions are defined exclusively by themselves. In their turn, the RNs are allocated to provide the best possible availability of links between the UNs. The CN sends a position and a radius, forming a range of mobility to each RN, and, in this range, the RNs have full autonomy to move and thus provide better links to the connected UNs. Periodically, the CN receives contextual information from all other network nodes, such as position, trajectory, and speed. The CN is responsible for positioning both the RNs and itself and defining the routing tables for each node.

Figure 4.1: Solution architecture demonstrating the flying basestations formed by RNs and CN interacting with UNs.



Source: The author

4.1.1 Scenario Modeling

The studied scenario consists of a square area of size D m^2, a CN controller node, a set RN = {r_1, r_2, ..., r_n} of n Relay Nodes, and a set UNs = {un_1, un_2, ..., un_{Z_s}} of n User Nodes. Each RN can sense the environment and communicate wirelessly with other peers. It is assumed that communication takes place in a multi-hop manner. Firstly, there is a channel $C_{control}$ for control communication between the RNs. In addition, there is another communication channel C_{data} for the data packets; for this channel, the source and destination nodes are the UNs in the network. As a consequence, the RN only performs packet switching on the C_{data} channel.

Without loss of generality, the time is divided into consecutive time slots T = {t_0, t_1, ..., t_m} of length equal to t_{slot}. Let $G(p_{r_1}, p_{r_2}, \ldots, p_{r_n})$ be a graph that, according to the positions of the relay nodes, tells us if the user nodes can communicate with each other. Let $\lambda(r_i, r_j)$ indicate the distance between nodes r_i and r_j. d_r^{max} is the maximum distance - i.e. the range of communication, and d_r^{min} is the minimum distance among the nodes to avoid their collision. If $d_r^{min} \leq \lambda(r_i, r_j) \leq d_r^{max}$, then r_i and r_j are neighbors. Let E(r_i,t_j)

be the function that returns the amount of energy the node r_i has in time t_j.

The following are the three main constraints that the coordination solution must meet to achieve mission success. Equation 4.1 indicates that if $t_j < t_{final}$ then $e > 0$ and $e \leq E^{MAX}$ $\forall$ $r_i \in RNs$.

$$e \leftarrow E(r_i,t_j); e > 0, E(r_i,t_j); e \leq E^{MAX} \qquad \forall t_j < t_{final} \tag{4.1}$$

Equation 4.2 indicates that, if $\forall$ $r_i \in RNs$ has a greater distance than d_r^{min} to the other nodes, then the non-collision of UAVs in operation is guaranteed.

$$\lambda(r_i,r_j) \geq d_r^{min} \qquad \forall r_i, r_j \in RN \tag{4.2}$$

Finally, (4.3) defines that, if G' is a subgraph of G, then $\exists$ C_{data} $\forall$ $G' \in G$. This equation assures us that, if $\forall$ $r_i \in RNs$ there is a channel C_{data}, then the channel $C_{control}$ must also exist. Moreover, this restriction does not allow a disconnected node in the topology.

$$G' \subset G : \exists C_{data} \qquad \forall G' \in G \tag{4.3}$$

4.1.2 Problem Formulation

This work focuses on deploying a UAV network forming flying base stations in 3D space, with restrictions in terms of area coverage and persistence of service. This is a classic problem in the literature, known as the Coverage and Persistence Aerial Network Deployment Problem (CCPANP) (Trotta et al., 2018). Formally, the CCPANP problem is defined as follows.

Definition 1 (CCPANP problem)**.** *Let t_{final} be the lifetime of the system defined by the smallest time slot $t_j \in T$ where $\exists$ $r_i \in RN$ such that $e \leftarrow E(r_i,t_j)$, and $e = 0$ - i.e., the UAV r_i runs out of battery. Given the set of UAVs RN, the problem is to determine the optimal topology such that the network lifetime t_{final} is maximized and the constraints (4.1), (4.2) and (4.3) are met.*

4.2 Proposed Approach

The approach proposed in this work comprises two models. The first model uses the PSO algorithm, a type of evolutionary computing, to perform UAV network coordination. The second model deals with topology management using SDN concepts. The management model implements the division of data plane and control plane and dynamic reconfiguration and uses a Decision Tree algorithm widely used in Artificial Intelligence to analyze and ensure network support according to the mission's parameters. This section is divided into three subsections, namely (i) UAV network coordination, (ii) UAV network management, and (iii) Complexity analysis.

4.2.1 UAV Network Coordination

The coordination model is based on STFANET (e Silva et al., 2019). Three main algorithms are used, namely, topology construction, adjustment, and node allocation. Remarkably, this work adopts the assumptions of STFANET, but modifies the utility functions and adds a virtual localization mechanism based on data before the disaster, as, for example, distribution of neighborhoods in the affected region. The primary motivation for the use of virtual localization is the flexibility for the construction of the topology. This allows the knowledge about the user nodes to be removed, making it easy to add new user nodes during operation without necessarily running the coordination algorithms.

4.2.1.1 Topology Construction

The Coordination Algorithm is based on the PSO, a non-deterministic population optimization method proposed by Kennedy in 1995 (Kennedy; Eberhart, 1995b). The algorithm simulates the movement of a swarm of particles in a multidimensional search space, progressing towards an optimal solution. In the PSO algorithm, each particle receives a vector of position and velocity in a multidimensional space, where the coordinates of each position represent a design value. The algorithm calculates the adequacy of each particle according to its objective function.

In the PSO algorithm, particles - or solutions - need to be compared with the local and the global best solutions at each iteration. This solution is based on a set of constraints and considers several properties in calculating the utility function. The restriction in (4.2) has a higher priority in the analysis, so every particle that does not meet this equation's condition receives utility $-\infty$. Then, a particle will be selected instead of another if the former one contains more active routes than the latter. If there is no difference in this property, then the number of jumps is checked: a reduced number of hops will lower latency and, consequently, a better quality of service for the user. In the end, the goal is to maximize the utility function that considers the sum of alternative routes - disregarding the shortest route and adding up all the other possible routes -, the number of neighbors and the length of links between the nodes.

Equation 4.4 aims to decrease the number of hops in the network. For each UN it adds up the number of hops for communication with any other UN in the network, so the solution with the fewest hops is considered the best the mission - that is, the optimal solution.

$$f_1(G, RNs, UNs) \leftarrow \sum_{j \in UN} \sum_{k \in UN} G(p'_1, \ldots, p'_n)(j,k) \tag{4.4}$$

Equation 4.5 aims to increase the number of neighbors in the network. Equation 4.5 assumes that the more neighbors an RN has the better the network management, although this is not an absolute truth, because a very dense network can lead to delays in packet delivery due to high interference. However, Equation 4.4 is concurrent with Equation 4.5, which causes a balance. Since at the same moment that you want to decrease the number of hops (Equation 4.4) you also want to increase the number of neighbors (Equation 4.5), in this scenario the equilibrium point is the average scenario of the two Equations 4.5 and 4.4.

$$f_2(RNs) \leftarrow \sum_{r_i \in RNs,\ \forall r_j \in RNs | \lambda(r_i, r_j) \leq d_r^{max},\ i \neq j} 1 \tag{4.5}$$

And finally, Equation 4.6 focuses on increasing the area covered by the RNs. Here it is observed that all Equations 4.6, 4.5, and 4.4 are intimately linked and that it can be concluded that the mission's desire is to maintain the connection of the UNs covering as much area as possible. In addition, Equation 4.5 gives the manageability condition when trying to provide the solution to the largest amount of possible routes to transmit traffic within the CCPANP problem.

$$f_3(G, RNs) \leftarrow \sum_{n \in RN | n \in G} Coverage(g'_1, g'_2, \cdots, g'_n) \tag{4.6}$$

Therefore, the topology strategy is mainly assessed through a utility function to be maximized during the execution of the PSO algorithm. The utility function is presented by (4.7), which is the sum of (4.4), (4.5) and (4.6). The operation of the PSO algorithm is described in detail in (Kennedy; Eberhart, 1995b; Kim; Lee, 2018; e Silva et al., 2019).

$$utility \leftarrow f_1(G, RNs, UNs) \; + \; f_2(RNs) \; + \; f_3(G, RNs) \tag{4.7}$$

4.2.1.2 Adjustment

The incremental adjustment of the nodes' locations is performed by monitoring the built topology. Basically, by measuring each node and the distance to its neighbors, a gradient function aims to distribute the nodes in space evenly. In this way, the adjustment algorithm performs no significant change regarding the topology. Instead, it only alters nodes' positions to best allocate them considering the current topology.

Both Equations 4.8 and 4.9 are in charge of performing the topology adjustment. In (4.8), the resulting position p_n^* referred to the node n is derived from the current state p_n and gradient value δ_{p_n}, which is on its turn determined based on its neighbors, as shown in (4.9). In addition, there is a threshold value in order to consider a speed limit in the adjustment strength, where ψ scales the gradient and ψ_r defines the maximum adjustment value (speed limit). In order to determine the gradient value δ_{p_n} referred to the node n, (4.9) takes into consideration each neighbor node v which belongs to one of the routes contained in G; $N_n(g)$ is the set of two neighbors of the node n belonging to the route g. Finally, α defines the degree of agility (or response) for reacting to network topology changes.

$$\begin{cases} p_n - \psi \cdot \delta_{p_n}, & \text{if } ||\psi \delta_{p_n}|| \leq \psi_r. \\ p_n - \psi_r \frac{\delta_{p_n}}{||\delta_{p_n}||}, & \text{otherwise.} \end{cases} \tag{4.8}$$

$$\Psi_{p_n}(P, G) \; \leftarrow \; \sum_{g \in G} \sum_{v \in N_n(g)} \left[\alpha ||p_n - p_v||^{\alpha - 2} (p_n - p_v) \right] \tag{4.9}$$

The input parameters are the nodes' positioning (p_c, P_r and P_l) and the current routing policy G. On its turn, the outputs of this algorithm are the desired positions of the CN p_c and the RNs p_r. As shown, the method computes each position - considering the CN and the RNs - individually according to Equations (4.8) and (4.9).

4.2.1.3 Node Allocation

After running the construction algorithm, the first step is to build the network topology. As seen earlier, after that, the topology is then periodically adapted by using the adjustment methodology. However, at some point, it may be needed to change the topology by performing the construction algorithm once again. In both cases, after the topology construction, the current formation needs to be remodeled to the newer proposed formation. The relay nodes need to be assigned.

In this work, the selection policy considers the location of current nodes and the future formation to allocate the nearest node to its stationary positions. To perform allocation, the strategy is to consider that $D_{|R|\times|R|}$ is a matrix that contains all combinations of distances from the current nodes to the desired locations. Since $\lambda(r_i, r_j)$ represents the distance from node r_i to node r_j, Equation 4.10 represents the content of the matrix D.

$$D_{r_i,r_j} \leftarrow \{||\lambda(r_i, r_j)||\}_{r_i,r_j\ \in\ RNs} \tag{4.10}$$

The algorithm then iteratively identifies the minimum value of the matrix D. The element containing the minimum value reveals the closest distance from the current node to its future location. After finding it, the column and row for that node are discarded from the matrix. For the next iterations, the algorithm continues to search for the minimum value of the nodes in the matrix. Consequently, the algorithm can identify the closest distances between the locations of the current nodes and the locations of the desired formation.

Equation 4.11 presents β as the function responsible for returning the ideal nodes' location r_i^* based on the current location r_i and the desired location $r_i^{'}$

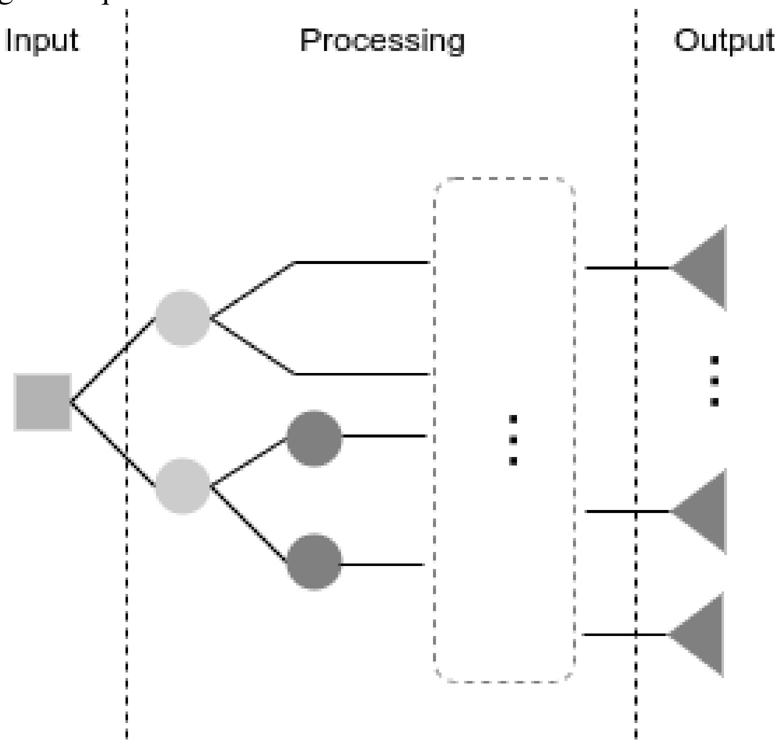
$$r_i^* \leftarrow \beta(r_i, r_i^{'}) \tag{4.11}$$

In addition, after processing the node allocation algorithm, the remaining operating time of the network is calculated by changing the current topology. The remaining operating time takes into account the energy consumption used to assemble the new formation. In the proposed solution, a new topology is assembled if the service life is at least equal to the one of the current topology and operation; otherwise, the new formation is discarded.

4.2.2 UAV Network Management

The proposed management approach is based on Decision Trees (Marcotte; Hamilton, 2017). Figure 4.2 illustrates how this approach works. The **Input** is the set of available routes for the flow in question. The set of requirements and rules forms the **Processing** to meet the transmission quality defined for that stream. As **Output**, a value is assigned to each route of the *input* set. This value is a quality indicator for each route. This set of quality indicators is considered a metric for the mission's success - i.e., after processing, a value is assigned to each of the routes.

Figure 4.2: Illustration of how the Decision Tree works. Its implementation takes the form of a graph. The vertices represent the requirements to be met, and the edges represent the cost of meeting the requirement.



Source: The author

To obtain the efficient use of the available UAV network and meet the quality requirements, a set of rules that have a quantitative character is adopted. These rules are based on estimates and the probability that each *rn* has in meeting the requirements defined for the request. To specify the actions that are executed for each request of a data flow, the proposal is the execution sequence described in the following.

The generated topology forms a graph. The SDN-based approach provides the updated view of this graph according to the current state of the network. Following the SDN approach, every flow not yet known by an RN triggers a request to the central controller. When receiving a flow request, the controller performs a search in the graph using the Breadth-First Search algorithm (BFS). If the return is more significant than one - i.e., there is more than one route for a transmission from the un_x stream to the un_y -, then the returned routes from the BFS algorithm run are used as inputs to the Decision Tree.

The processing of the Decision Tree is based on the estimate and probability that each *rn* offers to the flow - i.e., the result of each requirement is weighted by the probability associated with it in a given *rn*. This work uses the combination proposed in Ferguson and Huston (1998) to ensure quality in transmission - two types of messages are used to execute the experiments: (i) video transmission; and (ii) packet data transmission with a small payload. In this work, the following quality parameters are considered: (i) Delay; (ii) Variation of the delay (jitter); and (iii) Reliability.

The Decision Tree then returns the set of routes with the quality values associated with each route. Finally, the route with the highest quality value is elected as the most viable route and returned to the *rn*.

4.2.3 Complexity Analysis

To investigate the complexity of the proposed solution, the computational complexity was considered for each part of the proposed process - i.e., each algorithm was separately analyzed. Let *RN* be the set of UAVs that relay the package, *p* and *i* the number of particles and interactions of the PSO algorithm, respectively, and *n* the number of neighbors already defined by (4.5). The computational complexity of the three parts of the process are then as follows:

- **Topology Construction:** $O((i+RN)^2 * p * i)$
- **Adjustment:** $O(n * RN)$
- **Node Allocation:** $O(RN^2)$

4.3 Performance Evaluation

This section presents the results of the simulation experiments that were performed to validate the proposed approach. In Section 4.3.2, a comparison of the proposed approach with one of the related works, namely STFANET, is performed. With this analysis, this dissertation presents the gains of using the proposed intelligent management strategy when compared to an approach that does not apply any management criteria. It is emphasized that the two strategies discussed in this subsection use SDN techniques. In Section 4.3.3, the gains of using SDN techniques in a UAV network are analyzed. For this, the proposed approach using the SDN techniques is compared to the AODV protocol.

4.3.1 Setup and Benchmarks

Simulations of the proposed management of a UAV network in response to disasters were carried out using the Mobile Multi-Media Wireless Sensor Network (M3WSN) OMNet++ framework (Rosário et al., 2013). The OMNet++ is a network simulator for implementing and testing novel solutions. This work focus on the implementation of the proposal in the network layer. Therefore, by using this framework, it is possible to gather valuable results considering the already modeled physical layer constraints.

A campaign of 50 independent simulation runs was conducted, varying the UNs' movements and transmissions. As evaluation metrics, packet loss, latency, and connectivity index were assessed, and we present the mean value from the 50 runs. The scenario includes sets of 3, 9, 12 and 15 RNs in order to provide connectivity among 10 UNs moving randomly through a flat terrain of 10km $\times$ 10km. Each UN transmits a data packet to a random destination in intervals that vary from 100ms to 200ms. The simulation parameters were also set to allow wireless channel temporal variations, link asymmetry, and irregular radio ranges, as expected in a real scenario.

The simulation then comprises a post-natural disaster scenario. The rescue teams leave from a central point, usually where the probability of rescuing lives is higher and the damage occurs in greater intensity. During the operation, the teams start moving in a specific direction to reach the other affected regions. The dynamics presented are similar to an actual situation, supposing a weather disaster in a medium-size city (10km $\times$ 10km.). The center of this region is the commercial center of this city. The rescue team starts from this location. It begins the operation, and, as the group explores, it begins a process of displacement from the center to the edge of these regions. In this context, the UAVs will accompany the rescue team providing the necessary support.

The UNs are able to move from 5m/s to 10m/s, while the RNs and the CN are considered to be able to move at a maximum speed of 20m/s. The simulation was performed for 20 minutes long (simulation time, because OMNet++ [1] is a discrete event simulator,

[1] https://omnetpp.org/.

meaning that the processing resources of the computers used to run the simulations are disregarded, such that the simulation processing time does not affect the results), which was considered to be enough in order to have the nodes sufficiently spread through the environment, as they start at the center of the scenario. In the simulation, UAVs rely on the CSMA/CA MAC protocol, without using RTS/CTS messages and retransmissions. In the case of buffer overflow, the UAVs consider a drop tail mechanism to drop packets. All nodes are able to communicate in a link length of around 100m. The nodes are set to transmit their contextual information to the controller in intervals of 250ms.

The parameters referred to in both scenarios are presented in Table 4.1. Parameters used in mathematical expressions included in this chapter are presented along with their respective symbols. The parameters were set according to the related work. The results and discussions are presented in the following, namely, Section *4.3.2 Centrally managed UAV network using the SDN techniques* and Section *4.3.3 Gains from using SDN techniques in a UAV network*.

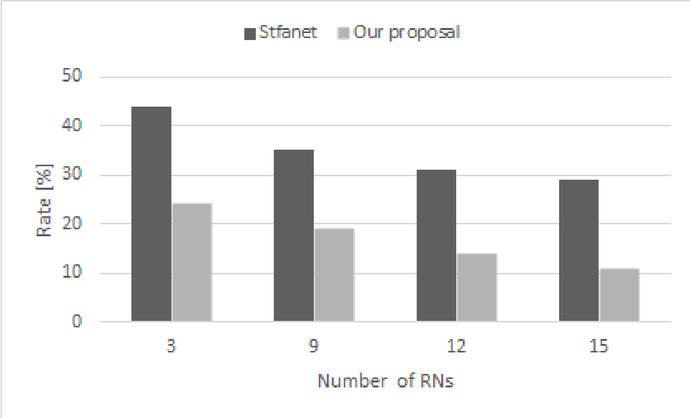
4.3.2 Centrally managed UAV network using the SDN techniques

The experimental results in Figures 4.3 to 4.5 are presented as follows: the first bar is the *STFANET* approach (e Silva et al., 2019) and the second bar presents the results of the proposed approach. For this scenario, two noises were added to assess the impact of context-sensitive management: (i) one of the RNs randomly stops working during the simulation; and (ii) in the case of rn_2, for every five received data packets, only three are retransmitted - i.e., two data packets are retained by rn_2. However, these noises are not applied to the network management packets.

The graph presented in Figure 4.3 shows the average percentage of packet loss. STFANET presents between 16% and 20% more packet losses than the new proposed approach. This is due to the use of context in route management. In the STFANET approach, routes are defined by the smallest path using the Dijkstra algorithm. In the proposed approach, the network context data and the application of a decision tree are used, so the defined route is always the one feasible to meet the requirements at that moment.

The noise added in the simulation explains the rate of package loss. However, as shown in Figure 4.3, the proposed approach was able to recover from the noise's failures and it was more successful in delivering the packages. Another observed fact is that the

Figure 4.3: Packet loss.



Source: The author

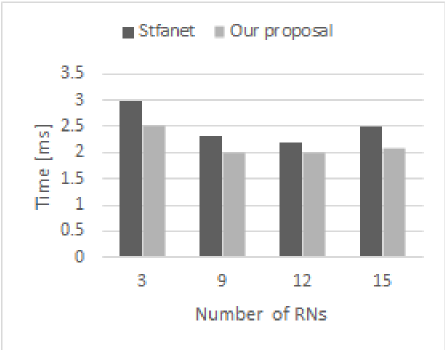
more RNs, the less package loss is observed. This is due to the more significant number of routes available for packet transmission.

The end-to-end delay is shown in Figure 4.4. In the end-to-end delay analysis, only valid and successful packets are considered - i.e., packets that left a un_x source and reached the recipient un_y, with $x \neq y$. In this case, two factors draw attention in analyzing the data: (i) When the number of RNs in the solution increases, a decrease in the delay rate is presented. This is explained by the larger number of channels generated by the UAVs, as more free channels for transmission give more outflow for the flow of the packets; and (ii) in the proposed solution, the gains over the STFANET proposal are more expressive when the number of jumps increases and also the number of RNs, which demonstrates the efficiency of the proposed management model, which, among many features, seeks to reduce the occurrence of collisions in the transmission of packages. The obtained results are easily explained, mainly because of the CSMA/CA MAC protocol resource, which implements a method that contributes to reduce the occurrence of collisions in a network. In this method from the CSMA/CA MAC resource, the packet is stored in the RN buffer until the medium is free for transmission, which means that the freer the medium is, the less time the package is stored in the buffer, which reduces the end-to-end delay.

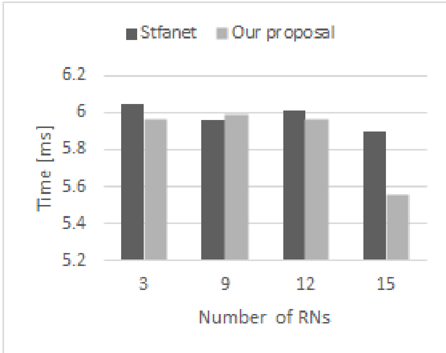
Figure 4.5 presents the results related to the jitter metric, which measures the variation in delay between delivered successive data packets. In this figure, a high delay variation (i.e., jitter) can be observed, which leads to an unsynchronized reception of the packets and, consequently, the need of buffering to allocate packets in the waiting list.

Figure 4.4: End-to-end delay.

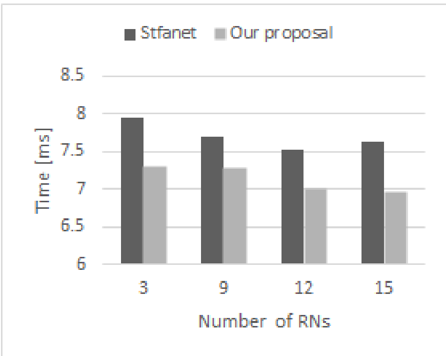
(a) 1 hop.



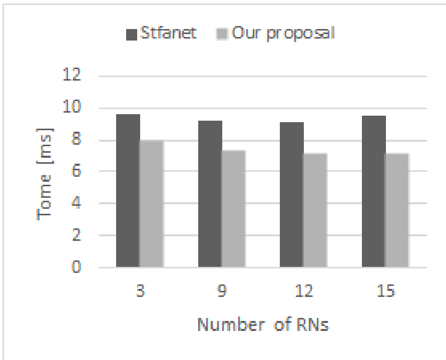
(b) 2 hops.



(c) 3 hops.

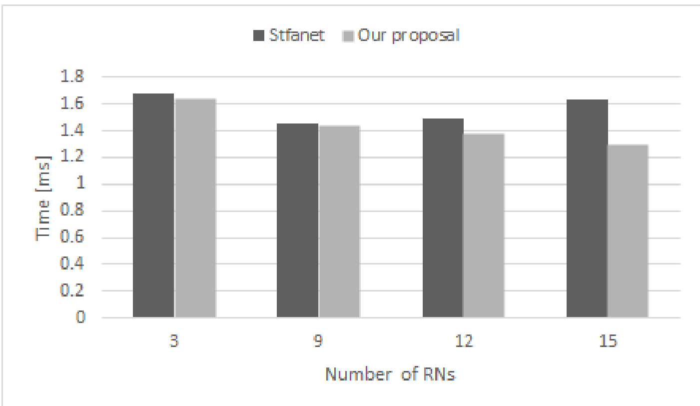


(d) 4 hops.



Source: The author

Figure 4.5: Jitter.



Source: The author

4.3.3 Gains from using SDN techniques in a UAV network

The proposed approach to manage a UAV network based on the SDN technique is compared to the same UAV network with the management of the AODV protocol. The main objective of the AODV routing protocol is to be adaptive to mobile nodes, which act as routers in the network, whilst reducing bandwidth and nodes' computational use. In the related works, the AODV protocol was widely used for the managing the formed topology and is therefore used for comparison with the proposed approach. Even though it requires the use of traditional routing tables, AODV is a reactive protocol - i.e., whenever there is a need to send data packets to an unknown destination node, the process of route discovery is initiated (Belding-Royer; Perkins, 2003). The implementation of this solution follows the guidelines of RFC 3561 (Perkins; Belding-Royer; Das, 2003). Simulation parameters that are different from the previous simulation experiments are presented in Table 4.2.

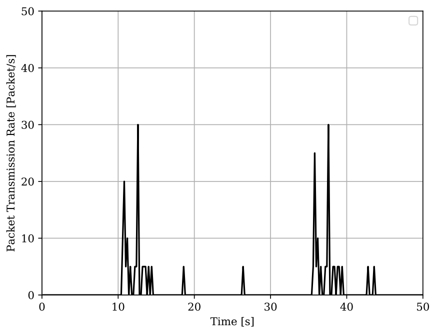
Using the AODV management protocol, the exchange of AODV_HELLO_PACKET packets aims to verify and maintain already established communication links among nodes. This packet exchange frequency is constant and takes place during the entire operation of the network. In (Misra; Woungang; Misra, 2009; Perkins; Belding-Royer; Das, 2003), there is an extensive discussion regarding the operation of AODV, for interested readers. Figures 4.6-(a), 4.6-(b) and 4.6-(c) present the AODV_HELLO_PACKET packet transmission rate performed by having 15, 30 and 45 users in the network, respectively. As can be seen, the packet transmission rate reaches 45 packets/s when there are 45 users assigned to the network. Considering that AODV is a distributed protocol and designed for dynamic networks, internal maintenance packages are indispensable. However, the consequent packet flooding might degrade high data traffic applications and consequently compromise the mission success.

The network usage over time by considering the AODV approach is presented in Figure 4.7. In very dense networks, the packets exchanged for the internal maintenance of the AODV protocol functions as a flooding mechanism of the network. The packet traffic for internal maintenance is a flow that competes with the data flow of the UNs, so the transmission rate of the data packets exchanged between the UNs does not stabilize during the entire operation.

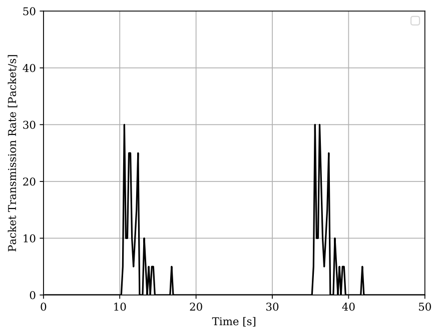
By considering the SDN approach, the network usage over time is depicted in Figure 4.8. As can be seen, a large proportion of topology management packages are exchanged between the RNs and the CN in the beginning of the simulation from 0 to 10s.

Figure 4.6: AODV_HELLO_PACKET packet transmission rate.

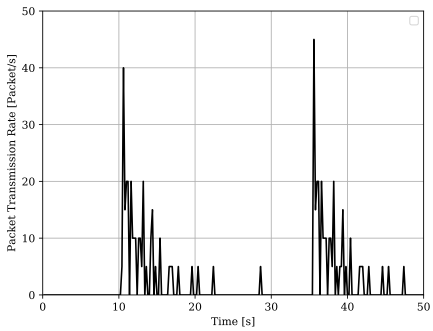
(a) 15 connected users.



(b) 30 connected users.

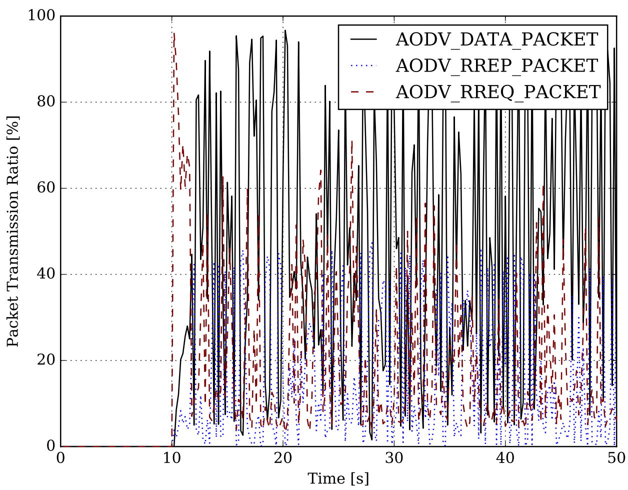


(c) 45 connected users.



Source: The author

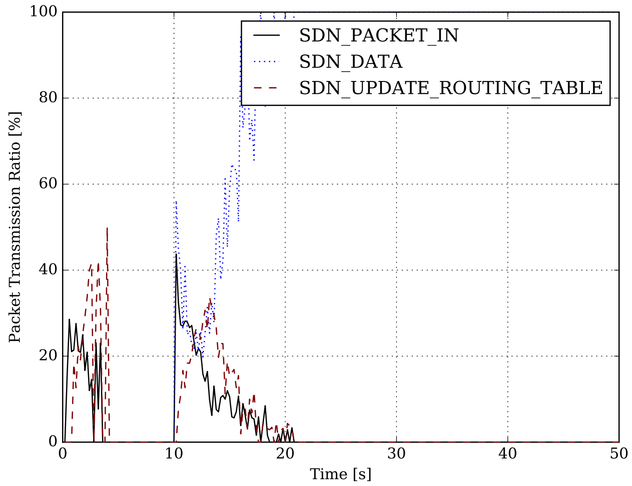
Figure 4.7: Infrastructure usage in network startup over time by using the AODV approach.



Source: The author

This occurs at network startup as part of the proposed solution, as the UNs are sending "Hello" messages to register themselves on the network. The RNs then forward these messages to the CN that processes these requests and performs the user registrations in the network. As a consequence, this model allows the CN to manage the nodes' topology and perform a load distribution in a centralized manner. After 10s in the simulation, data packets start to be transmitted among UNs. At this point, table requests and updates are transmitted between RNs and CN to set required routing table rules. It is possible to observe that, over time, the package traffic is stabilized, as the communication channel becomes highly available for data traffic packets in exchange between the UNs.

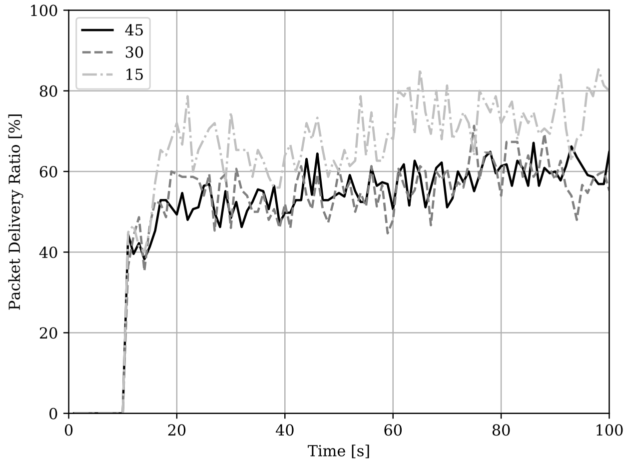
Figure 4.8: Infrastructure usage in network startup over time by using the SDN approach.



Source: The author

A centralized topology management proposed in the SDN approach takes the advantage of having a global view of the network while managing the entire set of nodes' communication links. In this context, the exchange of internal network maintenance packets occurs specifically when there is a significant topological change. It is true that the initial packet flow for network maintenance is much lower in the AODV protocol compared to the SDN-based approach, as can be seen in Figures 4.7 and 4.8, respectively. However, the decrease of network maintenance messages in the SDN-based approach leads to a lower medium competitiveness for data packet transmissions. Comparing the SDN-based solution with the AODV approach, it is clear that the SDN approach presents a drawback in the initialization phase. However, over time, the AODV protocol considerably increases the number of internal network maintenance messages being exchanged, as detailed in (Perkins; Belding-Royer; Das, 2003). In a post-disaster operation scenario, network availability is a critical factor for mission success (Ochoa; Santos, 2015). In this context, the SDN-based approach provides more efficient use of network resources, as a lower number of packets are being transmitted in the medium; as a consequence, the network becomes more efficient.

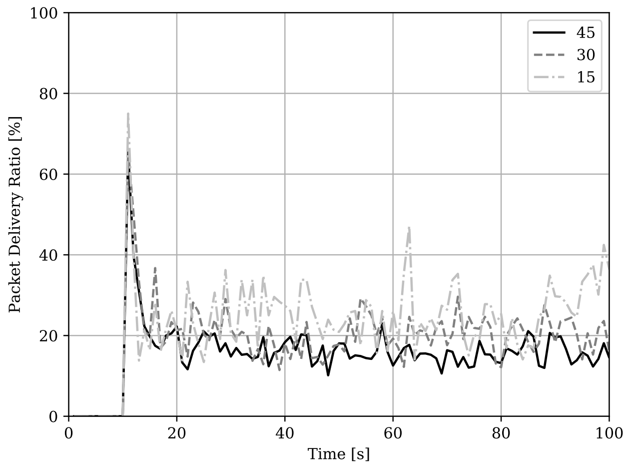
Figure 4.9: Data packet delivery ratio over time having 15, 30 and 45 connected users by using the SDN-based approach.



Source: The author

The data packet delivery ratio by using the AODV protocol and the SDN approach are illustrated in Figures 4.9 and 4.10 respectively, in which both consider 15, 30 and 45 users assigned to the network. In both approaches, the data packet delivery ratio is greater when there are less connected users. However, as can be observed, the data packet delivery ratio increases during the operation by using SDN. On the other hand, it tends to stabilize in a smaller value over the course of the operation when the AODV protocol is applied.

Figure 4.10: Data packet delivery ratio over time having 15, 30 and 45 connected users by using the AODV protocol.

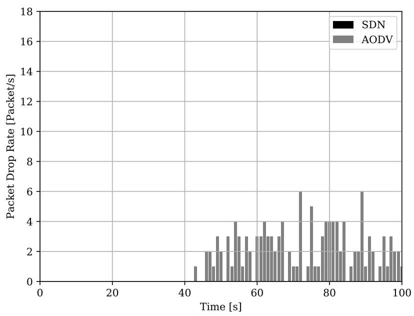


Source: The author

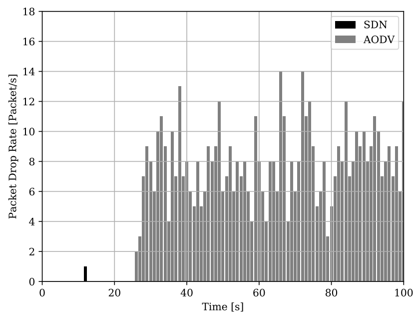
The amount of dropped packets due to the inefficient use of the network is a common concern as communication buffers became insufficient. Figures 4.11-(a), 4.11-(b) and 4.11-(c) present the dropped packet rate over time by having 15, 30 and 45 users in the network, respectively. In general, the amount of dropped packets by using the AODV protocol is greater than by using the SDN approach. By using the AODV protocol, it is noticeable that the packet drops starts to occur after 20s, as the routing table rules are filled and the maintenance of the communication links is necessary. On its turn, by considering the SDN approach, the packet drops are perceived exclusively in the case that 30 and 45 users are connected. In addition, packet drops occurred exclusively by 10s, in which users start to transmit constant data packets and routing table rules are consequently requested to the CN.

Figure 4.11: Packet drop rate over time.

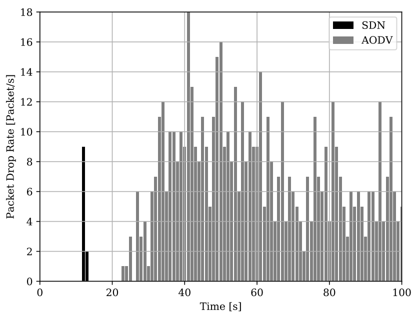
(a) 15 connected users.



(b) 30 connected users.



(c) 45 connected users.

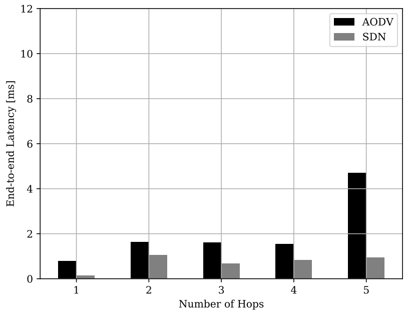


Source: The author

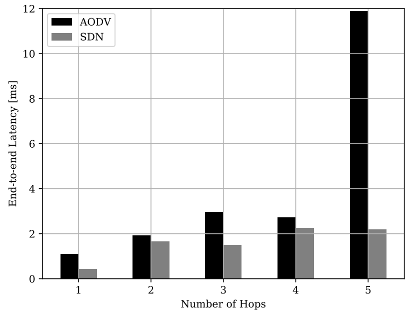
The end-to-end network latency is depicted in Figure 4.12 by presenting the average time of data packets per number of hops needed from the source to the final destination. The analysis is presented by having 15, 30 and 45 connected users in Figures 4.12-(a), 4.12-(b) and 4.12-(c), respectively. In general, the AODV protocol presented a higher data packet latency in comparison to the SDN approach, reaching a maximum difference of 10ms, as shown in Figure 4.12-(b). A relationship between network usage, end-to-end data packet latency and packet drops is noticeable. The increase of packet transmissions in a wireless network leads to a longer period of time during which packages are kept buffered waiting for transmission; as a consequence, a higher end-to-end data packet latency is noticed. In addition, the need for buffering also leads to constant package drops in such network.

Figure 4.12: End-to-end infrastructure latency.

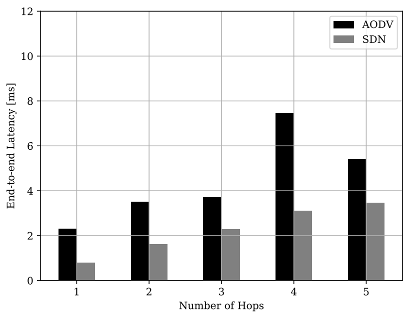
(a) 15 connected users.



(b) 30 connected users.



(c) 45 connected users.



Source: The author

Table 4.1: Parameters used in the simulation of the proposed centralized approach and STFANET approach.

Simulation Parameters	**Value**
Scenario	
Time	20min
Dimension	10 x 10km
Number of user nodes	10
Number of relay nodes	[3, 9, 12, 15]
User nodes' speed	[5..10]m/s
Relay nodes' speed	20m/s
Graph Refresh	
Beacon interval	250ms
Topology interval	500ms
Distances	
Minimum distance (d_s)	50m
Ideal link length (d_r^*)	70m
Maximum link length (d_r^{max})	100m
Construction	
Number of particles (N_ψ)	30
Number of iterations (N_k)	300
Stop threshold ($N_k{}^t$)	10
Inertia weight (w)	0.7
Cognitive parameter (c_1)	1.5
Social parameter (c_2)	1.5
Threshold for velocity clamping (V_{max})	20%
Sum of link length weight (σ)	.5
Ideal link distance weight (λ)	.3
Safety distance weight (μ)	.3
Adjustment	
Positive step size (γ)	.05
Maximum travel distance (γ_r)	2
Power of link distance (α)	5

Source: The author

Table 4.2: Parameters changed or added in the simulation evaluating the SDN-based proposal with the AODV protocol.

Simulation Parameters	**Value**
Coordination and Exploration Model	
Inertia weight (w)	[.9 ... .4]
Cognitive parameter (C_1)	1.4962
Social parameter (C_2)	1.4962
Infrastructure	
Radio	802.11g
Mode	11Mbps

Source: The author

5 A DISTRIBUTED APPROACH TO COORDINATE THE STATIONARY LOCATION OF A UAV NETWORK

This chapter presents a distributed model for the coordination of multiple UAVs that uses Algorithmic Game Theory techniques as a strategy. These strategies are used to prevent random distribution of UAVs while ensuring the efficiency benefits of centralized models, but with a quick convergence to the current context. The use of AGT in the proposed model also allows the analysis of network data for decision-making in network construction dynamics. The application of this model to the problem of stationary coverage of UAVs intends to guarantee (i) the fulfillment of coverage metrics defined for the mission and (ii) the connectivity of the formed network topology, maximizing the required persistent service.

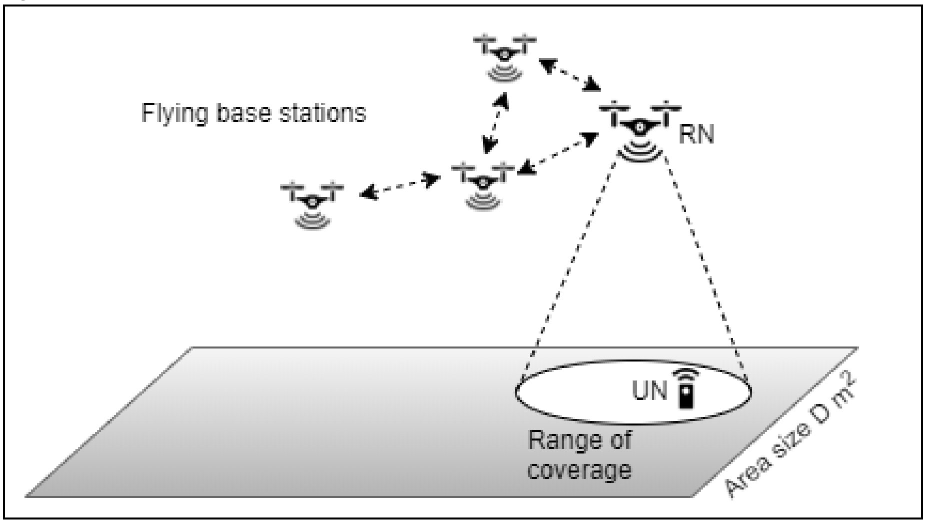
The model uses AGT techniques, which are widely explored in multi-agent autonomous systems showing great efficiency (Kovács; Grzybowska, 2015; Ellenbeck; Hartmann; Berlemann, 2008; Roldán; Del Cerro; Barrientos, 2018). Also, the model provides distributed coordination and cooperative intelligence for decision-making. The approach is comprised of n UAVs, called RN, to meet m UN.

The rest of the chapter is structured as follows. The system model and problem formulation are described in Section 5.1. The distributed approach for UAV positioning and coordination using AGT techniques is detailed in Section 5.2. And a performance evaluation is presented in Section 5.3.

5.1 System Model

This section introduces the system model and the assumptions adopted in the proposal, followed by a mathematical definition of the research problem. Figure 5.1 presents the architecture overview, where the UNs perform an arbitrary mission defined by a search for points of interest (De Moraes; De Freitas, 2018), and therefore their positions are defined exclusively by themselves. In turn, the RN nodes self-organize themselves to offer the best possible availability of links to the UNs. In addition, the RNs always seek to increase their area of coverage.

Figure 5.1: Solution architecture demonstrating the flying base stations formed by RNs interacting with UNs.



Source: The author

5.1.1 Scenario Modeling

The studied scenario consists of a square area of size D m^2 and a set RNs = {rn_1, rn_2, ..., rn_n} of n UAVs, and UNs = {un_1, un_2, ..., un_m} of m user nodes. Each RN can sense the environment and communicate wirelessly with other peers. It is assumed that communication takes place in a multi-hop manner. Firstly, there is a channel $C_{control}$ for control communication between the RNs. In addition, there is another communication channel C_{data} for the data packets; for this channel, the source and destination nodes are the UNs in the network. As a consequence, the RN only performs packet switching on the C_{data} channel. Let $G = G(p_{rn_1}, p_{rn_2}, \ldots, p_{rn_n})$ be a graph that, according to the positions of the relay nodes, tells us if the user nodes can communicate with each other.

Without loss of generality, the time is divided into consecutive time slots T = {t_0, t_1, ..., t_k} of length equal to t_{slot}. Let $\lambda(rn_i, rn_j)$ indicate the distance between nodes rn_i and rn_j. Also, let d_{rn}^{max} be the maximum distance - i.e. the range of communication, and d_{rn}^{min} the minimum distance among the nodes to avoid their collision. If $d_{rn}^{min} \leq \lambda(rn_i, rn_j) \leq d_{rn}^{max}$, then rn_i and rn_j are neighbors. Let $E(rn_i, t_k)$ be the function that returns the amount of energy the node rn_i has in time t_k. Also, let E^{MAX} be the maximum amount of energy.

Next, the function $\Phi(rn_i, t_k)$: RN, T $\rightarrow$ {-1, 0, 1} is introduced, indicating the UAV condition in a given time interval. More specifically, $\Phi_i(t_k)$ = 1 indicates that RN is in the stationary state (S_{sta}) at slot t_k, $\Phi_i(t_k)$ = 0 indicates that RN is in the flying state

(S_{fly}) at slot t_k, while $\Phi(t_k)$ = -1 indicates that RN is in the inoperable state (S_{ino}) at slot t_k. At each slot t_k, each rn_i can be in only one of the three states listed.

Let S = {S_{fly}, S_{sta}, S_{ino}} denote the RN state set. Based on its state at time slot t_{k-1}, each RN can execute different actions at slot t_k. More specifically, if rn_i is in state S_{fly} at time slot t_{k-1}, then one of the following two actions can be selected:

1. FLY_{NO}: Indicates that node rn_i will change its state from S_{fly} to S_{sta}.
2. FLY_{OK}: Node rn_i remains in state S_{fly}.

Similarly, if rn_i is in state S_{sta} at time slot t_{k-1}, then one of the following three actions can be selected.

1. STA_{NO}: Node r_i attempts to fly. If all its neighbors are in state S_{sta}, then r_i changes its state to S_{fly}, otherwise it remains in state S_{sta}.
2. STA_{OK}: Node rn_i remains in state S_{sta}.
3. STA_{FINAL}: Node rn_i enters state S_{ino} and stops operating.

5.1.2 Problem Formulation

It is denoted with $\Phi(rn_i, t_k)$ the scheduling function that defines the state for each UAV $rn_i \in RN$ at each time slot $t_k \in T$. Let s(rn_i, t_k) : RN, T $\rightarrow$ {-1, 0, 1} be the function that defines whether the UAV rn_i execute or not the action S_{fly} at the beginning of time slot t_i. The energy consumption of each UAV is given by ι and ϖ. ι and ϖ are static values defined by the firmware PX4[1]. ι corresponds to the energy consumption if the UAV is performing the S_{sta} action, and ϖ corresponds to the energy consumption if the UAV is performing the S_{fly} action.

This work is interested in deploying a UAV network forming flying base stations in 3D space, with restrictions in area coverage and service persistence. This is a classic problem in the literature, known as the Coverage and Persistence Aerial Network Deployment Problem (CCPANP). Formally, the CCPANP problem is defined in Section 4.1.2. However, to suit the proposed distributed model, the problem is redefined as follows. Let $\beta, \gamma, \varepsilon$, represent the importance given to each function in the probabilistic prediction process.

Definition 2 (CCPANP problem)**.** *Let t_{final} be the lifetime of the system defined by the*

[1]https://github.com/PX4/Firmware

smallest time slot $t_k \in T$ where $\exists\, rn_i \in RN$ such that $E(rn_i,t_j) = 0$ - i.e., the UAV rn_i runs out of battery. Given the set of UAVs RN and the factors $\alpha, \beta, \gamma, \delta$ and ε, we want to determine the optimal $\Phi_i(t_k)$ such that the network lifetime t_{final} is maximized. To do so, we propose a utility function and a set of 4 constraints - which will be detailed below - that seek to maximize t_{final} $\forall rn_i \in RN$ maintaining the connection of the entire network.

The first restriction concerns the coordination of the movement of UAVs. Equation 5.1 presents this coordination model. This restriction's main objective is to explore the coordinated area to guarantee greater space coverage and greater service to the UN. For this, a limitation in the number of UAVs that move in the same time slot is performed. The first step is to divide the RN set into subsets. We call these subsets RN'. An rn_i $\exists$ RN is part of RN_i' if and only if they are neighbors. Also any inoperative rn_i at the time slot t_k ($\forall t_k \exists T$) is excluded, i.e. $s(i,k) \not\to 1$. And finally, in any time slot, necessarily one and only one RN of each subset will perform some movement.

$$\sum_{rn_i \in RN'} \Phi_i(t_k) = 1 \qquad \forall t_k \in T \tag{5.1}$$

The second restriction concerns the operating time of the topology. Equation 5.2 presents the active time of the UAV network. In summary, the uptime is a variable dependent on the energy remaining in operation - i.e.,

$$\Delta = \sum_{rn_i \in RN} E(rn_i, t_k).$$

When building a UAV network, the desired goal is to keep the network active for the longest possible time. By making the operation time directly dependent on each rn's remaining power, the UAVs are encouraged to save their energy to stay active for as long as possible. Consequently, the UAV network will also be available for as long as possible.

$$0 < \Delta(t_k) \leq E^{MAX} \qquad \forall t_k < t_{final} \tag{5.2}$$

The third restriction is formulated so that there is no collision between the UAVs. Equation 5.3 presents the formal formulation of this restriction, where a minimum safe distance between the UAVs d_{rn}^{min} is defined, which must be respected by all UAVs during the entire operation period.

$$\lambda(rn_i, rn_j) \geq d_{rn}^{min} \qquad \forall rn_i, rn_j \in RN,\ i \neq j \tag{5.3}$$

Finally, the fourth restriction guarantees communication routes for UN, formally represented by Equation 5.4. Without loss of generality, we define G' as a subgraph of G, where G' is composed of a un_i and un_j so that $\lambda(un_i, un_j) > d_{un}^{MAX}$ and there must be a communication route C_{data} between un_i and un_j. As it is well known, the transmission of packets leads to higher power consumption, so restriction 5.2 is competing with the sending of packets, as this restriction requires a communication route for UN. Thus, we guarantee that if the UN is contained in G, it will communicate with any other UN in G.

$$G' \subset G : \exists C_{data} \qquad \forall G' \in G \tag{5.4}$$

It is assumed that all RNs know the whole network, which is equipped with a Global Positioning System (GPS) and a wi-fi module. The UNs connect as soon as an RN is over its communication range.

5.2 AGT-Based Distributed Approach

This proposal adopts an approach that aims to deal with the unpredictable and unknown dynamics of the environment. At every moment, all RNs will adapt their behavior to real internal and external conditions. In addition, the proposed solution is also capable of dealing with dynamic network scenarios in which the number of RNs can change over time.

From this moment on, the utility function of the game is defined. To define this function, we propose a heuristic that uses the known values of the time instant t_k and t_{k-1} to make a probabilistic definition of the instant t_{k+1}. The variables considered in this heuristic are (i) area coverage, (ii) number of UN served by the UAV network, and (iii) the number of routes formed by the current configuration of the UAV network.

Let $p'_i = (x'_i, y'_i, z'_i)$ be the position of rn_i, then $C(p'_1, p'_2, \ldots, p'_n)$ represents the area covered by the set of RNs at the instant of time t_k. $H = h_{G(p'_1, p'_2, \ldots, p'_n)}$ is defined as the function that according to the p'_i position of rn_i defines the UN that are connected to it, $\forall rn_i \in RN$. Finally, $R = r_{G(p'_1, p'_2, \ldots, p'_n)}$ is the function that returns all possible routes for the communication from a position p'_i to $p'_j \; \forall \; p'_i, \; p'_j \in C, \; i \neq j$.

Equation 5.5 defines the amount of area that was covered or the amount of area that lost coverage in the transition from time t_{k-1} to time t_k. Equation 5.6, in turn, defines the number of UN who are no longer served or the number of UN that have changed from the time instant t_{k-1} to the time instant t_k. Finally, Equation 5.7 defines how many routes were added or not during the transition from time t_{k-1} to time t_k

$$\begin{aligned} f_1(RN,T) = {} & C_{k-1}(p'_1, p'_2, \ldots, p'_n) \\ & - C_k(p'_1, p'_2, \ldots, p'_n) \end{aligned} \tag{5.5}$$

$$f_2(RN,T) = \sum_{rn_i \in RN} H_{k-1} - \sum_{rn_i \in RN} H_k \tag{5.6}$$

$$f_3(RN,T) = \sum_{rn_i \in RN} R_{k-1} - \sum_{rn_i \in RN} R_k \tag{5.7}$$

Thus, the utility function is defined by Equation 5.8. The values of $\beta, \gamma, \varepsilon$ represent the importance of each of the variables in the probabilistic prediction process for time instant t_{i+1}.

$$\begin{aligned} u_i^{t_{i+1}} = {} & \beta \cdot f_1(RN,T) + \gamma \cdot f_2(RN,T) \\ & + \varepsilon \cdot f_3(RN,T) \end{aligned} \tag{5.8}$$

Without loss of generality, we can formally define the game as:

Definition 3. *At each time slot $t_k \in T$, the game is defined as the triple $\langle RN, A, u^k \rangle$, where:*

1. *RN = {rn_1, rn_2, ..., rn_n}, is the set of RNs/players;*
2. *A = {FLY_{OK}, FLY_{NO}, STA_{OK}, STA_{NO}, STA_{FINAL}} is the action set available to each player;*
3. *$u^k = \{u^k_{r_1}, u^k_{r_2}, \ldots, u^k_{r_n}\}$ is the utility function of each player rn_i - i.e., $u^k : A \rightarrow R$.*

Let $\theta^{i,j} = \{(1-G_F^{i,j}), G_F^{i,j}, (1-G_S^{i,j}), G_S^{i,j}, (G_S^{i,j}-1)\}$ be the strategy for player rn_i at time slot t_j defining the probability distribution over the set of possible actions A. The values $(1-G_F^{i,j}), G_F^{i,j}, (1-G_S^{i,j}), G_S^{i,j}, (G_S^{i,j}-1)$ represent the probability of rn_i executing one of the actions FLY_{OK}, FLY_{NO}, STA_{OK}, STA_{NO}, STA_{FINAL}, respectively.

Table 6.3 describes the set of strategies for the game. It is defined $\theta^{i,j} = \theta_F^{i,j}$ as the set of all possibilities of strategies for node rn_i, if it is in the S_{fly} time slot t_j (flying).

According to the definitions in Section 5.1.1, the support of $\theta_F^{i,j}$ includes $(1-G_F^{i,j})$ and $G_F^{i,j}$. Therefore, it is defined $\theta_F^{i,j} = \{(1-G_F^{i,j}), G_F^{i,j}, 0, 0, 0\}$. Likewise, it is defined $\theta^{i,j} = \theta_S^{i,j}$ as the set of all possibilities of strategies for node rn_i, in case it is in the state S_{sta} in the time slot t_j (stationary). In this case, the support of $\theta_F^{i,j}$ includes $(1+G_S^{i,j})$, $G_S^{i,j}$ and $(G_S^{i,j}-1)$. Therefore, it is defined $\theta_S^{i,j} = \{0, 0, (1-G_S^{i,j}), G_S^{i,j}, (G_S^{i,j}-1)\}$.

Table 5.1: General Game Description.

S	**Strategy**	**A**	**U**
s_{fly}	$(1-G_F^{i,j})$	FLY_{OK}	$u^{i,j}(FLY_{OK})$
s_{fly}	$G_F^{i,j}$	FLY_{NO}	$u^{i,j}(FLY_{NO})$
s_{sta}	$(1-G_S^{i,j})$	STA_{OK}	$u^{i,j}(STA_{OK})$
s_{sta}	$G_S^{i,j}$	STA_{NO}	$u^{i,j}(STA_{NO})$
s_{sta}	$(G_S^{i,j}-1)$	STA_{FINAL}	$u^{i,j}(STA_{FINAL})$

Source: The author

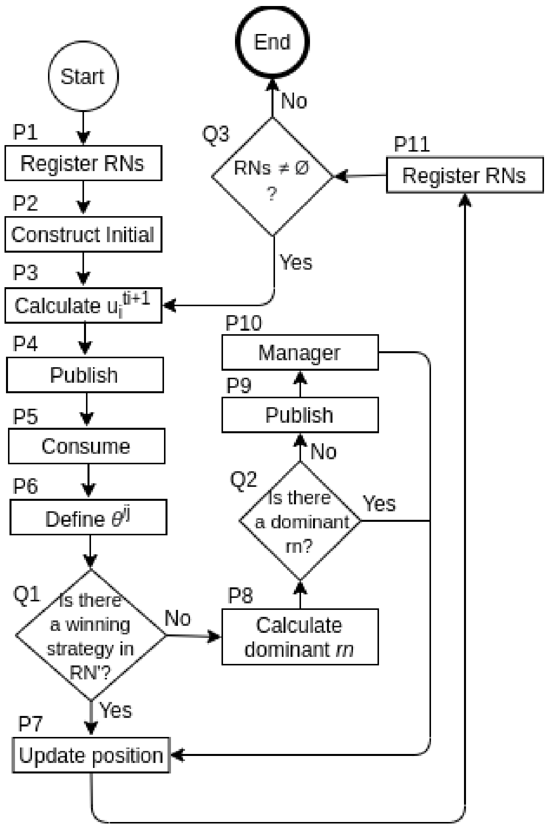
The goal of the proposed approach is to cover an area and, at the same time, serve as many UN as possible. To meet the two main objectives, a method is proposed that provides coordinated area coverage - i.e., area coverage is achieved step by step during the mission's execution. A strategy based on AGT is defined, where the RNs are the players. Figure 5.2 presents the game's execution flow, while the utility function of the game, i.e., the payoff, is defined by Equation 5.8.

The game dynamics are dictated by Figure 5.2, which presents an overview of the algorithm's execution. This dynamic is composed of 11 processes and three questions, given as (P1, P2, ..., P11) and (Q1, Q2, Q3), respectively. The processes P1 and P2 are executed only at the initial moment of the game. In P2, only restriction 5.3 is considered. The other processes are executed as long as restriction 5.2 is served.

P3 performs the node payoff calculation - i.e., $u_i^{t_{i+1}}$ -, where each RN performs its own calculation. This calculation is done as described in Equation 5.8, applying the four restrictions defined for the problem - Equations 5.1, 5.2, 5.3 and 5.4. Equations 5.5, 5.6 and 5.7 are executed joining with a predictive model taking into account the time slots t_{i-1} and t_i. This predictive model uses the UAV positioning algorithm that extends the virtual spring model described in (Di Felice et al., 2014) and (Derr; Manic, 2011). A virtual spring force $\vec{F}(rn_i, rn_j)$ acts between each pair of UAVs (rn_i, rn_j) located at a distance of one jump, that is, that can exchange messages directly. The intensity of $\vec{F}(rn_i, rn_j)$ is calculated by the position and amplitude of UAVs according to Hooke's law:

$$|\vec{F}(rn_i, rn_j)| = -(|\vec{x}_i - \vec{x}_j| - d_{EQ}) \cdot k_{ST} \tag{5.9}$$

Figure 5.2: The game flowchart representing the algorithm used to decide which *rn* will move in the t_j time window.



Source: The author

The processes P4 and P5 refer to the exchange of messages between the RNs. These messages are sent through the $C_{control}$ channel at a distance of one jump - i.e., a message is not sent back by the receiver. The message's content is exactly the sender's identification and the result of the previous process P3. P6, on the other hand, uses the data received in P5 to define its strategy - $\theta^{i,j}$.

The first question Q1 defines if there was any winning strategy in $\theta^{i,j}$. In this question, two paths are possible. In the first path (Yes), a strategy is taken as a winner; in this case, P7 is executed to perform the RN position update. This update happens according to the prediction performed in P3. In the second path (No), an equilibrium occurs - i.e., more than one RN from a subset G' have equivalent strategies, thus not meeting the restriction defined by Equation 5.1. In this context, P8 is executed. For P8, a set of two rules are applied, (i) it checks the number of UNs that the RN will attend at the new position and (ii) the amount of area gained by the RN at the new position, in this order.

The second question Q2 defines if there was a winning RN in P8, and two paths are possible. In the first path (Yes), P7 is executed. In the second path (No), a conflicting message is sent to a random RN, in process P9. This RN is then in charge of defining which strategy will be applied, in process P10. So the RN defined in P9 executes the process P7. P11 is executed by registering the RNs. Thus, by P11 new RNs can be added to the set and removed at any time during the operation. Finally, question Q3 checks if the set RNs is non-empty. If RNs is empty, then the mission is terminated. Otherwise, the algorithm continues its execution.

5.2.1 Complexity Analysis

To investigate the complexity of the proposed solution, the computational complexity was considered and the overload of the information dissemination process was also taken into account. These two aspects are analyzed separately.

1. Notice that $\Phi(rn_i, t_i)$: RN, T $\rightarrow$ {-1, 0, 1} is performed in $O(N)$ since it is characterized by the verification of the usefulness of its neighbors, a sequence of N terms. Even if these terms depend on the calculation of the variables $U(r_i,\ t_0)$ among the UAVs, it is possible to assume that these values are pre-computed before evaluation.
2. For the information dissemination procedure, the number of messages sent at $C_{control}$

is considered. To implement the dissemination of information about their context throughout the network, each RN must relay the message to any other RN. Therefore, the number of transmitted messages is N^2.

5.3 Performance Evaluation

This section presents the evaluation of the AGT-based proposal to coordinate multiple UAVs for defining their stationary locations and provide service persistence. A comprehensive set of simulation models for UAV mobility, battery use, and wireless communication protocols was designed and implemented. For the simulations, the Robot Operating System (ROS) (Quigley et al., 2009) and Gazebo were used, and different algorithms corresponding to the main approaches were compared. ROS is a framework that allows configuring the various parts of a drone to work together. To do this, a common transport layer is defined for all the software inside the drone, from sensors and actuators to decision making. Around the standard transport layer, there are tools to examine and diagnose execution results. Gazebo is a simulator that calculates body dynamics, generates sensor data, and allows interaction via a programming API and graphical interface. Furthermore, the simulator allows the definition of a mini 3D world, with obstacles and physical factors, such as wind and rain, making the simulation a more realistic process. Table 5.2 shows the parameters used in the simulations unless otherwise indicated. Each simulation lasted 20 minutes, which was considered sufficient to spread the nodes out in the environment.

The simulation then comprises a post-natural disaster scenario. The rescue teams leave from a central point, usually where the probability of rescuing lives is higher and the damage occurs in greater intensity. During the operation, the teams start moving in a specific direction to reach the other affected regions. The dynamics presented are similar to an actual situation, supposing a weather disaster in a medium-size city (10km $\times$ 10km.). The center of this region is the commercial center of this city. The rescue team starts from this location. It begins the operation, and as the group explores, it begins a process of displacement from the center to the edge of these regions. In this context, the UAVs will accompany the rescue team providing the necessary support.

Initially, the dynamics of the operation of each approach analyzed in these experiments is presented. Figure 5.3 presents an overview of the three approaches. Figure 5.3(a) uses the PSO algorithm to coordinate the UAVs. The optimization takes into account the

Table 5.2: Simulation parameters for the distributed coordination model

Simulation Parameters	Value
Scenario	
Time	20min
Number of user nodes	25
Number of relay nodes	[4, 8 and 15]
User nodes' speed	[5..10]m/s
Relay nodes' speed	20m/s
Infrastructure	
Radio	802.11g
Mode	11Mbps
Firmware	PX4
Battery	5200mAh
Distances	
Minimum distance (d_rn^{min})	50m
Maximum link length (d_rn^{max})	100m
Variables	
β	.5
γ	.1
δ	.2
ε	.3

Source: The author

global and local gains of the particles. Based on the patterns in nature, the natural solution is to form a path that leads to a solution classified as optimal by a utility function. Figure 5.3(b) presents the virtual spring method, where the method balances the push and pull forces and the solution is represented by a uniform distribution of the RNs in the environment. Figure 5.3(c), finally, presents the AGT-based approach, where, as in the virtual spring method, the objective is the uniform distribution of the RNs, but optimizing the utility function of each RN.

Then, the performance of the three solutions, varying the characteristics of the scenario, is analyzed - e.g., the number of RNs and the distribution of the UNs in the area. Figure 5.4 shows the area coverage on the x-axis and the variation in the number of RNs on the y-axis. The results are presented as follows: the first bar is the *PSOandADJUST* approach of (Kim; Lee, 2018), the second bar presents the *Stfanet* approach of (e Silva et al., 2019), the third bar presents the *spring-based* approach proposed by (Trotta et al., 2018), and finally the fourth bar presents the results of the proposed AGT-based approach.

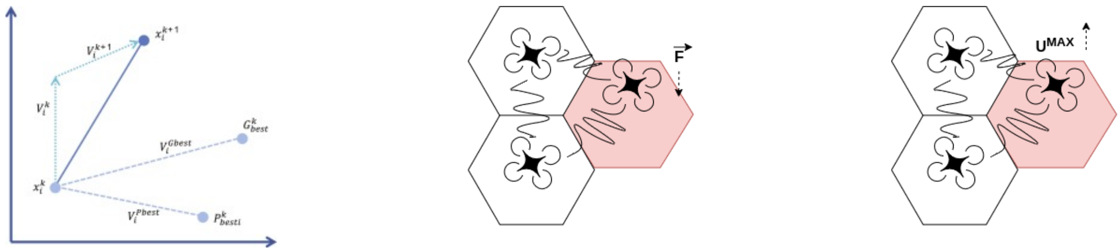
The results of Figure 5.4 take into account only the total coverage in the whole simulation, but do not consider energy restrictions. It is possible to observe that: first,

Figure 5.3: Particle update dynamics in the approaches evaluated in this chapter.

(a) G_{best}^{k} and P_{best}^{k} influencing the position of the particle x_i^{k+1}.

(b) In the spring method, $\vec{F}$ attracts the particle downwards in order to balance the particles.

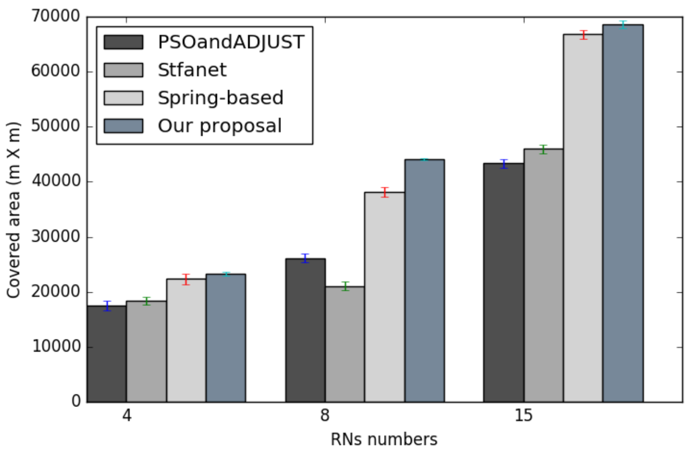
(c) AGT-based approach, U^{MAX} attracts the particle to maximize its gain.



Source: The author

the solutions based on the EC present the worst performance, as expected; second, the distributed approaches present similar performances. In other words, distributed solutions for stationary locations provide a good approach for an ideal solution. On the other hand, EC-based approaches present a worse performance for area coverage, and this behavior can be explained by the dynamics of the approach illustrated in Figure 5.3(a).

Figure 5.4: Total area coverage using 4, 8 and 15 RNs.

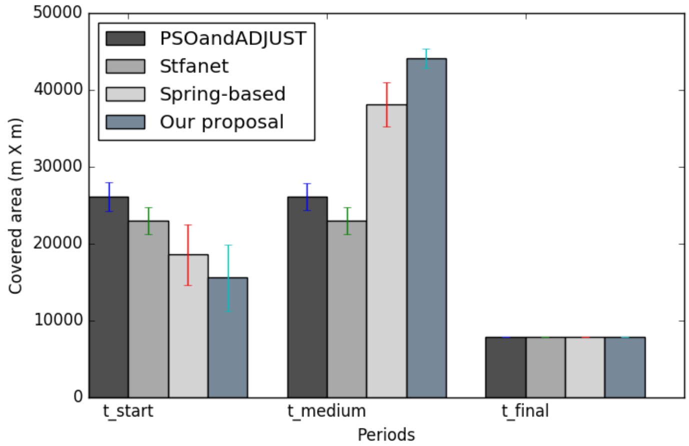


Source: The author

Figure 5.5 presents the results of area coverage taking into account the energy of the RNs. The results are presented in three different moments: t_{start} indicates the beginning of the simulation, considered as the moment when all the RNs are in movement; t_{medium} represents the moment when all approaches present their best solution in terms of area coverage; finally, t_{final} presents the solution with only 1 (one) RN in operation. Energy (re)load in UAVs is out of the scope of this current work.

Notice that: (i) for the approaches based on EC, at the moments t_{start} and t_{medium}

Figure 5.5: Total covered area with 8 RNs divided per period.



Source: The author

there is no variation in the covered area. This occurs because usually the EC methods are computed before going into operation, and each RN is allocated to the position considered the best one for that set of RNs; (ii) the distributed approaches present similar performances in terms of covered area, and the area increases during the simulation; and (iii) comparing the energy spent to reach the optimal formation for the set of RNs, the solutions based on EC present lower performance than the distributed solutions. This behavior is explained by the stability of the topology over time. The solutions using PSO present large changes in the formation at each execution of the algorithm, while the distributed approaches present smoother changes during the whole operation.

Table 5.3 presents the average number of UNs connected to the network at three different simulation times. In the time slot t_{start} the number of UNs connected to the UAV network is more significant in the PSO algorithm approaches. The behavior of the PSO approach can explain this because the algorithm calculates the stationary position before starting the operation. In the distributed approach, the stationary positions are reached over time. In the t_{medium} time slot, the proposed approach shows significant gains over the other three approaches. In the t_{final} time slot, the number of UNs connected to the UAV network is the same for all scenarios except for the last scenario, which presents five connected UNs.

Equation 5.9 is based on Hooke's law, detailed in (Trotta et al., 2018). Equation 5.10 guarantees that each RN in time slot t_j will always choose the best strategy from all possibilities. The mathematical formulation of the proposed approach is detailed in Section 5.2. For the approaches *PSOandADJUST* and *Stfanet* details can be found in

Table 5.3: Numbers of users connected to the network.

Approach	t_{start}	t_{medium}	t_{final}
4 RNs			
PSOandADJUST	6 UNs	7 UNs	4 UNs
Stfanet	7 UNs	7 UNs	4 UNs
spring-based	3 UNs	8 UNs	4 UNs
Our proposal	2 UNs	10 UNs	4 UNs
8 RNs			
PSOandADJUST	11 UNs	14 UNs	4 UNs
Stfanet	14 UNs	14 UNs	4 UNs
spring-based	3 UNs	10 UNs	4 UNs
Our proposal	3 UNs	14 UNs	4 UNs
15 RNs			
PSOandADJUST	18 UNs	19 UNs	4 UNs
Stfanet	21 UNs	20 UNs	4 UNs
spring-based	3 UNs	13 UNs	4 UNs
Our proposal	2 UNs	25 UNs	5 UNs

Source: The author

(Kim; Lee, 2018) and (e Silva et al., 2019), respectively.

$$\Phi_i^*(t_j) \tag{5.10}$$

An analysis of the cooperation between UAVs during the simulation is now performed. First, it is noticed that in all the approaches cooperation has been identified. However, a distinction is made in the way cooperation is used. As illustrated in Figure 5.3(a), the PSO-based approaches use global and local optimization methods. However, this optimization occurs in an isolated environment, not taking into account changes in the environment that occur dynamically in the real environment. In the second approach, shown in Figure 5.3(b), the virtual spring method cooperation occurs in the sense of network uniformity. Without any intelligence, the method shows effectiveness regarding area coverage. However, there is a loss of performance in the connectivity of the UNs. Finally, the proposed approach using AGT techniques, shown in Figure 5.3(c), present agent cooperation in an intelligent way, with a rigorous analysis within given performance limits. Using the virtual spring approach, it is possible to guarantee effectiveness in area coverage and, at the same time, the effectiveness in the connectivity of the UNs, thus guaranteeing the persistence of the network service taking into account the restrictions defined in Equations 5.1, 5.2, 5.3, and 5.4. The proposed cooperation model, with clear separation between ticks for calculating restrictions and ticks for decision, ensures effectiveness both in area coverage and in connectivity for a persistence service.

6 JOINT APPROACH TO COORDINATE AND TO MANAGE A UAV NETWORK

This chapter presents a joint approach for maintaining a UAV network. First, a distributed model is used for the coordination of multiple UAVs. This model uses AGT techniques - already detailed in Chapter 5 - integrated with the concept of virtual spring to coordinate the UAVs. Then a centralized model is used for managing the UAV network. The management model is based on the concept of SDN and Decision Trees - already detailed in Chapter 4.

The hybrid approach proposed in this work allows the use of each model's main advantages - distributed and centralized - to coordinate and manage the UAV network. The joint approach's main gains are reflected in the coordination model's improved efficiency and in management strategy. Also, it gives more dynamism to the coordination and management mechanisms using accurate data from the UAV network.

The rest of the chapter is structured as follows. The system model and problem formulation are described in Section 6.1. The proposed approach is presented in Section 6.2. Finally, the results and discussions are presented in Section 6.3.

6.1 System Model

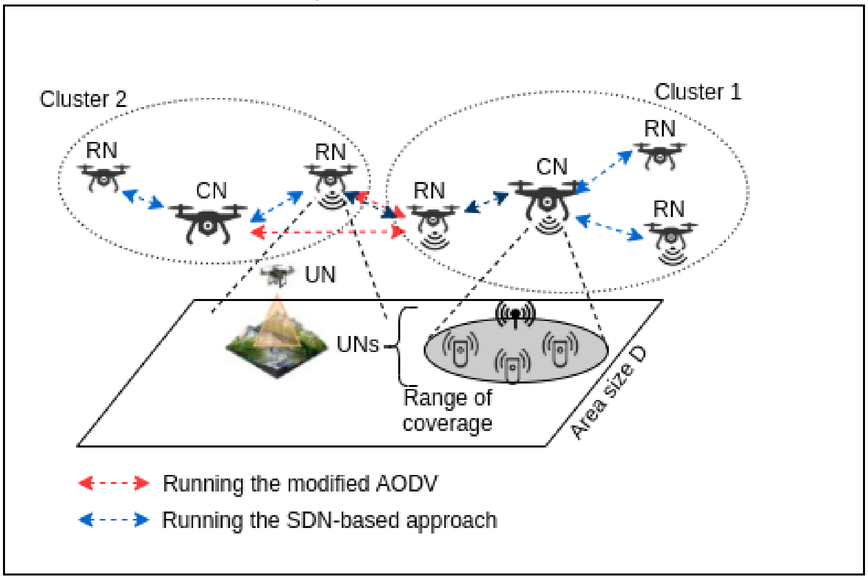
This section presents the system model and the assumptions adopted in the rest of the chapter. Figure 6.1 presents the architecture overview. The architecture is composed of three types of nodes - namely, a set of Controller Nodes (CNs), a set of Relay Nodes (RNs), and a set of User Nodes (UNs). The UNs perform an arbitrary mission - like searching for points of interest (De Moraes; De Freitas, 2018) - and, therefore, their positions are defined exclusively by them. The descriptions of these three types of nodes, as well as their internal functionalities, are presented below:

- The RNs are responsible for routing packets between UNs according to the rules specified in their routing tables and for positioning themselves in strategic locations to provide better links to connected UNs. The RNs are also responsible for sending network context packets and their operating status. All packets sent by RNs are multi-hop;
- The CNs are responsible for configuring and maintaining the routing table for the RNs of its cluster. Thus, the CN updates the routing tables whenever an RN makes

a request or a there is a need expressed by the management application to improve the network's quality. Although the CNs performs the role of the network manager, it also performs packet retransmission - i.e., it acts as RN and CN at the same time;

- The UNs are users of the network and perform an arbitrary mission, and their positions are defined according to their interests. Communication takes place through a wireless link, and the RNs are access points that allow communication between two or more different UNs.

Figure 6.1: Joint solution architecture for UAV network coordination and management formed by RNs and CNs interacting with UNs.



Source: The author

Tables 6.1 and 6.2 list all the symbols, notations, and variables used in this chapter. Their definitions and other information are listed in Chapter 5. We worked with the Coverage and Persistence Aerial Network Deployment Problem (CCPANP) defined formally in Chapter 5.

6.2 Joint Approach

The work proposed in this chapter comprises two approaches. The first approach uses AGT techniques and a spring motion-based model to perform coordination of multiple UAVs. The second approach deals with network UAV management using SDN concepts. The management model implements splitting data plane and control plane. The dynamic reconfiguration is used to implement the Decision Tree algorithm widely used in Artificial Intelligence to analyze and ensure network support according to the parameters

Table 6.1: Key notations used in this chapter

Notation	Explanation
D m^2	The total area of execution of the mission.
C_{data}	Channel intended for the transmission of data packets.
$C_{control}$	Channel intended for the transmission of control packets.
$T = \{t_0, t_1, ..., t_k\}$	Time Slotted of the Mission
d_{rn}^{max}	The maximum range for communication between UAVs.
d_{rn}^{min}	The minimum range for no collision between UAVs.
$\Phi(rn_i, t_i)$: RN, T $\rightarrow$ {-1, 0, 1}	Indicate the UAV condition in a given time interval.
$\Phi_i(t_k)$ = - 1	Indicates that RN is in the inoperable state (S_{ino}) at slot t_k.
$\Phi_i(t_k) = 0$	indicates that RN is in the flying state (S_{fly}) at slot t_k.
$\Phi_i(t_k) = 1$	Indicates that RN is in the stationary state (S_{sta}) at slot t_k.
$S = \{S_{fly}, S_{sta}, S_{ino}\}$	Set of states that an RN can assume.
FLY_{NO}	Indicates that node will change its state from S_{fly} to S_{sta}.
FLY_{OK}	Node remains in state S_{fly}.
STA_{NO}	Node attempts to fly. If all its neighbors are in state S_{sta}, then node changes its state to S_{fly}, otherwise it remains in state S_{sta}.
STA_{OK}	Node remains in state S_{sta}.
STA_{FINAL}	Node enters state S_{ino} and stops operating.
$G(p_{rn_1}, p_{rn_2}, \ldots, p_{rn_n})$	A graph that, according to the positions of the relay nodes, tells us if the user nodes can communicate with each other.
$\lambda(rn_i, rn_j)$	Indicate the distance between nodes rn_i and rn_j.
E(rn_i,t_k)	Function returns the remaining energy of rn_i at instant t_i.
ι_s	Corresponds to the energy consumption if the UAV is performing the S_{sta} action.
ϖ_s	Corresponds to the energy consumption if the UAV is performing the S_{fly} action.
$p'_i = (x'_i, y'_i, z'_i)$	The position of rn_i.
$H = h_{G(p'_1, p'_2, \ldots, p'_n)}$	Function that according to the p'_i position of rn_i defines the users that are connected to it.

Source: The author

Table 6.2: Continue key notations used in this chapter

Notation	Explanation
$R = d_{G(p'_1, p'_2, \ldots, p'_n)}$	Function that returns all possible routes for the communication of a position p'_i to $p'_j \; \forall \; p'_i, \; p'_j \in C, \; i \neq j$.
β	The importance of the variable in the probabilistic prediction process for instant t_{i+1}.
γ	The importance of the variable in the probabilistic prediction process for instant t_{i+1}.
ε	The importance of the variable in the probabilistic prediction process for instant t_{i+1}.
$C(p'_1, p'_2, \ldots, p'_n)$	Represents the graph of area covered by the set of RNs at the instant of time t_i..

Source: The author

defined for the mission. This section is divided into two subsections, namely (i) UAV network coordination, and (ii) UAV network management.

6.2.1 Distributed Coordination of Multiple UAVs

The proposal presented in this dissertation comprises the union of two algorithms - a motion algorithm based on the concept of virtual springs and a decision-making algorithm using AGT techniques. The concepts and definitions of these two algorithms are defined in Chapter 5. However, this work goes beyond and adds flow variables and network quality metrics to both the coordination and UAV network management models. In this section, the critical information on the operation and implementation of both models is highlighted. However, the details are presented in Section 5.2, except the modifications and new features that - when they exist - are explicitly indicated and detailed.

First, we present the UAVs' motion algorithm, an adaptation of the virtual spring algorithm, detailed earlier in Section 5.2. Equation 6.1 broadly defines the motion algorithm used in this work. However, this algorithm is used only in the first rounds of mission execution. From the moment a flow is performed or attempted to be performed, the movement strategy considers the quality metrics and variables of this flow to define the possible next movement to be performed.

$$|\vec{F}(rn_i, rn_j)| = -(|\vec{x}_{rn_i} - \vec{x}_{rn_j}| - d_{EQ}) \cdot k_{ST} \tag{6.1}$$

From the moment a flow is initiated in the UAV network, Equation 6.1 is adapted to take into account the following parameters:

1. **Flow Variables (FV)** are the flow counters that are implemented in each RN and are not shared to its neighbors. These counters are: (i) average number of packets transmitted to its peer, (ii) average number of packets discarded due to buffer overflow, and (iii) average number of packets retransmitted; and
2. **Metric Quality (MQ)** are the metrics related to each transmission and take into account the data provided by the network management model. In this work, we use the metrics proposed by Ferguson and Huston (1998): (i) Delay; (ii) Variation of delay (jitter); and (iii) Reliability.

Equation 6.2 defines the adapted virtual spring algorithm. A virtual spring force $\vec{F}(rn_i, rn_j)$ acts between each pair of UAVs (rn_i, rn_j) located at a distance of one jump, that is, that can exchange messages directly. The intensity of $\vec{F}(rn_i, rn_j)$ is calculated by the position and amplitude of the UAVs according to Hooke's law. Note that the adaptations in the algorithm are limited to the parameters $\vec{x}_{rn_i}$, $\vec{x}_{rn_j}$, and k_{ST}.

The current distance from rn_i gives the spring displacement to rn_j and the length of the spring equilibrium d_{EQ}. In this case, the distance d_{EQ} among the nodes should be appropriate for having them positioned adequately according to hexagonal patterns for optimal scenario coverage. The force is attractive when the distance among nodes is larger than d_{EQ} and repulsive otherwise. The positions of the RNs $\vec{x}'_{rn_i}$ and $\vec{x}'_{rn_j}$ are the original positions of the RNs if the sum of the FV counters is less than 0. Otherwise, the positions of the RNs $\vec{x}'_{rn_i}$ and $\vec{x}'_{rn_j}$ are replaced by virtual values so that the result of the equation $\lambda(rn_i, rn_j)$ equals d_{rn}^{max}. This will make the force attractive, consequently with the UAVs closer together the transmission will improve. The stiffness of the spring k'_{ST} is weaker if the MQ is considered excellent or optimal and stronger otherwise. The set value follows the patterns of Hooke's law.

$$|\vec{F}(rn_i, rn_j)| = -(|\vec{x}'_{rn_i} - \vec{x}'_{rn_j}| - d_{EQ}) \cdot k'_{ST} \tag{6.2}$$

With the proposed modification the algorithm tends to approximate the nodes when a packet loss occurs and ensures that one of the main problems identified in the literature and presented in Chapter 2, Section 2.2.3 (**Package delivery problems**) is addressed in the proposal. Also, by taking MQ into account, we avoid abrupt movements on UAVs' transmitting streams, since this movement impacts the quality of the transmission.

Table 6.3 defines the set of game strategies. These strategies are used to define which RNs will move, respecting the constraints defined in Section 5.1. The detailed description of each strategy and the algorithm's operation are presented in Section 5.2 and maintained in this proposal.

Table 6.3: General Game Description.

S	Strategy	A	U
s_{fly}	$(1-G_F^{i,j})$	FLY_{OK}	$u^{i,j}(FLY_{OK})$
s_{fly}	$G_F^{i,j}$	FLY_{NO}	$u^{i,j}(FLY_{NO})$
s_{sta}	$(1-G_S^{i,j})$	STA_{OK}	$u^{i,j}(STA_{OK})$
s_{sta}	$G_S^{i,j}$	STA_{NO}	$u^{i,j}(STA_{NO})$
s_{sta}	$(G_S^{i,j}-1)$	STA_{FINAL}	$u^{i,j}(STA_{FINAL})$

Source: The author

6.2.2 Centralized Management of a UAV Network

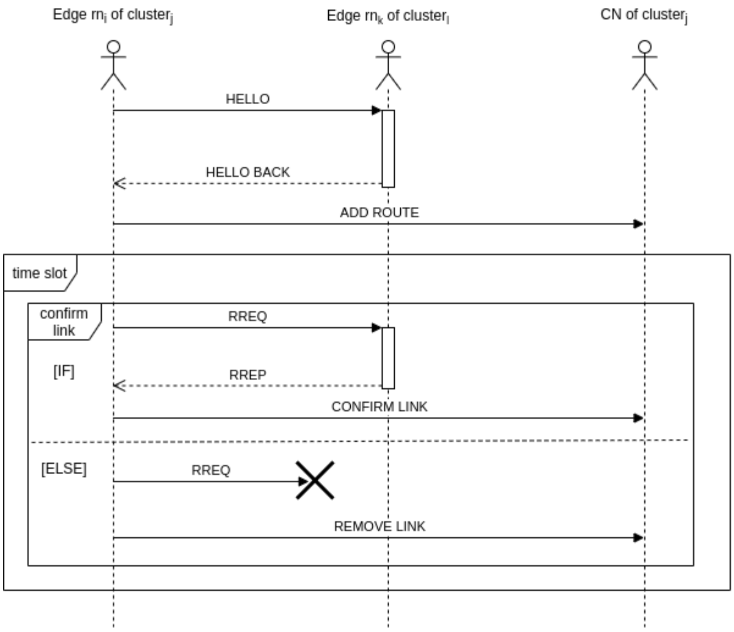
The management system uses SDN techniques, and this approach was proposed earlier in Section 4.2.2. However, unlike the architecture presented in Chapter 4, this architecture allows more than one CN in the UAV network. The proposal is consistent with the limited resources of a UAV. Just as the distributed model is proposed to decrease the processing load on a single UAV, the management model distributes the UAV network management processing among a few UAVs.

The proposal then uses a hybrid management model that divides the UAV network into sub-clusters. Each cluster has a CN responsible for managing the network intelligently and efficiently. Reactively reacting to changes in the network, the advantage of having a central network controller ensures dynamism in the network, making the routing rules reflect the current scenario of the available UAV network. This also allows a more robust and centralized control for applying security rules and identifying intruders and attacks on the UAV network.

The edge RNs - that is, the RNs located on the boundaries between the clusters - use a strategy that is similar to the AODV algorithm. However, we limit AODV messages to route discovery and route confirmation. The adopted strategy aims to avoid BSP while at the same time not limiting the amount of UAVs. Also, it avoids the bottleneck of processing route requests and context updates.

The execution flow of the adapted AODV algorithm is shown by Figure 6.2. After obtaining the information, the edge RNs forward it to the CN of the cluster. The first phase of the algorithm performs a "HELLO" message to its neighbor - the message is not retransmitted. Next, the neighbor that does not belong to the sender's cluster responds to the "HELLO BACK" message, then a route for intra-cluster communication is discovered. Next, the new route data is forwarded to the controller with the new route and cluster identification. At a time interval t, the RREP and RREQ messages are exchanged to check if the route is still active.

Figure 6.2: Modified AODV protocol workflow.



Source: The author

6.3 Performance Evaluation

This section presents the evaluation of the joint proposal for the coordination and management of a UAV network. A comprehensive set of simulation models for UAV mobility, battery usage, and wireless communication protocols were designed and implemented. For the simulations, the Robot Operating System (ROS) (Quigley et al., 2009) was used to run the coordination model. To evaluate the network management model, the mobile multimedia wireless sensor network (M3WSN) OMNet ++ framework (Rosário et al., 2013) was used.

Table 6.4 shows the parameters used in the simulation. A set of 50 independent simulation runs was conducted, varying the UNs' movements and transmissions. As evaluation metrics, packet loss, latency, and connectivity index were assessed, and we present the mean value from the 50 runs. Each UN transmits a data packet to a random destination in intervals that varies from 100ms to 200ms. The simulation parameters were also set to allow wireless channel temporal variations, link asymmetry, and irregular radio ranges, as expected in a real scenario.

Table 6.4: Simulation parameters for the joint approach to UAV network coordination and management

Simulation Parameters	Value
Scenario	
Time	20min
Number of user nodes	25
Number of relay nodes	[4, 8, 15 and 35]
User nodes' speed	[5..10]m/s
Relay nodes' speed	20m/s
Infrastructure	
Radio	802.11g
Mode	11Mbps
Firmware	PX4
Battery	5200mAh
Distances	
Minimum distance ($d_r n^{min}$)	50m
Maximum link length ($d_r n^{max}$)	100m
Variables	
β	.5
γ	.1
δ	.2
ε	.3

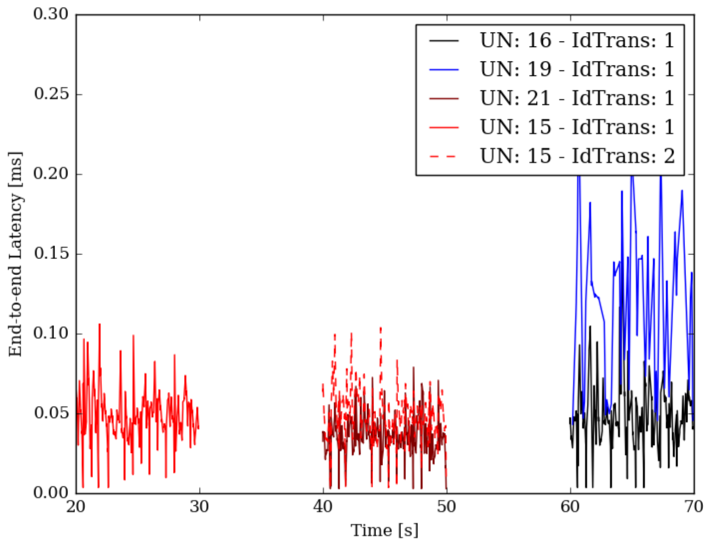
Source: The author

The UNs can move from 5m/s to 10m/s, while the RNs and the CNs are considered to be able to move at a maximum speed of 20m/s. The simulation was performed for 20 minutes long, which was considered enough to have the nodes sufficiently spread through the environment, as they start at the center of the scenario. In the simulation, UAVs rely on the CSMA/CA MAC protocol without using RTS/CTS messages and retransmissions. In the buffer overflow, the UAVs consider a drop tail mechanism to drop packets. The nodes are set to transmit their contextual information to the controller in intervals of 250ms.

Figure 6.3 presents the latency in video transmission over time. The X-axis shows time in seconds, and the Y-axis shows latency. The data are presented in three-time slots. Here we identify as tp_1 the time period from 20s to 30s, tp_2 the time period from 40s to 50s, and finally tp_3 the time period from 60s to 70s. At the period tp_1, we have only one transmission and latency between 0.00 to 0.10. At the period tp_2, we have three transmissions occurring at the same time. We can observe in the graphic that the data presented at tp_1 and tp_2 present an identical behavior. This behavior indicates that the management system presents the expected behavior regarding traffic concurrency management.

However, we observed a different behavior during period tp_3. This occurred because the application installed on the "UN: 19" is a mutant application that sends a very large amount of packets (from 5 to 6 times the amount sent normally), as in this particular case we wanted to evaluate the behavior of the network when overloading the transmission. We observed that the abnormal traffic transmitted by "UN: 19" did not affect the concurrent traffic. The graph shows that during tp_3 the traffic of the transmission "UN: 19" presents a latency between 0.05 and 0.20 ms while the traffic "UN: 16" presents the same behavior presented by the other transmissions during periods tp_1 and tp_2.

Figure 6.3: Latency over time in video packet transmission using the joint proposal.

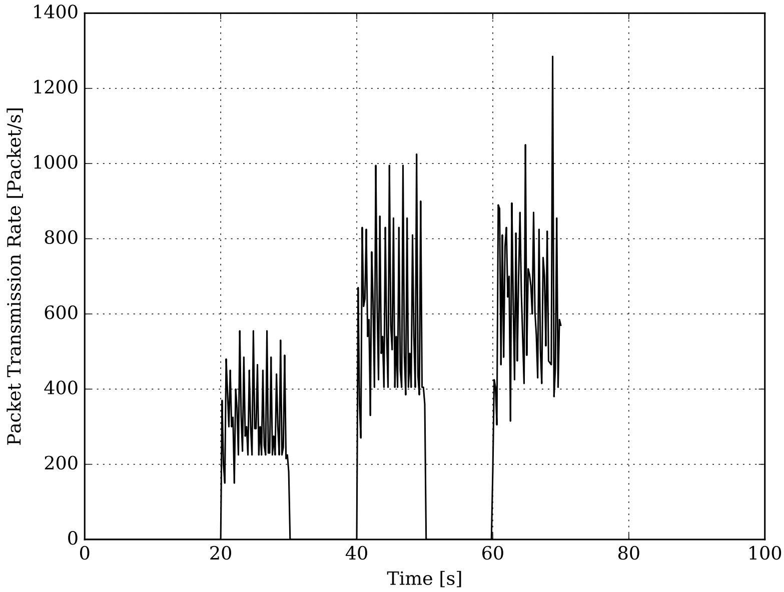


Source: The author

As in the previous figure, in the next two figures (Figure 6.4 and Figure 6.5), the time presented on the X-axis is presented in three intervals to facilitate the discussion of the results. We identify as tp_1 the time period from 20s to 30s, tp_2 the time period from 40s to 50s, and finally tp_3 the time period from 60s to 70s. Figure 6.4 shows the number of packets transmitted per second. In contrast, Figure 6.5 shows the rate of packets received by the receiving application. We identify as received packets only the packets that reached the application without any problems (corrupted packets during transmission, data loss, or any other transmission problem are not considered as delivered packets even if they have reached their destination).

We observe in Figure 6.5 that during time periods tp_1 and tp_2, the delivery rate

Figure 6.4: The average number of packets transmitted in relation to the simulation time.

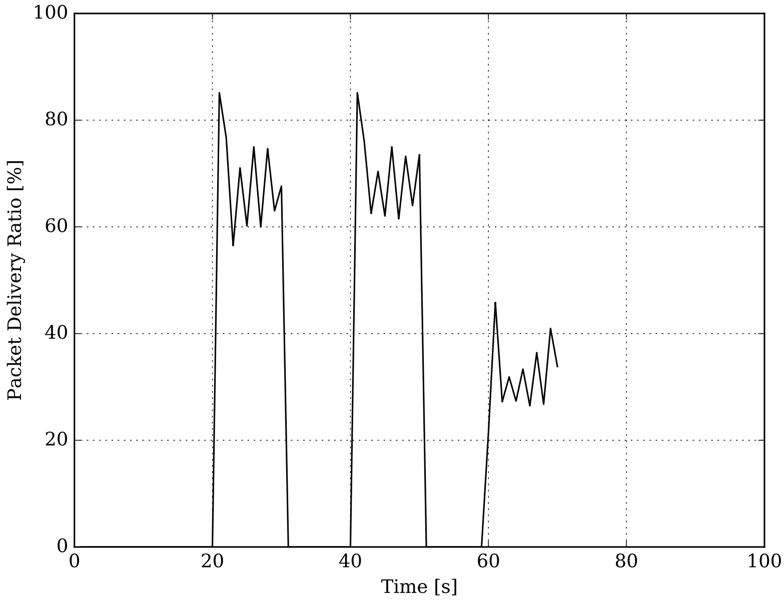


Source: The author

is similar, ranging between 60 and 80 percent. However, during time period tp_3, this delivery rate drops by half compared to time periods tp_1 and tp_2, and this is an isolated case and occurred due to the mutating application that started in time period tp_3. As we opted for the drop tail mechanism, the excess packets in the buffer on channel C_{data} are deleted without applying any rules.

The connectivity can be measured as the percentage of time during which all the UNs are able to communicate with each other. Having traced the routing tables' rules and nodes' positions through the simulation, it was possible to measure the period of time during which all the UNs were virtually connected - even if they were not in fact communicating. To present the results, we split the simulation period into three-time slots, where *sp* is the starting point of the simulation that comprises the time period from 0s to 60s, fm is the final moment of the simulation that comprises the last 40s of the simulation, and *cm* corresponds to the rest of the time. This is important to perform a more coherent analysis, as the virtual spring-based approach tends to form a convex line in graphic of area coverage. As presented in Figure 6.6, the data presented in *sp* for 4, 8, and 15 RNs have more or less the same percentage of connected users, close to 40 percent, while in the simulations with 35 RNs 53 percent of users were already connected. This can be explained by the approach that was proposed, where the division of RNs into clusters allows more RNs to move simultaneously and this makes the coverage of the area to be obtained faster, and consequently more users can be served. The *cm* time interval

Figure 6.5: Percentage of packets received by the application in relation to time, only packets received by the application are considered.

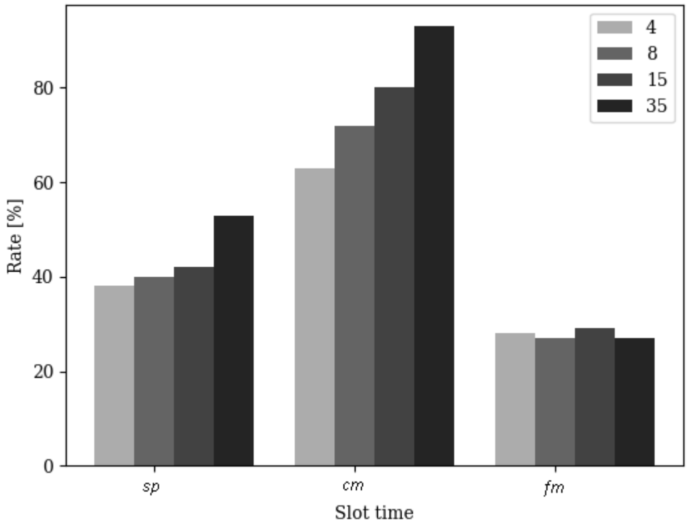


Source: The author

shows that the simulations with 35 RNs keep about 30 percent more users connected than the simulations with 4 RNs. This is explained by the fact that the more RNs present in the simulations the more area will be covered, thus keeping users connected longer. Finally, the fm time interval does not present much variation since this is the final moment of simulation and all simulations in this interval have the same amount of RNs. This occurs because, when an RN fully consumes its battery charge, it is neither replaced nor recharged.

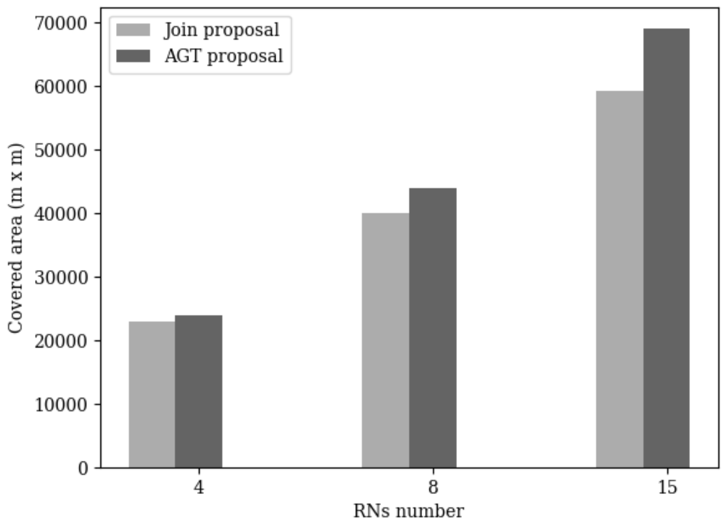
Figure 6.7 takes into account only the full coverage throughout the simulation. It can be seen that the solution proposed in this paper has a lower performance than the previous proposal presented in Chapter 5. This can be explained by the introduction of network variables and quality of service metrics in the solution. We point out that the proposal presented in Chapter 5 does not consider network quality issues, i.e., coverage tends to limit the allowed range. However, in this proposal in this chapter, we consider network issues for network coordination, which tends to decrease the total area coverage while maintaining a balance between area coverage and service quality of the UAV network.

Figure 6.6: Percentage of connected users in three-time slots.



Source: The author

Figure 6.7: Area covered by RNs during the mission operation.



Source: The author

7 CONCLUDING REMARKS

In this dissertation, we presented a joint proposal for autonomous coordination and intelligent management of a Unmanned Aerial Vehicle (UAV) network. Algorithmic Game Theory (AGT) and Software-Defined Network (SDN) techniques are used. In addition, an application inspired by Artificial Intelligence (AI) mechanisms was developed to efficiently manage traffic on the network. In this chapter, the conclusions are presented, future works are discussed, and finally, the publications and submissions resulting from this work are indicated.

7.1 Conclusions

This dissertation proposes an efficient approach for managing and coordinating a UAV network, evaluating it in a post-disaster scenario. First, in Chapter 4, we propose an improvement in the Particle Swarm Optimization (PSO) coordination algorithm's cost function to ensure the construction of a manageable UAV network. Also, a solution for tuning and node allocation for the formed topology is presented. Then a management model using decision tree principles is proposed. The proposed solution shows significant gains over a state-of-the-art approach found in the literature, namely the STFANET proposal. The gains are observed in the Quality of Service (QoS) metrics defined by Ferguson and Huston (1998) - namely, (i) end-to-end delay; (ii) jitter; and (iii) packet loss - which are defined as the validation metrics of the proposed approach.

Next, an evaluation of the use of SDN techniques in the UAV network is performed. The obtained results demonstrated the proposed solution's efficiency up to a 17.5 percent increase in packet delivery rate compared to the Ad-hoc On-Demand Distance Vector (AODV) protocol. The end-to-end latency of data packets was up to 10 ms lower in the SDN approach than using the AODV protocol. Although the SDN approach exhibited a higher proportion of topology maintenance packets at topology formation initialization, packet transmissions stabilized over time. In turn, the AODV management protocol increases the number of these packets considerably. Based on the results obtained and a detailed analysis of SDN and AODV resources, the SDN approach has proven to manage a network structure more efficiently in post-disaster operations. The efficient use of network resources is strongly linked to mission efficiency and success.

In Chapter 5 a model is proposed for coordinating a UAV network that addresses both area coverage and network connectivity using the AGT technique. The proposed model uses a distributed solution as well as a cooperation strategy of the agents represented by the UAVs that are members of the team. The simulation results show that the solution using AGT outperforms the compared solutions, which are based on Evolutionary Computing (EC), in area coverage. Regarding connectivity, the proposed solution shows better results than the virtual spring-based solution. We highlight that even the total area covered in the proposed approach takes a reasonable time to converge to the optimum. The result is considered satisfactory because the EC-based solutions need a pre-processing before the beginning of the mission for the allocation of Relay Nodes (RNs) that was not considered in the experiments. In this context, the proposed solution is optimal in terms of area coverage and connectivity according to simulation data.

Finally, in Chapter 6 a hybrid approach to UAV network coordination and management is proposed. The proposal adopts a coordination model similar to the one presented in Chapter 5. However, it adopts QoS metrics and UAV network flow metrics to define the positions of RNs in a distributed manner using AGT concepts. The management is performed with the approach proposed in Chapter 4. However, the UAV network is divided into clusters, allowing more than one Controller Node (CN) to be present in the network. Also, the AODV algorithm is adapted to intra-cluster route management. The simulation results proved the efficiency in terms of coordination and area coverage. And the network management data demonstrated efficiency, particularly regarding the quality metrics defined by Ferguson and Huston (1998) and analyzed in Chapter 4.

7.2 Future Works

We plan to include new features to the coordination and management model and continue investigating the model's application in new scenarios, mainly scenarios outside military and post-disaster applications. Some topics for further study and development are:

1. Investigate the Quality of Experience (QoE) of users of the UAV network.
   Outline – The QoE investigation was not part of the scope of this work. However, a line of investigation on this point can be an interesting work. Even analyzing the QoS level (part of the scope of this work), it is not possible to guarantee the same level of quality in terms of QoE. An initial starting point to be investigated is

the behavior of the proposed solution in applications with different requirements, measuring the QoE parameters and network saturation.

2. Investigate the proposal's application in the smart city scenario, aimed at decreasing the application of unnecessary resources by the connectivity service providers.
   Outline – This work was investigated in a post-disaster scenario. Still, the results demonstrate efficiency in traffic management and point to a solution for traffic problems (congestion) in different environments, such as smart cities and temporary events like a concert, which do not justify deploying a definitive infrastructure.
3. Investigate programmable suite mechanisms in UAVs.
   Outline – The use of a programmable suite allows the definition of the most appropriate protocols for each mission, meeting the critical level requirements locally, so the RN can define strategies without the need to consult the CN. As an example, a robot that discovers a buried survivor can give priority to this package, so the RN can handle this event without the need to consult the CN.
4. Investigate AI mechanisms at the routing and network management layer with the addition of In-Band Telemetry (INT) (Karaagac; Poorter; Hoebeke, 2019) capabilities to data traffic.
   Outline – By taking problem-solving to the application level, a range of opportunities opens up for investigation and improvement of traffic and management. The use of AI can significantly assist in decision-making and rapid learning of network behavior. The inclusion of INT can further decrease the control packet traffic since the control data is transmitted as an extension in the data packet header and gives the actual traffic situation since the control data starts to travel together with the data packets and use the same channel.
5. Investigate the proposal's use in conjunction with 5G infrastructure and gains and costs of its use as edge servers.
   Outline – As smart cities, the UAV network can be used as an on-demand mobile edge server to improve traffic in the final infrastructure when an abnormal event occurs.

7.3 Publications and Submissions

The work performed during the development of this MSc thesis provided the basis for the papers listed below.

1. SILVA, A. A. S.; E SILVA, T. D.; WAGNER, F. R. and FREITAS, E. P. **An efficient SDN-based approach to coordinate and manage a UAV network in disaster response systems**. In: Mobile Networks and Applications. Springer. (Submitted)
   Overview – This paper considers the problem of coordinating multiple UAVs to form a network topology and managing the formed topology using SDN techniques. Compared to previous work, the proposed approach presents a utility function with multiple objectives, namely, to increase the area of coverage and the number of neighbors of the RNs. At the same time, three restrictions are set to limit distances, ensure network availability, and reduce signal interference. Also, a new topology management strategy based on a behavior tree is proposed. In addition, an analysis of gains in using the SDN-based approach in a UAV network was performed.
2. SILVA, A. A. S.; SILVA, F. J. M.; SCHOUERY, R. C. S.; FREITAS, E. P. and WAGNER, F. R. **Ensuring stationary location and persistent network service using Algorithmic Game Theory techniques for coordination of multiple UAVs**. In: Journal to define. (In preparation)
   Overview – This paper considers the problem of the stationary location of multiple UAVs to guarantee a persistent network service. With this purpose, it proposes a distributed approach using techniques from the AGT. In comparison with previous works, the approach presented in this paper is different in two aspects: (i) A distributed approach with a joint solution to the problem of stationary location of multiple UAVs and the desired coverage rate; and (ii) Techniques to encourage the cooperation of agents with a rigorous analysis of network quality data within certain performance limits.
   Notes – The Paper was not accepted in the **International Conference on Intelligent Robots and Systems (IROS) 2020**. The reviewers' comments have been taken into consideration in this new version.
3. SILVA, A. A. S.; FREITAS, E. P. and WAGNER, F. R. **A hybrid approach for managing and coordinating a UAV network intelligently and efficiently**. In: Journal to define. (In preparation)
   Overview – This paper uses a hybrid approach that allows the use of each model's

main advantages - distributed and centralized - to coordinate and manage the UAV network. The joint approach's main gains are reflected in the coordination model's improved efficiency and in management strategy. Also, it gives more dynamism to the coordination and management mechanisms using accurate data from the UAV network.

4. SILVA, A. A. S.; E SILVA, T. D.; WAGNER, F. R. and FREITAS, E. P. **Trade-offs in the Topology Management of Autonomous SDN-based UAV Networks for Operation in Post Disaster Scenarios**. In: Computer Communications. Springer. (Not accepted)
   Overview – This paper proposes an efficiency evaluation of an SDN approach compared to the AODV protocol in a UAV network. For this purpose a PSO based coordination framework is used. This study targeted the post-disaster scenario, using UAVs as an infrastructure capable of providing communication links to ground users.
   Notes – The paper was not accepted and the direction of research has changed. The insights from this article were relevant for the development of the paper **An efficient SDN-based approach to coordinate and manage a UAV network in disaster response systems**.

The following papers have been published additionally:

1. BASSO, M.; SILVA, A. A. S.; VIZZOTTO, M. R.; CORRÊA, M. S. C. and FREITAS, E. P. **A Distributed Task Allocation Protocol for Cooperative Multi-UAV Search and Rescue Systems**. In: International Conference on Unmanned Aircraft Systems (ICUAS) 2021. (Accepted)
   Overview – This paper proposes a system composed of embedded hardware and a high-level communication protocol that serves as a basis for identifying, distributing, and allocating tasks in a simple and distributed way to be used by groups of UAVs. The setup is configured with two types of UAVs - namely, searchers (search for new tasks) and workers (execution of tasks). Also, a set of nine simulation experiments covering three different setups were performed. Then the proposal is evaluated by two sets of field experiments with real vehicles.
   Notes – The paper was developed in partnership with members of the Control Systems, Automation and Robotics Laboratory (LASCAR of Portuguese *Laboratório de Sistemas de Controle, Automação e Robótica*) of Graduate Program in Electrical

Engineering of UFRGS during the dissertation period.

2. CHEIRAN, J. F.; ; TORRES, L. A.; SILVA, A. A. S.; DE SOUZA, G. A.; NEDEL, L. P.; MACIEL, A. and BARONE, D. A. **Comparing Physical and Immersive VR Prototypes for Evaluation of an Industrial System User Interface**. In: Computer Graphics International Conference (pp. 3-15). Springer, Cham., 2020.
   Overview – This paper conducts a study on the use of Virtual Reality (VR) environments for testing in human-hazardous or resource-intensive environments. The main objective is to assess the feasibility of carrying out studies on user-based evaluation in industrial interactive systems through immersive VR simulation. To achieve this, we compared user assessment with a conventional prototype of an industrial system with its immersive VR simulation. We performed within-subjects user testing in both the physical and the VR setups and collected (i) experimenters' observations on usability issues and (ii) subjective and objective measures of 16 participants. Subjective measures were taken using standardized questionnaires and objective measures by logging the elapsed time to fulfill task scenarios.
   Notes – The paper was published as a result of work done in a project "Annelida" developed at the Institute of Informatics of UFRGS during the dissertation period.

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APPENDIX A — EXTENDED ABSTRACT IN PORTUGUESE (*RESUMO ESTENDIDO EM PORTUGUÊS*)

Este apêndice apresenta de forma resumida essa dissertação de mestrado, que se intitula "Uma abordagem conjunta para garantir a localização estacionária e o serviço de rede de VANTs persistente".

A.1 Introdução

Nos últimos 30 anos, houve um aumento nas perdas de vidas e materiais causadas por desastres - por exemplo, geofísicos, hidrológicos, climatológicos e meteorológicos - na ordem de 100-150 por cento (Erdelj et al., 2017). Assim, muitos esforços foram feitos para agir no cenário pós-desastre de modo que as regiões afetadas possam reagir a tempo e avaliar os danos de forma rápida e eficiente, resolver rupturas, restaurar a normalidade e, o mais importante, salvar vidas. Neste contexto, o uso de múltiplos veículos aéreos não tripulados (VANTs) tem sido cada vez mais considerado.

Os recursos excepcionais dos VANTs, incluindo mobilidade, dinamismo, implantação sem esforço, atitude adaptativa, agilidade, adaptabilidade e avaliação eficaz das funções do mundo real a qualquer hora e em qualquer lugar (Shakeri et al., 2019), têm demonstrado eficiência em sua implantação como estações base voadoras no cenário pós-desastre. Assim, els podem desempenhar um papel central no fornecimento de serviços de recuperação de rede, especialmente nas primeiras 72 horas após a ocorrência do desastre, que são o período mais crítico (Ochoa; Santos, 2015).

Por um lado, a tendência de miniaturização de sistemas microeletromecânicos e o desenvolvimento de sistemas embarcados deu origem a vários dispositivos tecnológicos para dar suporte às equipes de resgate (Bekmezci; Sahingoz; Temel, 2013), exigindo cada vez mais interação humano-robô, robô-robô e humano-humano (Murphy, 2012). Por outro lado, as restrições operacionais devido às limitações de recursos dos VANTs exigem cada vez mais um uso mais leve de recursos computacionais (Mahmoud et al., 2016), tornando essencial os esforços para desenvolver algoritmos eficientes para o trabalho cooperativo.

Este trabalho estende o problema conhecido como "Problema de implantação de rede aérea de cobertura e persistência" (CCPANP, do Inglês *Coverage and Persistence*

Aerial Network Deployment Problem), que é descrito como um algoritmo de controle que garante que múltiplos VANTs possam sustentar uma formação específica enquanto viajam em uma trajetória generalizada - ou seja, não necessariamente linear - e simultaneamente evitar colisões. Além disso, os VANTs devem permanecer conectados durante todo o período de operação (Shakeri et al., 2019). Em outras palavras, a coordenação de múltiplos VANTs com persistência de serviço é uma solução que visa otimizar a mobilidade, minimizar o consumo de energia mecânica, maximizar o tempo de vôo e evitar colisões entre os VANTs sem perder a conexão.

Neste trabalho, é apresentada uma solução para coordenar múltiplos VANTs para localização de posição estacionária usando um modelo distribuído e gerenciamento centralizado da rede de VANTs para fornecer serviço de rede persistente em um cenário pós-desastre.

A.1.1 Objetivos

O principal objetivo deste trabalho é a proposta de uma solução totalmente autônoma para a coordenação de múltiplos VANTs para posições estacionárias, bem como um mecanismo eficiente de gerenciamento da infraestrutura de rede de VANTs formada.

Além do objetivo principal, existem outros objetivos, que são:

- Revisão da literatura sobre a adoção do paradigma das Redes Definidas por Software (SDN do Inglês *Software-defined networking*) em redes móveis com ênfase em redes de VANTs, bem como a avaliação dos ganhos do SDN sobre o protocolo mais utilizado para o contexto em estudo, nomeadamente uso de múltiplos VANTs para fornecer comunicação no cenário de pós-desastre;
- Revisão da literatura sobre métodos e técnicas para coordenar múltiplos VANTs para posições estacionárias;
- Análise de técnicas e métodos para o gerenciamento eficiente de recursos em uma rede de VANTs;
- Mapeamento dos principais problemas de gerenciamento em uma rede móvel dinâmica, em particular, uma rede de VANTs.

A.1.2 Proposta de Pesquisa e Contribuições

Este trabalho propõe uma solução para coordenar múltiplos VANTs para localização de posição estacionária usando um modelo distribuído e gerenciamento centralizado para a rede de VANTs. A abordagem proposta usa dois algoritmos para coordenar os múltiplos VANTs. O primeiro algoritmo calcula as posições usando um conceito de molas virtuais, e o segundo algoritmo usa técnicas da Teoria Algorítmica de Jogos (AGT do Inglês *Algorithmic Game Theory*) para tomada de decisão inteligente. O gerenciamento da rede de VANTs é baseado nos princípios de SDN, e um aplicativo que usa técnicas de árvore de decisão é usado como mecanismo robusto para garantir a persistência do serviço. O modelo de gerenciamento divide a rede em grupos para não sobrecarregar o Nó Controlador (CN) e evitar gargalos na rede de VANTs.

Até onde sabemos, nenhuma solução aborda o problema da cobertura estacionária de VANTs em um modelo que garante (i) conformidade com as métricas de cobertura definidas para a missão e (ii) a conectividade da topologia de rede formada, maximizando o serviço persistente necessário. Assim, além de abordar os temas (i) e (ii), nosso modelo oferece coordenação distribuída e inteligência cooperativa para a tomada de decisões. A abordagem é composta de n VANTs, chamados Nó de Retrasmissão (RN), para atender x usuários, chamados Nó Usuário (UN), fornecendo as seguintes contribuições de pesquisa:

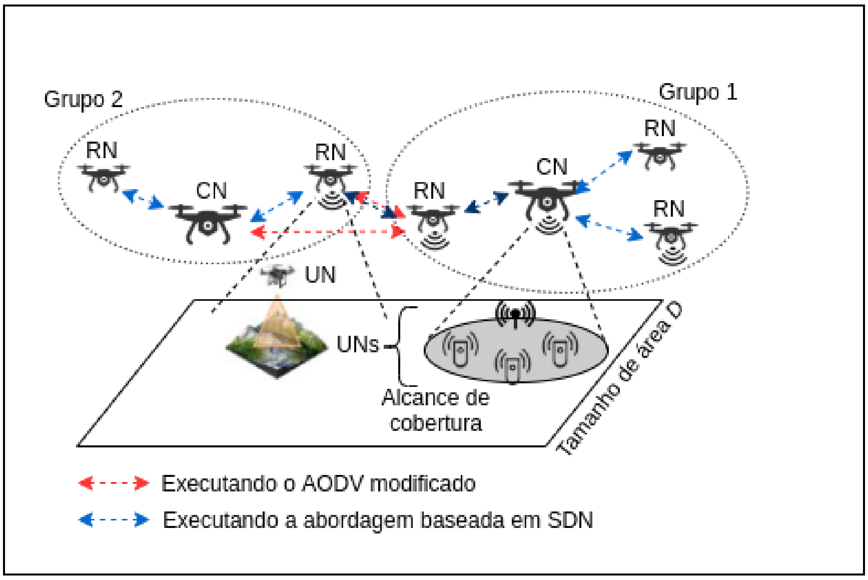
1. Uma abordagem com uma solução conjunta para o problema da localização estacionária de múltiplos VANTs para uma taxa de cobertura desejada;
2. Uma estratégia para incentivar a cooperação dos agentes com uma análise rigorosa dentro de determinados limites de atuação;
3. Gerenciamento robusto e estratégico da rede de VANTs usando os princípios de SDN.

A.2 Arquitetura

A Figura A.1 apresenta a visão geral da arquitetura. A arquitetura é composta por três tipos de nós - a saber, um conjunto de CNs, um conjunto de RNs e um conjunto de UNs. Os UNs desempenham uma missão arbitrária - como procurar pontos de interesse (De Moraes; De Freitas, 2018) - e, portanto, suas posições são definidas exclusivamente por eles. As descrições desses três tipos de nós, bem como suas funcionalidades internas, são apresentadas a seguir:

- Os RNs são responsáveis por rotear pacotes entre UNs de acordo com as regras especificadas em suas tabelas de roteamento e por se posicionarem em localizações estratégicas para fornecer melhores links para os UNs conectados. Os RNs também são responsáveis por enviar pacotes de contexto de rede e seu status operacional. Todos os pacotes enviados pelos RNs são *multi-hop*;
- Os CNs são responsáveis por configurar e manter a tabela de roteamento para os RNs de seu grupo. Assim, o CN atualiza as tabelas de roteamento sempre que um RN faz uma solicitação ou há uma necessidade expressa pelo aplicativo de gerenciamento para melhorar a qualidade da rede. Embora o CN desempenhe a função de gerenciador de rede, ele também executa a retransmissão de pacotes - ou seja, ele atua como RN e CN ao mesmo tempo;
- Os UNs são usuários da rede e realizam uma missão arbitrária, e suas posições são definidas de acordo com seus interesses. A comunicação ocorre através de um *link* sem fio, e os RNs são pontos de acesso que permitem a comunicação entre dois ou mais UNs diferentes.

Figure A.1: *Caption in Portuguese* - Arquitetura de solução conjunta para coordenação e gerenciamento de rede de VANTs formada por RNs e CNs interagindo com UNs.



Source: O autor

A.3 Conclusões

Este trabalho apresenta uma abordagem eficiente para gerenciar e coordenar uma rede de VANTs, avaliando-a em um cenário pós-desastre, com o objetivo de fornecer serviço de rede persistente, utilizando múltiplos VANTs. A solução proposta apresenta ganhos significativos em relação às abordagens do estado da arte analisadas. Os ganhos são observados nas métricas Qualidade de Serviços (QoS) definidas por Ferguson and Huston (1998) - a saber, (i) atraso de ponta a ponta; (ii) jitter; e (iii) perda de pacotes - que são definidas como as métricas de validação da abordagem proposta.

Na avaliação dos ganhos da abordagem proposta baseada em SDN, comparando-a com o protocolo *Ad-hoc On-Demand Distance Vector* (AODV) em uma rede de VANTs, alcançamos uma eficiência na solução proposta em até 17,5 por cento de aumento na taxa de entrega de pacotes. A latência ponta a ponta dos pacotes de dados e até 10 ms menor na abordagem baseada em SDN. Embora a abordagem baseada em SDN exibiu uma proporção maior de pacotes de manutenção de topologia na inicialização da rede, as transmissões de pacotes se estabilizaram com o tempo. Por sua vez, o protocolo de gerenciamento AODV aumenta consideravelmente o número desses pacotes no decorrer da operação.

O modelo para coordenar os múltiplos VANTs usando técnicas da AGT mostrou ganhos significativos quando comparado com as soluções baseadas na Computação Evolutiva (CE), principalmente na cobertura de área. Em relação à conectividade, a solução proposta apresenta melhores resultados do que a solução baseada em molas virtuais. Ressaltamos que mesmo a área total coberta na abordagem proposta leva um tempo razoável para convergir para o ótimo. O resultado é considerado satisfatório porque as soluções baseadas em CE precisam de um pré-processamento antes do início da missão para a alocação dos RNs que não foi considerado nos experimentos.