الجمهورية الجزَائِرية الديمقرَاطية الشعبية
PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
وزَارة التعليم العَالي و البحث العلمي
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
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FACULTY OF SCIENCES
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Field : Mathematics and Computer Science
Option : Computer Science
Specialization : Systems and Computer Science Networks

Dissertation Submitted in Partial fulfillment of the requirements for the Master degree in Computer Science

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THEME

Multicast Routing in Swarm of UAVs

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2020

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Domaine : Mathématiques et Informatique
Filière : Informatique
Option : Systèmes et Réseaux Informatiques

Mémoire de Master

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THÈME

Routage multicast dans un essaim de drones (UAVs)

Soutenu publiquement devant le jury composé de :

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2020

بسم الله الرحمن الرحيم

DEDICATION

We would like to dedicate this work to our dear parents who taught and raised us. Thanks to them we are here today, we wish for nothing but to make them proud.

Dedications also go to our dear families, brothers and sisters, who have always been there for us.

ACKNOWLEDGMENTS

We wish to express our deepest gratitude to our supervisor, Dr. Fatima Zohra Bousbaa who has convincingly encouraged and guided us through this work, we wouldn't have been able to achieve it without her persistent help.

We would also like to show our sincere appreciation to the committee members, Prof. Nasreddine Lagraa and Dr. Zohra Abdelhafidi, we thank them for taking the time to consult our humble work, and we are looking forward to hear from them and consider their constructive critics and valuable advice to improve it.

Youssra & Soumia, June 2020

ABSTRACT

Recently, the deployment of a swarm of cooperative Unmanned Aerial Vehicles (UAVs) to pursue a task is enjoying increasing success, since a group of UAVs instead of one single UAV leads to many advantages, for example the possibility to extend the mission coverage, to guarantee a reliable ad-hoc network, or to enhance the service performance. However, it also poses many challenges in designing networking protocols such as, the dynamic topology change.

In this work, we study the multicast routing problem in swarm of UAVs, which aims at delivering information to specific members of flying nodes. Our objective is to provide detailed classification of existing swarm routing protocols considering transmission strategies and to propose a new Energy efficient Multicast Routing Protocol for UAVs Swarm (SEMRP) taking into consideration the aforementioned challenges and aiming to satisfy COronaVirus Disease 2019 (COVID-19) applications.

The results of the simulation conducted using NS-2 simulator advocate for the efficiency of our method through two proposed versions (SEMRP-V1 and SEMRP-V2) in term of reducing the total emission energy (at least by 10 dBm), optimizing the End-to-End Delay by 44%, and increasing the packet delivery ratio by more than to 22% compared to SP-GMRF protocol.

Keywords: UAVs, Swarm of UAVs, Multicast Routing Protocol, SEMRP-V1, SEMRP-V2.

مُلَخَص

شهد العالم استخداما واسعا للطائرات بدون طيار في مختلف المجالات، فقد ساهم التقدم التكنولوجي في ابتكار أنواع صغيرة من هاته الطائرات مما سمح بتنوع استعمالاتها في المجالات المدنية بعدما كانت مخصصة للتطبيقات العسكرية فقط.
و هذا ما سهل من عملية تكوينها في شكل أسراب تعاونية محققة نجاحا و فاعلية أكبر في تأدية مهامها مظهرة العديد من المزايا مقارنة مع الأنظمة أحادية الطائرة، كإمكانية تمديد مساحة المهمة، ضمان موثوقية الشبكة و تحسين أداء الخدمة.
و على الرغم من المزايا البارزة للأنظمة متعددة الطائرات الا انها تفرض العديد من التحديات في تصميم بروتوكولات توجيه فعالة، مثل التغيرات المتكررة في هيكل الشبكة الناتجة عن الحركة ثلاثية الأبعاد داخل السرب.

في هذا العمل، ندرس مشكلة التوجيه المتعدد في سرب من الطائرات بدون طيار، الذي يهدف الى توصيل المعلومات الى وجهات محددة داخل السرب. نهدف من خلال هذا العمل أولا الى تصنيف بروتوكولات التوجيه الخاصة باسراب الطائرات مع أخذ استراتيجيات النقل بعين الاعتبار. ثم اقتراح بروتوكول توجيه متعدد الإرسال في سرب من الطائرات يعمل على استهلاك الحد الأدنى من الطاقة آخذين بعين الاعتبار التحديات المذكورة سابقا.كما ان البروتوكول المقترح في هذا العمل موجه لدعم التطبيقات الخاصة بمحاربة جائحة كوفيد-19.

أثبتت نتائج المحاكاة كفاءة و فاعلية الطريقة المقترحة بنسختيها الأولى والثانية (SEMRP-V1 و SEMRP-V2). حيث انها سجلت انخفاضا معتبرا في اجمالي الطاقة المستهلكة و مدة التوصيل مع زيادة في نسبة تسليم الحزم.

الكلمات المفتاحية: طائرات بدون طيار، سرب طائرات بدون طيار، بروتوكول التوجيه المتعدد، SEMRP-V1، SEMRP-V2.

RÉSUMÉ

Au cours de la dernière décennie, l'utilisation d'un groupe de drones (UAVs) coopératifs de poursuivre une tâche au lieu d'un seul drone connaît un succès croissant. Parmis les avantages offerts par ce déploiement est la possibilité d'étendre la couverture de la mission, de garantir un réseau ad-hoc fiable et aussi d'améliorer les performances du service. Cependant, il existe des défis tels que les déconnexions causées par le mouvement des drones en 3D, et les changements fréquents dans la topologie du réseau.

Dans ce travail, nous étudions le problème de routage multicast dans un essaim de drones, qui vise à fournir des informations à des membres spécifiques de drones. Notre objectif est de présenter une classification d'ensemble de protocoles de routage dans des essaims de drones en tenant compte les stratégies de transmission et de proposer un nouveau protocole de routage multicast fiable pour un essaim de drones qui permet de minimiser l'energie totale prenant en considération les défis susmentionnés et de viser à satisfaire aux applications du nouveau Coronavirus.

Les résultats de simulation réalisés à l'aide du simulateur NS-2 montrent l'efficacité de notre méthode à travers de deux versions proposées (SEMRP-V1 et SEMRP-V2) en terme de réduction d'énergie d'émission totale (au moins de 10 dBm), d'optimisation de délai de bout en bout en 44% et d'augmentation de taux de livraison des paquets de plus de 22% par rapport au protocole SP-GMRF.

Mots clés: UAVs, essaim de drones, protocole de routage multicast, SEMRP-V1, SEMRP-V2.

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LIST OF ALGORITHMS

LIST OF ACRONYMS

ACO Ant Colony Optimization. 17, 18, 25

AODV Ad hoc On Demand Distance Vector. 18

APAR Ant colony optimization based Polymorphism Aware Routing algorithm. 17, 18, 25

BCO Bee Colony Optimization. 18, 19, 25

CA-BCO Compact Artificial BCO. 19, 25

COVID-19 COronaVirus Disease 2019. iv, 27, 28

DPTR Distributed Priority Tree-based Routing protocol. 20, 23, 24, 25

DSDV Destination-Sequenced Distance-Vector. 18

DSR Dynamic Source Routing. 17, 18

FANET Flying Ad hoc NETwork. 1, 18, 19, 20, 23, 25, 44

GBS Ground Base Station. 6, 7, 12

GeoUAVs Geocast routing protocol for fleet of UAVs. 19, 25

GPS Global Positioning System. 14, 20

HAUs High Altitude UAVs. 5

IPv6 Internet Protocol version 6. 23

LAUs Low Altitude UAVs. 5

LoS Line-of-Sight. 6, 7

MAUs Medium Altitude UAVs. 5

PDR Packet Delivery Ratio. 45

QoS Quality of Service. 14, 25, 50

SATCOM Satellite Communication. 6, 7

SEMRP Energy efficient Multicast Routing Protocol for UAVs Swarm. 27, 28, 29, 35, 38, 40, 43, 45, 46, 48, 49, 50, 51

SI Swarm Intelligence. 15, 16

SNIR Signal-to-Noise-and-Interference Ratio. 44

SP-GMRF Predictive geographic multicast routing protocol in flying ad hoc networks. 20, 22, 23, 25, 43, 45, 46, 48, 49, 50

U2G UAV-to-Ground. 6

U2U UAV-to-UAV. 6, 44

UAVs Unmanned Aerial Vehicles. iv, vi, ix, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19, 27, 28, 29, 43, 45, 48, 49, 50

CHAPTER 1

INTRODUCTION

Contents

1.1 Context

With the technological evolution of wireless communication in aviation systems and the increasing use of Unmanned Aerial Vehicles (UAVs), there has been an ever-rising need for coordination, communication, safety, and information sharing among these devices in order to be a practical choice for various applications including search and rescue operations, managing wildfire, patrolling, delivery of goods, monitoring and surveillance [1].

In order successfully achieve a mission in an efficient manner, carrying out a group of cooperative UAVs rather than a single UAV has gained a lot of interest, thus enhancing the multitasking ability, increasing the network lifetime, and growing the scalability [2]. When UAVs are cooperatively organized as an Ad-hoc network, thus creating a new type of network called Flying Ad hoc NETwork (FANET). Nevertheless, it also poses many challenges in designing networking protocols such as, the 3D mobility of UAVs, which causes frequent changes in network topology. That can lead to packet loss, excessive re-transmissions and eventually increased delay. [3].

1.2 Problem Statement and Motivations

As the technology of UAVs grows and their cost decreases, they become an interesting way to undertake several difficult applications, especially when the drones form a swarm. Although the deployment of swarm UAVs and their attractive advantages, it still poses several challenging characteristics that may affect the reliability and stability of these networks. To support their various applications, to keep their functioning stable, and to well exploit their features, it is necessary to design efficient routing protocols according to the targeted missions. To this end, many swarm routing protocols have been proposed and studied in FANET, which can be divided into three main classes: (i) meta-heuristic-based [4, 5, 6, 7] , (ii) geographical location-based [8], and (iii) multicast-based [9, 10]. In this work, we interest to the last category. The solutions presented in this category do not address both the power consumption and the scalability. Therefore, we attempt to design a new efficient multicast routing protocol for swarm-based systems that distribute data from one source node to a specific group of mobile drones, while minimizing the number of connections in the network, ensuring the scalability, and optimizing the global energy, which directly influence the system's lifetime.

1.3 Contributions

In this work, we propose SEMRP [11], a Swarm energy-efficient multicast routing protocol for UAVs flying in group formations. The main purpose of SEMRP is to facilitate the control and information delivery between UAVs while minimizing inter-UAV packet loss, packet re-transmission, and end-to-end delay. In this study we show how SEMRP achieves these objectives by taking into account various Quality-of-Service parameters like the network throughput, the UAVs mobility, and energy efficiency to ensure a timely and accurate information delivery to all members of a UAV swarm. The results of the conducted simulation using NS-2 advocate for the efficiency of our proposal through its to two presented versions (SEMRP-v1 and SEMRP-v2) in term of reducing the total emission energy (at least by 10 dBm), optimizing the End-to-End Delay by 44%, and increasing the packet delivery ratio by more than to 22% compared to SP-GMRF protocol. This work was published in the 2020 IEEE/ACM 24th International Symposium on Distributed Simulation and Real Time Applications (DS-RT).

1.4 Organization of the Thesis

This thesis is organized as follows:

- **Chapter 2** introduces UAVs and discusses their classifications. It also gives an overview of swarm-based systems and their main features, applications, and architectures.
- **Chapter 3** concerns the state-of-the-art in which we illustrate different routing protocols in swarm of UAVs with a detailed description and comparison of all discussed protocols.
- **Chapter 4** presents our new multicast routing protocol in a swarm of UAVs while taking into account the total energy consumption. It is based on calculating distances between UAVs to choose the shortest paths from the source node to the swarm members.
- Finally, we conclude the work with a conclusion and some future perspectives.

CHAPTER 2

SWARM OF UAVS: BACKGROUND

Contents

2.1 Introduction

Unmanned Aerial Vehicles (UAVs) have recently attracted significant interest in civilians and military applications, such as search and rescue operations, managing wildfire, agricultural applications, monitoring and surveillance. Swarms of UAVs may further increase the effectiveness of these tasks. In instance, the possibility to enable larger mission coverage, to guarantee a reliable ad-hoc network, and to improve the operation performance through multi-UAV cooperation.

Along with this chapter, we start with the presentation of UAVs and their categories. Then, we study the swarms of UAVs, their applications, features, and challenges.

2.2 Unmanned Aerial Vehicles

Unmanned Aerial Vehicle (UAVs), also called drone, is a pilotless aircraft that does not require any direct human intervention for flying, is powered by a jet or reciprocating engine, and can navigate autonomously according to a pre-programmed flight plans or can be controlled remotely [4][12]. Owing to their flexibility, autonomy, ease of installation, relatively small operating expenses, and wide range of application domains, UAVs have been subject of concerted research over the last few years [13]. The following presents the main categories of UAVs and their different communication types.

2.2.1 Classification

The flexible features of UAVs made it plays an essential role in different fields, even it led the researchers to think about new needs and applications to facilitate the human being lives and touch more and more domains. For this purpose, there is a remarkable effort to develop and produce new UAVs under certain standards geared to accomplish specific missions. As a result, we distinguish various types of UAVs, as shown in Figure 2.1.

Mainly, UAVs are classified based on their **type**, into fixed-wing and rotary-wing UAVs. Fixed-wing UAVs such as small air-crafts have more weights, higher speed than rotary-wing UAVs, they can fly for several hours, and they need to move forward to remain aloft where rotary-wing UAVs such as quad-rotor drones can hover and remain stationary over a given area [14].

Further, according to their **altitudes**, there are (i) High Altitude UAVs (HAUs), (ii) Medium Altitude UAVs (MAUs), and (iii) Low Altitude UAVs (LAUs), each with its features. The HAUs are almost stationary with altitudes above 20km and long endurance (days or months), such as satellites, airships, and hot air balloons. The MAUs fly at medium altitudes up to 11 km, such as aircraft, and can move more quickly from the point of view of ground nodes. LAUs fly at altitudes of tens of meters up to a few kilometers for several hours, can move quickly, and they are flexible, such as drones or copters [15].

Moreover, their **size** can be varied from micro and mini UAVs ($<$2kg and $<$ 20 kg, respectively) to large UAVs ($>$ 600 kg) [16]. Their **flight duration** could be short or long depends on several factors such as energy source, type, weight, speed, and trajectory of the UAV.

Furthermore, UAVs are classified based on their **applications**, namely, civil (e.g., surveillance, transportation, environmental monitoring, and industrial monitoring) and military (e.g., target localization, tracking, and anti-terrorism arrests).

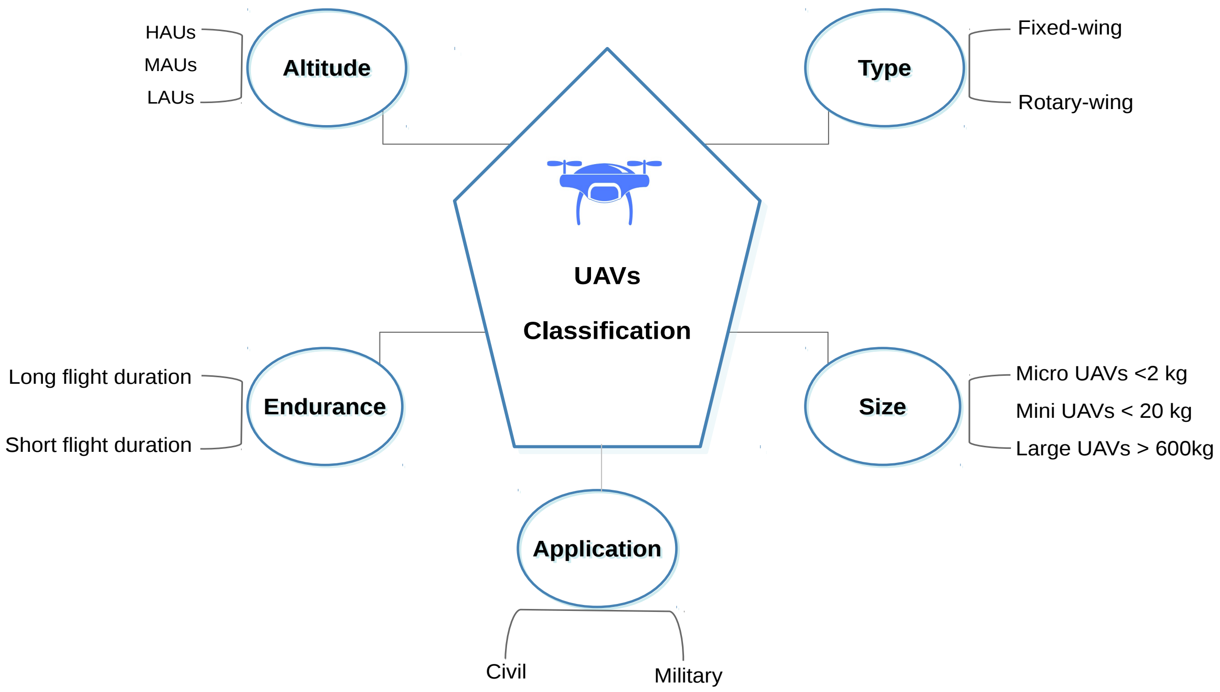


Figure 2.1 – UAVs classification

2.2.2 Communication

Each node in the network (UAVs, Ground Base Station (GBS), or Satellites) can act as an end system. However, the communication of two distant nodes is exposed to different constraints, such as the packet losses and the permanent fragmentation of the network. Therefore, all these nodes can cooperate and organize themselves as relays in order to cope well with the frequent topology variation [14][17]. Thus, there are three types of communication: (i) UAV-to-UAV (U2U), (ii) UAV-to-Ground (U2G), and (iii) Satellite Communication (SATCOM), are discussed and detailed in this sub-section.

1. **UAV-to-UAV Communication**: In order satisfy the needs of different missions, UAVs directly communicate by frequently exchanging data packets with each other. However, due to the restrictions on the transmission ranges, multi-hop communication is carried out over other UAVs. This is crucial to extend the coverage of a specific area of interest. In the majority of cases, the Line-of-Sight (LoS) is predominant in U2U communications since no obstructions exist between UAVs in the sky [13].

2. **UAV-to-Ground Communication**: For a better control of flying UAVs, infrastructures in the form of GBSs are fixed on the ground in order to exchange critical control and command messages. In addition, GBSs are also used to link different groups of

UAVs between each other. In order to decrease the congestion of the network and to enhance throughput and connectivity, backbone UAVs are used to collect data from the member UAVs (through U2U and then relays the aggregated data to the ground station using U2G communication. In general, if UAVs fly at low altitudes, the LoS is not guaranteed due to the existing obstructions on the ground causing the reflection and diffraction phenomenon [18][19].

3. **Satellite Communication**: UAVs are often deployed in complex environments, where it is difficult to install GBSs or when a group of UAVs requires continuous connectivity and the network is severely partitioned. For this purpose, there is a need for a centralized entity ensuring permanent connectivity like using satellites as an adequate option to serve as relays controlling UAVs in a centralized manner and also providing an important LoS coverage, thus establishing Satellite Communication SATCOM [20].

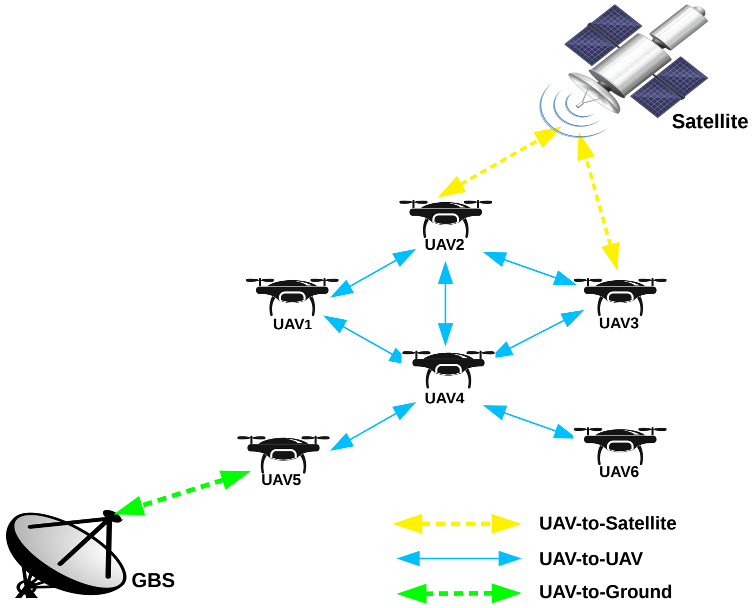


Figure 2.2 – UAVs communication

2.3 Swarm of UAVs

2.3.1 Need for Swarm Communication

Along with the progress of embedded systems and the miniaturization tendency of micro-electro-mechanical systems, it has been possible to produce small UAVs at a low cost [21], and make them operate in groups in a coordinated and collaborative way to form a multi-UAV system. Further, the ability of swarming many UAVs to perform complex tasks becomes attractively recommended because it treats the limitations of single UAV systems like the limited payload and flight time. It also adds more functionalities and advantages including time-savings, reduction in manpower, and reduction in operational expenses. In a single UAV system, if the UAV or a sensor/hardware fails, the UAV should return to the base. However, in swarm-based systems, other UAVs have the ability to share tasks among themselves and this increases the fault tolerance of the system. For example, in search missions using a swarm of UAVs can parallelize the individual tasks, thus decreasing the completion time of the mission, extend the coverage range, and can also provide real-time images and videos which may improve the quality of the operation.

2.3.2 Applications

The technological advancement in the capabilities of UAVs enable its use for different purposes in the sector of unmanned operations. The application scenarios that can benefit from UAV technologies are diverse, but in this section, we introduce a brief overview of the most prominent swarm-oriented applications.

- **Search and Rescue Operations**: In search and rescue situations, where time may mean the difference between a life saved or a life lost, it is recommended to benefit from the abilities of a swarm of UAVs. It can be used to save time and manpower, by providing real-time images of affected places and facilitating access to dangerous and damaged areas. We could imagine UAVs in a swarm equipped with first aid kits, that can be delivered to a person in need of medical assistance. Furthermore, it can be equipped with sensors to search for hostages. So, there will be more chances of saving someone's life. Figure 2.3 shows a swarm of UAVs in a search and rescue mission.

Figure 2.3 – Search and Rescue Operations

- **Security, Monitoring, and Surveillance**: UAVs have widely been used in military surveillance missions and defense. Currently, versatile and low-cost drones are used in surveillance and monitoring in numerous fields such as cartography, geophysics, and agriculture. For example, a swarm of UAVs could be used to cover and monitor large areas efficiently, and with minimum efforts contrary to the traditional scenarios as shown in the Figure 2.4.

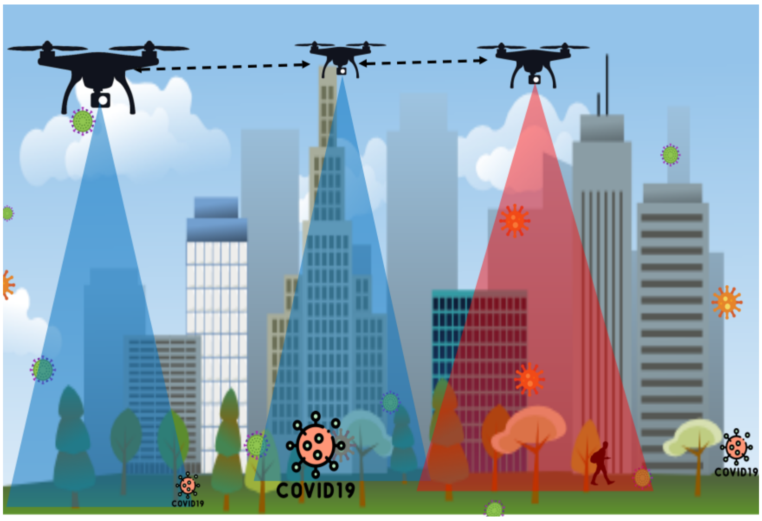


Figure 2.4 – Security, Monitoring, and Surveillance

- **Agricultural Applications**: Recently , the benefits of UAVs in agriculture are becoming more apparent to farmers. One specific example of an agricultural application that would see an increase in efficiency using swarms of UAVs is precision agriculture. Which refers to the way farmers manage crops to ensure the efficiency of inputs such as water and fertilizer, and to maximize quality and productivity. Using Swarm of UAVs equipped with cameras and other data-gathering devices, allows farmers to constantly monitor crop conditions to quickly find problems that would not become apparent in ground-level spot checks. Moreover, it can be used for spraying and dusting crops automatically with far more precision than traditional ways, as shown in Figure 2.5.

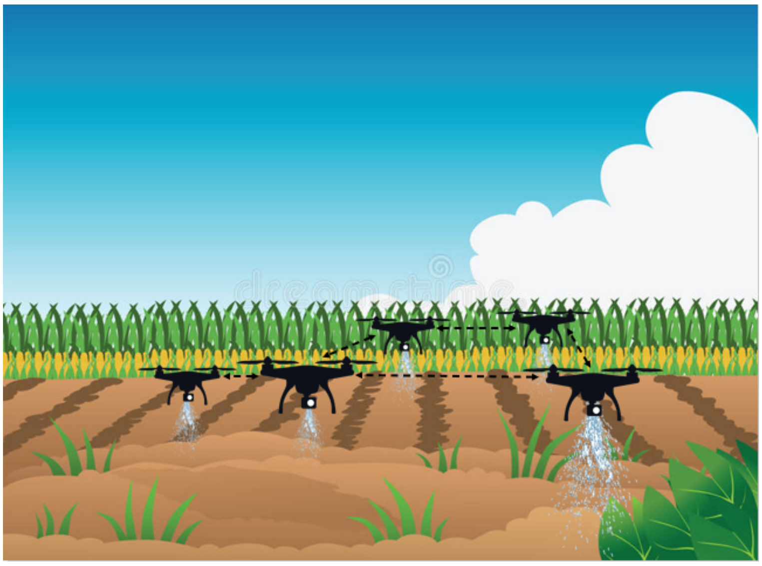


Figure 2.5 – UAVs for Precision Agriculture

- **Applications in the Covid-19 Pandemic**: More recently, during the corona virus pandemic, governments recommend applying UAVs more than before. Using UAVs for delivering essential goods and services can certainly have a positive impact (Fig.2.6.a). Unusually, UAVs have been used for battling the spread of the Virus. Swarms of UAVs have been used for broadcasting useful information to encourage physical distancing and staying home, spraying streets with water and disinfectant, and delivering medical supplies (Fig.2.6.c). Coupled with the artificial intelligence, new UAVs have been developed for body temperature scanning (Fig.2.6.b). Further, UAVs can enhance situational awareness by helping enforce lockdowns and sanitary cordons during the pandemic. Certainly, these setups would not require single UAV systems, but swarms of UAVs.

(a) (b) (c)

Figure 2.6 – The Covid-19 Pandemic Swarm Applications

2.3.3 Features

Though the feasibility of developing UAVs with attractive features like the low size and cost, single UAV systems can only provide limited tasks. Otherwise, using a swarm of cooperative UAVs would be better for accomplishing complex missions, by assigning simple synchronized functions to each UAV in the swarm. Moreover, the collaboration facilitates the usual tasks and improve performance [22]. Compared to a single UAV, a swarm of UAVs has the following advantages:

- **Time and cost:** For example, the deployment and maintenance of small UAVs is less expensive than one large UAV equipped with complex devices and heavy payload. Indeed, the required task can be completed faster with a swarm of UAVs rather than single UAV systems.
- **Coverage:** Using swarms of UAVs can provide an effective solution to cover a large area in surveying, mapping, or monitoring scenarios. Moreover, UAVs can play the role of temporal connectivity coverage to ground users when the terrestrial infrastructures are damaged [23]. Besides, the swarm size can be easily increased by adding UAVs and adopting efficient dynamic routing protocols.
- **Fault tolerance:** If a member from the swarm becomes unavailable due to weather conditions or unexpected failure, the mission can still proceed with the rest of the

flying UAVs and this increases the fault tolerance of the system. However, it is not the case in a single UAV system where the UAV represents the backbone of the system.

2.3.4 Swarm Communication Architectures

Designing a fully cooperative swarm of UAVs system requires a set of rules and mechanisms that determine how information should be exchanged between multiple UAVs and GBS. According to [24] and [25], there are two types of swarm communication architectures: centralized and decentralized. This sub-section presents these architectures and highlights their strengths and weaknesses.

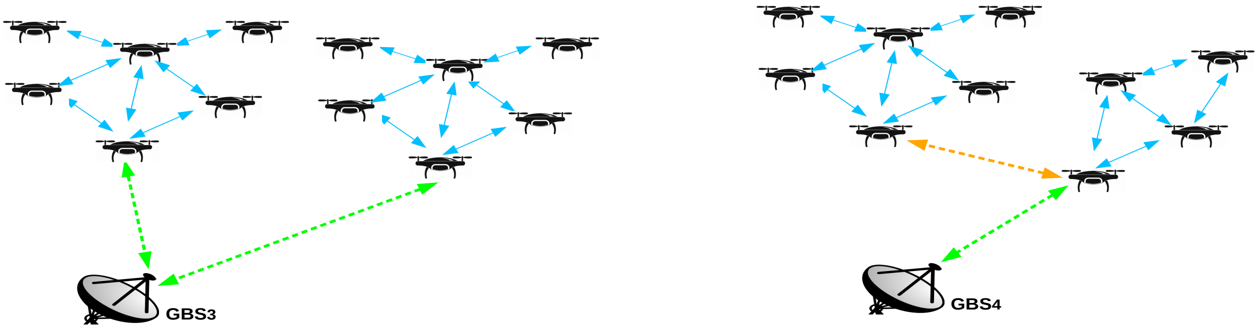
- **Centralized Architecture:** The centralized architecture consists of a GBS that receives information from all UAVs in the swarm. The UAVs are directly connected to the GBS that can communicate with each UAV simultaneously, as shown in Figure 2.7.a. Since inter-UAV communications are not possible, all data traffic has to be routed through the GBS. Thus, the data exchanged between two UAVs will take a relatively long delay. Besides, this architecture is centered at the ground station which represents a single point of failure in which its breakdown can disrupt the overall network. Moreover, the UAV to GBS communication requires heavy hardware that may not be supported by the limited payloads of the small UAVs.

- **Decentralized Architecture:** In this type, the UAVs in the swarm are connected in an ad-hoc manner. So, they can communicate with each other either directly or indirectly without the need for a central node. This implies that information data that are not destined to the ground station can be routed through any UAV from the swarm instead of the ground station [24]. Three types of decentralized architecture are introduced in the following [26][27]:
    - **UAV Ad-hoc Network:** In this specific architecture, a backbone UAV acts as a gateway between the ground station and the other UAVs as shown in Figure 2.7.b. The backbone UAV is normally equipped with two radios: Low power short-range radio used for communication between the UAVs, and high power long-range radio required to communicate with the GBS.
    - **Multi-Group UAV Ad-hoc Network:** Basically, this architecture is an integration of both Ad-hoc networks and centralized networks. As shown in Figure 2.7.c, the UAVs are connected in an Ad-hoc manner within a group, and the groups are further connected via the backbone UAVs to the ground station in a centralized manner. Intra-group communication is done without involving the ground station, but inter-group communication is performed with the help of the ground station.

- **Multi-Layer UAV Ad-hoc Network:** As illustrated in Figure 2.7.d, in this architecture multiple groups of heterogeneous UAVs form an Ad-hoc network within an individual group. The lower layer is used for communication between the UAVs and the upper layer is used for communication between the backbone UAVs of all the connected groups and the ground station. All backbone UAVs are connected with each other and only one backbone UAV is further directly connected to the ground station.

In summary, a decentralized architecture can provide extended coverage through multi-hop transmissions, it is more robust since it does not present a single point of failure, and offer more communication efficiency without requesting wide-band links to the ground station [25].

(a) centralized architecture **(b) UAV Ad-hoc Network**



(c) Multi-Group UAV Ad-hoc Network **(d) Multi-Layer UAV Ad-hoc Network**

Figure 2.7 – Swarm Communication Architectures

2.3.5 Challenges

Connecting the UAVs in an ad-hoc manner is the most reliable for the establishment of any swarm-based applications and services. Despite the advantages of using these networks, it still faces many challenging issues due to the high node speed, high topology changes, mobility model, and limited storage.

- **Routing protocols**

  Routing protocols are the brain of an ad-hoc network and manages all flow between UAVs and other devices connected to them. Due to the fast movement of UAVs, the network topology can change quickly. Thus, data routing between UAVs faces a serious challenge, which is different from the low mobility environment. The routing protocols should be able to update routing tables dynamically and frequently according to topology changes [12][28].

- **Quality of Service (QoS)**

  Different types of data can be exchanged in the swarm between the UAVs, which include Global Positioning System (GPS) locations, streaming video/voice, images, simple text messages, etc. It is important that such data must pass to the base station in good quality condition, with low error rates, and timely delivered.

- **Mobility model**

  Mobility model shows how the different UAVs can move together within a specified zone to accomplish a targeted mission. Hence, defining a mobility model compatible with the characteristics of the small UAVs in the swarm is very important to provide better performance and greater flexibility.

- **Security**

  Ensuring confidentiality, availability, and integrity of information during the communication between the different nodes in the swarm is one of the major issues. Therefore, it is important to save data from unauthorized parts to prevent the misuse of the transferred information.

2.4 Conclusion

This chapter presented a background on UAVs, with the main characteristics, applications, challenges, and communication architectures of swarm UAVs. The next chapter will present and analyze the existing routing protocols in swarm UAVs.

CHAPTER 3

SWARM ROUTING PROTOCOLS: STATE OF THE ART

Contents

3.1 Introduction

In order to increase success rates of a mission, carrying a swarm of UAVs is necessary in certain applications. One of the most popular applications for swarm UAVs is for military purposes [9], however in the recent time their civilian applications are attracting attention. Indeed, low-cost drones and their swarms provide a promising platform for innovative research projects and future commercial applications that will help people in their work and everyday lives [29]. In this chapter, we will be presenting the existing routing protocols in swarm UAVs with description and comparison of all discussed protocols.

3.2 Swarm-based protocols

A swarm is generally defined as a group of behaving entities that together coordinate to produce a significant or desired result or behavior [16]. In nature, many species move in group manner for biological and survival reasons, such as birds, fish, bees, and ants. Swarm behavior is a characteristic that specializes these creatures, in order to communicate and increase their chances to stay alive.The communication systems between individual creatures was the inspiration for "Swarm Intelligence (SI)" which is the part of Artificial Intelligence based on study of actions of individuals in many decentralized systems [30]. SI is a multi-agents system of intellectual optimization with self-organized behavior [31].

Collective system is capable of solving complex dynamic problems of collaborative work that cannot be performed by a single element of the system under diverse circumstances without an external management, control or coordination [31].

SI systems are applied in various communication systems including Fanets in order to establish an efficient and reliable communication in order to achieve a specific mission among the cooperative UAVs [31].

Efficient routing protocols are required for a successful communication among the cooperative UAVs in swarm. There are many routing protocols used in this category of network, which can be classified into three mains categories: (i) meta-heuristic-based, (ii) geographical location-based, and (iii) multicast-based as shown in Fig 3.1.

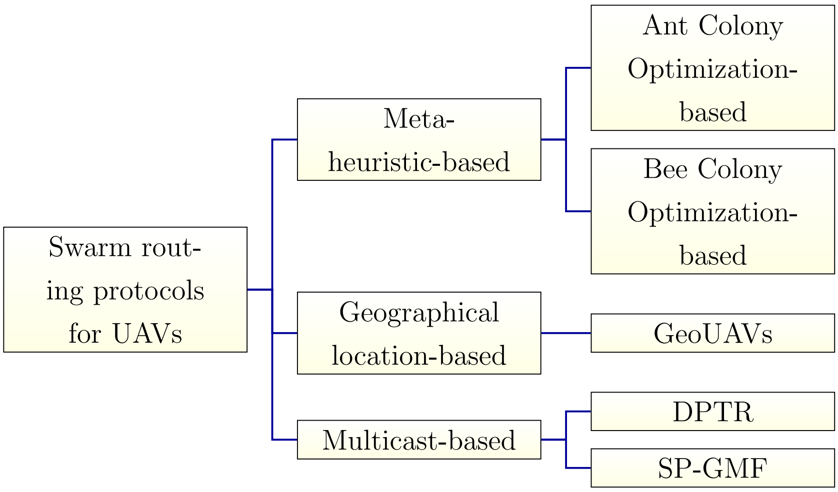


Figure 3.1 – Classification of the routing protocols in swarm of UAVs

3.2.1 Metaheuristic-based

Swarm algorithms are used in order to realize SI systems, they are based on modeling social behavior of various creatures, and are suitable for complex optimization problems that require finding the most optimal solution if possible.

Various algorithms based on the swarm intelligence which can be successfully adapted for cooperative UAVs, they fall into category of meta-heuristic algorithms. In metaheuristic algorithms values of several algorithm components and parameters have to be set, due to their significant impact on the algorithm's efficacy and performance. Therefore, it is important to study how the algorithm parameters affect the performance [32]. The algorithms are classified into two categories:

1. Ant colony optimization-based.
2. Bee colony optimization-based

Ant Colony Optimization-based

The Ant Colony Optimization (ACO) algorithm is a bio-inspired meta-heuristic algorithm based on the social behavior of ants on the way to find the shortest path to the source of food. During their trip, the ants follow one another by sensing the pheromone laid by other individuals. The high concentration of pheromone indicates the freshness and the validity of the road [33][34]. Routing data are stored in pheromone tables represented as a distance-vector two-dimensional matrices.

The main procedure [34] in ACO algorithm consists of the selection by ants of subsequent nodes from the n element set $N = \{\mu_1, \mu_2, ...\mu_n\}$ and $\tau(t) = \{\tau_1, \tau_2, ...\tau_n\}$ with the probability specified by the formula.

$$P_j^i(t) = \begin{cases} \frac{[\tau_j(t)]^\alpha \times [\eta_j]^\beta}{\sum_{k \in K} [\tau_k(t)]^\alpha \times [\eta_k]^\beta} & \text{, if } j \in K; \\ 0, \text{ otherwise.} \end{cases} \tag{3.1}$$

Where $P_j^i(t)$ is the probability of transition to node j by the ant i at time t, which in this case will mean the iteration number of the algorithm. The symbol τ_j represents (numerically) the amount of pheromones left in the μ_j node, while η_j is the heuristic factor described by the expression.

$$\eta_j = \frac{1}{\delta_j} \tag{3.2}$$

Where δ_j is the value of the fitness function (transition cost) to node j. The coefficients α and β determine the effect of the pheromone and the heuristic coefficient respectively on the process of selecting the next node. The probability is calculated only for nodes from the set K, which contains all nodes from the set N, for which the transition is not prohibited in any way, thus $K \in N$.

Initially, the ACO algorithm was proposed by Marco Dorigo et al [33] to solve the problem of TSP (Traveling Salesman Problem). Then, it was used to solve different problems in different fields especially to ensure an efficient communication in ad hoc networks. The analysis of swarm routing protocols based on ant colony optimization is done by the following works:

1. In [4], a meta heuristic algorithm named "Ant colony optimization based Polymorphism Aware Routing algorithm (APAR)" was proposed to solve communication problems in multi-UAVs systems. APAR integrates ACO algorithm with the well-known Dynamic Source Routing (DSR). APAR detects the congestion level, and the stability of a route according to the level of pheromone in routes which are gained in routing discovery process.

    - **Advantages**: APAR avoids congestion and link breakage by establishing standards to choose routes based on sensing the distance of a route, the stability of a route and the congestion level of a route.
    - **Drawbacks**: This protocol introduces overheads and delays and prevent high mobility nodes from participating in route discovery.

2. AntHocNet is an ACO based routing protocol proposed by Maistrenko et al in [5] to solve the problem of high mobility in FANET. The AntHocNet presented better results compared to Ad hoc On Demand Distance Vector (AODV), Destination-Sequenced Distance-Vector (DSDV) and DSR protocols in terms of packet delivery ratio and end to end delay especially in large networks.

    - **Advantages**: AntHocNet is more suitable for large networks with high mobility.
    - **Drawbacks**: AntHocNet is less effective because off high costs for routing service information transfer.

Bee colony optimization-based

Bees behavior in the nature is the main inspiration for the Bee Colony Optimization (BCO) metaheuristic. The algorithm is the sub-class of a bio-inspired algorithms and models bee behavior in natural habitat [31]. In wildlife the bee hive operating principle is based on a clear distribution of responsibilities among the bees, the Figure 3.2 illustrates bees colony behavior in wildlife. All bees of the hive can be divided into three groups [35] [36]:

1. Employed bees.
2. Onlookers.
3. Scouts.

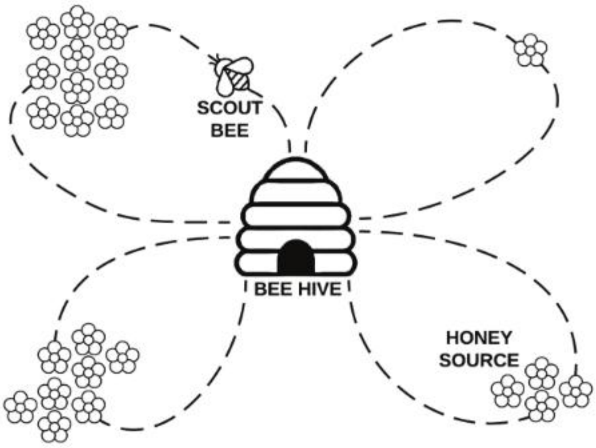


Figure 3.2 – Bee colony behavior in wildlife

One of the existing solutions applying BCO algorithm is BeeAdHoc which has two different stages during the functioning of BeeAdhoc: Scouting stage and resource foraging stage. In the first stage, forward and backward scouts including the source ID, the number of hops, and the minimal residual energy, are flooded across the network to establish multiple paths between the communicating nodes [6]. In the second stage which is the resource foraging stage, the data packets are delivered from the source to the destination using the forager bees [6].

- **Advantages** : The simulation results show that BeeAdHoc gives more effective results than traditional FANET routing algorithms in most cases [8].
- **Drawbacks** : Complex behavior modeling [6].

An improved version of BCO algorithm is a Compact Artificial BCO (CA-BCO) which is dedicated for UAV route planning problem. In CA-BCO algorithm, probabilistic representation of the population is used to replace the design variable of solutions search space of BCO algorithm [7].

- **Advantages**: CA-BCO can provide the performance of optimization significantly as within the category of memory-saving algorithms [8].
- **Drawbacks**: It has the same drawbacks as BeeAdHoc because it uses the same BCO algorithm [8].

3.2.2 Geographic-based

Communication is necessary between UAVs in certain types of missions such as video monitoring, search for disaster victims, and managing wildfire in a specific geographic area.

One source may need to establish paths to destinations in certain region, therefore geocast routing protocols are used [8]. One of the geocast solutions which have been proposed is Geocast routing protocol for fleet of UAVs (GeoUAVs) designed for managing wildfire, especially in the zones which hard to reach, which aims at delivering data to a specific group of mobile UAVs identified by their geographical location to manage an active fire. It takes into account the mobility of nodes, dynamic changing topology with 3D movement, and reliability [8].

- **Advantages**: This method reduces average delay and maximized throughput [8].
- **Drawbacks**: It does not take into consideration power consumption.

3.2.3 Multicast-based

During a mission, a source may need to send data to a specific group of nodes, therefore multicast routing is used [9]. Multicast routing is an effective way to establish the group communication when the same message or the same stream of data needs to be sent to multiple receivers. Multicast routing has attracted a lot of attention in group oriented computing due to supporting data transmission from a single source node to multiple destinations concurrently. The advantage of multicast routing lies in its capability of reducing the communication cost and saving the network resources by sending only one copy of the message over the shared link leading to different destinations [37]. Multicast routing is used in order to reduce transmission overhead , control message overhead, power consumption, and network partitioning [9].

One of the categories of multicast routing is tree based where a tree is composed of a unique path from the multicast source to each of the multicast receivers [37]. Many types of tree based multicast routing protocols have been proposed for wireless networks communication, some more recent existing solutions are the following:

- (i) Predictive geographic multicast routing protocol in flying ad hoc networks (SP-GMRF) [9].
- (ii) Distributed Priority Tree-based Routing protocol (DPTR) [10].

(i) SP-GMRF

One of the challenges in multicast routing in FANETs is the frequent topology changes that are resulted from the mobility of drones. Therefore, SP-GMRF is proposed in [9], which is a predictive geographic multicast routing approach in FANETs. (i) In this method, Hussen et al. proposed a new mechanisms which are necessary for GPS- enabled flying nodes in FANETs due to their importance in their localized operation, reduced computation, and

reduced bandwidth consumption.
In a network, the following conditions are considered:

- A source node S which acts as the root of the geographic multicast tree.
- S has knowledge of the geographical location of multicast destinations D.
- Flying nodes are aware of their own positions.
- N acts as forwarding neighbor nodes.
- Geographic multicast tree construction on demand basis.

When a source node S needs to build knowledge about its one-hop direct neighbor nodes position, it discovers its neighboring through the exchange of periodic hello packets which carries information about nodes identication and position. A neighbor node Ni in N, the edge E contains undirected edge (S, Ni) if and only if the Euclidean distance between S and Ni (i.e. E dist (S,Ni)) is less than or equal to the communication range r. The Euclidean distance between two points in n-dimensional space is calculated as the following.

$$E_{dist}(P_1, P_2) = \sqrt{\sum_{i=1}^{n}(P_1 i - P_2 i)^2} \tag{3.3}$$

The minimum distance between the pair of N and D, indicated by min Edist(N,D) knowing that L is the set of forwarding neighbor nodes, m is the multicast destinations, min Edist(N,D) , is expressed as the following.

$$\begin{aligned} minE_{dist}(N, D) = min(i, j)\{E_{dist}(N_i, D_j)\}, i = 1, 2, ... \\ L\&j = 1, 2, ..., m \end{aligned} \tag{3.4}$$

When the source have to send data, it needs to calculate the predicted position for the one hop neighbor nodes Ni(Xprev loc, Yprev loc, Zprev loc) to specify whether they are still in the range of communication, the following equations are used as follows.

$$X_{pred\_loc} = X_{current\_loc} + Spd_{x\_direction} * (t_{current} - t_{n\_discovery}) \tag{3.5}$$

$$Y_{pred\_loc} = Y_{current\_loc} + Spd_{y\_direction} * (t_{current} - t_{n\_discovery}) \tag{3.6}$$

$$Z_{pred\_loc} = Z_{current\_loc} + Spd_{z\_direction} * (t_{current} - t_{n\_discovery}) \tag{3.7}$$

- Where pred loc specifies the predicted coordinate value of Ni, and current loc is the current coordinate value of Ni at the beginning of neighbor discovery.

- Tcurrent is the current time value immediately after neighbor discovery timeout, tn discovery is the time value at the beginning of the current neighbor discovery.
- Spdx direction, Spdy direction, and Spdz direction are the current speed of Ni in the x-, y-, and z-axis direction, respectively.
- Speed in 3D is computed as the following where prev loc is the coordinate value of Ni in the previous forwarding neighbor discovery.

$$Spd_{x\_direction} = \frac{(X_{current\_loc} - X_{prev\_loc})}{(t_{n\_discovery} - t_{prev\_discovery})} \tag{3.8}$$

$$Spd_{y\_direction} = \frac{(Y_{current\_loc} - Y_{prev\_loc})}{(t_{n\_discovery} - t_{prev\_discovery})} \tag{3.9}$$

$$Spd_{z\_direction} = \frac{(Z_{current\_loc} - Z_{prev\_loc})}{(t_{n\_discovery} - t_{prev\_discovery})} \tag{3.10}$$

To illustrate the functionality of SP-GMRF, a simple example is presented in Fig 3.3. The scenarios contain one multicast source, 15 mobile nodes, and 5 destinations. The source S calculates the predicted positions as shown in Fig 3.3.A , then it selects n7 and n5 as one-hop forwarder nearest to the multicast destinations d1, d2 and d3, d4, respectively. For multicast destination d5, since the source S did not find one-hop mobile node nearest to d5 than itself, the source S initiated perimeter forwarding until it reaches a mobile node nearest to d5 than S. Finally, the geographic multicast tree that spans from source S to multicast destinations d1, d5 is constructed as shown in 3.3.B [9].

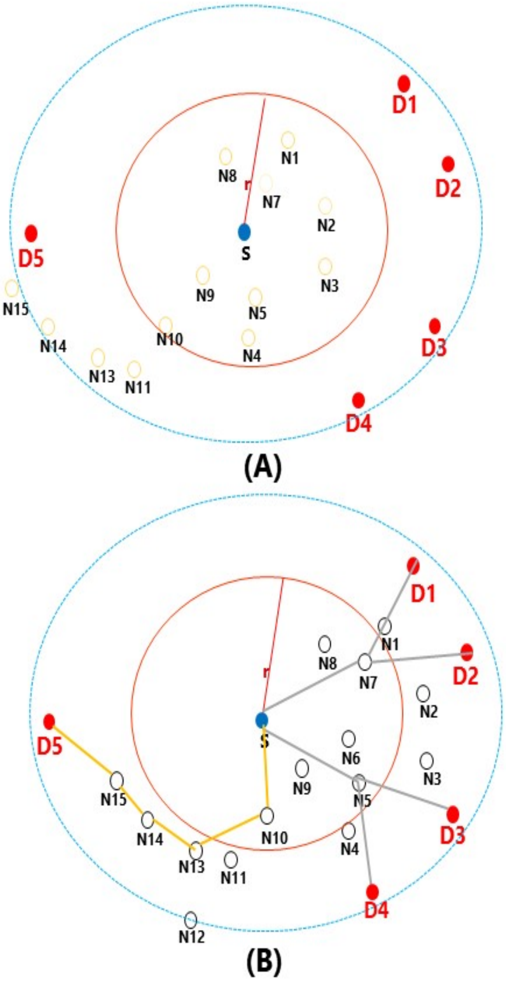


Figure 3.3 – SP-GMRF example scenario

- **Advantages**:
  - SP-GMRF reduces end-to-end delay and overhead because of knowledge of destination positions and minimizes control messages.
  - Prediction of positions process which eliminates nodes that are exiting the communication range as the next hop.
- **Drawbacks** :
  - Does not take into consideration challenges such as power consumption and node stability.
  - No tree updates which could result link breakage.

(ii) DPTR

In [10], V.Sharma et al proposed a Distributed Priority Tree-based Routing protocol (DPTR) for FANETs to handle transmission in collaborative ad hoc networks.
By adding certain rules to the formation of the Red-Black (R-B) trees, a distributed priority tree is formulated. This tree forms a priority network that allows selection of an appropriate node and a channel for relaying to avoid network fragmentation. Internet Protocol version 6 (IPv6) is also used to provide an addressing support for such networks. The routing protocol utilizes a neural framework for its operability and senses the tree formation to form a routing table comprising both aerial and ground nodes.
The DPTR operates in three phases: (i) Identification of ground node, (ii) Identification of aerial node, (iii) Interfacing using neural structure.

DPTR protocol starts by selecting the interacting nodes from both networks by forming the ground ad hoc network and the aerial ad hoc network as two distributed priority Red-Black and Green tree. The selection is carried out on the basis of certain priority given to each node. The node with the highest priority interacts with the other network. Then, the coordination between the two distinguished ad hoc networks is handled using the cooperative framework which provides network connectivity between them, and routing is supported using neurons of the cooperative framework.

The three trees formed in the three phases are combined to form the final routing tree that allows the formation of the adjacency matrix to coordinate amongst nodes of the different network, as shown in Fig 3.4.

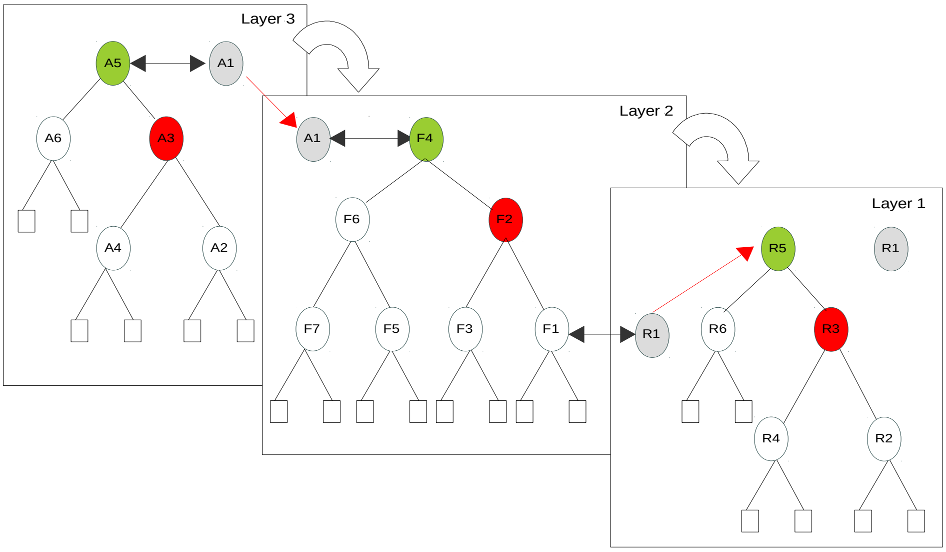


Figure 3.4 – Final routing tree–DPTR

- **Advantages**:
  - DPTR overcomes network fragmentation.
  - Scalable for large networks.
  - It determines routing paths to all nodes.
- **Drawbacks** :
  - DPTR does not support mobility.
  - It provides a considerable effort of management and control [6].
  - It does not consider energy consumption.

3.3 Comparison and summary

In this section, a comparative study of swarm routing protocols is presented. Table 3.1 summarizes the main characteristics of the discussed categories, where swarm routing protocols are classified according to their transmission strategies, QoS requirements, and other criteria such as energy awareness and scalability.

By studying these methods and as presented before, we can say that scalability and power consumption are widespread phenomena in FANET. Hence, any practical swarm routing protocol must take into consideration these phenomena. However, existing swarm routing protocols have partially considered these criteria.

First, the meta-heuristic-based methods allow the power consumption. However, The majority of these methods have a problem of struggling with the calculation especially, the reliability and scalability [8].

Second, one of the proposed algorithms in the geocast category is GeoUAV. According to the simulation results of this protocol, give more effective results than the meta-heuristic routing protocols. However, the power efficiency is not considered in this method.

Third, as for the multicast-based protocols, they do not address both the power consumption and the scalability. Therefore, we have attempted to design a new multicast routing protocol, which addresses the aforementioned issues. The following Section describes the details of our new solution.

Table 3.1 – Classifications of swarm routing protocols for UAVs

	Routing Strategy				Simulated parameter			Other Criteria	
Routing Protocol	Meta-heuristic based		Geographical location based	Multicast based	PDR	Minimization Delay	Throughput	Scalability	Energy awareness
	ACO	BCO							
APAR [4]	✓	✗	✗	✗	✓	✓	✗	✗	✓
AntHocNet [5]	✓	✗	✗	✗	✓	✓	✗	✗	✓
BeeAdhoc[6]	✗	✓	✗	✗	✓	✓	✗	✗	✓
CA-BCO [7]	✗	✓	✗	✗	✓	✓	✓	✗	✓
GeoUAVs [8]	✗	✗	✓	✗	✓	✓	✓	✓	✗
SP-GMRF [9]	✗	✗	✗	✓	✗	✓	✓	✗	✗
DPTR [10]	✗	✗	✗	✓	✓	✓	✓	✗	✗
Our proposition	✗	✗	✗	✓	✓	✓	✓	✓	✓

CHAPTER 4

ENERGY EFFICIENT MULTICAST ROUTING PROTOCOL FOR UAVS SWARM: OUR CONTRIBUTION

Contents

4.1 Introduction

In this chapter, a presentation for our new Energy efficient Multicast Routing Protocol for UAVs Swarm (SEMRP), which is targeted towards corona virus (COVID-19) pandemic applications. Swarm of UAVs have been used for delivering essential goods or spraying streets with water and disinfectant.

It takes into consideration the power consumption of the UAVs, the scalability, and the reliability of the connection between the nodes for better communication. Also, a comparison to existing routing protocols and performance analysis will be presented. The results of our simulations conducted using NS-2 simulator depicts that the proposed solution is able to reduce the Total Emission Energy, and provide more reliable data delivery with smaller delay. The rest of this chapter is organized as follows: The first section includes the presentation and description of the multicast routing protocol, then the next section will be discussing the evaluation of the performance. Finally, the chapter is sealed with a conclusion.

4.2 Energy efficient Multicast Routing Protocol for UAVs Swarm

In this section, we will be explaining the basic functioning of our solution. First, we will discuss the system model which provides an overview of our routing protocol, in addition to its main objectives. Next, we will explain steps followed to achieve the multicast routing protocol using two versions (SEMRP-V1 and SEMRP-V2) with different perspectives, yet having the same objectives discussed in system model.

4.2.1 System model

The proposed protocol can be applied in COVID-19 applications such as surveillance for purposes such as respecting physical distance, in addition to applications such as spraying areas with disinfectants. The use of swarm of UAVs is highly beneficial for these types of applications, due to low operational costs and high spatial resolution of imagery, especially in large and hard to reach zones. For this purpose, we have the motivation to propose a new multicast approach in a swarm of UAVs in order to choose the shortest distance between UAVs, lower the global consumed energy in the network, and expand the duration of labor.

Our protocol aims at constructing a multicast tree delivering data from one source to the swarm members UAVs (U). We consider the following assumptions:

- We consider that each UAV is aware of its position in the 3D environment with the help of a Positioning Service. The UAVs are equipped with cameras, sensors and other necessary equipment according to the application.
- We assume that the transmission range of a drone can be changed flexibly by adjusting its transmission power. The Maximum Transmission Range of each drone is restricted by MTR, which represents the communication range that can be achieved using Maximum Transmission Power (MTP). For the sake of clarity, Table 4.1 summarizes the used notations.
- To facilitate the movement of the drones and the delivery of data, we assume that the infected city area to be sprayed has a uniform shape rectangular or square for example.

Table 4.1 – Main notations

Parameter	Signification
U	A swarm of UAVs
u_i	UAV with an identifier i
T	Delivery tree for sending multicast messages
u_s	Source of tree
$\mathbb{N}_u$	Number of drones $\mathbb{N}_u = \|U\|$
$N(u_i)$	Neighbors of u_i
$N^T(u_i)$	Neighbors of u_i in T
$D_{(u_i,u_j)}$	Distance between drones u_i and u_j
TR_i	Transmission Range of drone u_i
MTR_i	Maximum Transmission Range of drone u_i
$P_{(u_i,u_j)}$	Required transmission power for drone u_i to reach drone u_j
MTP_i	Maximum Transmission Power of drone u_i | $P_i^M = Max\{P_{(u_i,u_j)} \mid u_j \in N^T(u_i)\}$
MR^T	Multicast Routing Tree rooted at u_s
MD	Multicast Destinations UAVs
X_s	X-coordinate of u_s
Y_s	Y-coordinate of u_s
Z_s	Z-coordinate of u_s
X_i	X-coordinate of $u_i \in N(u_s)$
Y_i	Y-coordinate of $u_i \in N(u_s)$
Z_i	Z-coordinate of $u_i \in N(u_s)$
P_{MinS}	Minimum received signal power level
u_f	forwarder node in T

Our main objective of the two versions is to design an optimal multicast tree by choosing the nearest route to the multicast destination nodes and switching to a closer route if found. This process helps to minimize transmission energy of forwarders and reduce the number of hops in the tree.

4.2.2 Phases of SEMRP Algorithm

In this section, we present the steps and working logic utilized by the both versions, each version is described below for creating a multicast routing tree that spans the multicast group UAVs members.

The First Version Algorithm SEMRP-V1

The construction of the multicast routing tree commences on demand-basis when a source has data to send to multiple multicast destinations. The formal description of the tree construction process is presented in Algorithm 1. The SEMRP-V1 process is carried out in seven phases:

(1) Initially, the multicast tree only contains the root which is source u_s. The source begins by discovering its one-hop neighbors through broadcasting a hello message, which they reply to with their positions so the source can calculate the distance as highlighted in step 2 of Algorithm 1.

(2) The source u_s initiates the construction of the tree by adding the node with the shortest distance to the tree and adjusting the transmission power to reach it, the necessary steps are highlighted in steps 3, 4, 5, and 6 of Algorithm 1.

(3) Next, u_s starts verifying its other one-hop neighbors to potentially increase its transmission power by testing the condition shown in step 7 and following its sub-steps of Algorithm 1.

(4) The source proceeds by notifying its added nodes to the tree so they can continue the construction of the tree as shown in step 8 of Algorithm 1. The notified nodes that are in the tree act as the new source and repeat steps of the Algorithm starting from Step 2 of Algorithm 1 along with updating their neighbors distances from the source. The source also notifies the neighbors that are not members of the tree, so they can discover their new one-hop neighbors (Algorithm 1: step 9).

(5) After reaching a leaf node, the leaf node begins finalizing the first phase of the multicast tree construction by returning to its parent node (Algorithm 1: step 10), the parent node waits for leaf returns from all its tree branches so it can return to a superior parent level as highlighted in steps 3 and 4 of Procedure 1 , the procedure is repeated until reaching the initial source.

(6) The source then begins the second phase of multicast tree construction which is searching for the remaining nodes as highlighted in steps 1 and 2 of Procedure 1, in order to add them to the multicast tree.

(7) To ensure the optimal connectivity of the tree, the remaining nodes are added to the tree with the shortest distance tree member as a parent. The source initiates searching for non tree members by broadcasting a special message to its neighbors, tree members forward the message until it reaches nodes that are not yet in the tree as shown in step 1 in Procedure 2. The non tree members could be either isolated nodes that were not discovered during the first phase of tree construction, or nodes that were discovered, however did not satisfy conditions in steps 3 and 7 of Algorithm 1.

The isolated nodes are added to the tree, with associating the Sender node as the parent as shown in steps 2.a in Procedure 2. While the other non isolated nodes choose the shortest distance one hop tree member as the parent as shown in steps 2.b in Procedure 2. The parent nodes initiate adjusting their transmission power in function of the distances to the recently added child (Procedure 2: step 2.3a).

After adjusting the transmission power of the parent,its neighbors that satisfy the condition in 2.4a in Procedure 2, change their parent node.

In parallel,during the construction of the multicast tree, the source sends the data packets which include the multicast destinations in the header, the packets are forwarded in the tree until reaching the multicast destinations.

Algorithm 1: Multicast Construction Tree of SEMRP-V1

```
Input : $u_s$, $\mathbb{N}_u$ ;
Output : $MR^T$ Multicast Routing Tree rooted at $u_s$ ;
Steps
1. $u_s$ adds itself to the tree $T$ ;
2. for each node $u_i \in N(u_s)$ do
    $D_{(u_S,u_i)} = \sqrt{(X_i - X_s)^2 + (Y_i - Y_s)^2 + (Z_i - Z_s)^2}$ ;
end
3. Add the nearest neighbor $u_i$ of $u_s$ with $D_{(u_s,u_i)}$ to $T$;
4. Mark $u_s$ as the parent of $u_i$;
5. $u_s$ adjusts its transmission power $P_{(u_s,u_i)}$ to reach $u_i$;
6. Increase number of branches of $u_s$;
7. for each node $u_j \in (N(u_i) \cup N(u_s))$ do
    if $(D_{(u_s,u_j)} - D_{(u_s,u_i)}) < D_{(u_i,u_j)}$ then
        7.1 – Add $u_j$ to $T$ and make $u_s$ the parent of $u_j$;
        7.2 – $u_s$ adjusts its transmission power $P_{(u_s,u_j)}$ to reach $u_j$;
        7.3 – Increase number of branches of $u_s$ ;
    end
    else
        7.4 – Add $u_j$ to $T$ and make $u_i$ the parent of $u_j$;
        7.5 – $u_i$ adjusts its transmission power $P_{(u_i,u_j)}$ to reach $u_j$;
        7.6 – Increase number of branches of $u_i$ ;
    end
end
8. Notify the added nodes to the tree ;
9. Notify the rest of the nodes that are not yet in the tree ;
10. if Current Node is leaf then
    return ToParent (ParentId) ;
end
```

```
Procedure 1 ReturnToParent(int ParentId):
    Input : int ParentId
    Output : void
    Steps
    1. if ParentId == S then
        2. if NumberOfReturns == NumberOfBranches then
            SearchForRemainingNodes()
        end
    end
    else
        3. if NumberOfReturns == NumberOfBranches then
            ReturnToParent()
        end
    end
```

Procedure 2 `SearchForRemainingNodes():`

```
Output : void
Steps
1. if $CurrentNode \in Tree\ T$ then
    SearchForRemainingNodes()
end
else
    2. if $CurrentNode \notin Tree\ T$ then
        if CurrentNode is isolated then
            2.1a Add CurrentNode to the tree
            2.2a Make Sender node the parent of node CurrentNode
            2.3a Adjust transmission power of the parent node
            2.4a for each node $\in$ N(Parent Node 'P') do
                2.5a if $D_{(i,p)} < D_{(CurrentNode,p)}$ then
                    Make node P the parent of node i
                end
            end
        end
    end
    else
        if CurrentNode is $\neg$ isolated then
            2.1b Add CurrentNode to the tree
            2.2b Make shortest distance node the parent of node CurrentNode
            2.3b Repeat steps 2.3a,2.4a ,2.5a
        end
    end
end
```

The Second Version Algorithm SEMRP-V2

This algorithm is an improved version of SEMRP-V1, which bases on two-hop discovering. In the following, we explain the main phases of the SEMRP-V2 algorithm.

(1) In the first phase, the source u_s broadcasts a hello message to discover its one-hop neighbors N(u_s), which they reply with their 3D positions to allow it to calculate the distances. Then, the source notifies all its one-hop neighbors to launch their one-hop discovery process.

(2) Then, the source u_s adds its nearest neighbor(s) to the tree and adjust its transmission power to reach it.

(3) In the third phase, u_s should decide which new node will be added to the tree with the minimum power (i.e minimum distance). Here, two alternatives are distinguished: the source u_s should either increase its power to reach another node(s) (this include an adjustment in its transmission power), or select a forwarder node u_f. The selection of the best forwarder is based on comparing the distances to the next closest neighbors of the $N^T(u_i)$ inserted by the source , and choosing the minimum one. In this case, the source marks u_f as its best forwarder and send a selection alert to it. This third phase should be repeated until all nodes are included in the tree.

After that, if a node u_i receives a selection alert, it verifies if its status is set as ready (complet its one hop discovery and notify all its neighbors), then it will execute the above three phases in which it plays the role of the source. Otherwise, it mark itself as selected to be a forwarder. When all neighbors of an u_f are in the tree, it sends an alert to its parent to allow it re-execute the third phase. The formal description of this tree construction process is presented in Algorithm 2 and Function 1.

Algorithm 2: Multicast Construction Tree of SEMRP-V2

```
Input: $u_s$, $\mathbb{N}_u$ ;
Output : $MR^T$ Multicast Routing Tree rooted at $u_s$ ;
Steps
1. $u_s$ discovers its one hop neighbors; ;
2. for each node $u_i \in N(u_s)$ do
    $D_{(u_S,u_i)} = \sqrt{(X_i - X_s)^2 + (Y_i - Y_s)^2 + (Z_i - Z_s)^2}$ ;
end
3. for each node $u_i \in N(u_s)$ do
    if $u_i$ is not notified yet then
        1.Notify($u_i$) // to launch their one-hop discovery process ;
        2.Mark as notified;
    end
end
4. if all $u_i \in N(u_s)$ finish their one-hop neighboring process then
    1. if $myID == u_s$ then
        1. $u_s$ insert myself in $T$;
        2. BuildTree(myID);
    else
        1. Set my status ready;
        2. if I am marked as selected to be a forwarder then
            BuildTree(myID);
        end
    end
end
5. if I receive a selection alert then
    BuildTree(myID);
end
6. if I receive a forwarder finished alert then
    if $N(u_s)$ != $N^T(u_s)$ then
        BuildTree(myID);
    end
end
```

.

```
Function 1 BuildTree(int myID):
    Steps
    1. $u_s = myID$ // Set the function caller as the current source
    2. Add the nearest neighbor $u_i$ of $u_s$ with $D_{(u_s,u_i)}$ to T
    3. $u_{nearest} = u_i$
    4. Set $u_s$ as the parent of $u_{nearest}$
    5. Adjust the transmission power of $u_s$ to reach $u_{nearest}$
    6.while $N(u_s)$ != $N^T(u_s)$ do
        1. int decision = decide($u_s$)
        2. if $decision < 0$ then
            // means: increment power to reach the node $u_{decision}$
            1. int incremental= decision*(-1)
            2. Set $u_s$ as the parent of $u_{incremental}$
            3.Increment the transmission power of $u_s$ to reach $u_{incremental}$
            4. for each node $u_i \in N^T(u_s)$ do
                if $(D_{(u_s,u_i)} < D_{(u_s,u_{incremental})}) and (Hops_{(u_s,u_i)} < Hops_{(u_i,parent(u_i))})$
                 then
                    1. Update the parent of $u_i$ to $u_s$
                end
            end
        else
            // means: select the node $u_{decision}$ as the forwarder of $u_s$
            2. $u_f = u_{decision}$
            1. if $u_f$ is ready then
                1. Send a selection alert to $u_f$
            else
                1. Mark $u_f$ as selected as a forwarder
            end
        end
    end
    7. if $N(u_s) == N^T(u_s)$ then
        if i am not the source node then
            1. send a forwarder finished alert to my parent
        end
    end
```

Summary comparison of SEMRP-V1 and SEMRP-V2

In order to highlight the main differences between SEMRP-V1 and SEMRP-V2, Table 4.2 summarizes the differences in methods used in the key steps of the approach.

Table 4.2 – Differences of SEMRP-V1 and SEMRP-V2

Procedure	SEMRP-V1	SEMRP-V2
Neighboring Discovery	1 Hop	2 Hops
Nearest Neighbor u_n Insertion	After neighbors of 1 Hop reply.	1. **if the network size** $<$ **30:** After neighbors of 2 Hops reply. 2. **if the network size** $\geq$ **30:** After neighbors of 1 Hop reply.
Incremental-Power Neighbor u_j Insertion	1. **if** $(D_{(u_s,u_n)} + D_{(u_n,u_j)}) > D_{(u_s,u_j)}$ **:** u_j is added by u_s 2. **if** $(D_{(u_s,u_n)} + D_{(u_n,u_j)}) < D_{(u_s,u_j)}$ **:** u_j is added by u_n	u_j is added by u_s or u_f
Phases of tree construction	1. **Phase 01 :** Add Nearest Neighbors, Incremental-Power Neighbors of nodes. 2. **Phase 02 :** Add Remaining nodes and Isolated nodes.	1. **Phase 01 :** Add Nearest Neighbors, Incremental-Power Neighbors of nodes, Remaining nodes and Isolated nodes.

4.2.3 Examples Scenario of SEMRP

To illustrate the functionality of SEMRP Algorithms, we consider a simple example presented in the figure 4.1, the network contains 11 UAVs. The creation process starts on demand basis when the source u_s has packets to send to its multicast destination nodes. The tree construction process is described below for both versions.

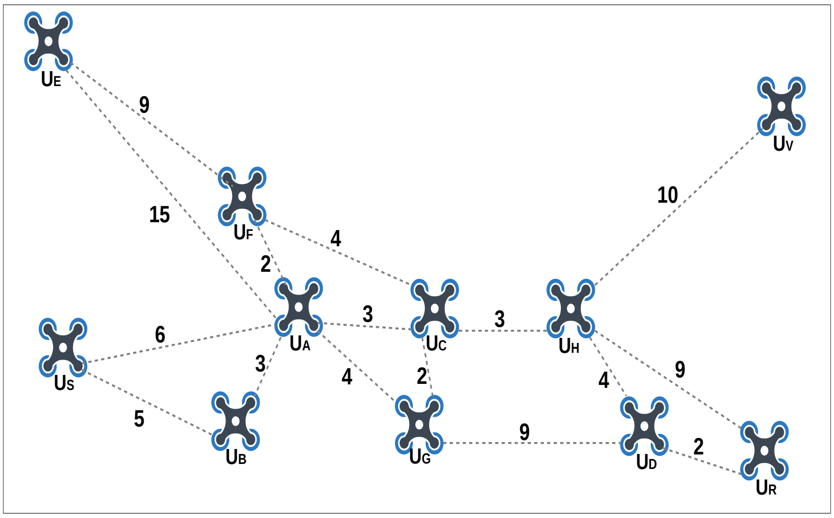


Figure 4.1 – The example scenario topology

1. **Example Scenario of SEMRP-V1:**

   - In the figure 4.2.(a), the multicast tree only contains U_S. The source U_S starts constructing the tree by selecting the closest node which is U_B, thus U_B is added to the tree, U_S adjusts its transmission power to reach U_B and increases its number of branches. Next, U_S calculates the incremental cost of U_A, which is $D_{(U_S,U_A)} - D_{(U_S,U_B)} = 1$, and the selected forwarder U_B calculates the distance to U_A which is $D_{(U_S,U_B)} + D_{(U_B,U_A)} > D_{(U_S,U_A)}$ therefore U_A is added to the tree which results U_S adjusting its transmission power to reach U_A directly and increases its number of branches again.
   - The process is repeated as shown in figure 4.2.(b) : $U_A \longrightarrow U_F$, $U_A \longrightarrow U_C$, $U_A \longrightarrow U_G$, $U_C \longrightarrow U_H$, $U_H \longrightarrow U_D$, and $U_D \longrightarrow U_R$.

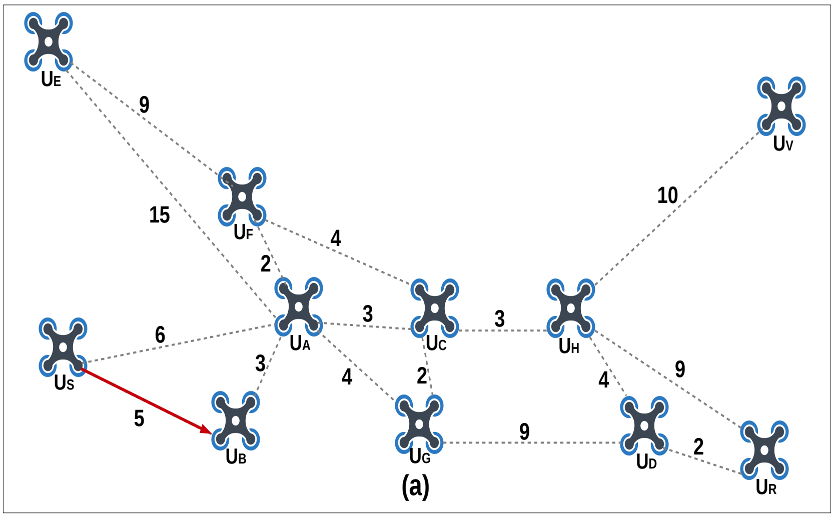
     After reaching the leaf nodes which are U_B, U_R, U_F, and U_G, the leaf nodes begin returning to their parent nodes until reaching U_S, for example U_A waits for U_C, U_G, and U_F by comparing number of branches to number of received return messages so it can return to its parent node S. After all leafs return to the source U_S, U_S initiates broadcasting a message to search for nodes not included in the tree, the message is forwarded by tree members in the network until reaching the targeted nodes. When the message reaches U_E, it selects the closest neighbor tree member from the source as its parent, $U_F \longrightarrow U_E$ which is equal to 17 as shown in figure 4.2.(c).

- The next remaining node is U_V, the closest node is $U_H \longrightarrow U_V$ with $D_{(U_V,U_H)}$= 22, therefore U_H increases its transmission power to reach U_V directly in function of its one hop distance which equals to 10, neighbors closer to U_H than U_V such as U_R with one hop distance equals to 9 can be reached directly from U_H after increasing the transmission power, therefore U_R's new parent is U_H, as shown in figure 4.2.(c). This step has the advantage of minimizing number of messages and number of hops. After adding all nodes to our multicast tree, the delivery of packets that started in parallel with tree construction, continue until reaching the multicast destinations.

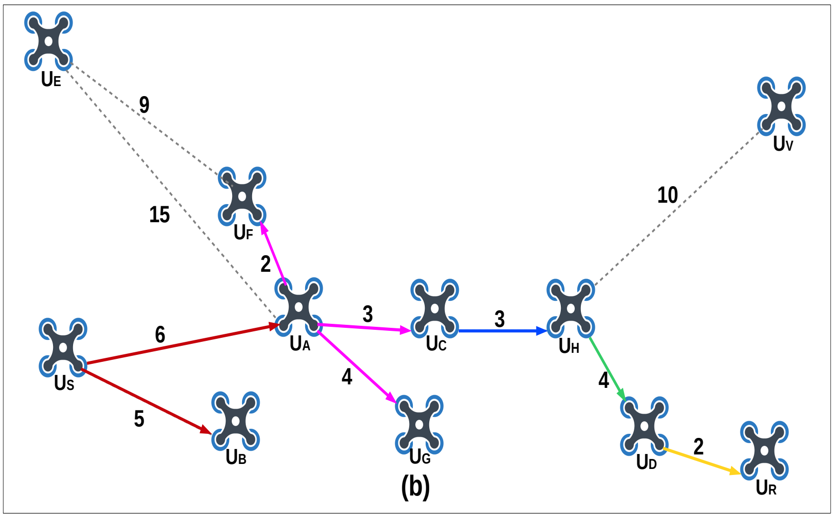
2. **Example Scenario of SEMRP-V2:**

   Let U_S be the source vehicle.

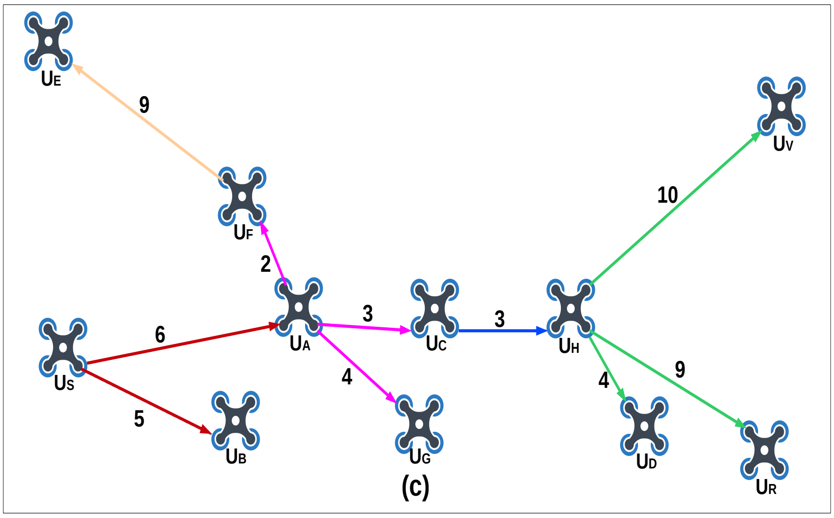
   - Initially, U_S inserts itself as the root of T and adds the nearest neighbor which is U_B as showing in Fig:4.2.(a).
   - Then, the nearest neighbor of U_B is U_A with $D_{(U_B,U_A)} = 3$. And the next near of U_S is U_A with $D_{(U_S,U_A)} = 6$. Because $U_S \longrightarrow U_A$ through U_B is 8 and $U_S \longrightarrow U_A$ directly is 6, U_S chose to increment its power to reach U_A directly. Then, U_S select U_A as next forwarder. At this level, when U_A receives a selection alert it finds itself ready to execute the BuildTree procedure. A inserts its nearest neighbor which is U_F. Then, U_A decides to increment its power to reach U_C then U_G. After that, U_A permits U_C to be its next forwarder. And, the node U_C repeats the same process as U_S and U_A as shown in Fig: 4.2.(b): $U_C \longrightarrow U_H$, $U_H \longrightarrow U_D$, $U_D \longrightarrow U_R$.
   - When increasing the power of a node, we will verify whether its neighbor that is already in the tree can be covered by this node. If this neighbor can be covered and the hop-counts to the source vehicle U_S can be reduced, we will adjust the delivery path for this neighbor and change its parent to the current forwarder node. As shown in (Fig:4.2.(c)), when U_H increases its power to reach U_V it could reach U_R with less number of hops to the source so it becomes its parent rather than U_D. The Data delivery phase could be started in parallel with the tree construction process or after adding all nodes to the resulted tree (Fig:4.2.(c)).



Step: 1



Step: 8



Step: 10

Figure 4.2 – Example scenario of multicast tree construction

> **Note:** SEMRP-V1 and SEMRP-V2 do not always result the same multicast tree because of the operations order differences, and dissimilar methods in adding the nodes. The choice of parameters such as nodes mobility can affect the resulted multicast tree, this can be observed in results provided in the following section.

4.3 Performance Analysis and Numerical Results Discussion

To evaluate our proposal performances, we used the NS-2 [38] simulator. we compare our algorithms with the state-of-the-art routing protocol SP-GMRF [9] through two different scenarios. The performances are recorded taking Nomadic Community mobility model and increasing gradually drone density. The number of UAVs ranges from 10 to 40. The physical and MAC layer protocol used in this simulation is the 802.11p protocol. The rest of two scenarios are described below:

1. In the first scenario, we compare our algorithms using the same simulation parameters as SP-GMRF [9]. The speed of UAVs varies from 5 m/s to 20 m/s, the network size of 1000m x 1000m, the number of destination nodes is 5, the maximum transmission range of UAVs is set to 250 m, and the simulation time is 100 seconds.
2. In the second scenario, we use a network of 2500m x 2500m, the number of destination nodes varies from 5 to 20, the speed of UAVs varies from 10m/s to 35m/s, the maximum transmission range is set to 350m, and duration of simulation is 300 seconds. Simulation parameters are summarized in Table 4.3.

The resulted parameters leads to the conclusion that routing protocol performs better or otherwise worse in a specific scenario. The parameters are the following:

- **Packets Delivery Ratio:** It is defined as the ratio of number of received packets successfully at the destination nodes over the number of packets transmitted by the source nodes.
- **Average End-to-End Delay:** It is the average time from the sending of a packet at a source node until packet delivery to a destination node.
- **Throughput:** It is defined as the average number of packets successfully obtained their destinations per the time it takes for the receiver to get the last packet. This parameter is calculated as the number of bits delivered per second.

- **Total Emission Energy (in dBm):** It signifies the global transmission energy in a network.

  A drone u_i may establish a connection to drone u_j, if u_j is covered by the transmission range of drone u_i. In our model, we adopt the Friis' power transmission formula, which is expressed as follows:

  $$\frac{P_j}{P_i} = G_i G_j \left(\frac{\lambda}{4\pi D_{(u_i,u_j)}} \right)^{\alpha} \tag{4.1}$$

  Where P_i is emission power of the transmitting drone u_i, P_j is the receiving power at the end of drone u_j, G_i and G_j are the antenna gains of the transmitter and the receiver respectively, and λ is the wavelength. The parameter α is typically in the range of 2 to 4, depending on the characteristics of the communication medium [39]. In FANET applications α is set 2. $D_{(u_i,u_j)}$ is the distance between drones u_i and u_j.

  The connectivity of the network depends on the transmission power. Each UAV can adapt its transmission range according to the requirement while its power level can not exceed some maximum value MTP_i .

  When constructing a muticast tree from the source drone u_s to all destination nodes, it is necessary to consider the Signal-to-Noise-and-Interference Ratio (SNIR) requirement for wireless communications. In the free-space propagation model, the path loss is generally a function of the distance between UAVs. The SNIR ratio requirement should be satisfied for each UAV to receive multicast messages. Thus, the received signal power level at each drone should be above the minimum sensitivity level noted as P_{MinS}. As specified in IEEE 802.11p, the minimum sensitivity level equals -68 dBm for the throughput of 27 Mb/s, and the 5.9 GHz band is used for U2U communications. Thus, the transmitting power should hold:

  $$P_i \geq \frac{P_{MinS}}{G_i G_j} \left(\frac{4\pi \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}}{\lambda} \right)^2 \tag{4.2}$$

  Our objective is to design an optimal tree for delivering multicast messages such that the total power consumption can be maximally reduced, then the objective function can be expressed by:

  $$\min \left(\frac{P_{MinS}}{G_i G_j} (\frac{4\pi}{\lambda})^2 \cdot \sum_{u_f \in T} \max_{k \in N(u_f)} D^2_{(u_f,u_k)} \right) \tag{4.3}$$

  The total energy obtained from equation 4.3 is in Watt unit and we transform it to regular dBm expression as follows:

$$10log\left(\frac{P_{MinS}}{G_iG_j}(\frac{4\pi}{\lambda})^2 \cdot \sum_{u_f \in T} \max_{k \in N(u_f)} D^2_{(u_f,u_k)}\right) + 30 \tag{4.4}$$

- **Number Of Hops:** It signifies the number of levels of the constructed tree.

Table 4.3 – Simulation configurations

Parameter	Value: 1^{st} scenario	Value: 2^{nd} scenario
Mobility Model	Nomadic Community	Nomadic Community
Number of UAVs	10, 20, 30, 40	10, 20, 30, 40
Velocity	[5-20] m/s	[10-35] m/s
Simulated area	1000 m x 1000 m	2500 m x 2500 m
Destination nodes	5	5, 10, 15, 20
Transmission range	250 m	350 m
Simulation time	100 seconds	300 seconds
MAC layer protocol	802.11p	802.11p
Packet size	128 bytes	128 bytes
G_i, G_j	1	1
P_{MinS}	$10^{-9.8}$ watt	$10^{-9.8}$ watt
α	2	2
λ	$\frac{c}{f}$ m	$\frac{c}{f}$ m

Figure 4.3 represents the Packet Delivery Ratio (PDR) of SEMRP-V1, SEMRP-V2, and SP-GMRF as a function of UAVs density. The curves show that SEMRP-V1 and SEMRP-V2 perform better than SP-GMRF when it comes to PDR for all network densities in both scenarios.

In the first scenario, both SEMRP-V1 and SEMRP-V2 reach 100% of destination nodes in all network densities. The reason for this packet delivery rate is the absence of disconnections, which allows destination nodes to receive the packets successfully. Nonetheless, it is noted that packet delivery rate of SP-GMRF is decreased to 75%. This can be explained by the increase of time to construct the multicast tree when UAVs density is increased, which means it is frequent for a child node to exit the communication range.

In the second scenario, we also observe that SEMRP-V1 and SEMRP-V2 have a packet delivery rate up to 22% larger than SP-GMRF and both versions kept a high PDR that decreases to 94,33% and 90% respectively comparing to SP-GMRF that is reduced to 50%. The decrease of PDR amount in the second scenario can be explained with links breakage resulted from high mobility of the nodes and packet loss.

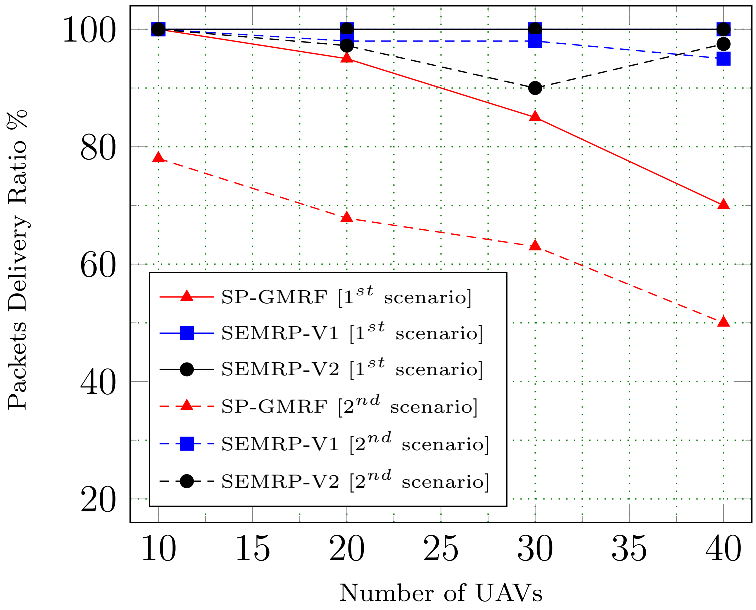


Figure 4.3 – Packets Delivery Ratio vs. UAVs density

Figure 4.4 shows End-to-End Delay of each transmitted data packets during the simulation time as a function of UAVs density. From the curves, we observe that SEMRP-V1 and SEMRP-V2 significantly reduce the average delay in comparison of SP-GMRF in both scenarios.

In the first scenario, we notice that both SEMRP-V1 and SEMRP-V2 kept a reduced End-to-End Delay (at least by 59 ms). The reason for this is the optimality of the route by reducing the number of hops in the tree. Whereas in SP-GMRF we notice an increase in the End-to-End Delay, which is a result of the increase in number of hops and the computation of links in tree construction phase.

We also observe in the second scenario that SEMRP-V1 and SEMRP-V2 significantly reduce End-to-End Delay (at least by 39 ms) compared to SP-GMRF. It is also worth noting that End-to-End delay increases while increasing velocity and destination nodes density. This is mainly due to the increase of the number of hops in SEMRP-V1 and SEMRP-V2, in addition to the high mobility of the nodes which causes packet retransmissions. Whereas, the increase in SP-GMRF is a result for not being able to find the shortest path to the destination during the tree construction phase. In combination with collisions, it causes packet loss in the packets delivery phase and retransmissions.

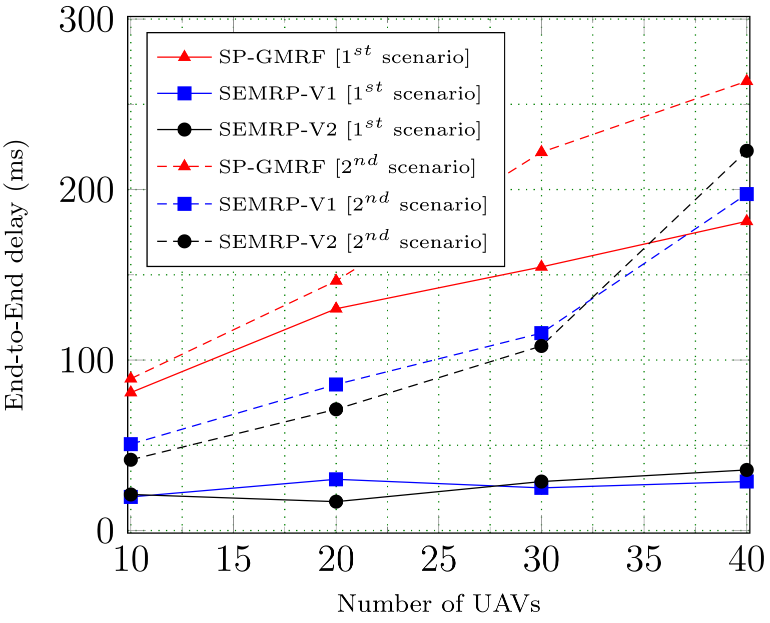


Figure 4.4 – End-to-End delay vs. UAVs density

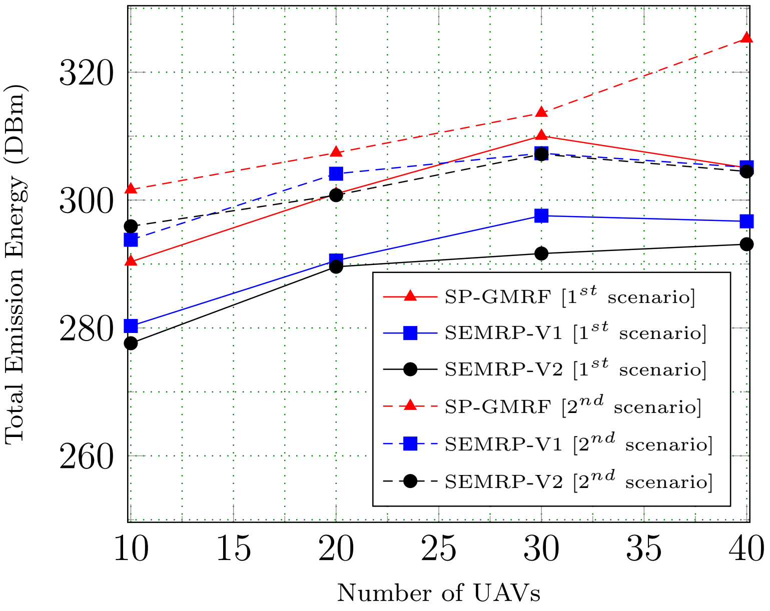


Figure 4.5 – Total Emission Energy vs. UAVs density

Figure 4.5 illustrates the Total Emission Energy for delivery data packets in function of UAVs density. It is noted that SEMRP-V1 and SEMRP-V2 protocols provide less Total Emission Energy in the network for both scenarios (at least by 10 dBm) compared to SP-GMRF. Thus, our solution achieves better results for delivering multicast messages in swarm of UAVs because of our packets forwarding strategy and the efficiency of adjustment of transmission power of the forwarders, which also reduces the number of hops. Thus the Total Emission Energy is accordingly reduced, whereas in SP-GMRF the resulted Total Emission Energy can be explained with the choice of longer routes and increased number of hops.

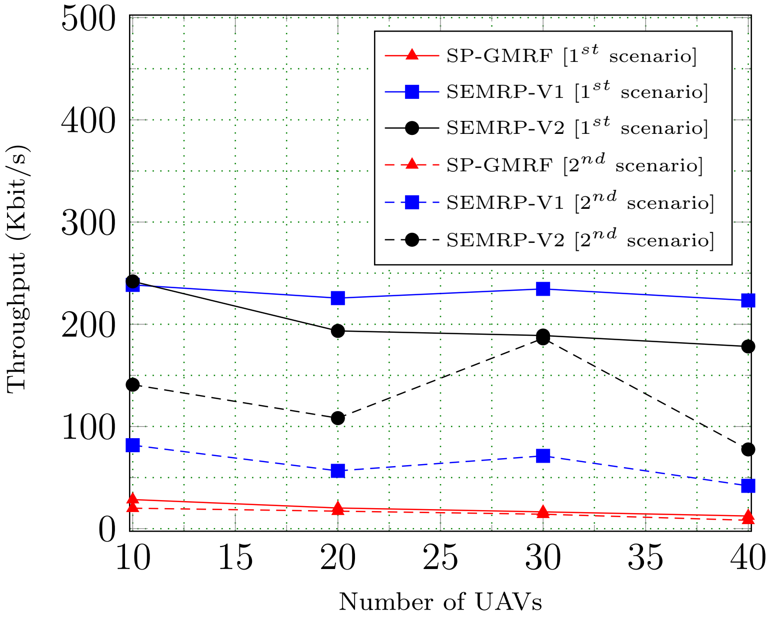


Figure 4.6 – Throughput vs. UAVs density

The utilization of throughput is presented in Figure 4.6. We observe that SP-GMRF performs less when it comes to throughput in both scenarios compared to SEMRP-V1 and SEMRP-V2 protocols. The reason for that is the increased delay to reach destinations, while we notice a higher Throughput for SEMRP-V1 and SEMRP-V2 which indicates a superior rate of packets arrival in minimal delay which confirms the results in Figures 4.3 and 4.4.

Figure 4.7 shows that SEMRP-V1 and SEMRP-V2 algorithms require fewer relays than SP-GMRF algorithm in both scenarios. The reason for that is SEMRP-V1 and SEMRP-V2 provide adjustment of transmission power procedure to each forwarder to potentially reach more UAVs, which helps decrease number of hops in the tree. While SP-GMRF can result increased number of hops when selecting closest forwarders to the destinations in each step. As adding more relays in a wireless path may degrade the transmission reliability, we can say SEMRP-V1 and SEMRP-V2 are more reliable for wireless packet delivery.

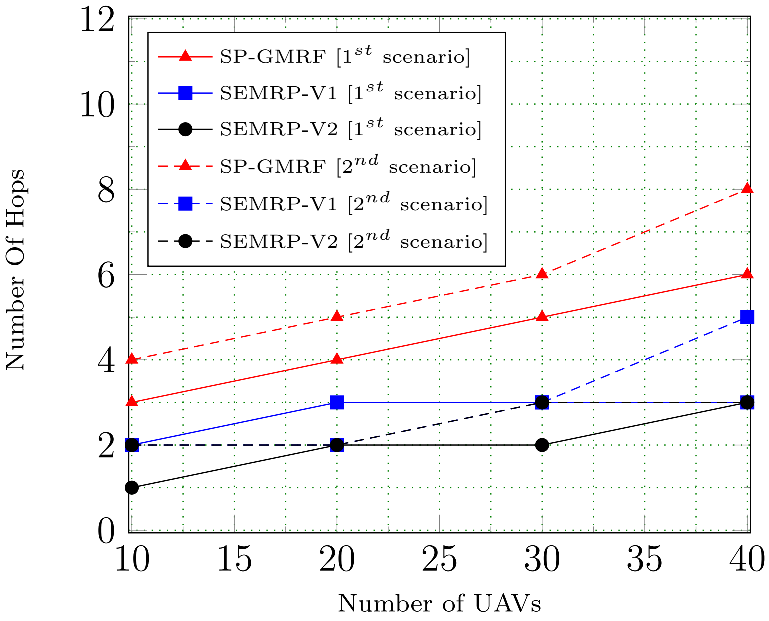


Figure 4.7 – Number of hops vs. UAVs density

4.4 Conclusion

In this chapter, we presented our multicast routing protocol for a swarm of UAVs and discussed its performance. Simulation results demonstrated that the proposed algorithms are more performant compared to SP-GMRF algorithm. SEMRP with its two versions are able to reduce the Total Emission Energy (at least by 10 dBm) and able to provide more reliable data delivery (sending up to 22% more packets) with smaller delay (optimizing the End-to-End Delay by 44%).

CHAPTER 5

CONCLUSION AND FUTURE PERSPECTIVES

Contents

5.1 Summary of our Work

Recently, swarm UAVs are growing in importance and play an essential role in a wide range of applications and complex missions in several domains. Indeed, muticast routing plays a crucial role in ensuring the right functionality and efficient cooperative network operations. In this work, we have presented a new multicast routing protocol named Reliable Multicast Routing Protocol for Swarm of UAVs using Minimum Energy (SEMRP).

As a first step, we have introduced UAVs and discussed their classifications. We have also presented the main features, applications, architectures, and challenges of swarm of UAVs.

As a second step, a brief state-of-the-art of the existing routing protocols in swarm of UAVs is undertaken. The presented swarm routing protocols are also classified according to their transmission strategies, QoS requirements, and other criteria such as energy awareness, simulator, and scalability.

As a third step, we have presented our solution (SEMRP). Moreover, to evaluate the performance of our proposal, we have compared it with the state-of-the-art routing protocol

SP-GMRF through two different scenarios. Effectively, the simulation results demonstrated that our solution outperforms SP-GMRF by reducing average delay, total emission energy, and number of hops. Simulation results also confirmed that our proposal is able to provide more reliable data delivery and higher throughput.

5.2 Future Perspectives

To build on the work accomplishments, some future perspectives should be considered to design new multicast approaches. One of the future work directions is to implement other multicast routing protocols that would provide more realistic comparative results. Another direction for extending SEMRP by adding maintenance mechanisms to react in case of network partitioning and to overcome disconnection problems. Finally, future work will be mainly focused on the use of another simulators.

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