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Thèse

En vue de l'obtention du diplôme de Doctorat en Informatique

Optimisation de l'économie d'énergie dans les réseaux Ad Hoc de drones (UAANETs)

Présentée par :

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For obtaining the diploma of Doctorate in Computer Science

Optimization of energy saving in Unmanned Aerial Ad Hoc Networks (UAANETs)

Presented By:

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Abstract

Unmanned Aerial Vehicles (UAVs) are the output of advanced concepts in leading fields, such as autonomous systems, remote control, wireless communication, etc. They were mainly an exclusive military technology serving as a saver of pilots' lives, where they take over all forms of perilous missions. For years, such a use kind was that common; the notable success in accomplishing tasks was behind the idea of going through a civilian experience. As expected, the UAVs were a game-changer for civil applications; outstanding achievements and a new lifestyle were there. Such a new form of use case gets an extended range once multi-UAV systems take place, where powerful features come out, overcoming the shortcomings the reason behind was the UAV's limited resources. Adopting the Ad Hoc mode for communication, multi-UAV systems become Unmanned Aerial Ad Hoc Network (UAANET)—the new Ad Hoc networks kind—where nodes are UAVs and the deployment environment is the sky. Despite how UAANET was the momentum of UAVs applications' efficiency, productivity, and simplicity, prominent challenges are letting performance mediocre that way needs are not met. Topping the list is the limited energy as a result of using very limited energy sources along with the constraints imposed on payloads. Consequently, energy-efficient solutions for UAANET are deemed of utmost importance due to the positive impact they could bring regarding applications' efficiency, yield, and scope. In this context, intending to optimize energy saving in such an environment, we proposed the ElectriBio-inspired Energy-Efficient Self-organization model for UAANET (EBEESU), for a monitoring scenario, where a collection of contributions were involved in different levels under different forms. The notable positive impact of our contributions regarding average energy dissipation, cluster heads lifetime, data loss ratio, and End-To-End delay has been numerically proven through simulation results. Furthermore, an analysis of the achieved results and their comparison with other solutions adopted in the simulation scenario were presented.

Key words

Unmanned Aerial Vehicles (UAVs); Unmanned Aerial Ad Hoc Network (UAANET); Energy-efficient; Self-organization model; Mobility Model; Clustering

Résumé

Les véhicules aériens sans pilote (UAVs) sont le fruit de concepts avancés dans des domaines de pointe, tels que les systèmes autonomes, la télécommande, la communication sans fil, etc. Ils étaient principalement une technologie militaire exclusive servant à sauver la vie des pilotes, où ils prennent en charge toutes formes de missions périlleuses. Pendant des années, un tel type d'utilisation était si courant ; le succès notable dans l'accomplissement des tâches était à l'origine de l'idée de vivre une expérience civile. Comme prévu, les UAVs ont changé la donne pour les applications civiles ; des réalisations exceptionnelles et un nouveau style de vie étaient là. Une telle nouvelle forme de cas d'utilisation a pu obtenir une portée étendue une fois que les systèmes multi-UAV sont mis en place, où des fonctionnalités puissantes ont apparu, surmontant les lacunes dues aux ressources limitées de l'UAV. En adoptant le mode Ad Hoc pour la communication, les systèmes multi-UAV deviennent un réseau Ad Hoc de véhicules aériens sans pilote (UAANET)—le nouveau type de réseaux Ad Hoc—où les nœuds sont des UAVs et l'environnement de déploiement est le ciel. Bien que l'UAANET a été l'élan de l'efficacité, la productivité et de la simplicité des applications des UAVs, des défis importants influent négativement la performance. Par conséquent, les besoins ne peuvent pas être satisfaits. L'énergie limitée représente le défi principal résultant de l'utilisation de sources d'énergie très limitées et les contraintes imposées aux charges utiles. En conséquence, les solutions éco-énergétiques pour UAANET sont jugées de la plus haute importance en raison de l'impact positif qu'elles pourraient avoir sur l'efficacité, le rendement et la portée des applications. Dans ce contexte, dans le but d'optimiser l'économie d'énergie dans un tel environnement, nous avons proposé un modèle d'auto-organisation économe en énergie pour UAANET (EBEESU), pour un scénario de surveillance, où une collection de contributions a été appliquée à des niveaux différents sous différentes formes. L'impact positif notable de nos contributions concernant la dissipation d'énergie moyenne, la durée de vie des têtes de cluster, le taux de perte de données et le délai de bout en bout a été prouvé numériquement à travers les résultats de simulation. De plus, l'analyse des résultats obtenus et leur comparaison avec d'autres solutions adoptées dans le scénario de simulation ont été présentées.

Mots clés

Véhicules Aériens sans Pilote (UAVs) ; Réseau Ad Hoc de Véhicules Aériens sans Pilote (UAANET) ; éco-énergétique ; Modèle d'auto-organisation ; Modèle de mobilité ; regroupement

الملخص

المركبات الجوية غيرالمأهولة (UAVs) هي نتاج مفاهيم متقدمة في مجالات رائدة، على غرارالأنظمة الذاتية، التحكم عن بعد، الاتصالات اللاسلكية، وما إلى ذلك. لقد كانت بشكل أساسي تقنية عسكرية حصرية منقذة لحياة الطيارين، حيث تتولى جميع أشكال المهام المحفوفة بالمخاطر. لسنوات، كان هذا النوع من الإستخدام هوالمعتاد ؛ حيث أن النجاح الملحوظ في إنجازالمهام كان وراء فكرة المروربتجربة مدنية. كما هومتوقع، فإن الطائرات بدون طياركانت عامل تغيير في قواعد اللعبة بالنسبة للتطبيقات المدنية ؛ كانت هناك إنجازات بارزة وأسلوب حياة جديد. توسع نطاق هذا الشكل الجديد من الإستخدام بمجرد ظهورأنظمة الطائرات بدون طيارالمتعددة (Multi-UAV systems)، حيث تكون هناك ميزات قوية، مما ساعد في التغلب على النقائص التي كان السبب في وجودها الموارد المحدودة للطائرة بدون طيار. باعتماد نمط Ad Hoc للاتصال، تصبح أنظمة الطائرات بدون طيارالمتعددة شبكة مخصصة للمركبات الجوية غيرالمأهولة (UAANET)—نوع جديد من الشبكات المخصصة—أين تكون العقد هي الطائرات بدون طيار وبيئة النشر هي السماء. على الرغم من كيف أن UAANET كانت بمثابة قوة دافعة لزيادة كفاءة تطبيقات الطائرات بدون طياروإنتاجيتها وبساطتها، فإنه هنالك مجموعة من التحديات البارزة تجعل الأداء متواضعًا بعيدا عن مستوى تلبية الاحتياجات. يتصدر القائمة الطاقة المحدودة التي تعتبر نتيجة لإستخدام مصادرطاقة محدودة للغاية إلى جانب القيود المفروضة على الحمولات. وبالتالي، تعتبرالحلول الموفرة للطاقة لـ UAANET ذات أهمية بالغة نظرا للتأثيرالإيجابي الذي يمكن أن تحدثه فيما يتعلق بكفاءة التطبيقات والعائد والنطاق. في هذا السياق، بهدف تحسين توفيرالطاقة في مثل هذه البيئة، اقترحنا نموذج تنظيم ذاتي موفرللطاقة (EBEESU)، لسيناريوالمراقبة، حيث تم تضمين مجموعة من المساهمات في مستويات مختلفة تحت أشكال مختلفة. من خلال نتائج المحاكاة تم إثبات التأثيرالإيجابي الملحوظ لمساهماتنا فيما يتعلق بمتوسط تبديد الطاقة، عمررؤساء المجموعات، نسبة فقدان البيانات، ومدة التأخيرالمتعلقة بتسليم البيانات بين العقد المرسلة والمرسل إليها. كما تم تقديم تحليل للنتائج المحققة ومقارنتها مع الحلول الأخرى المعتمدة في سيناريو المحاكاة.

الكلمات المفتاحية

المركبات الجوية غير المأهولة ؛ الشبكة المخصصة للمركبات الجوية غيرالمأهولة ؛ كفاءة الطاقة ؛ نموذج التنظيم الذاتي ؛ نموذج التنقل ؛ التجميع

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General introduction

UAVs, standing for Unmanned Aerial Vehicles, are a prominent form of sophisticated technology used to serve humans. Mainly, the aim was to save pilots' lives, where, in some cases, due to sudden attacks or technical troubles, the aircraft could be lost or ruined; consequently, the pilot would be affected. For years, the use was exclusive for military tasks; such adoption was outstanding regarding missions' flexibility and simplicity. The successful military experience was behind the emergence of the civilian one, where diverse civil applications have become UAV-based (traffic monitoring, agriculture, inspection, etc.) However, with the increasing requirements and needs of nowadays applications, the single-UAV use case is no longer practical nor able to meet different applications' specifications. The notable shortcomings give rise to the multi-UAV systems, where a set of UAVs are used to perform tasks cooperatively. Cooperation between the system members calls for communication; indeed, adopting the Ad Hoc mode is deemed the most efficient, simple, and affordable solution, forming the new Ad Hoc network: Unmanned Aerial Ad Hoc Network (UAANET). The UAANET has a significant role in presenting the UAVs in a more robust and productive way, increasing the popularity and widespread of UAVs' applications.

Despite the UAANET's wide use and new shots coming out for different sectors due to UAV-based applications, many significant challenges take place, which harmfully affects UAANET's performance. Those challenges mainly result from the new environment and features of nodes forming such a network. These challenges differ regarding the impact each could have; when it comes to their classification, the limited energy is the one topping the list since it directly affects performance, lifetime, yield, and applications' range. Due to this fact, going through solutions that will boost the efficient use of energy and increase energy saving is deemed a hot topic. Indeed, limited energy constraint has already been addressed in other networks kinds, such as MANETs (Mobile Ad Hoc Networks) and WSNs (Wireless Sensor Networks). However, for UAANET, energy is deemed more crucial due to the fact that there is an additional subsystem in need of energy, namely the propulsion subsystem allowing UAVs to move through the air. Moreover, the propulsion subsystem consumes an amount of energy that exceeds the other common subsystems (communication, sensing, computing) [1, 2], explaining why energy in UAANET is more crucial compared to other environments.

Due to the significant impact of limited energy on UAVs' performance and consequently the whole network performance, energy-efficient solutions for UAANET are the area of interest getting much attention, particularly energy-efficient communication [3]. Indeed, considering such a problematic could be highlighted from different perspectives due to the fact of being multidisciplinary. Literature into this context is an amalgam of propositions, where researchers from different fields and with different backgrounds (networking, mechanical engineering, electrical engineering, electronics, etc.) have presented numerous solutions that aim to overcome the limited energy constraint in UAVs' environment. Those proposed solutions were about going through new energy sources, developing hybrid propulsion systems, boosting energy efficiency through energy-efficient communication algorithms, optimized trajectories, energy-efficient design and configuration, etc. Therefore, each proposed solution involved contributions related to the treated aspect.

Since we are interested in UAVs forming a network, the aspect to be addressed in our case is communication—as it is the gist of networking—where energy saving will be considered through adopting an energy-efficient collaborative environment for UAVs. To this end, we proposed the ElectriBio-inspired Energy-Efficient Self-organization model for UAANET (EBEESU), where we have involved multi-level contributions to maximize energy saving. Our model considers mobility and communication in a complementary mode, where both boost the efficient use of energy. The main idea was to decrease energy waste in relation to communication within the network, increasing energy saving. Furthermore, the proposed mobility model contributes to strengthening the adopted communication algorithm efficiency. For the mobility model, the motion pattern ensures a collective motion, maintaining connectivity, reducing thus the loss ratio. Furthermore, this model eliminates the overhead of group motions due to eliminating broadcasting information about speed and direction. The reduced loss ratio and overhead would consequently save energy. On the other hand, we adopted an energy-efficient cluster-based communication algorithm, where energy saving has been carefully taken into account through introducing significant contributions regarding the clustering approach, communication scheme, data aggregation, etc.

The content mentioned above will be presented in detail in the form of consecutive and coherent chapters; five chapters are considered as follows:

- **Chapter 1: Unmanned Aerial Vehicles Technology Presentation:** in this chapter, we present basic concepts related to UAVs technology: definitions, nomenclature, classification, components, history, applications' domain, etc.

- **Chapter 2: Multi-UAV systems & Unmanned Aerial Ad Hoc Network:** this chapter presents the advantages of multi-UAV systems over the single UAVs; also, it introduces the new kind of Ad Hoc networks, UAANET, and its new features. Furthermore, a comparison with the MANET and VANET is also given.

- **Chapter 3: Energy constraint in UAANET:** this chapter presents the impact of limited energy on performance and prominent factors affecting UAVs' energy consumption.
- **Chapter 4: State of the art:** in this chapter, we present literature content addressing the limited energy constraint in the UAVs' environment.
- **Chapter 5: ElectriBio-inspired Energy-Efficient Self-organization model for Unmanned Aerial Ad Hoc Network (EBEESU):** this chapter presents in detail the main concepts of our proposed solution and gives justifications regarding those concepts. Also, the main contributions of our model are explained and proven through simulation results.

Part 1: Overview on Unmanned Aerial Vehicles (UAVs) Technology

Chapter 1

Unmanned Aerial Vehicles Technology Presentation

Highlights:

- Introduce the UAVs technology to the reader by shedding light on basic notions: definitions, nomenclature, classification, components, etc.
- Review the significant historical stations of the UAVs technology.
- Present prominent domains the UAVs are involved in.
- Explore the fundamental physics concepts building a UAV.

1.1 Introduction

Unmanned Aerial Vehicles, abridged as UAVs, are an epoch-making technology—new lifestyle comes out. The expeditious growth of leading fields, such as wireless communication technologies, sensing, miniaturization of electronic equipment, embedded systems, etc., is behind such technology glory. The military field was the first having a shot at using UAVs technology; an outstanding experience was the military one, giving rise to the idea of switching to the civil domain. In turn, the civil experience has been very prosperous, where various use cases were considered: agriculture, search and rescue, and monitoring, etc. The conspicuous kickoff of that experience was about 2016 when the FAA (Federation Aviation Administration) gave the go-ahead to many companies petitioning to involve UAVs in their activities. The United States of America (USA), China, and India are the top three countries with a grown rate of UAVs' civil applications use.

This chapter will be in the form of a short overview pointing out the basic concepts related to the UAVs; in-depth details will be the purpose of the coming chain of sections.

1.2 Definitions and Nomenclature

Due to the UAV term's widespread among different social segments in both the industry and academia, renowned official bodies have adopted specific definitions explaining what a UAV is about. We give emphasis to the most prominent ones:

1. **According to the United States Department of Defense (US DoD):** "A powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or non-lethal payload. Ballistic or semi ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles [4]."

2. **According to the American Institute of Aeronautics and Astronautics (AIAA):** "An aircraft which is designed or modified, not to carry a human pilot and is operated through electronic input initiated by the flight controller or by an on-board autonomous flight management control system that does not require flight controller intervention [5]."

There are two popular kinds the term UAV encapsulates, namely, the fixed-wing (Fig. 3.6(a)) and the multi-rotor—aka multi-copter (Tri-copter, Quad-copter, Hexa-copter, etc.)—(Fig. 3.6(b)). A hybrid version blending those two kinds' features also exists (Fig. 1.1(c)). Each of those kinds has specific features, and the choice of the

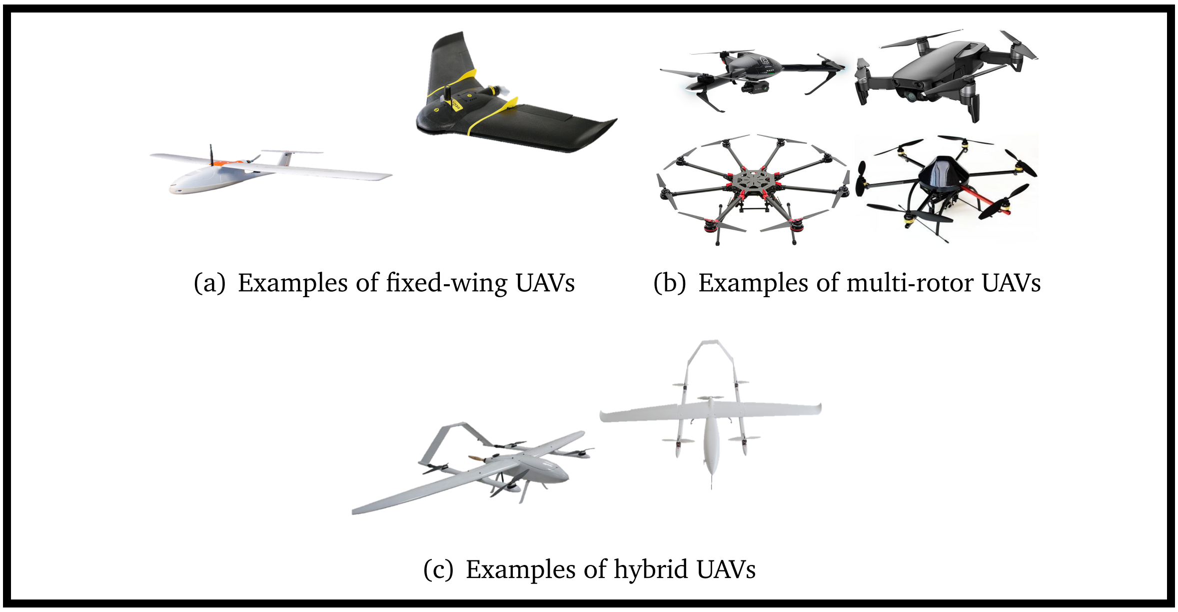


Figure 1.1: *UAVs' main kinds*

appropriate one depends entirely on how much that UAV kind fits the application scenario and makes it easier and efficient. In our case, we are interested in multi-rotor UAVs; that is why most of the chapter's content gives focus to them.

Indeed, numerous other terms the UAV shares the same meaning with are encountered; Unmanned Aircraft System (UAS) used by the FAA. Remotely Piloted Vehicles (RPVs), where the first use was during the Vietnam War. The RPV has been changed by the USAF (United States Air Force) to be RPA (Remotely Piloted Aircraft), whereas the United Kingdom has replaced it with RPAS that stands for Remotely Piloted Air System [6]. However, the **"drone"** term has the highest usage frequency among people—mostly referring to the multi-rotor kind. The drone meaning has many variants; the ones that seem the most fitting are mentioned as follows:

1. **According to the *Oxford English Dictionary*:**

    - Drone [noun]: "A remote-controlled or autonomous vehicle or robotic device which operates in an environment or setting too dangerous or difficult for a human..."
    - Drone [noun]: "A small remote-controlled flying device, typically a small four-rotored helicopter, which has a relatively short range..."
    - Drone [verb]: "intransitive. With adverbs or adverbial phrases expressing direction: to make a continuous hum, buzz, etc., while travelling in the direction..."

The third definition explains why the drone term is mostly used for the UAVs of type multi-rotor, where those UAVs make out a sound when they move through the air, resulting from their rotating motors.

2. **Other sources state that the term DRONE stands for Dynamic Remotely Operated Navigation Equipment.**

1.3 Brief on UAVs' history

Indeed, talking about the UAVs' history will not be that clear one identified by a specific date; such a history may be a collection of hyperlinks toward many other concepts' history, such as aviation, autonomous systems, remote control, etc. For this reason, we only highlight the essential stations of the UAVs' booming experience; some of the most important dates, according to [7], are given as follows:

- In 1883, Douglas Archibald, an Englishman, appended an anemometer to a kite to measure the wind velocity in case of altitudes up to 1200 ft. In 1887, cameras were involved and appended to those kites, giving one of the first UAVs used for reconnaissance in the world. In the military side, hundreds of photographs have been taken from those kites during the Spanish-American war.

- A biplane UAV, known as ”Kettering Bug” sometimes only ”Bug,” has been developed by Charles Kettering (of General Motors fame) for the Army Signal Corps. A predefined set of controls has been used to guide the Bug to its target. Similar to Charles Kettering's one, a UAV has been developed, in 1917, by Lawrence Sperry. It was called ”The Sperry-Curtis Aerial Torpedo,” which has performed successful manifold flights; however, it was not involved in the military field.

- On September 3, 1924, Archibald Montgomery Low, known as the “Father of Radio Guidance Systems,” made the first successful radio-controlled flight in the world.

- The British, in 1933, lived the experience of steering three biplanes by remote control from a ship. A series of UAVs called RP-1, RP-2, RP-3, and RP-4 have been developed by the Englishman, Reginald Leigh Denny, and two Americans, Walter Righter and Kenneth Case. They create their own company called the ”Radioplane Company” in 1939; thousands of UAVs were built by this company during World War 2.

- During the Vietnam War, the UAVs' use became very extensive, with a success rate of 90 %.

- In 1971, the United States decided to work again on UAVs; mini-RPVs have been used to spot artillery's target. In 1974, an office for RPV weapons system management had been established by the Army's Materiel Command.

1.4 UAVs' classification

Indeed, the classification process could be performed based on various features, parameters, and aspects. We consider prominent classification kinds, namely based on key physical features: Mass, Range, Flight Altitude, and Endurance, as depicted in Table 1.1 taken from [6]. Also, a classification based on the platform type: HAP (High Altitude Platform) and LAP (Low Altitude Platform) is presented in Table 1.2 mentioned in [8].

	Mass (kg)	Range (km)	Flight alt. (m)	Endurance (h)
Micro	<5	<10	250	1
Mini	<20/25/30/150[1]	<10	150/250/300	<2
Tactical				
Close Range (CR)	25–150	10–30	3,000	2–4
Short Range (SR)	50–250	30–70	3,000	3–6
Medium Range (MR)	150–500	70–200	5,000	6–10
MR Endurance (MRE)	500–1,500	>500	8,000	10–18
Low Altitude Deep Penetration (LADP)	250–2,500	>250	50–9,000	0.5–1
Low Altitude Long Endurance (LALE)	15–25	>500	3,000	>24
Medium Altitude Long Endurance (MALE)	1,000–1,500	>500	3,000	24–48
Strategic				
High Altitude Long Endurance (HALE)	2,500–5,000	>2,000	20,000	24–48
Stratospheric (Strato)	>2,500	>2,000	>20,000	>48
Exo-stratospheric (EXO)	TBD	TBD	>30,500	TBD
Special Task				
Unmanned Combat AV (UCAV)	>1,000	1,500	12,000	2
Lethal (LET)	TBD	300	4,000	3–4
Decoys (DEC)	150–250	0–500	50–5,000	<4

Table 1.1: *UAVs' classification based on mass, range, flight altitude, and endurance*

1.5 Domains holding UAVs' applications

Plenty of applications have become UAV-based ones, in both the military field and the civil. This section provides in-depth details about how UAVs are involved in accomplishing different tasks in different contexts. Also, an assortment of pictures illus-

[1]Varies with national legal restrictions

Issues	HAP			LAP		
Type	Airship	Aircraft	Balloon	VTOL	Aircraft	Balloon
Endurance	long endurance	15-30 hours JP-fuel >7 days Solar	Long endurance Up to 100 days	Few hours	Few hours	From 1 day To few days
Max. Altitude	Up to 25 km	15-20 km	17-23 km	Up to 4 km	Up to 5 km	Up to 1.5 km
Payload (kg)	Hundreds of kg's	Up to 1700 kg	Tens of kg's	Few kg's	Few kg's	Tens of kg's
Flight Range	Hundreds of km's	From 1500 to 25000 km	Up to 17 million km	Tens of km's	Less than 200 km	Tethered Balloon
Deployment time	Need Runway	Need Runway	custom-built Auto launchers	Easy to deploy	Easy to launched by catapult	Easy to deploy 10-30 minutes
Fuel type	Helium Balloon	JP-8 jet fuel Solar panels	Helium Balloon Solar panels	Batteries Solar panels	Fuel injection engine	Helium
Operational complexity	Complex	Complex	Complex	Simple	Medium	Simple
Coverage area	Hundreds of km's	Hundreds of km's	Thousands of km's	Tens of km's	Hundreds of km's	Several tens of km's
UAV Weight	Few hundreds of kg's	Few thousands of kg's	Tens of kg's	Few of kg's	Tens of kg's	Tens of kg's
Public safety	Considered safe	Considered safe	Need global regulations	Need safety regulations	Safe	Safe
Applications	Testing environmental effects	GIS Imaging	Internet Delivery	Internet Delivery	Agriculture application	Aerial base station
Examples	HiSentinel80	Global Hawk	Project Loon Balloon (Google)	LIDAR	EMT Luna X-2000	Desert Star 34cm Helikite

Table 1.2: *UAVs' classification based on platform type*

trated in Fig 1.2 (Fig 1.2(a), Fig 1.2(b), Fig 1.2(c), Fig 1.2(d), Fig 1.2(e), Fig 1.2(f), Fig 1.2(g), Fig 1.2(h), Fig 1.2(i)) present examples of UAV-based applications.

1.5.1 Military applications

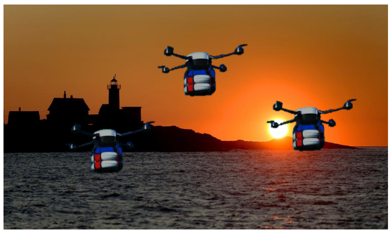
The military field is deemed the UAVs' native land; the UAVs have been used for hazardous situations where the human presence is not that handy solution. They are mainly used for border surveillance, spying, air support, reconnaissance, attack and air raids, etc. The great success of the military experience is behind the emergence of the civil one.

1.5.2 Civil applications

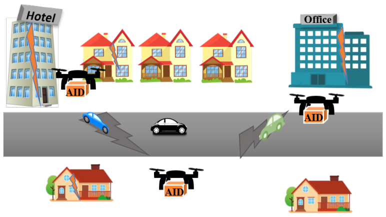
A: Search and Rescue (SAR)

UAVs for SAR is one of the most prevalent use cases. They are used in emergency interventions to access quarantined areas, rescuing people, and getting information from damaged regions, which helps to make swift and apt decisions. Such a use case is of great avail since it saves time and rescues affected people, whereas, with

(a) Surveillance and attack



(b) Search and rescue



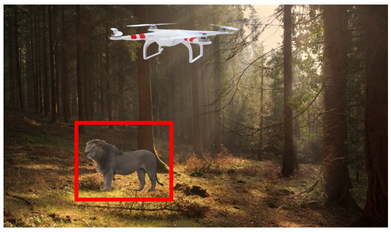
(c) Delivering first aids

(d) Fire-fighting

(e) Traffic monitoring

(f) Agriculture

(g) Delivering goods



(h) Tracking

(i) Inspection

Figure 1.2: *Examples of UAVs applications*

conventional solutions, rescue teams are obligated to directly access perilous regions. Moreover, this solution is cost-effective and extremely practical, thanks to low-cost UAVs. Among prominent SAR scenarios, using UAVs:

- Delivering food and medical supplies to isolated regions, for example, due to epidemics or natural disasters.
- Intervention to extinguish fires.
- Searching for lost persons in mountains, forests, deserts, etc.
- Serve as backup base stations to provide wireless coverage for out-coverage regions because of destroyed communication's infrastructure after natural disasters.

In this context, a well-known Irish startup called DroneSAR (Drone Search And Rescue) develops platforms specifically for search and rescue missions. Those platforms aim to make the SAR less expensive and less complex as much as possible.

B: Monitoring

UAV-based monitoring scenarios are broadly used nowadays due to the handy UAVs' features boosting such application domain yield; among those features:

- The flexibility, simplicity, and rapidity of deployment allow smooth monitoring of suddenly-happening events, e.g., accidents, crimes, etc.
- The mobility facilitates collecting data from different places within the monitored region, increasing thus the coverage rate and providing rich information regarding the phenomena to be studied, e.g., air pollution, congestion in routes, etc.
- The ability to fly at different altitudes allows controlling the desired resolution by choosing the fitting altitude for monitoring.
- The ability of hovering (for multi-rotor UAVs) allows monitoring a particular region within the area of interest.

Among prominent monitoring scenarios involving UAVs:

- Monitoring route traffic, accidents, and crimes' sites.
- Wildlife monitoring to prepare documentary videos and research missions.
- Monitoring post-disaster areas by capturing up field images and videos, which gives important details about the affected area.

- Study and evaluate the biodiversity of forests and vegetation for scientific research purposes.
- Perform statistical studies regarding the evolution of water sources maps, such as rivers, dams, sweet water swamp, etc.
- Monitoring official events, e.g., sport events, festivals, outdoor conferences, etc.

C: Agriculture

The agriculture sector has promising horizons due to the UAVs technology that has opened up new prospects by introducing modern strategies to build modern agriculture. The UAVs have powerfully proven that their use brought new efficient work techniques to accomplish different agriculture activities in a simple yet productive way. Many vital tasks the UAVs are involved in to perform, we cite:

- Inspect and identify areas in need of fertilizers and chemicals.
- Track and assess crop growth and estimate productivity level, which provides farmers with analytical information swiftly and efficiently.
- Use of 3-D maps to study the soil, which helps to make plans to increase productivity and improve quality by improving, for example, the distribution of fertilizer levels.
- Preview the plants' health status by processing multi-spectral images to determine the disease spots' early spread, thanks to the infrared sensors appended to the UAVs.
- Planting; well-known experiment, in this context, is that of the British company "BioCarbon," which used UAVs loaded with seeds to be planted.

Due to the fabulous success of the UAVs' experience in the agriculture domain, leading companies, such as DJI, Ag Drones & Sensors, AgEagle, etc., are interested in building UAVs mainly used to accomplish agriculture activities.

D: Delivery

This domain is flourishing with an unprecedented rhythm, where UAVs are widely used to deliver different kinds of items, namely, food, medical supplies, parcels, etc. Examples of popular UAV-based delivery experiences driven by different companies around the world are listed below:

- Food delivery: Wing Aviation, Uber, Domino's, KFC, Ele.me, Zomato.

- Medical supplies delivery: Zipline, Antwork.
- Parcels delivery: Amazon, United Parcel Service of America, DHL International GmbH.

E: Tracking

UAV-based object tracking applications are noticeably attracting attention; the UAV is used to track a specific object (human, animal, etc.), either only to get its location continuously or to execute specific predefined instructions once it is detected. Among prominent tracking scenarios, using UAVs, we mention:

- A recent and popular experience was during the COVID-19 epidemic, where the UAVs have been used to track people in the streets to admonish the ones not putting masks and invite them to take the necessary precautions seriously.
- Pursue fugitive criminals, where the UAVs provide police with information regarding criminals' location.
- Track wild animals within forests and mountains to carefully observe their behaviors and routines, to prepare documentaries about animals' lifestyle.

F: Infrastructures and installations inspection

UAV-based inspection is one of the modern applications knowing an increased use rate. Thanks to the UAVs' flexible use, inspection tasks achieve a high level of simplicity and accuracy. Examples of scenarios in this context are: inspecting gas pipes, electrical wires, solar panels, wind turbines, etc.

1.6 Operating systems for UAVs

UAVs' performance gets a notable professional level, bringing the opportunity for highly complex applications to be considered. Therefore, effective platforms are needed to hold those applications in a more flexible, cost-effective, skillful, yet simple design. To this end, UAV-special operating systems for resource management, synchronization, scheduling, Input/Output operations, communication [9] are strongly recommended. Indeed, the literature's content dealing with UAVs' operating systems is neither that rich nor in-depth; among the most often mentioned operating systems: FreeRTOS, LynxOS 7.0 Real-Time Operating System (RTOS), and Flytos.

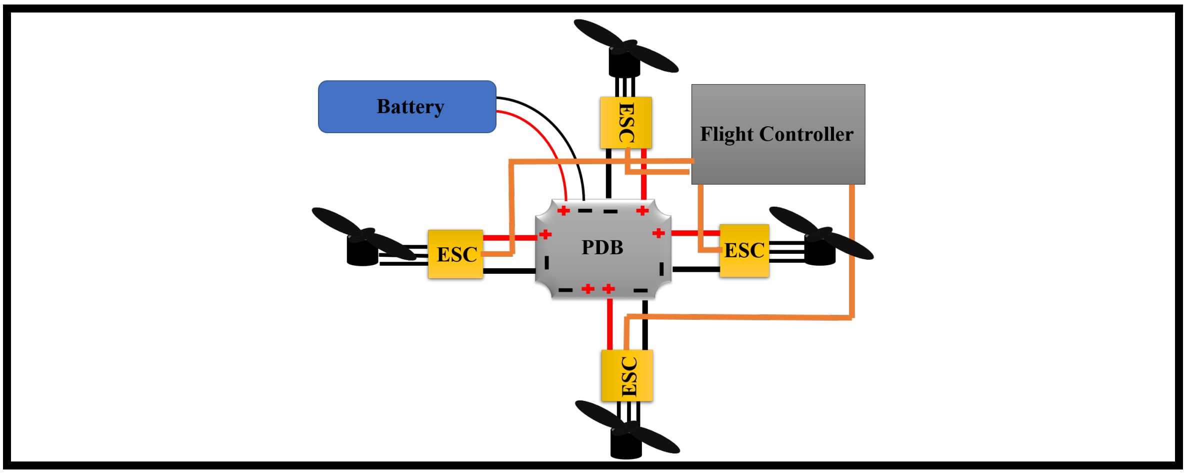


Figure 1.3: *UAV main components*

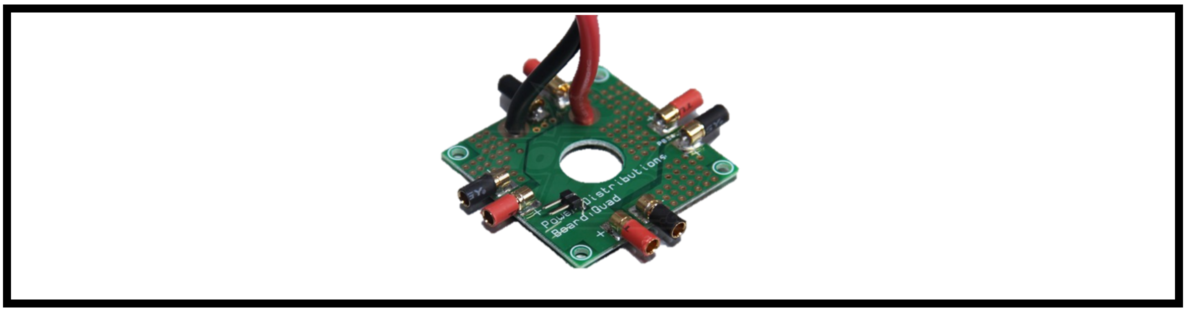


Figure 1.4: *Example of a power distribution board*

1.7 UAV components

A simple illustration of UAV's main components and connections between them is given in Fig. 1.3. The following subsections present those components in detail.

1.7.1 Power Distribution Board (PDB)

Mainly, it distributes the power taken from the energy source (Battery) to the electronic speed controllers. However, with the new versions of PDBs, other components also could be connected to get the necessary power, such as the camera, video transmitter, flight controller, etc. An example of a PDB is depicted in Fig. 1.4.

1.7.2 Flight Controller (FC)

The drone's mind, the flight controller (Fig.1.5), an electronic circuit board controlling all drone's parts and actions; serves as an intermediate between the drone and the user. It interprets the different commands, which are either previously programmed or remotely received, into actions, such as change the motors' speed, change direction, change altitude, transmit data, etc. Recently, in new flight controllers, a power distribution board is integrated to form one component (FC+PDB).

Figure 1.5: *Example of a flight controller*

1.7.3 Propulsion system

The propulsion system is one of the most vital components in a UAV. This system is responsible for transforming the energy taken from the battery into kinetic energy. The kinetic energy is used to produce the necessary thrust and lift forces to overcome gravity and drag, allowing the UAV to move and hover flexibly in the air. The prominent components making the propulsion system are:

A: Energy source

It is deemed the crucial component since it provides the UAV's parts with the necessary energy. There exist many types of energy sources adopted for UAVs (electric batteries, fuel cells, solar energy, etc.;) each of them has its pros and cons regarding its use. However, the ones used the most are Lithium-Polymer batteries (Li-Po). Details about these prominent energy sources will be at the heart of Chapter 3.

B: Electronic Speed Controller (ESC)

The electronic speed controller is an electronic circuit ensuring essential functions; among them:

- Converts the direct current (DC) taken from the battery to an alternating current (AC) to be passed to the motors.

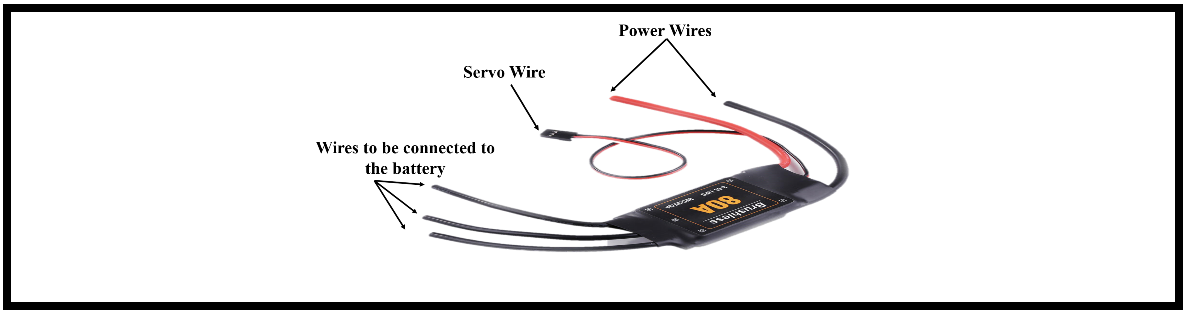


Figure 1.6: *Example of an electronic speed controller*

- Controls the motors' speed according to the flight controller's signal by controlling the amount of power to be passed to them.
- It can provide a current of 5 V for some of the UAV's components, such as the receiver.

The ESC, as depicted in Fig. 1.6, has several kinds of wires; three of them (on one side) are attached to the three ones of the motor. On the other side, two main wires (black and red) are connected to the battery's negative and positive sides or to the power distribution board. Along with these two wires, there is a servo cable that delivers a current of 5V to other UAV components. The servo cable also allows the ESC to receive signals coming from the receiver or the flight controller. Each ESC is characterized by the maximum electric current it can handle; the chosen ESC must exceed the motor by at least 5 Amps. How the three wires of the ESC are connected to the motor's three wires decides the latter's rotation direction (clockwise or counterclockwise)—Fig. 1.7 depicts the two possible situations.

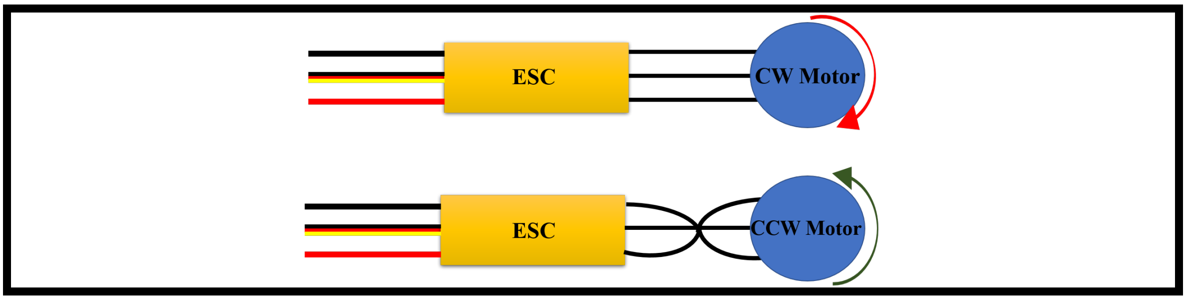


Figure 1.7: *The connection between the electronic speed controllers and motors in case of clockwise and counterclockwise rotation*

Figure 1.8: *Examples of propellers*

C: Propellers

Propellers are formed of blades and attached to motors. They are responsible for generating the necessary lift and thrust to overcome gravity and drag, which allows the UAV to hover, move in different directions, and change altitude. Fig. 1.8 gives examples of propellers of different shapes and sizes. For each propeller, some key-descriptive parameters are frequently used, namely:

- **Diameter:** reflects the propeller length, which is measured tip to tip.
- **Blades' number:** in most cases, UAVs' propellers come with two blades; however, more than two blades (3, 4, etc.) is also possible.
- **The pitch:** "The pitch is a measurement of how far the propeller would move forward if it were passing through a solid matter with one revolution [10]." The pitch speed is calculated as given in Equation (1.1):

$$PitchSpeed = pitch * \omega \tag{1.1}$$

  - ω: the number of revolutions per second.

  This parameter could be used to get an idea about the UAV's theoretical speed over the different axes (X,Y,Z).

D: Motors

The motors convert the energy taken from the battery to kinetic energy (rotational kinetic energy). Four main parameters are mentioned on each motor, namely:

- The stator diameter in mm.
- The stator height in mm.

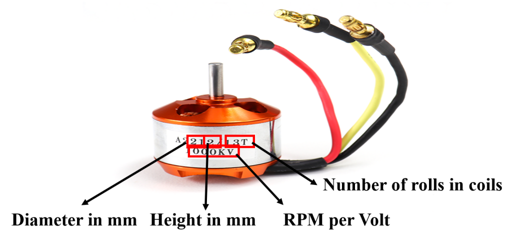


Figure 1.9: *Example of a UAV's brushless motor*

- Number of rolls in the coils.
- The RPM (Revolution Per Minute) per volt, also called the motor KV.

Fig. 1.9 highlights the above-mentioned parameters. Indeed, the kv reflects the number of revolutions a motor can achieve per minute when one volt is applied, in a free-load situation. For example, a motor of 1100 kV, using a 3S battery (11.1 V), will spin 1100 * 11 = 12210 revolutions per minute when no load is attached to it.

1.7.4 Inertial Measurement Unit (IMU)

The IMU is a component of utmost importance; it allows the UAV to get a professional and accurate flight. It is basically composed of two elements: an accelerometer and a gyroscope. The IMU's upshots are transmitted to the flight controller to control the UAV's motion—the two kinds: the linear motion and the rotation. In addition to the IMU, other sensors could also be sources of data used by the flight controller, such as the GPS (Global Positioning System) to pursue the location information and the barometric pressure sensor to control the UAV's altitude. Overall, the main objective of the IMU and the other attached sensors (GPS, magnetometer, barometric pressure sensor, etc.) is to provide the necessary data to enable the flight controller to ensure a simple, stable, and safe flight for the UAV.

1.8 Main physics concepts building UAVs

1.8.1 Basic forces

For flying objects, there are four fundamental forces are considered, namely:

- Weight: a force acted on objects due to earth gravity—also known as gravity force. It is an earthward force—directed toward the earth's center.

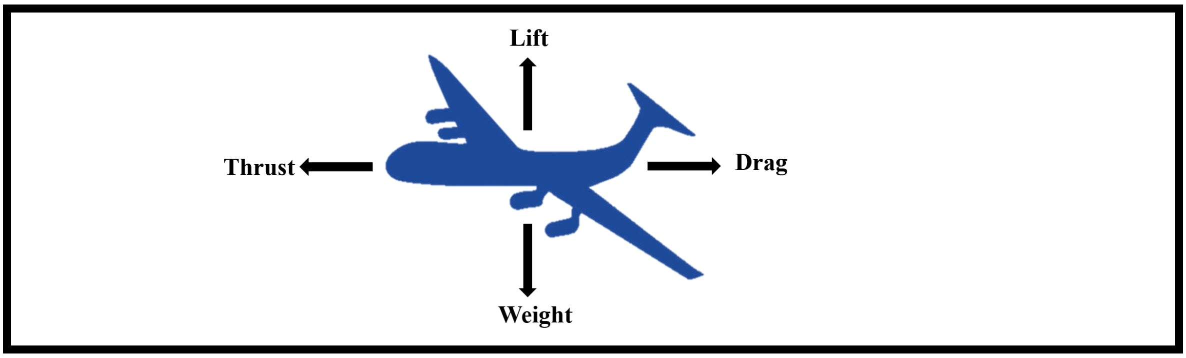


Figure 1.10: *Flying objects' main forces*

- Lift: a force produced by the flying object to overcome gravity and fly at a given height away from the ground.
- Thrust: allows the flying object to overcome the drag force and move in the air in different directions.
- Drag: hinders the flexible motion of flying objects due to friction with air molecules.

These described forces are depicted in Fig. 1.10.

1.8.2 Why are both clockwise and counterclockwise rotation directions considered?

This consideration is the result of a popular concept in physics concerning actions and reactions. An object that spins in a given direction generates a torque in the opposite direction of its spinning, which is stated in Neuton's third law as follows: "for every action, there is an equal and opposite reaction."

In the UAV case, if all the propellers are, for example, in a clockwise rotation, torque will be produced on the UAV's body, making the UAV rotates in a counterclockwise direction (opposite direction of the propellers' rotation) around its central axis. Hence, a strategy must be used to cancel that torque. The solution was to use propellers in a clockwise rotation by the side of the ones rotating in a counterclockwise direction so that the produced torque be canceled (Fig. 1.11).

This concept is also used to decide how to attach propellers to the UAV's motors, where the motor spinning in a clockwise direction will be attached to a counterclockwise propeller and vise versa.

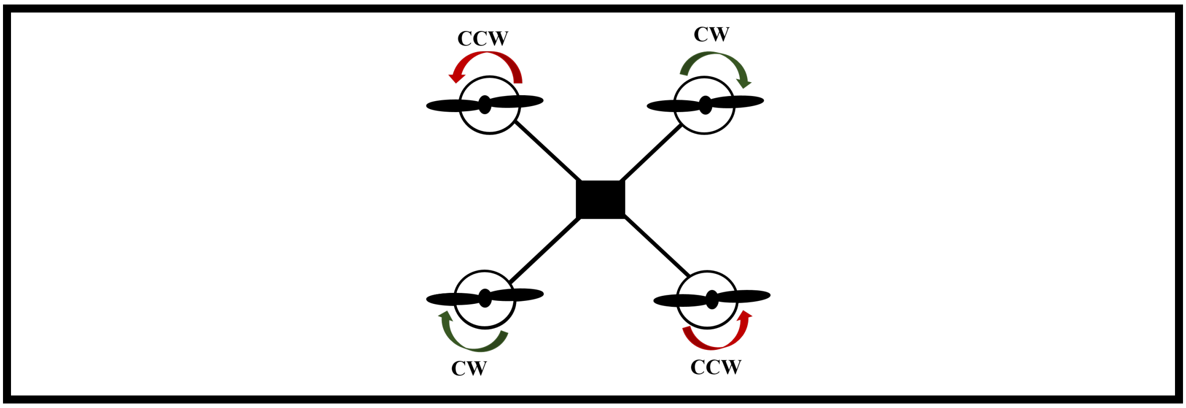


Figure 1.11: *Clockwise and counterclockwise configuration*

1.8.3 Frames of reference

There are two main frames of reference, namely: the inertial frame and the body frame, as depicted in Fig. 1.12.

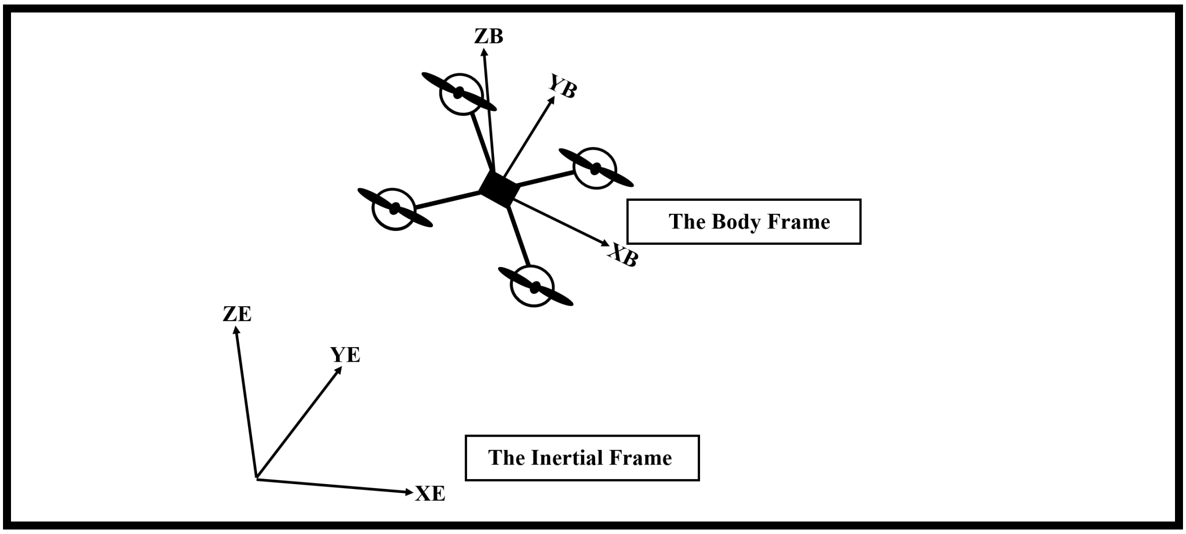


Figure 1.12: *UAV's principal frames of reference*

1.8.4 Rotation forms

Three main rotation forms are possible (Fig. 1.13); these rotation forms control the direction and orientation of UAVs' motion over time.

- Pitch: refers to the rotation around the Side-to-Side axis by α. The rotation

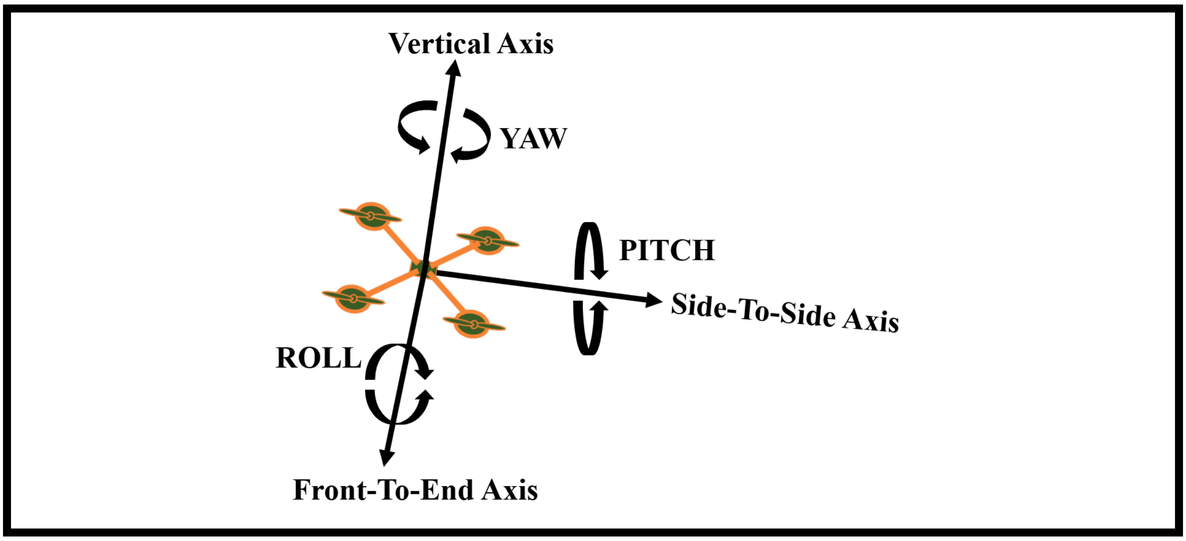


Figure 1.13: *Rotation around the axes X, Y, and Z*

matrix is as follows:

$$R_{SidetoSideAxis}(\alpha) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix}$$

- Roll: refers to the rotation around the Front-to-Back axis by β. The rotation matrix is as follows:

$$R_{FrontToBackAxis}(\beta) = \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix}$$

- YAW: refers to the rotation around the vertical axis by φ. The rotation matrix is as follows:

$$R_{VerticalAxis}(\varphi) = \begin{pmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

1.8.5 Flying rules

Indeed, the UAVs can move in different directions (horizontal motion), change altitude (vertical motion), or stay hovering in a fixed location. For each motion kind, some conditions must be met regarding a set of parameters: the produced lift, torque, motors' speed, rotation forms, etc. In-depth details about these conditions are given for each case—Hovering, Vertical Motion, Horizontal Motion—as follows:

A: Hovering

- Lift: the overall produced lift must be equal to the weight force (Equations (1.2, 1.3)).

$$\sum_{i=1}^{n} lift_i = -weight \tag{1.2}$$

  Hence,

$$\sum_{i=1}^{n} lift_i = -mg \tag{1.3}$$

  where:

  - n: number of propellers or motors
  - m: UAV's mass
  - g: gravity

- Torque, in this case, equals zero (Equation (1.4)).

$$\sum_{i=1}^{n} \tau_i = 0 \tag{1.4}$$

- Motors' speed: the same speed for all motors.
- Rotation form: none of the previously-mentioned rotation forms is considered.

B: Vertical motion (change in altitude)

- Lift: the produced lift, in this case, differs according to the vertical motion kind (Up or Down).

  - Going up (Equation (1.5)):

$$\sum_{i=1}^{n} lift_i > -mg \tag{1.5}$$

  - Going down (Equation (1.6)):

$$\sum_{i=1}^{n} lift_i < -mg \tag{1.6}$$

- Torque, in the two cases, equals zero (Equation (1.7)).

$$\sum_{i=1}^{n} \tau_i = 0 \tag{1.7}$$

- Motors' speed: the same speed for all motors.
- Rotation form: none of the previously-mentioned rotation forms is considered.

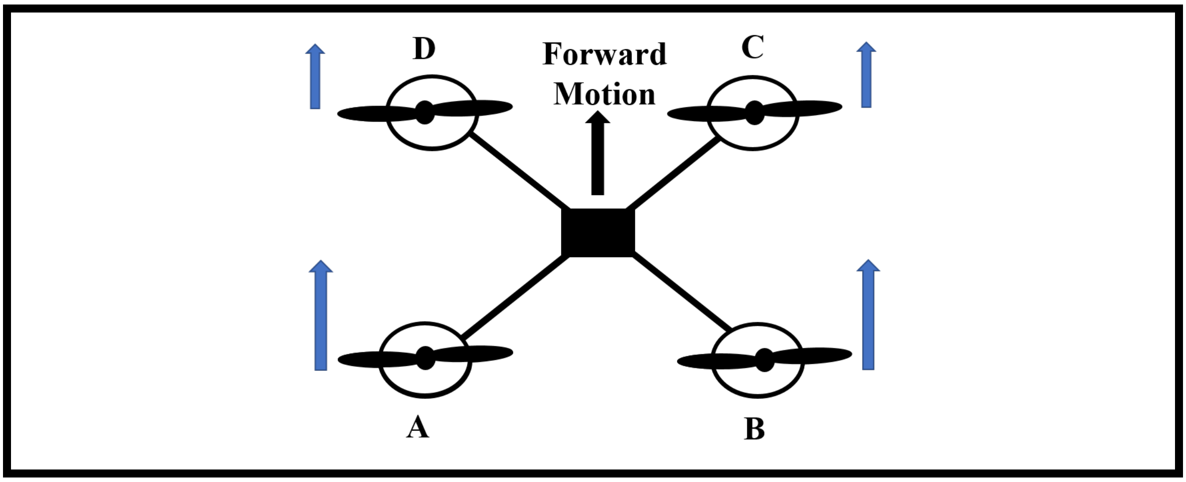


Figure 1.14: *Motors' speed in the forward motion*

C: Horizontal motion (change in direction)

- Lift: the lift force must be equal to the weight force (Equation (1.8)).

$$\sum_{i=1}^{n} lift_i = -mg \tag{1.8}$$

- Torque is not zero (Equation (1.9)).

$$\sum_{i=1}^{n} \tau_i \neq 0 \tag{1.9}$$

- Motors' speed: the speed value is not the same for all the motors. For example, in the case of a forward motion as illustrated in Fig. 1.14, motors A and B's speed is much greater than the motors C and D—that is why the overall torque value will not be zero. The same principle of motors' speed variation is used to get other possible directions (backward, left, right, etc.), where the motors to be with the higher speed are decided according to the desired direction.

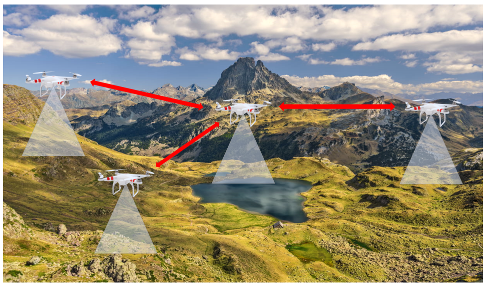
- Rotation form: different rotation forms are considered, according to the chosen direction, namely:
  - Positive Pitch (Forwards) and negative Pitch (Backwards)
  - Positive Roll (Right) and negative Roll (Left)
  - Positive YAW and negative YAW for other possible directions

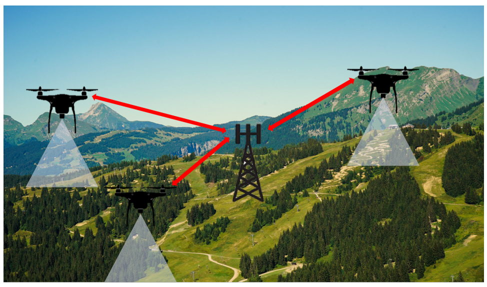
1.9 Conclusion

The Unmanned Aerial Vehicles have made the applications in different domains simple, more efficient, and practical, explaining UAVs' unprecedented growth use rate nowadays. Highlight the different concepts concerning this outstanding technology is a perpetual literature focus; the chapter's content was a kind of a short overview, where fundamental notions were carefully presented. In-depth concepts are the next chapter's objective, which will focus on multi-UAV systems that are deemed the powerful picture of the UAVs technology, where more yield and cost-effectiveness are taking place, going beyond the limited upshots of a single UAV.

Chapter 2

Multi-UAV systems & Unmanned Aerial Ad Hoc Network (UAANET)





Highlights:

- Present Multi-UAV systems and their notable advantages over a single UAV.
- Highlight the communication aspect in multi-UAV systems.
- Discover the new Ad Hoc network kind—the so-called Unmanned Aerial Ad Hoc Network (UAANET)—its advantages and new features.
- Compare the UAANET with pre-existing Ad Hoc networks, namely: MANET (Mobile Ad Hoc Network) and VANET (Vehicular Ad Hoc Network).

2.1 Introduction

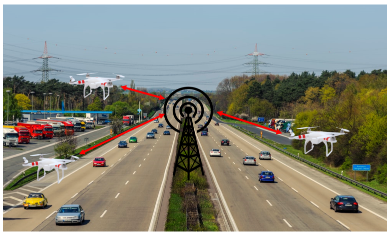
The UAVs' first use case was based on a single UAV, where, for a specific task, a specific single UAV is assigned. However, with the increasing requirements and constraints of nowadays applications, such a solution kind is being unsatisfactory. Single UAV use deficiencies, lapses, and limited yield are among the main reasons behind the emergence of multi-UAV systems that opened up new horizons for UAVs' applications thanks to the powerful cooperation taking place. Indeed, that cooperation is achieved once communication is established; to this end, various communication architectures and schemes are used. Since simple, flexible, and cost-effective solutions are the most recommended, an Ad Hoc network is deemed the most attractive solution encapsulating simplicity, flexibility, and cost-effectiveness. Once the Ad Hoc mode is used for communication between the multi-UAV system members, the new kind of Ad Hoc networks, called Unmanned Aerial Ad hoc network (UAANET), is formed.

In this chapter, we will highlight significant aspects related to the multi-UAV systems and their substantial profit compared to the single UAV use case. Moreover, more details about the new kind of network, the UAANET, will be at the heart of the chapter content.

2.2 Multi-UAV systems

Multi-UAV systems consist of a collection of UAVs working cooperatively to achieve a shared predefined purpose (Fig. 2.1: Fig. 2.1(a), Fig. 2.1(b), Fig. 2.1(c)). The UAVs take advantage of communication to perform missions in a more productive yet easy-manageable and straightforward way. Indeed, the multi-UAV systems are with notable advantages over single UAV; prominent ones, according to [11, 12, 13], are:

- The cost, affordability, maintenance process, and flexibility of use are much better with multiple small UAVs than a single large UAV.
- Multi-UAV systems extend tasks' lifetime, where a faulty UAV will not affect the overall process. In contrast, for a single UAV, the task accomplishment is deemed no longer possible once the used UAV is out of service.
- Multi-UAV systems extend the coverage scale, allowing a practical coverage of large areas, whereas the situation is very restricted with a single UAV.
- The performance, productivity, and rapidity of missions accomplishment are much better with Multi-UAVs, where the UAVs cooperate for a specific task.



(a) Multi-UAV system for traffic monitoring

(b) Multi-UAV system for agriculture activities

(c) Multi-UAV system for search and rescue

Figure 2.1: *Examples of multi-UAV systems use cases*

- Multi-UAV systems boost efficiency; with a group of UAVs, several tasks could be accomplished simultaneously, where each UAV can, for example, use a different sensor (fire, humidity, etc.) Hence, various phenomena could be studied at the same time. Such a situation is not possible with a single UAV due to the imposed constraint regarding payload.
- Improve transmission efficiency, where multiple UAVs could relay data to the final destination in a multi-hop mode. Moreover, coordination and collaboration among UAVs can improve information-preprocessing capability.
- Boost adaptability, scalability, and fault tolerance thanks to supported self-organization.
- Increase energy efficiency, where cooperation can reduce energy consumption through reducing transmission distance, due to multi-hop communication, and using sleep mode for some members.

2.3 Communication in multi-UAV systems

Indeed, communication is the core of multi-UAV systems since it is behind UAVs' coordination and cooperation through sharing information—that is why communication is deemed a critical aspect because efficient cooperation needs efficient communication. The shared information among the UAVs could be of control or environment—directly collected from the area of interest the UAVs are deployed within. The communication aspect involves basic concepts to be considered, namely:

- Communication link type
- Traffic type
- Communication architectures
- Communication protocols
- Wireless communication technologies

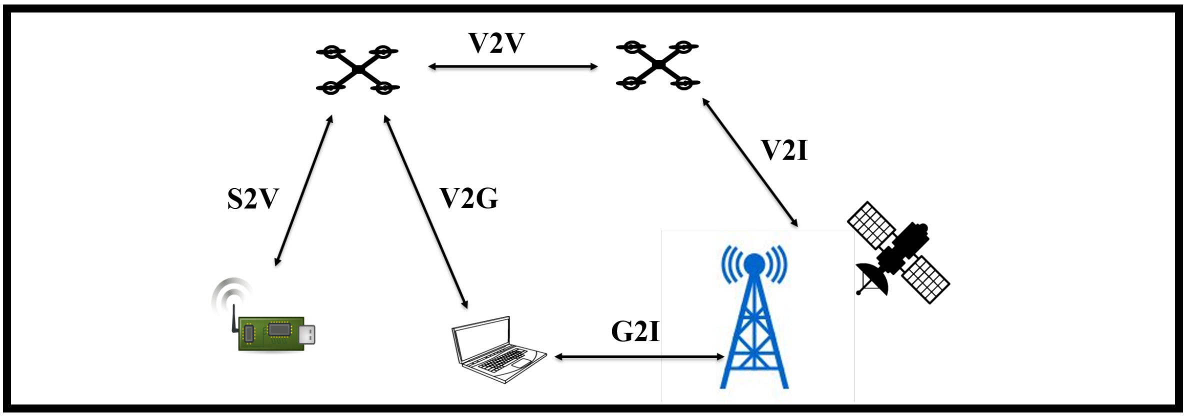


Figure 2.2: *Communication link types in multi-UAV systems*

2.3.1 Communication link type

The UAV-based systems are built of three main elements: UAVs, the Control Station (CS), and the communication link. The latter could be one of the following kinds [14]:

- V2G (Vehicle-to-Ground): is a two-direction communication, where data could be sent from the vehicle to the control station and vise versa.
- V2V (Vehicle-to-Vehicle): kind of communication among UAVs; it takes place when there is a multi-hop communication.
- V2I (Vehicle-to-Infrastructure): could be used to connect the UAVs to cellular networks.

- S2V (Sensor-to-Vehicle): used when communication is needed between UAVs and sensors on the ground.
- G2I (Ground-to-Infrastructure): in this case, the ground station is connected to other networks, such as the internet.

These communication link types are illustrated in Fig. 2.2 [14].

2.3.2 Traffic type

The communication traffic within a multi-UAV system could be of different types and for different reasons. Mainly, it could be [15]:

- A configuration traffic
- Heartbeat messages
- Telemetry (data captured through the payload: image, video stream, etc.)
- Command and control

2.3.3 Communication architectures

The communication architecture reflects the mode under which the data will be exchanged within the multi-UAV system—whether direct communication between the UAVs is supported or a central intermediate is required. Indeed, communication architectures significantly contribute to making data transmission simple and efficient. Since each architecture may come with its pros and cons, the choice about it is deemed scenario-based, where the application needs and features are at the origin of the architecture type decision. Mainly, two kinds are more frequently mentioned:

A: Centralized architecture

The centralized version allows a UAV-to-infrastructure communication mode. In this case, direct communication among UAVs is not supported. The communication could be direct with the Ground Control Station (GCS) (Fig. 2.3(a)), via satellite (Fig. 2.3(b)), or using a cellular network (Fig. 2.3(c)).

a: Direct communication with the ground control station

Such a communication pattern is of low complexity, especially once a small scale is considered. However, notable shortcomings related to centralized solutions arise, including [15]:

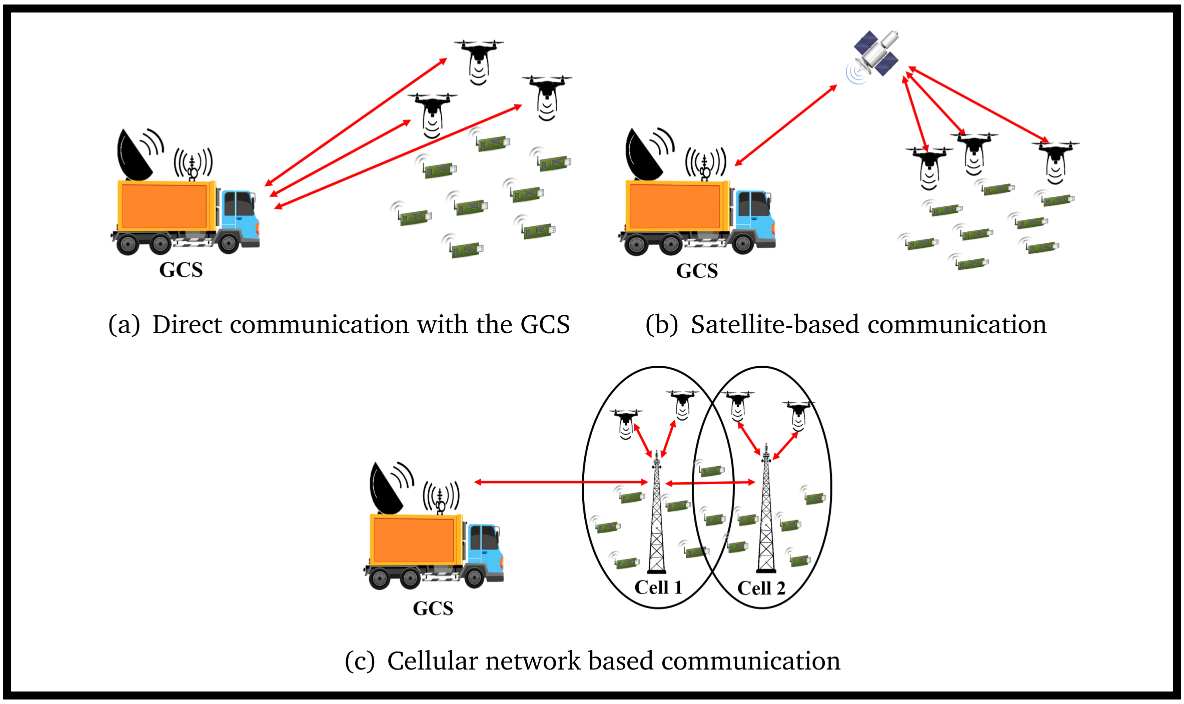


Figure 2.3: *Communication in multi-UAV systems using a centralized architecture*

- Single Point of Failure (SPoF): once the central station responsible for communication is out of service, the mission is deemed no longer possible.
- Transmission delay: if communication between the UAVs is needed, a considerable delay would be obtained since the communication is established by the central point.
- Bandwidth: since each UAV requires a dedicated bandwidth, it is expected that the total amount of bandwidth to be used will be proportional to the number of UAVs, which would be more complicated in the case of a dense network.
- Limited area coverage: geographical barriers, such as mountains, can affect transmitted signals, preventing the proper transmission of data. Therefore, the UAVs would have to fly close to the GCS or to use powerful devices to generate high-power signals, which is mainly not a practical solution for small UAVs due to payload constraints.

b: Satellite-based communication

In this case, the satellite establishes communication between the UAVs and the GCS, as well as between the UAVs themselves. It receives signals, from the GCS, to be forwarded to the UAVs and vice versa. Also, it allows communication among the

UAVs in case of cooperation. This solution ensures coverage better than the direct communication case [16] because the UAVs are not restricted by the communication range—as is the case for the direct communication with the GCS. However, the drawbacks of centralized solutions persist.

c: Communication via cellular networks

The cellular networks are basically used for mobile telecommunications; they consist of a set of cells, where each of them holds a base station allowing communication between multiple devices. For a multi-UAV system using a cellular network, each cell is equipped with an infrastructure (base station) that forms multiple cellular beams where one or multiple UAVs are located. The base station ensures communication among UAVs either within the same cell or a neighboring cell, where data will be forwarded to that cell's base station. This solution kind extends coverage and operations' scale through deploying multiple base stations as needed. However, the cost would be high and not recovered (in contrast to mobile telecommunication where cost is recovered); further, as with any centralized solution, vulnerability is always present due to possible attacks on the central point responsible for communication [15].

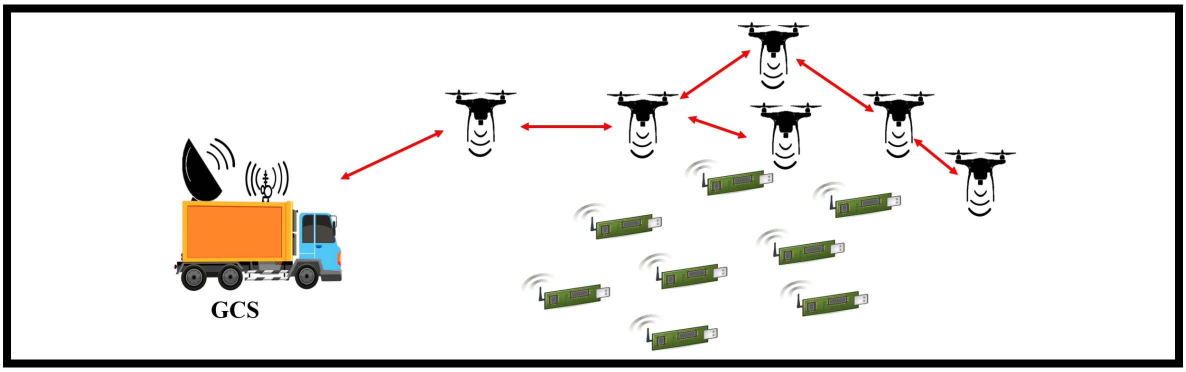
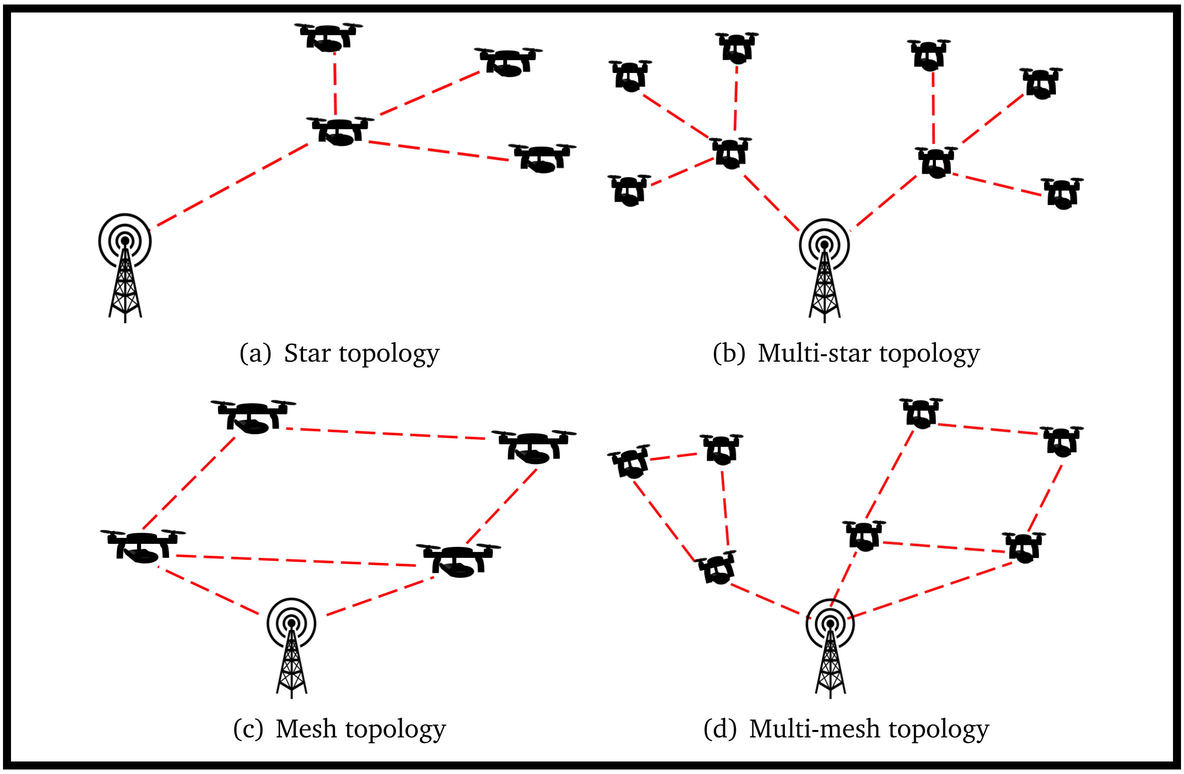


Figure 2.4: *Communication in multi-UAV systems using a decentralized architecture*

B: Decentralized architecture

In this case, communication could be realized independently from any central point; the UAVs can directly communicate with each other. Furthermore, each UAV could serve as a relay node for neighboring UAVs, where a multi-hop communication is used, as illustrated in Fig. 2.4. This communication architecture class uses various topologies, as outstanding examples (Fig. 2.5): star topology (Fig. 2.5(a)), multi-star (Fig. 2.5(b)), mesh (Fig. 2.5(c)), and multi-mesh (Fig. 2.5(d)).



(a) Star topology (b) Multi-star topology

(c) Mesh topology (d) Multi-mesh topology

Figure 2.5: *Examples of topology in the decentralized architecture*

2.3.4 Communication protocols

The communication protocols define a set of rules for data transmission between nodes forming a network. Each protocol involves important functionalities boosting the simplicity, accuracy, and reliability of the transmission process. To reduce complexity and facilitate maintenance, the concept of layers is used, where each layer encapsulates essential aspects necessary for networking. The communication protocols aspect is modeled via two layers: the Data Link layer and the Network layer.

2.3.5 Wireless communication technologies

Indeed, various wireless communication technologies exist; choosing the suitable one depends on the application [17]. Many parameters are considered before picking out the communication technology to be used, namely:

- Application-related parameters: application type, tolerance to delays, required throughput, security, reliability, the mobility model, energy consumption, maximum allowed altitude for UAVs, the communication architecture, etc.

- Node-related parameters: UAV type, speed, communication range, antenna design, energy source, computation resources, etc.

That is why each application calls for a technology meeting its needs and features. Many research works were based on famous existing technologies, such as WiFi, WiMax, XBee, LTE, LoRa, 6LoWPAN, etc.

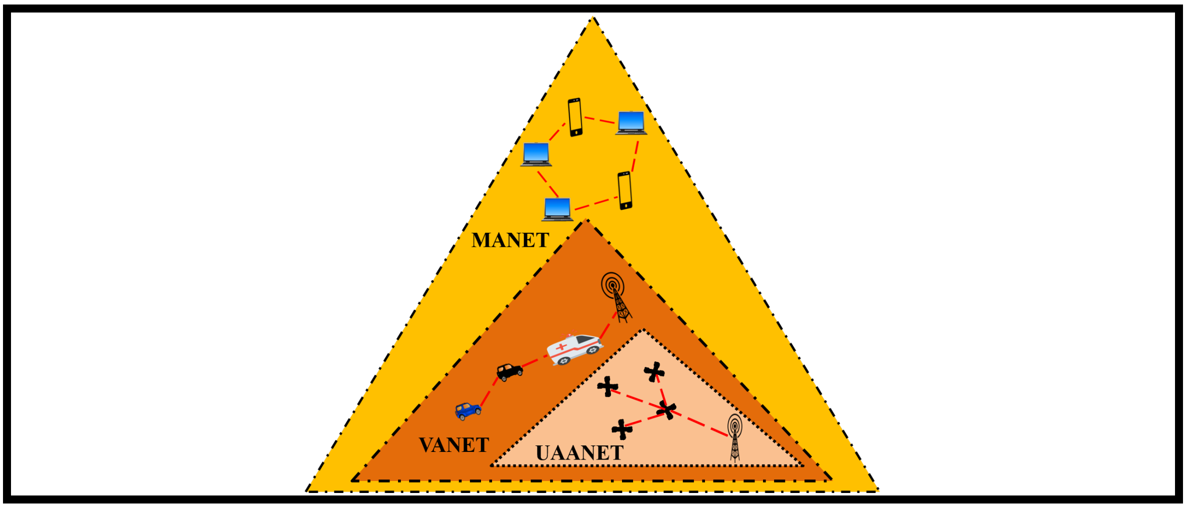


Figure 2.6: *MANET, VANET, and UAANET*

2.4 Unmanned Aerial Ad Hoc Network (UAANET)

As the name suggests, a UAANET—aka FANET (Flying Ad Hoc Network)—is an Ad Hoc network deployed in the air and formed of a special kind of nodes—the UAVs. Basically, the UAANET is a multi-UAV system using a decentralized communication architecture, where the Ad Hoc mode is activated for communication. A UAANET could be seen as a subclass of pre-existing Ad Hoc networks (Fig. 2.6), MANET (Mobile Ad Hoc Network) and VANET (Vehicular Ad Hoc Network), where nodes forming the network are not static, and communication among them is infrastructure-less. Without loss of generalities, a UAANET is formed once an Ad Hoc-based communication takes place among multi-UAV system members. Indeed, some standard traits make the UAANET officially shares the Ad Hoc membership with other Ad Hoc networks. However, the particularity regarding nodes kind and the deployment environment gives rise to some new features and challenges to be that special for UAANET, making such a network distinguishable from any other Ad Hoc network.

2.4.1 Benefits of the Ad Hoc mode for multi-UAV systems

Communication in Ad Hoc mode among UAVs ensures simplicity, increases productivity, and enhances performance, extending thus the use range of multi-UAV systems applications. We summarize the impact of such a communication mode on multi-UAV systems according to what has been mentioned in [11]:

A: Extend scalability

In an infrastructure-based environment, direct communication is only possible between the UAV and the infrastructure. Consequently, the applications' scale will be very limited because once the UAV is out of the infrastructure range, the communication is deemed impossible. In contrast, for infrastructure-less environments (Ad Hoc network), the UAVs directly communicate with each other, which means no constraint is considered regarding the operation scale, where the UAVs themselves relay data to reach the final destination.

B: Increase reliability

Due to weather troubles or technical problems, affected UAVs cannot maintain contact with the infrastructure. However, with the Ad Hoc mode, the other UAVs within the network can maintain the connectivity for the affected ones. This maintained connectivity enhances the multi-UAV systems' reliability.

C: Overcome the restricted capabilities of small UAVs

Small UAVs are very limited in terms of their capabilities. If an infrastructure-based communication architecture is used, each UAV must be equipped with a UAV-to-Infrastructure hardware for communication, which is not a handy solution due to the hardware's weight that may raise problems due to the limited payload constraint. However, in an Ad Hoc network, UAV-to-UAV communication can be realized with lighter and cheaper hardware.

2.4.2 UAANET new features

This new kind of network has a range of standard features that make it that close, in terms of classification, to MANETs and VANETs. However, additional exclusive features make the UAANET a brand-new, unique, yet challenging environment. About those new features, we highlight the most significant ones; the following:

A: Deployment environment

Instead of the usual situation—deployment on the ground—the UAANET is deployed in the sky. This new environment is behind the new constraints coming up with the UAANET.

B: Mobility

Indeed, the mobility aspect presents important parameters that make the difference between MANET, VANET, and UAANET that crystal-clear, namely:

a: The dimension of the motion space (2D or 3D)

The UAVs move in a 3D space. However, a 2D space could also be considered—the UAVs' altitude is constant in such a case. Like other parameters, the dimension to be used is also scenario-based, where the decision about it must consider how the chosen dimension (3D or 2D) would boost performance and efficiency. A 2D space is considered when there is no need to change altitude during mission accomplishment. On the other hand, the 3D motion space is mandatory once the application requires that the UAVs change altitude for a specific purpose, such as delivery scenarios where the UAVs should put goods on the ground. Also, in rescue missions, the UAVs must be close to persons to be rescued. In other situations, the motion in a 3D space is used to optimize certain system's parameters. For example, in UAV-assisted WSN (Wireless Sensor Network) applications, UAVs collect data from a set of wireless sensors deployed on the ground. In this case, the UAVs should change the altitude to get closer to the sensors, where, with such a strategy, the transmission distance will be reduced as much as possible, minimizing the sensor nodes' energy consumption during the transmission process.

b: The Pattern

The mobility pattern reflects a general description of nodes' organization and how the motion parameters are changing over time—it gives information about the mobility model's class (entity, group, etc.) In UAANET, the mobility pattern is an application-related decision, where each application requires a mobility model that meets its features. Moreover, a given application's mobility model is not practical for other applications in most cases. For example, a mobility model for delivery or search and rescue cannot be used for a surveillance scenario and vice versa.

c: The speed

Speed in UAANET is an application-based parameter. The speed value is utterly dependent on applications' requirements and features. For example, the UAVs will be fixed at a given point (speed is 0) when the application implements a continuous surveillance scenario of a fixed object or fixed region—hovering state. The speed could also achieve maximum values once a time constraint is considered, such as searching and rescue or delivery applications. In other cases, the UAVs' speed must be proportional to other objects' speed, for example, in object tracking applications.

Further in-depth considerations regarding speed value are taken when the speed is calculated according to some key parameters in relation to system performance, such as energy consumption. A practical example of this situation is when mobility models are based on a path planning strategy, where the final planned path must involve waypoints with a minimum amount of energy to be consumed once traveling from one waypoint to another, giving an energy-aware path. Also, for other application kinds, the constant speed is considered the most fitting. So, the UAANET members' speed is within the interval [0, UAV's Max Speed], and the application's type, needs, constraints, and features will decide the suitable value to be used.

d: The direction change process

The direction change process considers the three main rotation forms around the three axes (X, Y, Z), namely the PITCH, ROLL, and YAW.

C: The radio propagation model

Indeed, the signal propagation model for Ad Hoc networks deployed on the ground is, in most cases, assumed to be Non-Line-Of-Sight (NLOS), where the signal is exposed to reflections and diffraction due to different obstacles' kinds. In contrast, for UAANET, since the UAVs are moving at a given height where ground obstacles are not considered, a Line-Of-Sight (LOS) communication is assumed. More precisely, the LOS preponderates in the case of communication between UAVs (UAV-To-UAV) [18].

2.4.3 Comparaison between MANET, VANET, and UAANET

Indeed, as we have previously mentioned, there is an apparent correlation between the three Ad Hoc network kinds, namely, MANET, VANET, and UAANET. They share many features, making them considered of the same class. However, each of them has distinctive traits making them apart from the other networks. Basically, MANET is deemed the mother class; VANET is the subclass that encapsulates another subclass, namely: UAANET. In literature, there exist numerous key parameters to be considered when it comes to comparing those networks. Prominent ones are mobility, speed, topology, energy constraint, etc. Regarding mobility, it is about two main aspects. The first is the motion space (2D in MANET and VANET, 3D in UAANET, but we can also consider a 2D motion space for UAANET when the altitude is constant). The second is the mobility model; there are multiple models used for each network. Regarding the node speed, it could be lower, medium, or high. On the other hand, the topology change directly depends on the nodes' speed, which means it also could be low, medium, or high according to the adopted speed. The energy constraint is one of the most critical parameters since it affects the network lifetime, but the degree of being that critical differs from one network to another. A comparison between MANET, VANET, and UAANET is presented in Table 2.1, according to [18].

Characteristics	MANET	VANET	UAANET
Node Mobility	Lower (2D)	Low (2D)	RW-UAV: High (3D) FW-UAV: Medium (3D)
Node Speed	Lower	Medium-High	RW-UAV: Medium FW-UAV: High
Mobility Model	Random	Manhattan models	RW-UAV: Random Way Point FW-UAV: PPRZM, ST
Topology Change	Low	Medium	High
Energy Constraint	Medium	Low	RW-UAV: High FW-UAV: Medium

Table 2.1: *Descriptive comparison between the different Ad Hoc networks*

2.5 Conclusion

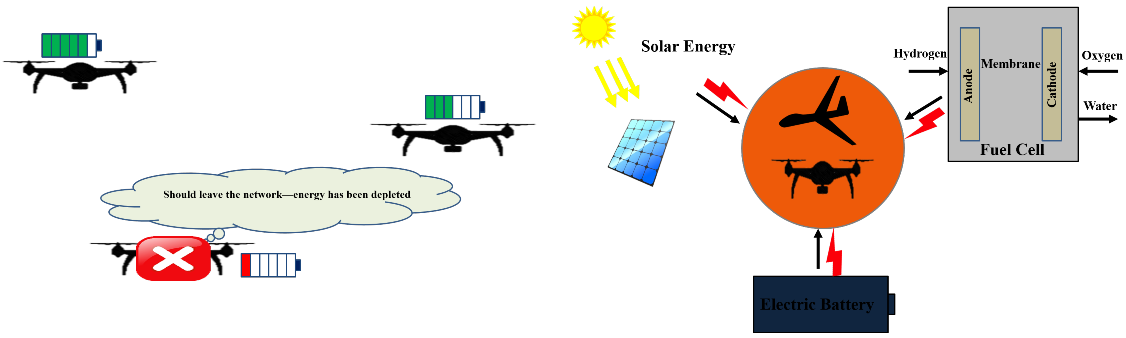
The multi-UAV systems made the UAV use more efficient and popular due to coordination and cooperation opportunities among UAVs, overcoming what a single UAV could not get. Similarly, using the Ad Hoc mode form communication within a multi-UAV system to form a UAANET made the multi-UAV systems that simple, scalable, efficient, and robust environment, overcoming what other communication architectures could not provide.

Despite how the UAANET seems advantageous and practical, profound challenges are encountered, which deeply affect performance and productivity. Those challenges will be among the central topics of the next part's chapters.

Part 2: Energy constraint in UAANET & State of the Art

Chapter 3

Limited energy constraint in UAANET



Highlights:

- Introduce the limited energy constraint in UAANET and its notable impact
- Present the main UAV energy sources
- Highlight prominent factors affecting UAVs' energy consumption and flight time

3.1 Introduction

No doubt, UAANETs have opened new horizons for many applications in different sectors, due to their affordability, low complexity, and efficiency. However, they also meet the ”nothing is perfect” fact, where a variety of challenges are encountered, hindering the efficiency of 100 %. At the top of the challenges’ list comes the limited energy constraint, which is a logical result of limited energy sources and payload restrictions. Indeed, the energy constraint is frequently cited in many environments, such as the WSNs and MANETs; however, it gets more crucial in the UAANET since new factors affecting energy consumption emerge in addition to the ones habitually discussed. Based on this fact, plenty of research works focused on exploring practical energy sources to overcome the faced deficiency, where diverse sources have been considered, namely, electric batteries, fuel cells, solar energy, etc. Furthermore, due to the significant impact the limited energy could bring out in terms of performance, it has been extensively highlighted in the literature.

With a review tone, this chapter attentively discusses the above-introduced challenge by exploring its significant impact, common energy sources the UAVs are based on, and outstanding factors behind UAVs’ energy exhaustion.

3.2 Limited energy impact

The use of limited energy sources and the restrictions imposed on payloads are behind the crucial energy constraint. Typically, incorporating batteries with an increased size or using multiple ones increases the UAV weight, affecting the flight time that is inversely proportional to weight [19]. Limited energy is a standard feature characterizing environments based on limited energy sources. The UAANET is undoubtedly affected by such a constraint by reason of nodes forming such a kind of network, namely, the UAVs, which are very limited regarding on-board energy [1, 3, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29]—in the most of cases, battery-based. The overall power consumed depends on three outstanding aspects: UAV motion, circuit power, and transmission power [20]. In spite of the notable batteries’ technological advancements, a long endurance is not guaranteed once an electric battery is used as the sole UAV energy source [24]. Indeed, the deficiency regarding energy is with a high criticality level since it directly affects the UAVs’ endurance, efficiency, and productivity, and, consequently, the entire network performance. This constraint is behind the limited flight time along with many encountered issues within the network, such as the short range of transmitted signals, giving rise to an urgent need for an efficient use of energy to improve the communication performance and extend the UAVs flight time and endurance [27].

We point out how a limited energy source could affect vital aspects related to the

UAV and network performance as follows:

- The adopted energy source's specific power significantly affects the maximum speed, supported load, flight altitude, and rate of climbing. On the other hand, the specific energy affects the flight endurance [30].
- Limits the flight time and ultimately usability [23].
- Limits the applications' types [31, 32], where the ones requiring powerful energy sources may not be feasible.
- Frequent topology change [33] due to nodes suddenly leaving the network as their energy is exhausted.
- Short transmission range due to weak radiated signals.
- Increases loss ratio due to frequent topology change and weak signals that may not be properly received due to attenuation.

3.3 Prominent UAV energy sources

3.3.1 Electrochemical batteries

These batteries are formed of electrochemical cells (Fig. 3.1); the cells' chemical energy is converted to electrical energy. They are widely used due to their simple principle of work, affordability, and ease of use.

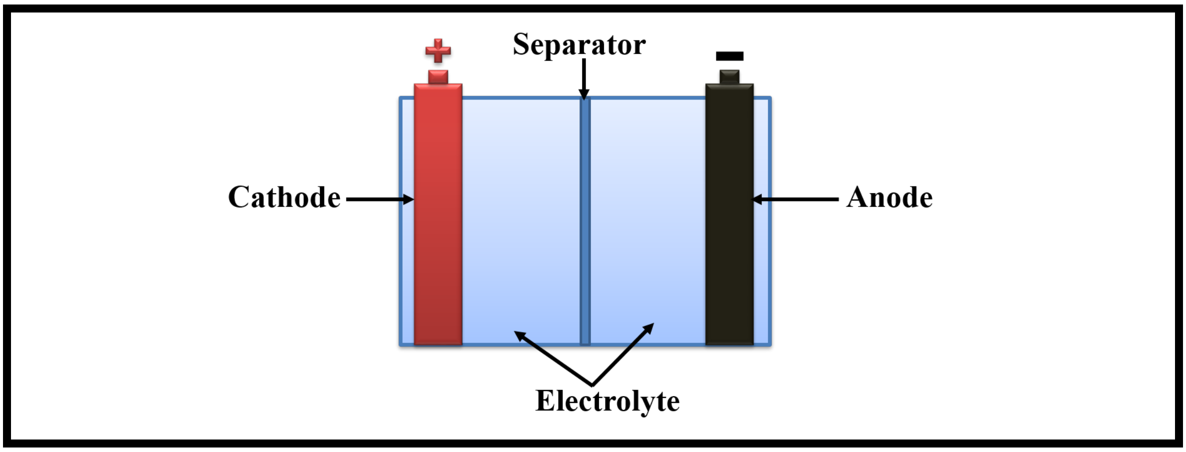


Figure 3.1: *The basic design of electrochemical cell*

Lithium-Ion (Li-Ion) and Lithium-Polymer (Li-Po) are deemed of high capacity, making them more fitting for applications in need of high energy or high power

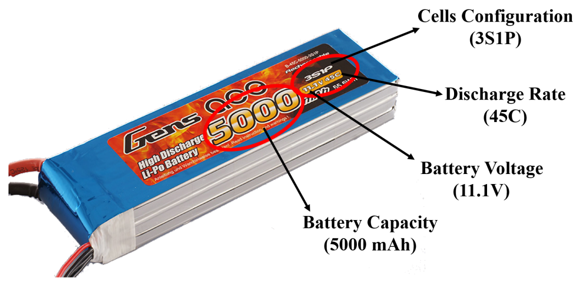


Figure 3.2: *Li-Po battery key features*

[34]. Furthermore, due to the continuous progress of their specific energy, these eco-friendly energy sources are favored for all UAVs kinds (small, medium, and large size) [35]; however, the Li-Po is the most utilized. The main difference between Li-Po and the famous Li-Ion battery is that the former is based on high conductivity gel polymers forming its electrolyte, which explains the fact that with the same energy density, Li-Po batteries are being 20% lighter than the Li-Ion ones. That is why they are mainly preferred for use since they decrease the overall weight and consequently decrease energy consumption that increases with heavier weights [36]. Indeed, energy density is deemed a key parameter used to assess the performance of rechargeable batteries. It reflects the amount of energy stored in a given system per unit mass, or region of space per unit volume [37].

We summarize the main reasons making Li-Po batteries that highly recommended for UAVs, as follows:

- Rechargeable Battery (aka secondary battery).
- The electrolyte within the battery is in the form of a gel instead of a liquid, as usual, making the battery lighter and safer.
- Li-Po batteries have a high energy density to weight and size ratio, which means a high amount of energy could be held within a light and small battery.
- Li-Po allows high discharge rate values (C-rate)—because of the weak internal resistance—which provides high amperes.

For a Li-Po battery, key features are considered (Fig.3.2); namely:

- **The battery capacity:** this parameter gives information about the amount of electric current the battery could provide to the attached load for a given period. Mainly expressed in milliamps per hour (mAh), the capacity also allows estimating the amount of energy the battery holds. Indeed, the larger the battery capacity, the higher the amount of energy exists. However, a tradeoff takes place between capacity and weight, where the higher capacity means more massive batteries, which are not a comfortable solution for UAVs. Technically, a battery, for example of 5000 mAh as a capacity, could deliver a continuous current of 5 Amps for one hour. With the capacity parameter, the battery lifetime could be calculated as follows (Equation (3.1)):

$$BatteryLifetime = BatteryCapacity/PulledCurrentValue \tag{3.1}$$

- **C-rate:** this parameter pertains to the battery's charging and discharging rate; it measures how a battery could be fast charged or discharged according to its capacity C.
  - Charging rate: in this case, the C-rate reflects the maximum amount of current the battery could be safely charged under. If the charging rate is not mentioned, then the battery must be charged under 1C.
  - Discharging rate: in this case, the C-rate reflects the maximum amount of current the battery could safely provide to the load. For a battery of 5000 mAh, with 35 C as a C-rate, the maximum electric current that could be continuously pulled would be 5*35 = 175 Amps.
- **Cells' number and configuration:** Li-Po battery consists of a set of cells themselves deemed batteries. Each cell stores an amount of energy with a given voltage. The cells inside the battery could be in different configurations: in series, parallel, or hybrid (parallel chains). Each kind of configuration has a different purpose. Making a set of cells in series increases the battery voltage, where the battery voltage is the sum of voltages of the cells forming the series (Equation (3.2)).

$$BatteryVoltage = TheCellVoltage * NumberOfCellsFormingTheSeries \tag{3.2}$$

The parallel configuration doubles the capacity, where the battery capacity is the sum of capacities of the sets of cells combined in parallel (Equation (3.3)).

$$BatteryCapacity = CellCapacity * NumberOfParallelSetsOfCells \tag{3.3}$$

On the other hand, the hybrid configuration increases both the voltage and capacity. For example, the notation 2S3P means that, within this battery, there are three sets of cells combined in parallel (3P), and each set consists of two cells forming the series (2S), which means that the battery contains six cells in total.

- **Voltage:** there are three kinds of voltage, namely, the nominal voltage, the maximum, and the minimum. The nominal voltage reflects the average voltage of the battery. For each cell, the nominal voltage is about 3.7 V; hence, for a battery 3S, the nominal voltage would be 3.7*3= 11.1 V. That is why the Li-Po batteries' voltage values are about 3.7 V, 11.1 V, 14.2 V, etc., which means that the battery voltage directly depends on the number of cells in the series. On the other hand, the minimum and maximum voltage values are the lower and higher tolerable voltage; their values are usually about 3-3.2 V for the minimum and 4.2 V for the maximum.

3.3.2 Fuel cells

Fuel cells are deemed a promising solution to increase UAV's endurance. Through chemical reactions, electric energy is produced (Fig. 3.3) [24]. Different fuel cell kinds are used; Table 5.2 [38] presents the most prominent ones.

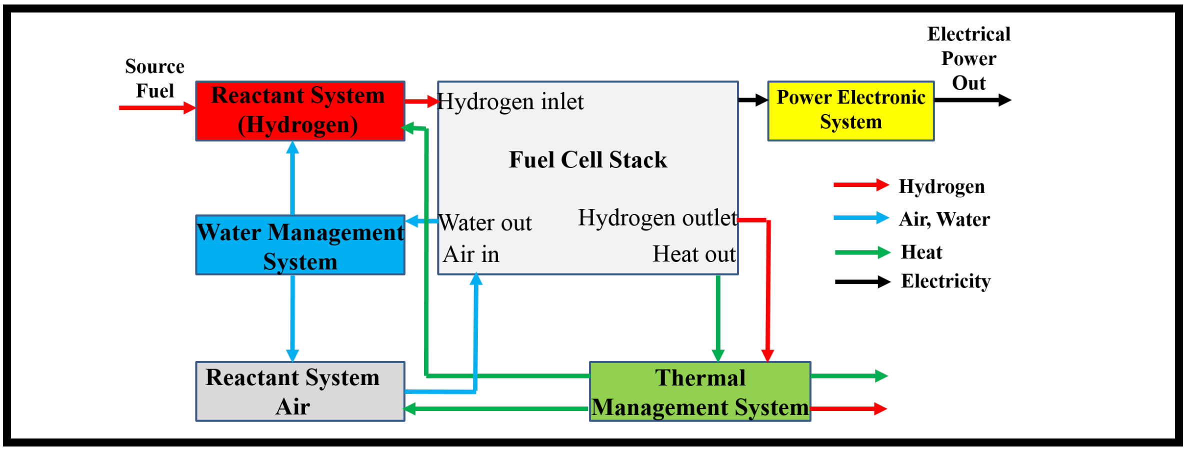


Figure 3.3: *Hydrogen fuel cell's subsystems*

Fuel cell type	Fuel	Efficiency (%)	Temp.(C)	Stack Specific Power (W/kg)	System Specific power (W/kg)
PEMFC	Hydrogen	40-60	30-100	>500	>150
DMFC	Methanol	20-30	20-90	>70	>50
SOFC	Hydrocarbon	30-50	500-1000	>800	>100

Table 3.1: *Characteristics of commonly used fuel cells*

Indeed, the increased endurance for electric-powered UAVs could be achieved using energy sources with higher specific energy; hydrogen fuel cells with advanced hydrogen storage systems could be an attractive candidate since they could meet the condition regarding specific energy [38]. Fig. 3.4 [39] presents the specific power vs. specific energy for common energy sources; it shows that the fuel cells are with the highest specific energy value compared to the other sources.

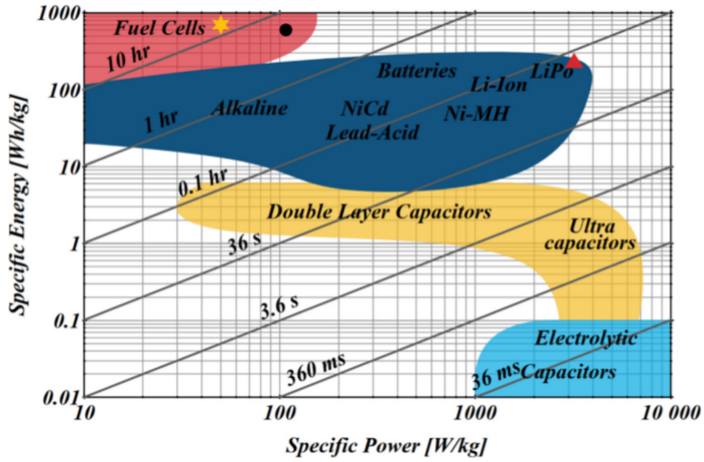


Figure 3.4: *Comparison between common energy sources in terms of specific power and specific energy*

Examples of popular UAVs based on fuel cells are shown in Fig. 3.5(a) [40] and Fig. 3.5(b) [41].

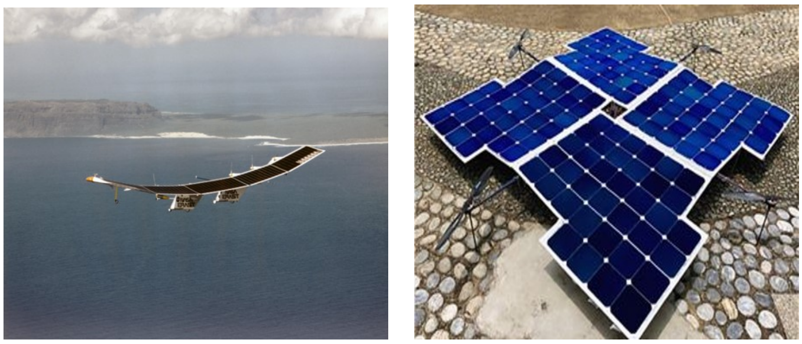
(a) UAV based on fuel cell from Intelligent Energy company

(b) The HYDRA-1A UAV from Royal Netherlands Aerospace Centre

Figure 3.5: *Examples of fuel-cell-based UAVs*

3.3.3 Solar energy

Solar is a source of free, clean, and not exhausted energy. The produced power is used to supply electric-based equipment, especially in environments with limited energy sources. Since the UAANET is one of those environments, heightened attention is given to solar-powered UAVs (Fig. 3.6(a) [42], Fig. 3.6(b) [43]). Essential components, called power components, are used, namely: photovoltaic cells and energy storage system—in most cases, rechargeable batteries—[37]. A block chart of a solar-powered UAV is illustrated in Fig. 3.7 [44].



(a) NASA Pathfinder solar-powered UAV (fixed-wing) (b) Solar-powered UAV (multi-rotor)

Figure 3.6: *Examples of solar-powered UAVs*

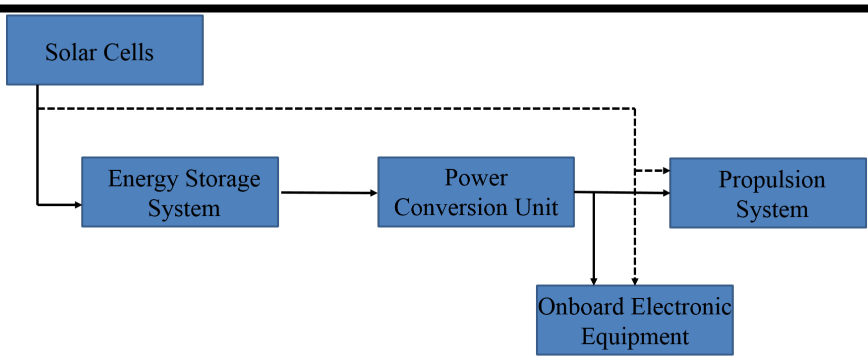


Figure 3.7: *Illustrative diagram of a solar-powered UAV*

The photovoltaic cells convert the solar radiations into electric power to supply the propulsion system and electronic components. On the other hand, a rechargeable battery is used to store the surplus energy to be used when the flight is being under particular conditions—for example, at night or cloudy weather. Indeed, the amount of harvested energy depends on key factors: the sun's rays' incident angle on the solar cells, the daylight duration, air mass, and cells' altitude [45].

For more efficiency regarding energy extraction and use, two main elements must be present: an Energy Management System (EMS) and Maximum Power Point Tracking (MPPT) controller that aims to maximize extracted energy. In most cases, the MPPT is being included within the energy management system, as depicted in Fig. 3.8 [37]. In Table 3.2 [44], popular solar-powered UAVs are mentioned.

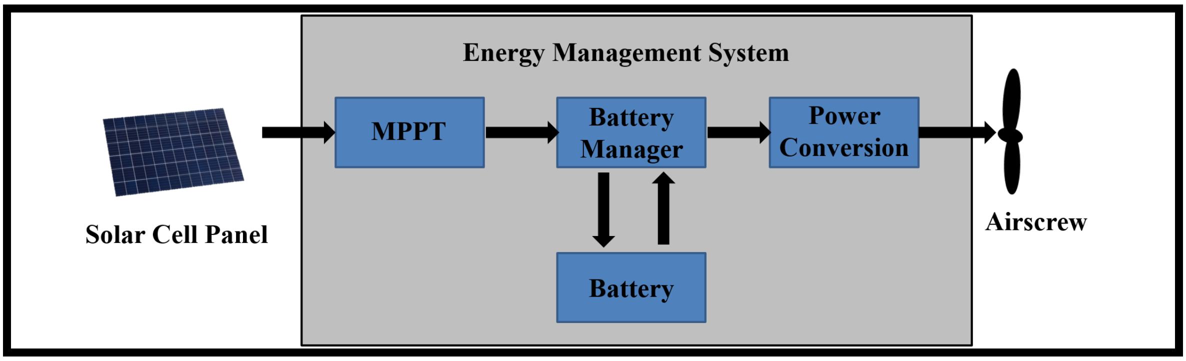


Figure 3.8: *Energy management system's structure*

UAV	Number of PV Cells	Cells efficiency (%)	Energy conversion efficiency (%)	Power (W)	Altitude (ft)	Endurance (hr)	Weight (N)	Year
SoLong	76	-	96	225	-	48	12.8	2005
Zephyr 7	96	19.6	90	320	70740	336	28.0	2010
Helios	62120	-	-	40000	96863	30	720	2001
Zephyr 8	-	28	-	-	70000	630	62	2018
Atlantic Solar 2	88	23.7	-	450	-	28	6.93	2015
Aquila	-	-	-	5000	60000	2760	400	2016

Table 3.2: *List of prominent solar-powered UAVs*

3.3.4 Strong and weak aspects of UAV energy sources

In fact, each of the formerly presented energy sources has its benefits and limitations when adopted for UAVs; Table 3.3 summarizes the strong and weak aspects of each of them [19, 24, 30, 37, 38, 39, 46, 47, 48].

Energy source	Strong aspects	Weak aspects
Electrochemical batteries	+ Affordable—low cost + low weight + No constraint regarding recharging process—charged almost anywhere + Low complexity	- Low energy density - Low recharge cycles - Low flight time - Recharge period significantly longer - Limited applications
Hydrogen fuel cells	+ Green and efficient technology regarding energy conversion + High specific energy + Low heat, noise, and infrared signals + Fast refueling—almost instantly refueled + The amount of produced energy is limited only by the availability of fuel + Can carry large payloads + The chemical reactions inside the hydrogen fuel cells give out only water, which means zero-emission	- Large size—increased weight - Low specific power - Quite expensive - Acquisition of hydrogen—hydrogen source - An efficient strategy to store hydrogen must be used - Lower energy efficiency compared to electric batteries due to complex power management requirements
Solar energy	+ Free and not exhausted + Clean—environment protection + The flight time could be extended to exceed 24 hours + Powerful applications could be performed due to long endurance + Heavy and powerful sensor payloads could be used + High flight altitude + Strong stability + Wide coverage area—extends the applications range	- Significantly with larger cost - Large area is needed for solar panels, increasing the UAV size and weight - Design and conception more complex - Not practical under certain conditions (night, cloudy weather) - Maximum power point tracking (MPPT) algorithm is required - Constraints on the UAV trajectory to get the best exposure to solar radiation - Optimal placement of solar panels is needed - Efficient storage system is necessary - Endurance depends on the efficiency of the power system that converts and store energy

Table 3.3: *Strong and weak aspects of popular energy sources used for UAVs*

3.4 Factors affecting UAVs energy consumption

UAVs' energy consumption involves an assortment of relevant factors from different aspects, which is a result of UAVs' particular features regarding their design and deployment environment, making energy being affected by new and unique factors alongside those habitually highlighted—as illustrated in Fig. 3.9 [49] and Fig. 3.10 [50]. We give details about the prominent of them as follows:

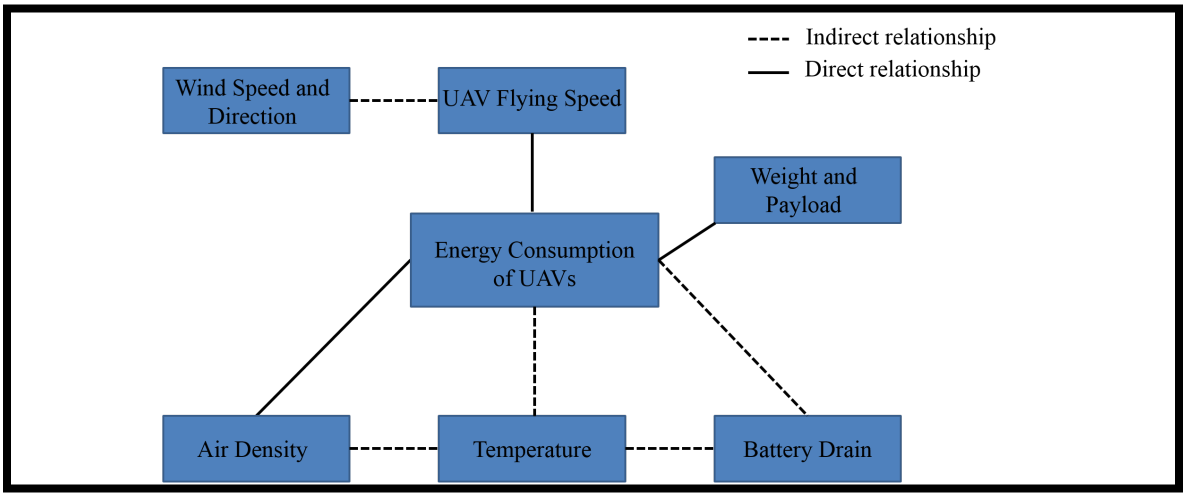


Figure 3.9: *Examples of factors affecting UAVs' energy consumption*

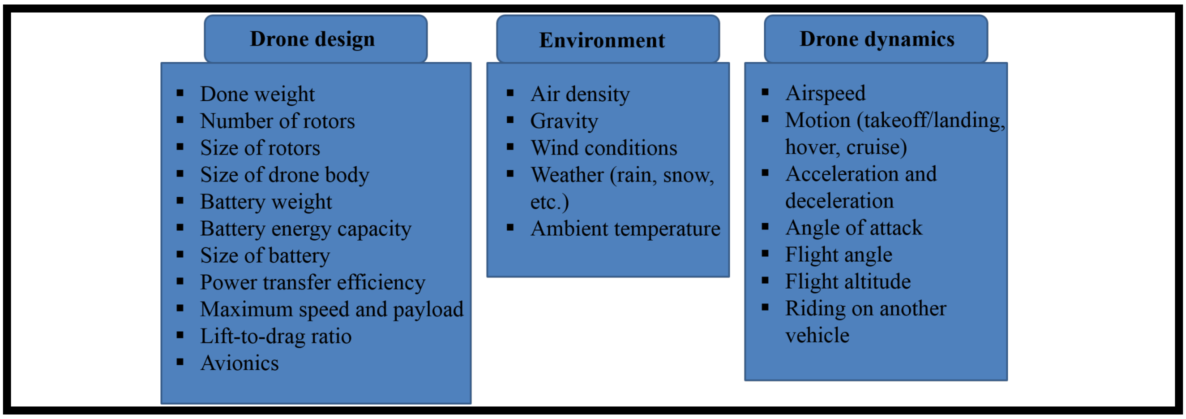


Figure 3.10: *Example of factors' classes affecting UAVs' energy consumption*

3.4.1 Subsystems impact

A set of fundamental subsystems—depicted in Fig. 3.11—form the whole UAV; each of them consumes energy to perform essential functions.

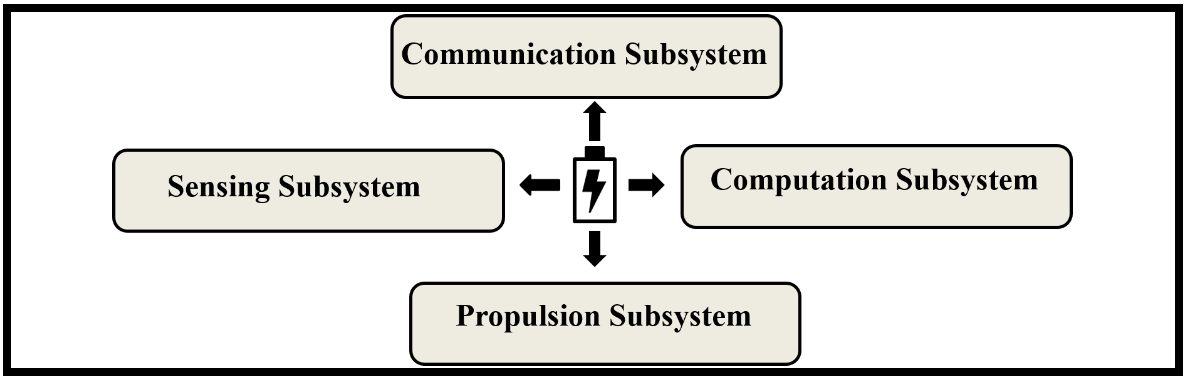


Figure 3.11: *UAV's subsystems*

A: Propulsion subsystem

The propulsion subsystem is a critical part in terms of energy consumption [23]; almost all energy stored in the battery is used for developing the thrust force [51] and lift, which keep the UAV aloft and ensure its mobility [52]. That is why the energy consumed by the propulsion subsystem is deemed higher than the other subsystems [1, 2, 23, 52, 53]. Fig. 3.12 [54] illustrates the power transmission process in this subsystem.

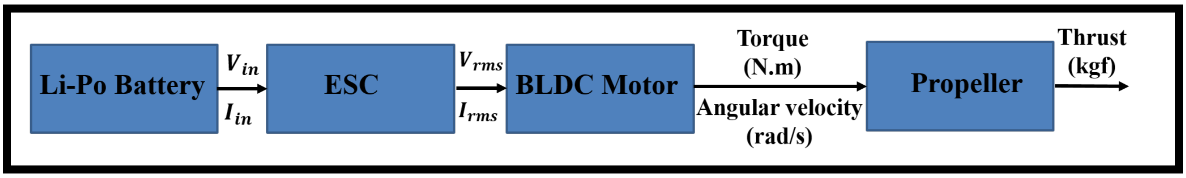


Figure 3.12: *Propulsion system's power transmission process*

B: Communication subsystem

The communication subsystem consumes energy for radiation, circuitry and signal processing, etc. According to [25], the energy consumed by this subsystem depends on main parameters, namely:

- The amount of transmitted data
- The transmission distance
- Number of nodes transmitting data to the base station

C: Computing subsystem

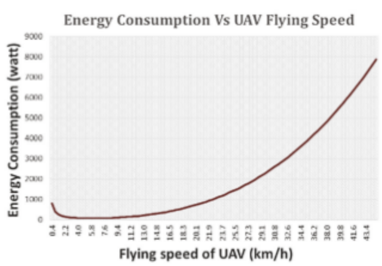
Used for computation and storage; it performs the required computation operations.

D: Sensing subsystem

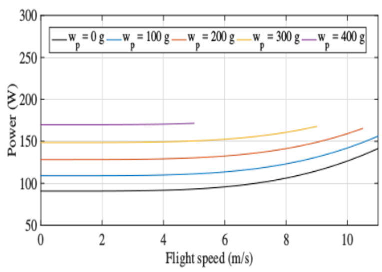
Responsible for capturing key parameters and properties of a given object or phenomena to be studied.

3.4.2 Motion impact

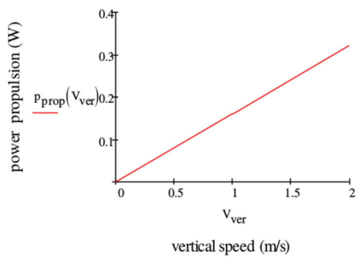
The UAV motion is about three kinds: hovering, vertical, and horizontal. In [55], energy consumption for each of those motion kinds has been studied. The results show that a notable difference takes place; in the hovering case, the UAV can maintain a sufficiently steady flying altitude with steady power consumption. For the vertical motion, more significant power fluctuations have been observed. Furthermore, power consumption increases slightly when the UAV ascends steadily. On the other hand, the horizontal motion, with a constant altitude, shows smaller power fluctuations. The same observations regarding power fluctuation in both vertical and horizontal motion have been mentioned in [36]. Also, in [56], it has been stated that in horizontal flight, the consumed power is often reduced due to translational lift, where the horizontal air flowing along the rotor produces additional lift.



(a) UAV energy consumption vs. UAV flying speed



(b) UAV motor power vs. flight speed



(c) Electric power for the propulsion of one motor vs. vertical speed

Figure 3.13: *Examples of the flight speed impact on energy/power consumption*

3.4.3 Flight speed impact

In [57], A. Thibbotuwawa et al. investigated the impact of several factors; among them was the flight speed (Fig.3.13(a)). They stated that for lower-flying speed, the energy consumption is clearly convex non-linear. On the other hand, the energy consumption tends towards a linear relationship with higher-flying speed. Also, in [58], an analysis of the amount of power consumed in a horizontal flight under different speed values and payloads was presented—depicted in Fig.3.13(b). The power consumption at a horizontal speed equals to 0 was the same as the hovering case. Furthermore, when the UAV flight speed was less than 4 m/s, the power consumption was almost constant; however, it increases with an increased speed due to increased drag. In [59], it has been mentioned that "the electric power consumption of the propulsion motor increases slightly and linearly when the drone ascends steadily"—as shown in Fig.3.13(c).

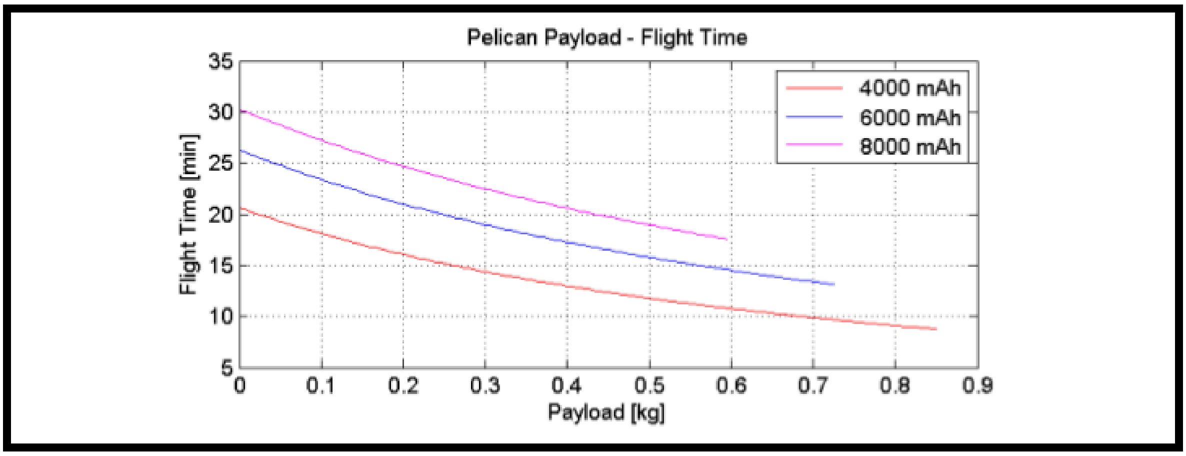


Figure 3.14: *Payload vs. flight time for different batteries*

3.4.4 Weight and payload impact

Payloads are of different types, sizes, and purposes. They are anything a UAV could carry without being among the basic body elements; examples of them: cameras, sensors (temperature, humidity, pressure, fires, etc.,) GPS, microphones, delivery packages, etc. The impact of payloads comes in two forms; the first is the direct impact, where they consume energy for their functioning. The second is indirect, where payloads increase the weight, increasing energy consumption since more thrust is needed. Overall, the UAV weight mostly affects the average power state [36]; with heavier payloads, the consumed power increases [60], and the endurance and flight time decreases [61, 62]. In [63], M. C. Achtelik et al. mentioned that in case of higher payload requirements, small batteries are recommended to reduce weight;

however, a short flight time will be gotten as shown in Fig. 3.14. According to experiments' results about energy consumption, in a multi-rotor UAV, presented in [56], the consumed energy varies approximately linearly with payloads and battery weight. For this reason, picking out suitable payloads in terms of their size, weight, and power consumption is crucial [64].

3.4.5 Design and configuration impact

This kind of impact could be highlighted from different angles; as an instance, in [65], D. Aleksandrov et al. have studied the design impact from the perspective of rotors number (2,3,4,6,8). The results show that the UAV's number of rotors could really affect power consumption and, consequently, the flight time. Also, in [66], such a parameter's impact has been mentioned. In [67], B. Theys et al. investigated the influence of propellers configuration (pusher and puller configuration, number of blades, arm's shape and dimension, etc.) on propulsion efficiency in hovering state. They also highlighted how the propeller and propulsion system configuration could raise losses because of interference that could occur with the multi-rotor arms as well as the mutual interference between propellers, as depicted in Fig. 3.15.

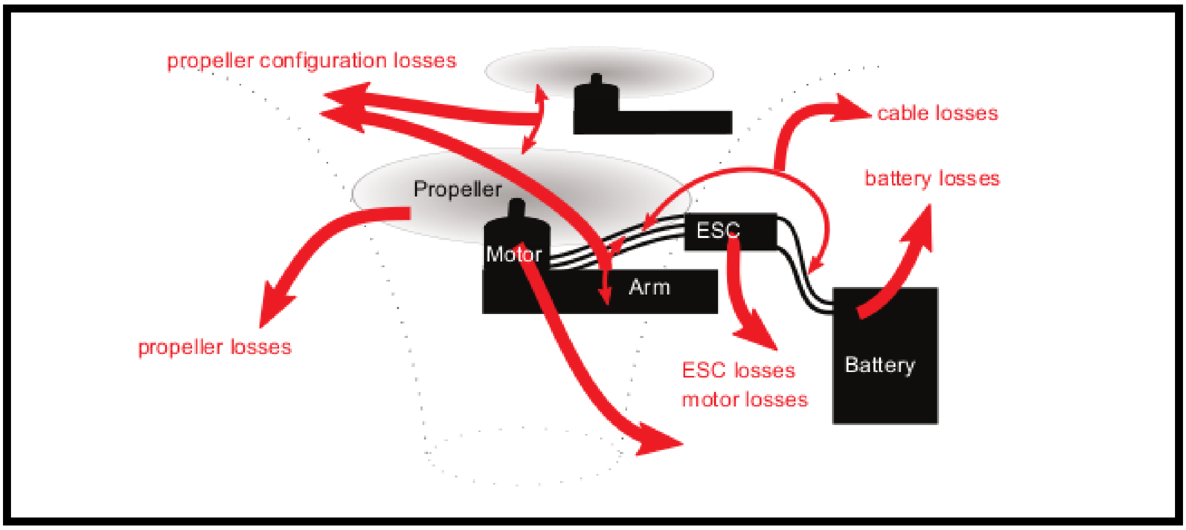


Figure 3.15: *Overview of losses from energy source to kinetic energy in the air*

3.4.6 Weather impact

Stochastic weather conditions have a remarkable impact; two principal factors are frequently considered: wind and temperature. The latter can affect the on-board battery performance. On the other hand, wind can increase resistance to the UAV motion. However, under some conditions, wind may serve the UAV during its motion [49], which positively affects energy consumption. Studying wind impact involves two main parameters: speed and direction [68]; air density, also, is often mentioned [69]. Fig. 3.16 [55] shows the power consumption under two distinct situations: headwind, where the UAV flies against the wind direction, and tailwind, where the flight is being along the wind direction. In [70], a UAV has been used for inspecting wind turbines in a wind farm. The main aim was to estimate the demanded energy and time to inspect wind turbines' blades. To this end, the authors investigated the impact of different factors on task accomplishment regarding energy consumption and time; among them, the wind speed and direction, which were with a significant impact.

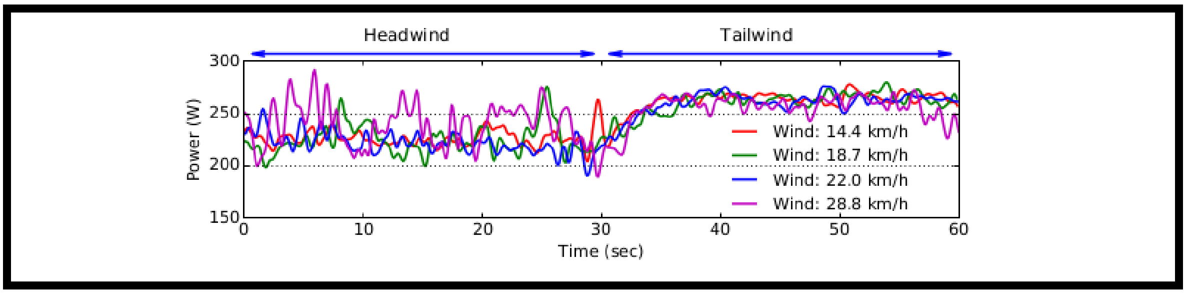


Figure 3.16: *Battery power consumption of test UAV 3DR Solo under different wind conditions*

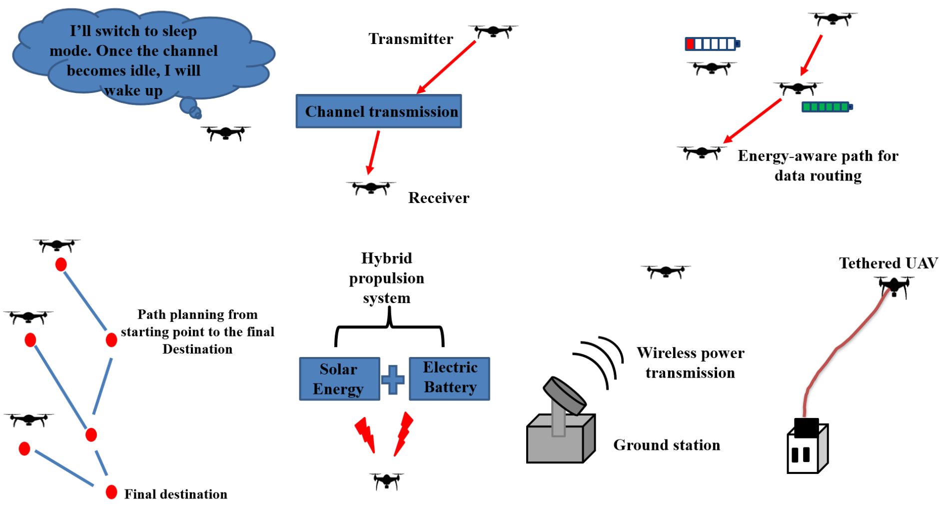
3.5 Conclusion

In this chapter, we gave focus to the main challenge UAANET is facing, namely, the limited energy of battery-powered UAVs. Energy sources commonly used were discussed, each with its pros and cons. As seen, the electric batteries deficiency regarding energy density could be overcome by using more powerful solutions, such as hydrogen fuel cells and solar energy; however, their use comes at the cost of more complexity, expense, and increased weight. Regardless of the energy source to be adopted for UAANET members, another important fact is about the energy being affected by numerous and various factors related to different aspects, explaining the criticality of energy in such an environment.

Indeed, many research works have shed light on this challenge from distinct standpoints. In this context, the next chapter, to be in the form of state of the art, will explore those works and their main contributions.

Chapter 4

State of the art



Highlights:

- Present main aspects through which the limited energy has been addressed.
- Review the contributions of prominent existing solutions.

4.1 Introduction

As permanently mentioned, the limited energy is deemed a barrier for UAVs' perfect performance, consequently, for UAANETs. The significant impact that energy could present is behind the particular attention it acquires as days go by. Indeed, such a challenge is broadly addressed by researchers in diverse domains and with different scientific backgrounds. Many contributions were presented, where they tackled the problem from different standpoints. Their shared goal was to overcome the restrictions coming out and prolong the flight time and endurance, which pushes up the network's overall performance.

This chapter gives details on how this challenge has been highlighted and treated and what are the notable literature contributions about it.

4.2 Prominent literature solutions for UAVs' limited energy

Actually, the limited energy in the UAVs environment is the focus of many research works, where diverse aspects were considered as presented in Fig. 4.1; details about each of them will be given in this chapter.

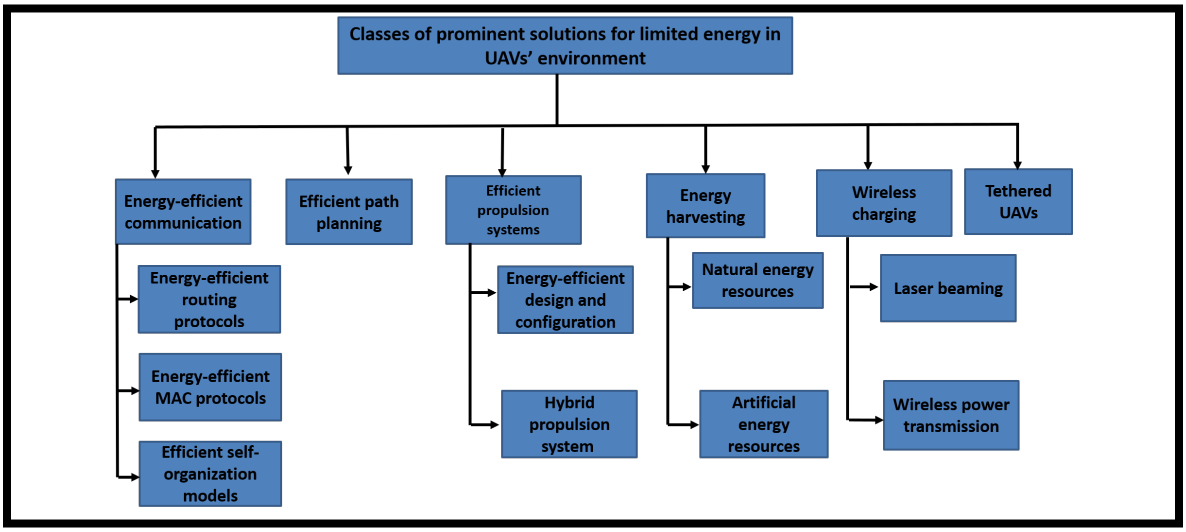


Figure 4.1: *Classes of solutions for UAVs' limited energy*

4.2.1 Energy-efficient communication

The works aiming to get energy-efficient communication are interested in the two communication layers, namely the network layer and the MAC. Furthermore, another category of solutions focuses on efficient self-organization models that will boost communication energy efficiency as much as possible.

A: Network layer

In this case, the proposed solutions aim to make different activities related to the network layer being energy efficient, through efficient communication schemes, optimal and energy-aware data routing paths, etc. Building energy-aware paths, in most cases, considers nodes' energy level; we mention prominent papers in this category as follows. In [71], I. U. Khan et al. proposed the nature-inspired protocol, AntHocNet, based on ant colony metaheuristics. A parameter named energy stabilization threshold (es-threshold) controls the nodes processing and forwarding packets to ensure energy efficiency and increase lifetime. In [72], the routing protocol ECaD uses a technique for energy conservation and considers connectivity measurement. It aims to establish on-demand multiple and robust routing paths by taking into account, at each hope, the link quality and the energy level.

The OLSR protocol has been widely studied for UAVs networks. Since this protocol performance is mainly based on the algorithm selecting the MPR nodes, the new versions were presenting new algorithms according to the desired objective. As an example, in [73], the proposed multi-objective OLSR (MO-OLSR) has considered an assortment of parameters, namely: energy, node load, traffic load, End-to-End latency, packet overhead, and mobility (communication link's stability). Also, in [74], the Multidimensional Perception and Energy Awareness OLSR (MPEA OLSR) considers the node's connection time, the congestion degree in the link layer, and the node's remaining energy. A modified version of the traditional DSR protocol, called UAV Energy Dynamic Source Routing (UEDSR) [75], gives preference to nodes with high energy level to forward the route request packet. Also, nodes with low energy level are deleted from the route cache.

On the other hand, as the clustering significantly optimizes energy consumption, many works were interested in clustered schemes. In [76], M. Y. Arafat et al. have proposed a bio-inspired clustering scheme (BIC) based on the gray wolf leadership hierarchy. The aim was to increase energy efficiency through optimizing cluster formation and clusters size, etc. In [77], a localization and energy-efficient routing strategy were presented; a fuzzy-logic-based system was used to estimate the UAV position using RSSI information. The calculated position is used for data routing and to select the cluster heads. In [78], the bio-inspired clustering process was formulated in the form of an optimization problem. Then, an algorithm based on bee intelligence is adopted to solve the formulated clustering problem. The cluster head selection process takes into account: nodes mobility, residual energy, and communication load. In [79], the proposed Energy-Aware Link-Based Clustering algorithm uses the K-means density clustering, where the calculated fitness values are the input of the K-means sorted fitness that forms a set of cluster heads and their cluster members. In [80], N. Shi et al. presented the Cluster-Based Location-Aided DSR, which uses an intra-cluster and inter-cluster routing. The intra-cluster communication uses a one-hop neighbors table. And the inter-cluster communication uses the Location-Aided DSR protocol based on LAR and DSR protocols.

B: MAC layer

In this layer, there are many strategies through which energy could be saved. Most proposed solutions work on eliminating origins of energy loss, such as idle listening, collisions, packet overhead, etc. Also, time-slot-based protocols are widely adopted due to their efficiency, where collisions are absent; also, nodes' energy will be saved since they could switch to sleep mode once they are not involved in the communication. Furthermore, directional antennas get attention due to their ability to reduce overhead and collisions, saving energy.

Examples of papers involving the concepts mentioned above, we cite: In [81], the CC-MAC protocol implements a hybrid coordination technique (combination of CSMA/CA and TDMA). The proposed technique efficiently coordinates between nodes for a simultaneous transmission without collision, reducing overhead. In [82], the proposed LODMAC uses directional antennas since they help to increase capacity, spatial reuse, and range of communication, which means a more efficient MAC protocol. Furthermore, estimating neighbors' location is considered for more accurate transmission toward the receiver. In [83], G. Wu et al. have proposed a multi-channel MAC protocol for FANET (FM-MAC), which takes advantage of the multi-channel and directional antennas to improve the quality of service. Regarding the use of time slots, in [84], S. Vashisht et al. presented a new strategy based on a fire-fly optimization algorithm to form an efficient time slotting. They aimed to implement an energy-efficient and location-aware MAC to enhance the quality of service in UAVs' networks. For the LDMAC [85], a propagation delay-aware access protocol for long-distance UAV networks, the base station was responsible for ensuring optimized time slots allocation without collision, fair, and with temporal reuse. Mainly, this protocol considers the collision-free condition since the permanent retransmission due to collision would be costly, particularly in wireless networks with a long-distance transmission, as is the case for the UAVs. Also, in [86], an opportunistic cooperative TDMA scheme was proposed for UAANET.

C: Self-organization models

Self-organization models involve a set of rules that ensure an autonomous and efficient organization of the swarm members; they are concerned by nodes' behavior regarding motion, communication, etc. The efficient organization allows practical cooperation among the UAVs and allows efficient use of resources, among them energy. Most of the existing self-organization models are nature-inspired, where nature concepts are mimicked. There are prominent proposed models based on famous nature-inspired algorithms, such as Particle Swarm Optimization (PSO), Boids of Reynolds (BR), Ant Colony Optimization (ACO), Bee Colony (BC), Grey Wolf Optimization (GWO), Virtual Force Algorithm (VFA), etc. We present notable works in this context as follows. In [87], X. Li et al. proposed the Particle Swarm Mobility Model (PSMM) based on the particle swarm optimization algorithm; it allows a group motion for a swarm of UAVs and aims to maintain connectivity among them. It uses a temporal correlation for each UAV regarding speed value and a spatial correlation among the group of UAVs regarding the new position. The Distributed Flocking Model (DFM) presented in [88] is designed for UAVs moving in the form of a swarm. This model also aims to ensure a high connectivity degree among UAVs. It uses basic concepts of Boids of Reynolds: cohesion, separation, and alignment. The UAVs are classified as leaders and followers, where leaders should broadcast information about their speed and heading to their followers. According to the received values of the leader's speed and heading, the follower will take the appropriate decision about cohesion, separation, and alignment, maintaining connectivity. In [89], et al. presented a fault-tolerance self-organizing flocking approach for a swarm of multi-rotor UAVs performing an aerial survey. This model considers several parameters, such as UAV mutual distances, dynamic leader selection, path planning, and fault tolerance. This approach aims to get the flock of UAVs organized efficiently with fault tolerance consideration, minimize the mission time, and decrease overhead. Pheromone-based models are also widely considered, such as in [90], where a bio-inspired algorithm using pheromone is presented, which aims to control multiple UAVs and ensure their coordination to be spatially self-organized. Also, a pheromone-based mobility model was presented in [91], where the pheromone in this model was used to identify the percentage of coverage to guide the UAVs over the area of interest regarding regions to be covered. Also, the virtual force concept is frequently involved in controlling UAVs' motion to be self-organized, as presented in [92, 93, 94, 95]. In [96], Lenovo has performed an experimental analysis about the applicability of AntHocNet and BeeAdHoc (Bio-inspired algorithms inspired by ant and bee colonies) in FANET. The conducted experiments aim to explore the efficiency of those two protocols if adopted for routing in UAVs' environment. Furthermore, there exist works that consider self-organization models to improve link quality and data routing of a given routing protocol, as proposed in [97], where the AODV protocol has been used, and the Boids of Reynold is involved to ensure and maintain connectivity during data transmission between two points to decrease data loss and delay while increasing throughput.

4.2.2 Efficient propulsion system

This category of solutions focuses on optimizing the propulsion system's design and configuration to avoid energy waste. Furthermore, hybrid propulsion systems are widely adopted, where more than one energy source is used.

- **Design and configuration perspective:** in [98], X. Dai et al. have mathematically modeled the propulsion system's main components. For each component, fundamental parameters are estimated and calculated through mathematical derivations to maximize efficiency. The paper [23] presented a tool to determine the optimal combinations of propellers and motors according to the mission profile. The presented tool was validated by testing experimental flights to demonstrate energy saving. The proposed configuration scheme for a quadcopter, presented in [99], uses a triangular configuration of small rotors along with a large rotor placed at the center. Analytical tests showed the efficiency of such configuration compared to the conventional one regarding many parameters, including the required hovering power. In [100], H. Xiong et al. have studied the power consumption optimization of a quadcopter by making arms rotate to fitting positions; the calculation of those positions was based on the quadcopter dynamics model and rotors' power-thrust curve. Due to performed analysis, an arm-rotation approach has been proposed to optimize energy efficiency during the hovering state.
- **Hybrid propulsion system:** for hybrid propulsion systems, the combination of different energy sources could be adopted to extend flight time and increase endurance [101, 102, 103, 104]; an example is given in Fig. 4.2 [105].

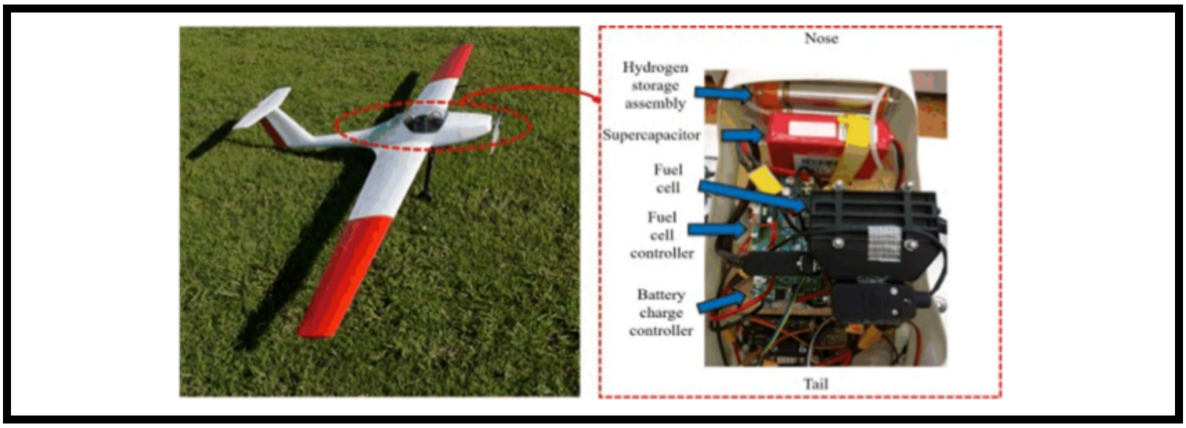


Figure 4.2: *UAV based on a hybrid propulsion system*

4.2.3 Energy-efficient path planning

An energy-efficient algorithm/method for path planning must guarantee a safe and optimal path minimizing travel duration and conserving energy. There exist many approaches for path planning; Fig. 4.3 summarizes popular ones [106]. Reviews about those approaches could be found in [106, 107, 108, 109].

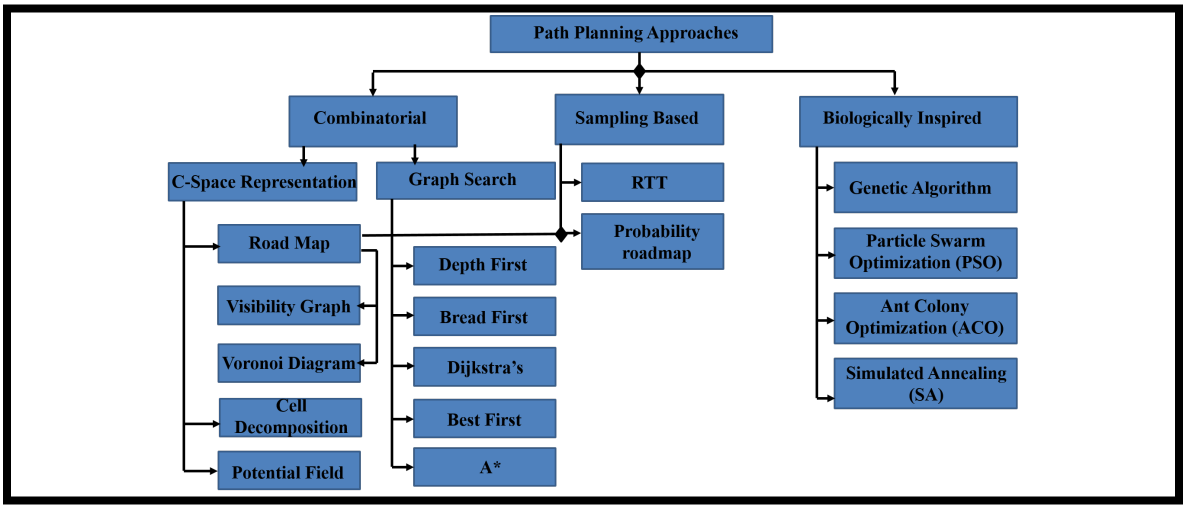


Figure 4.3: *Path planning algorithms classification*

4.2.4 Wireless charging

Wireless charging is a practical solution since it allows the UAVs to be charged without landing and human intervention. We present two of the most popular wireless charging techniques: laser beaming and wireless power transfer.

A: Laser beaming

In this case, a laser power beacon is used to charge the UAVs at flight through sending laser beams [110]; Fig. 4.4 [111] illustrates this solution's principle. Optical receivers are used to convert received light into electricity. Among central shortcomings: the UAVs should be at that close distance from the ground station, bringing restrictions regarding flight altitude and range—affecting long-range applications. Furthermore, the cost is high, and lasers of high intensity are dangerous to human health [39, 111].

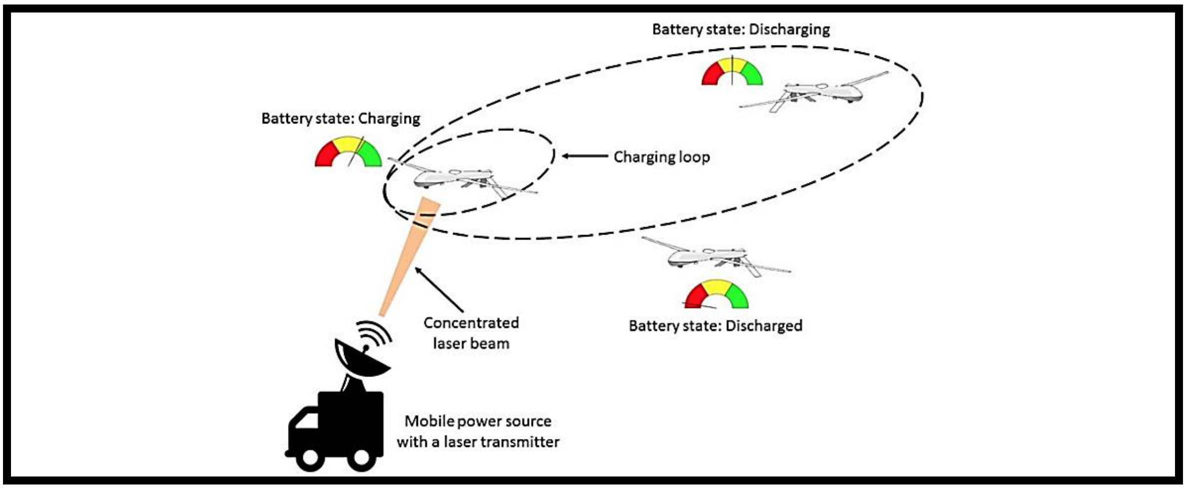


Figure 4.4: *UAV charging using laser beaming*

B: Wireless power transfer

The Wireless Power Transfer (WPT) was first introduced by the scientist Nicola Tesla over the twentieth century. This technique proposes to transmit energy through propagating electromagnetic filed without any cable-based connection. The transmitter generates an electromagnetic field, and then the receiver converts it back to an electric current [111]. Like the laser beaming approach, this technique brings some constraints related to flight altitude and range, along with increasing cost and complexity. Furthermore, with the WPT, interference with the UAVs' communication traffic could take place [112]. Besides, the environmental obstacles (buildings, cars, trees, etc.) could affect the propagating electromagnetic field, meaning that such a solution may not be practical in the presence of those obstacles.

4.2.5 Energy harvesting

Another alternative to boost endurance is to take advantage of the environment to seek energy [113], where energy harvesting became a promising solution to power autonomous electric devices [114, 115]. Many surrounding resources are considered, such as solar [19, 43, 46, 47, 116, 117], wind [113, 118], vibration [119], thermals [120], and electromagnetic fields [121]—Fig. 4.5 [122] summed up prominent ones. Hybrid solutions are also possible, as shown in Fig. 4.6 [119], where an RC glider aircraft involves two harvesting systems; the first one harvests energy from the aircraft's wing vibrations and rigid body motions, and the second is a solar-based one. Also, in [115], C. Van Nguyen et al. have proposed a hybrid energy harvesting system that uses solar and radio frequency (RF). A popular application allowing UAVs to harvest energy during mission accomplishment is the power lines inspection,

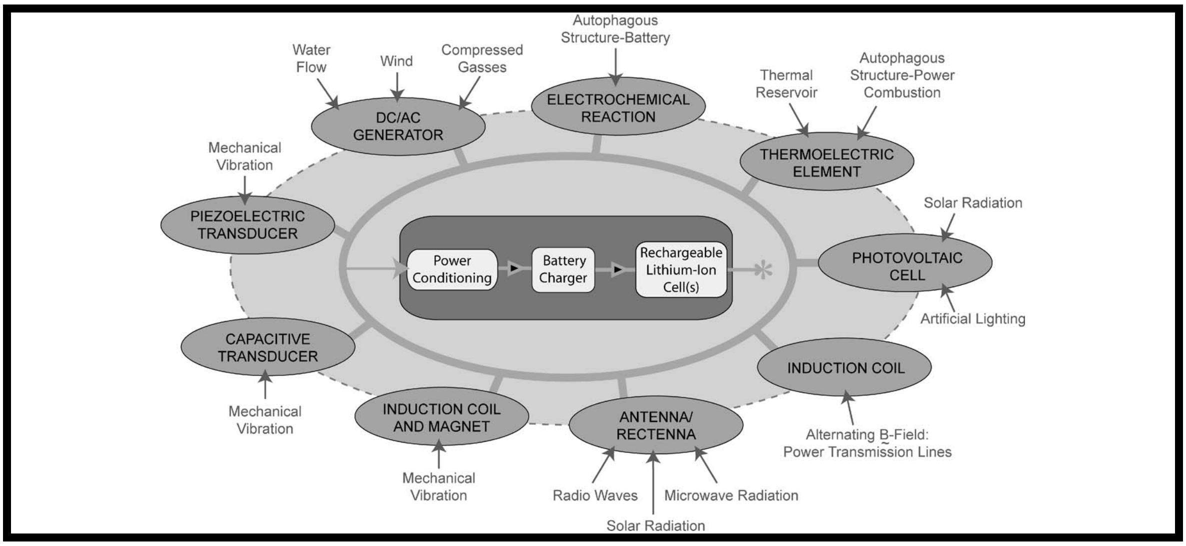
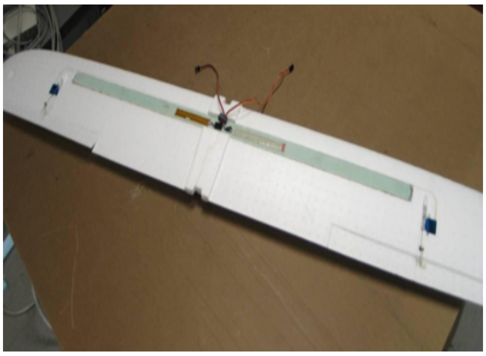


Figure 4.5: *Various sources used for energy harvesting*

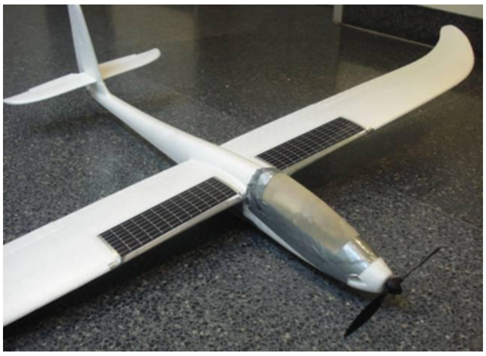
where energy could be harvested from the electromagnetic field surrounding those lines, as depicted in Fig. 4.7 [121].

4.2.6 Tethered UAVs

In this solution kind, the UAVs are tethered, where a power line is attached to the UAV from one side, and the other side is attached to the ground station. This solution provides a stable power supply, allowing endless endurance; furthermore, it ensures less constraint on payloads and more robustness to wind [123]. Usually, copper wires are used; however, fiber optic cables are also widely considered, where kilowatts of power are provided through a light of high intensity [39]. Fig. 5.21 and Fig. 5.22 [124] show field examples of tethered UAVs of the famous "Elistair" known as "Tethered Drone Company." Since the UAV must be permanently connected to the ground station through the cable, the application range will be very limited, which is the main drawback of this solution. Many researchers are interested in applications based on tethered UAVs, where the patent presented in [125] has considered data gathering applications. In [126], M. A. Kishk et al. have studied an optimization problem for 3D placement of tethered UAVs serving as airborne base stations. Also, in [127], the UAVs provided cellular coverage in a post-disaster area. The papers [128] and [129] have presented relevant contributions about tethered UAVs' applications.



(a)



(b)

Figure 4.6: *Example of a UAV with two energy harvesting systems*

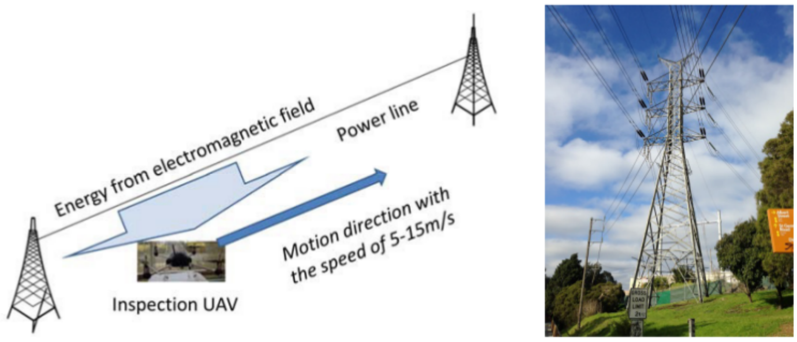
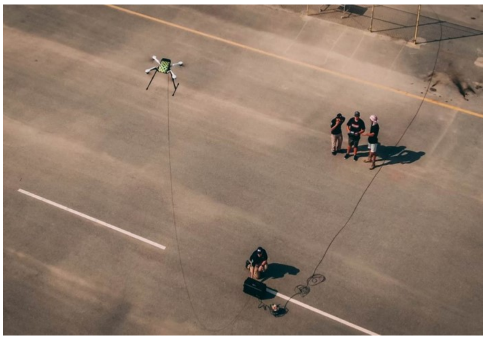


Figure 4.7: *Harvesting energy while inspecting power lines of high voltage*

(a)



(b)

Figure 4.8: *Example of tethered UAVs*

4.3 Conclusion

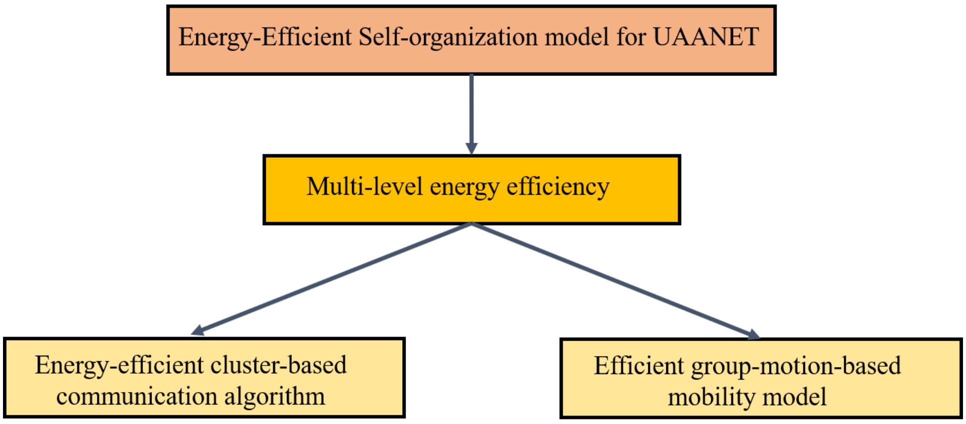
As seen, this chapter shed light on outstanding literature solutions for limited energy constraint at all levels. The proposed solutions were classified according to the aspect they were interested in (communication, propulsion system, wireless charging, etc.) Regardless of those solutions' different nature, the main target was the same, namely, getting more flight time and more endurance.

Indeed, we share the same objective as well, where our proposed solution mainly aims to boost energy efficiency in UAANET. In the coming chapters, we will go through more details about our contributions.

Part 3: Contributions

Chapter 5

ElectriBio-inspired Energy-Efficient Self-organization model for Unmanned Aerial Ad Hoc Network



Highlights:

- Present and justify basic concepts of our proposed self-organization model
- Present the notable contributions of our model

5.1 Introduction

A UAANET can hold various kinds of applications in a modern, efficient, and more productive way, explaining the particular attention it gains recently. Actually, the prominent focus is on maximizing performance efficiency through highlighting major challenges and minimizing their potential impact. When it comes to challenges classification, the limited energy is topping the list. Therefore, intending to boost productivity, efficiency, simplicity, and get an increased lifetime for the deployed network, we propose our ElectriBio-inspired Energy-Efficient Self-organization model for UAANET (EBEESU) [130], which encapsulates a set of contributions meeting the stated needs. Unlike existing literature, our model considers multi-level contributions regarding energy saving, where mobility and communication are taken as complementary aspects, and each of them involves different parameters increasing energy saving.

In this chapter, we give elucidations and justifications about how our proposed model ensures vital contributions in terms of crucial network performance parameters, namely: energy consumption, packet loss ratio, and End-To-End delay.

5.2 Justifications about concepts involved in our proposed self-organization model

5.2.1 Why is communication considered?

As permanently mentioned, tackling limited energy in the UAVs environment could be considered from different perspectives since many subsystems, inside a UAV, are concerned by energy consumption (propulsion, communication, computation, and sensing). In our case, we gave emphasis to the communication aspect, as a result of important facts given as follows:

- Our research context is about UAVs forming an Ad Hoc network (UAANET), where communication is the building block of such an environment.
- We consider a monitoring scenario, which is a cooperative-based application that requires communication for UAVs coordination and cooperation.
- Communication has a significant impact on network performance—efficient communication enhances performance.
- Proposed solutions into communication context consider multi-UAV systems, unlike propulsion system solutions that consider single UAVs.

- The energy consumed for communication exceeds the other subsystems, sensing and computation [25].
- Regardless of the continuous interest given to batteries technology to extend endurance and promote performance, the UAVs should use their energy efficiently to get an enhanced communication performance independently of the available energy budget. This gives rise to an outstanding research topic in the UAVs domain: energy-efficient UAV communications [3].
- The communication energy consumption depends on flexible parameters, such as transmission distance and amount of data, where these parameters could be adjusted to get an efficient use of energy [25].
- The solutions considering the communication aspect do not need to know about environmental parameters as, for example, in the case of solutions into propulsion aspect where some parameters such as weather conditions should be taken into account.

5.2.2 How did we consider communication's impact?

Indeed, our aim is to get a high level of energy saving; to this end, we have introduced a multi-level communication impact consideration, where that impact has been highlighted under different forms in different levels, namely:

- **Explicit impact:** the addressed impact was related to the communication policy used for cooperation among the network members. The impacting parameters, considered in this case, are:
  - The communication architecture (clustered, flat)
  - The communication type (direct, multi-hop)
  - The amount of data transmitted within the network (data aggregation)
- **Implicit impact:** we were interested in communication impact from another perspective with no relation with communication protocols; we consider the mobility model. The impacting parameters addressed in this case are data loss and group motions' overhead.

5.2.3 Why do we consider mobility?

Mobility has been highlighted in our case due to its significant impact on energy consumption, where we intended to increase energy saving by reducing communication energy waste related to the mobility model due to data loss and overhead of group motions. Indeed, we have studied the impact of mobility models on energy consumption related to data loss ratio in detail in another paper [131], where it has been clearly demonstrated that the consumed energy differs according to the kind of the adopted mobility model, which proves the impact of mobility on energy consumption.

5.2.4 Why Ad Hoc mode?

The Ad Hoc mode is deemed a simple, flexible, efficient, and affordable solution allowing communication among the multi-UAV system's members. On the other hand, the Ad Hoc mode reinforces energy efficiency through the opportunity of multi-hop communication that reduces transmission distance, remarkably saving energy. Also, in [132], it has been mentioned that the Ad Hoc mode allows less energy consumption compared to the infrastructure-based mode.

5.2.5 Why multi-rotor UAVs?

We were interested in multi-rotor UAVs due to their high maneuverability and hovering ability [61, 94]. Furthermore, low speed could be adopted for this kind of UAVs, unlike the fixed-wing. These features make multi-rotor UAVs more suitable for monitoring applications, which is our considered scenario.

5.3 Proposed solution

We have proposed an ElectriBio-inspired energy-efficient self-organization model for UAANET; this model allows a set of UAVs to perform monitoring scenarios cooperatively in an efficient way, taking energy saving as the central plan. It involves a mobility model and a cluster-based communication algorithm, where both aim to increase energy saving and promote performance.

5.3.1 The mobility model

Our mobility model encapsulates two aspects, namely: the structural and the functional, detailed as follows.

A: Structural aspect

It describes the pattern of UAVs' motion within the monitored area of interest. Our mobility model's structural aspect is Electrical-inspired, mainly inspired by the three-phase electric system; in-depth details are presented below.

A1: The three-phase electric current system (three-phase load case)

A three-phase electric current system consists of three sinusoidal currents with the same frequency and amplitude; they are shifted by 120 degrees in typical installations. The system configuration could be in two kinds: delta or star; the latter is the one by which our model's structural aspect is inspired. In the star configuration, a neutral point connects three wires where an alternating and periodic electric current flows (Fig. 5.1 [130]). Due to these three currents, a rotating magnetic field is created; in the ideal conditions, this magnetic field changes direction at a constant angular rate.

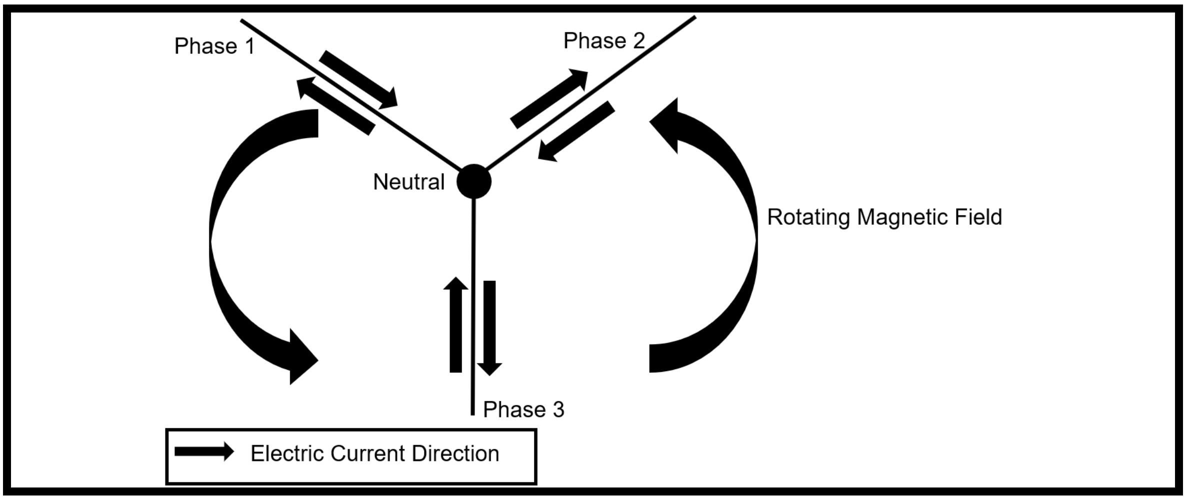


Figure 5.1: *Three-phase star-connected system*

A2: Electrical-inspired model

Based on the three-phase electric current system in the case of star configuration, we inspired a mobility model for a swarm of UAVs performing a monitoring scenario. We consider an area of interest divided into three subareas, and the base station is centering the whole area. The three subareas simulate the three wires, and the base station simulates the neutral central point (Fig. 5.2 [130]). The electrons move inside each wire, creating a back and forth electric current; likewise, the UAVs move inside each subarea, forming a back and forth moving swarm. The motion of all electrons inside the wire forms one moving electric current; similarly, the motion of all the UAVs inside the subarea forms one moving swarm. In the case of the electric current, the motion is a straight back and forth motion from one side to another; however, in our model, it is a back and forth motion in a rotating mode (from and to the base station). Indeed, the rotation here does not refer to the common rotation around a particular axis or point. Instead, the rotating motion takes place in this

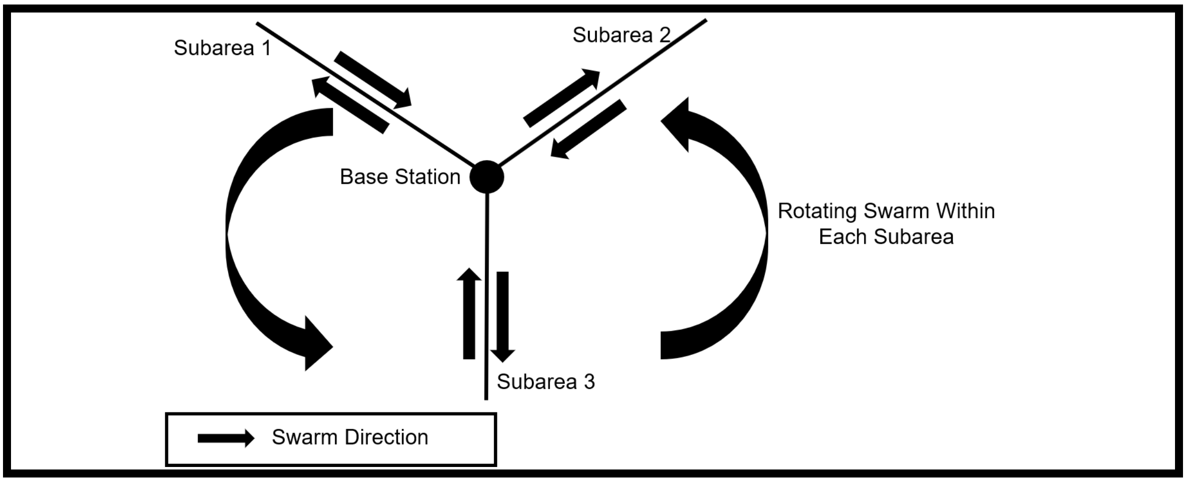


Figure 5.2: *Electrical-inspired model*

Comparison aspect	Three-phase current system	Our model
General description	* Three wires * Neutral central point * The three wires are connected to a central neutral point	* Three subareas * Central base station * The three subareas are connected to a base station centring the area of interest
Motion	* Electrons move inside each wire * The motion of all electrons inside each wire forms one moving current	* UAVs move inside each subarea * The motion of all the UAVs inside each subarea forms one moving swarm
Alternation and periodicity	* Alternating and periodic electric current	* Alternating and periodic moving swarm
Voltage levels	* Two voltage levels: phase voltage and line voltage	* Two area levels: level 1 and level 2

Table 5.1: *The analogy of our model concepts to the three-phase system ones*

case since each UAV goes through a continuous process of direction change using the YAW rotation until it gets the 2π round, making a coverage round. Indeed, this process is performed periodically, which simulates the periodicity feature of the electric current. Consequently, the monitoring scenario, according to our model, would be a collection of coverage rounds accomplished by the swarm of UAVs over time. No transition between subareas takes place, which means each UAV should move within the subarea it belongs to; also, the motion of each swarm in a given subarea is independent of the other swarms in other subareas.

There are two voltage levels in the three-phase star configuration: the phase voltage (between the phase and the neutral) and the line voltage (between two phases). The line voltage is much higher than the phase voltage. We make use of this concept in our model by defining two distinct levels in each subarea: level 1 and level 2.

Level 1 represents the area within the base station's transmission range; on the other hand, level 2 is out of the base station's scope. Indeed, in our model, the voltage level refers to the amount of needed transmission power to reach the base station. This power is low in level 1 since the nodes are close to the base station (similar to the low phase voltage); however, in level 2, nodes need high power for transmission since they are far from the base station (similar to the high line voltage).

Table 5.1 presents the analogy of our model concepts to the three-phase system ones. Also, their projection on the area of interest is shown in Fig. 5.3 [130], where a set of UAVs are deployed to monitor three subareas with two levels.

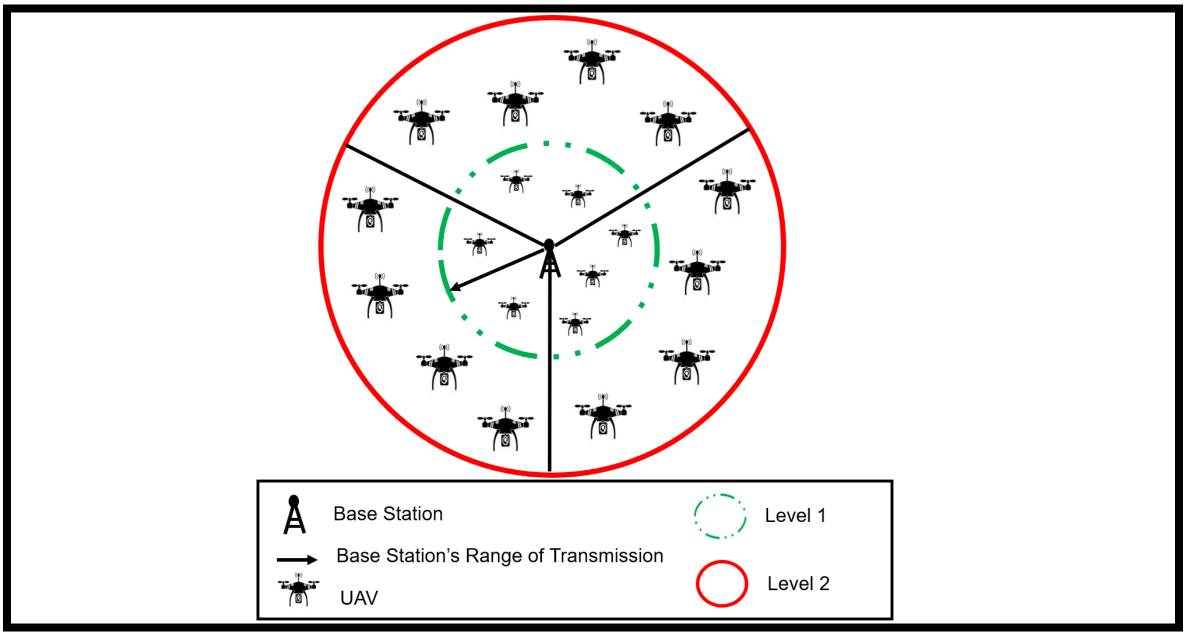


Figure 5.3: *Projection of the electrical-inspired model concepts on the area of interest*

B: Functional aspect

It describes how UAVs decide on changing their motion parameters over time; it is a bio-inspired model inspired by the "Cohesion-Tension (CT) Theory." It aims to let the UAVs move in the form of one coherent swarm inside each subarea, allowing an efficient collective motion.

B1: Cohesion-Tension theory

Plants need water for their vital functions. For years, researchers were interested in figuring out what allows water to move from the plant's roots to upper parts against gravity for high altitudes. The famous "Cohesion-Tension Theory," by Henry Horatio Dixon and John Joly [133, 134], has explained water motion inside the plant's stalk. They stated that due to hydrogen bonds, a cohesion force is created that makes molecules connected, making thus water move in the form of a connected column. Moreover, those molecules are attached to the xylem cells via adhesion force, allowing the water column to suspend against the gravity force [135]. Indeed, the cohesion force refers to an attraction between similar molecules (water molecules in this case), while the adhesion force represents an attraction between dissimilar molecules (water molecules and the xylem cells' molecules in this case). Furthermore, this theory mentioned a vital process behind water transportation, namely: the transpiration, where plants drive out water molecules through stomata. Losing water during transpiration creates a concentration difference, regarding water molecules, between the upper and lower plant's parts. This concentration difference makes water molecules move as a coherent stream towards the upper parts, where after the loss, the molecules move upwards to make up the lost ones. Therefore, those molecules move from regions of high concentration to regions of low concentration, which is known as the "simple propagation principle." Fig. 5.4 [130] visualizes the cohesion-tension theory's fundamental concepts.

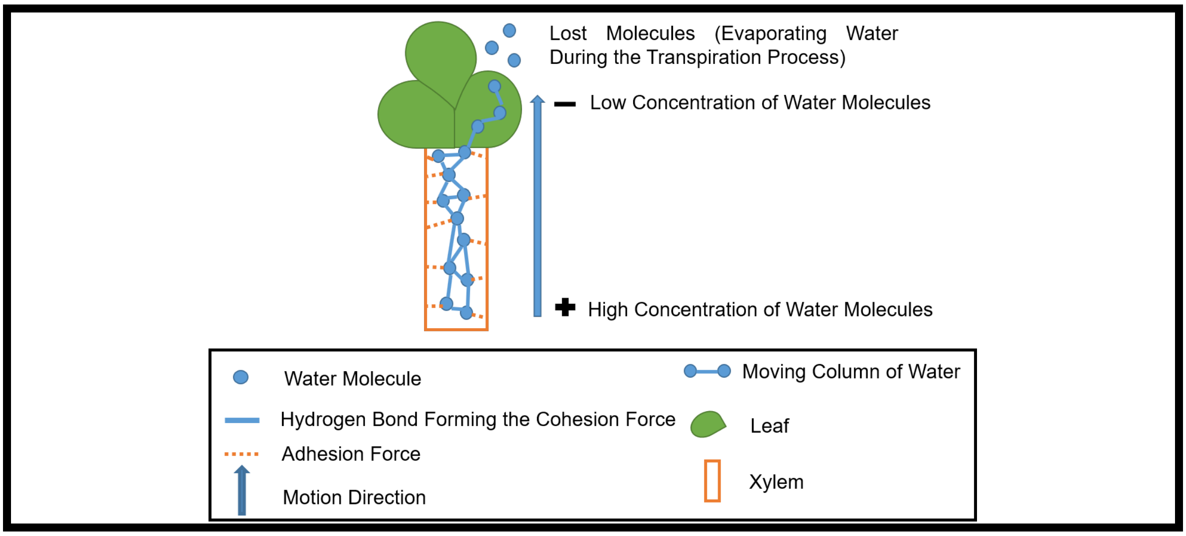


Figure 5.4: *Cohesion-Tension theory main concepts*

B2: Bio-inspired model

Indeed, our bio-inspired model involves concepts related to the above-described theory, namely: the cohesion force and concentration difference. The aim was to get a coherent moving swarm inside each subarea in the same way water molecules move in the form of a connected column inside the plant's stalk. Details about how these concepts have been considered are given as follows:

- **Concentration difference:** this concept is used to describe UAVs' propagation principle within the area of interest. We consider the visited directions as regions of high concentration; on the other hand, not visited directions are of low concentration. In Fig. 5.5 [130], these two kinds of concentration levels are modeled for each UAV, where the symbol (+) refers to directions of high concentration (visited), and the symbol (-) presents directions of low concentration (not visited). Accordingly, a concentration difference will take place, over the 2π directions, inside the monitored area, due to visited and not visited directions. Based on this consideration, each UAV will move from regions of high concentration (visited) to the ones of low concentration (not visited), simulating the water molecules' propagation principle.

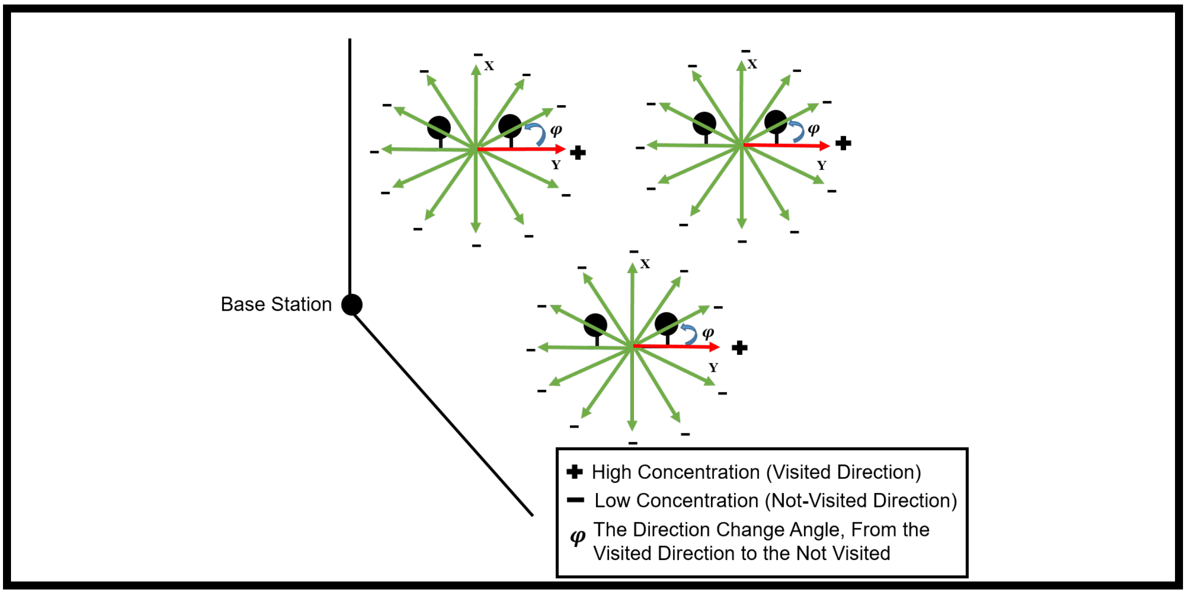


Figure 5.5: *Concentration difference in our Bio-inspired model*

- **Cohesion force:** the cohesion force in our model reflects the level of temporal and spatial correlation regarding speed and direction values, which allows the UAVs to move in the form of a coherent swarm. To this end, all the UAVs use the same speed value and direction change angle over time. Accordingly, in our model, the virtual cohesion force between the UAVs is taking place due to the 100 % temporal and spatial correlation over time by going through the same direction at the same speed. This high level of these two forms of correlation maintains connectivity and avoids the random propagation of UAVs within the area of interest. Fig. 5.6 [130] shows a virtual hydrogen bond between the UAVs.

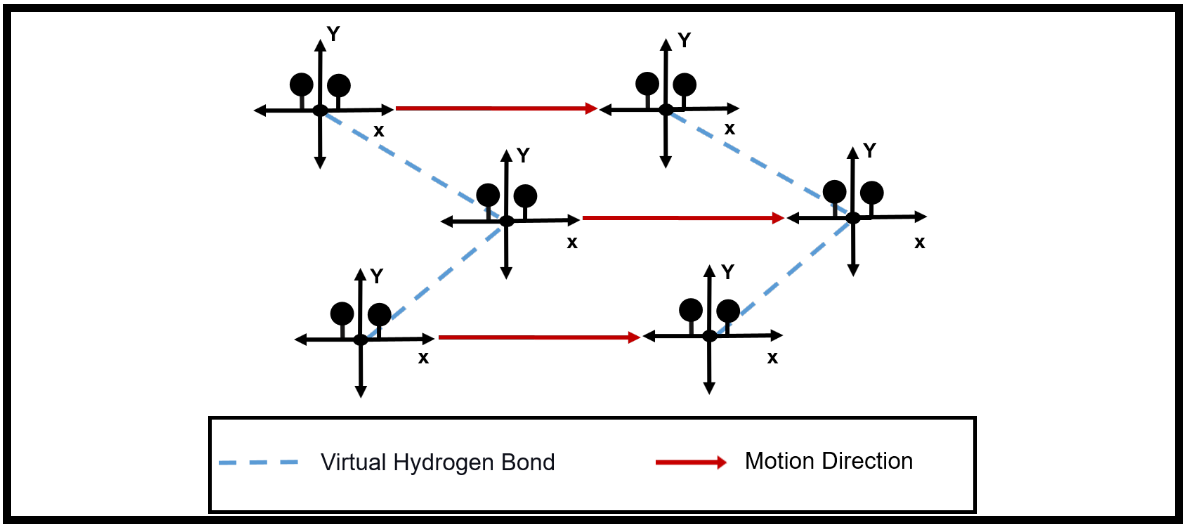


Figure 5.6: *The virtual hydrogen bond in our Bio-inspired model*

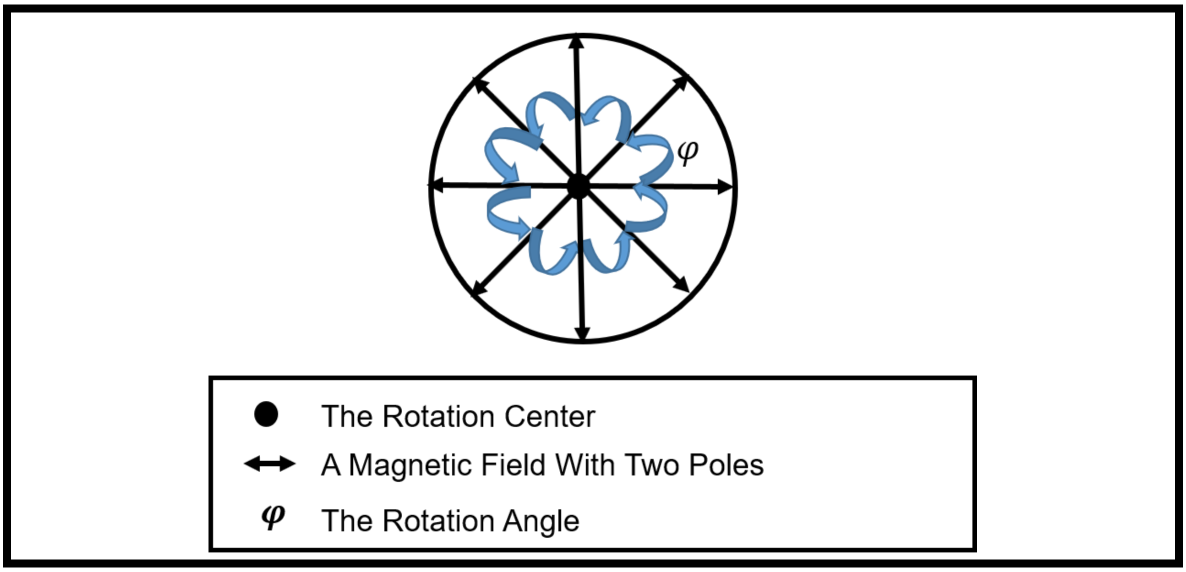


Figure 5.7: *Rotating magnetic field*

C: Direction and speed change

- **Direction change process:** UAVs' direction change considers three angles, known as Euler angles, which allow three rotation forms: PITCH, ROLL, and YAW (explained in Chapter 1). These angles describe a rigid body's direction in a 3D space. In our model, the direction change process simulates the concept of a rotating magnetic field (where poles' direction changes over the 2π directions over time); likewise, we consider a periodic change of direction for each UAV. To this end, we define a parameter called "CommonDirection" used to decide the UAV's next direction. The reason behind defining such a parameter as constant is to model the case of an ideal rotating magnetic field that changes direction at a constant angular rate (Fig.5.7 [130]).

- **Rotation forms:** about rotation forms, two of them are considered, namely: the YAW (Z-axis, Fig. 5.8 [130]) and ROLL (Y-axis, Fig. 5.9 [130]). The YAW rotation will align the UAV toward the desired direction (Equation 5.1), and the ROLL allows it to go through that direction—the starting direction is the same for all the UAVs, and it equals 0 in this case. When aligning toward the wanted direction using the YAW rotation, the UAV will move through the positive X-Axis for a predefined period, using the ROLL rotation. Indeed, in our

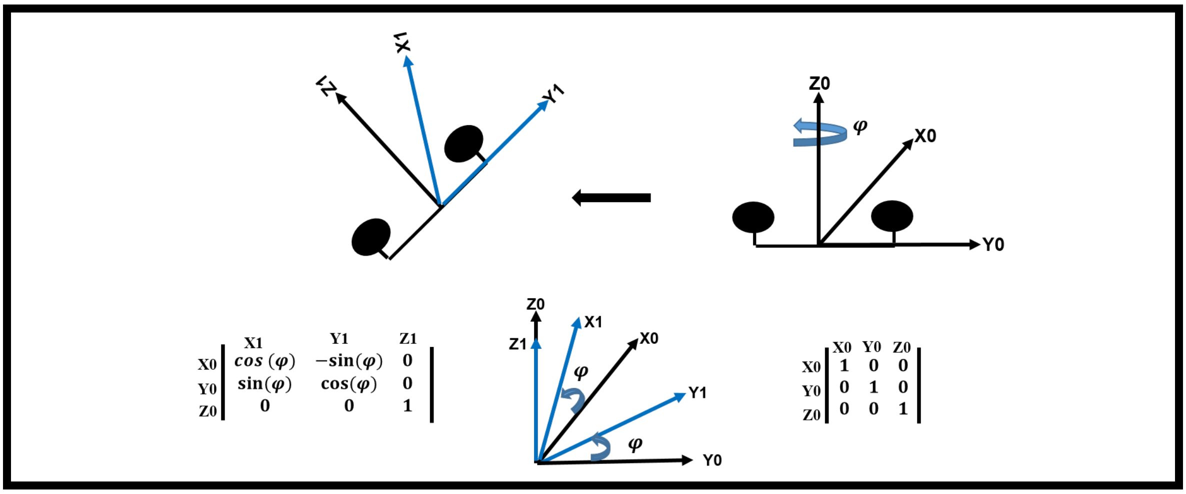


Figure 5.8: *YAW rotation*

case, the YAW angle is the defined parameter "CommonDirection" (Equation 5.2), which is assumed to correspond to the optimal YAW value that ensures changing direction with minimum energy consumption.

$$TheNewDirection = YAWAngle \tag{5.1}$$

Hence,

$$YAWAngle = "CommonDirection" \tag{5.2}$$

The periodic direction change (after a predefined constant period) simulates the alternating electric current reversing direction periodically, with a regular time interval. When the sum of directions the UAV went through gets 2 π, a coverage round is completed, and a new one should start through initializing the next direction to be the starting direction. For each UAV, achieving the 2 π round is due to the continuous direction change process using the YAW angle over time, where the number of

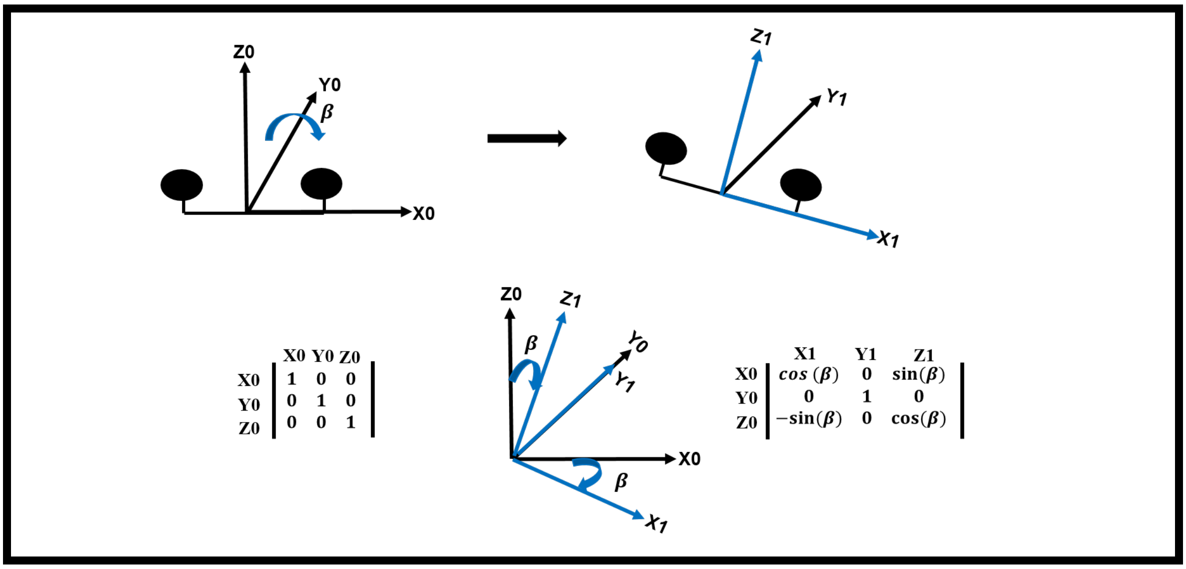


Figure 5.9: *ROLL rotation*

iterations giving the 2 π round depends on the used YAW angle as follows:

$$NumberOfIterations = \frac{2\pi}{YAWAngle} \tag{5.3}$$

The time spent in performing the 2 π round would be:

$$RoundTotalTime = t * \frac{2\pi}{YAWAngle} \tag{5.4}$$

t: The time spent in a given direction
As an example, Fig. 5.10 [130] shows a $\pi/4$-based 2 π round (number of iterations = 8).

- **Speed:** the adopted speed is constant (assumed as energy-efficient speed allowing low energy consumption). The velocity on the X and Y axes would be:

$$v_x = Speed * \cos(DirectionAngle) \tag{5.5}$$

$$v_y = Speed * \sin(DirectionAngle) \tag{5.6}$$

In one coverage round, for each UAV, the traveled trajectory's length is modeled as follows:

$$\frac{2\pi}{YAWangle} * t * \sqrt{(Speed * \cos(DirectionAngle))^2 + (Speed * \sin(DirectionAngle))^2} \tag{5.7}$$

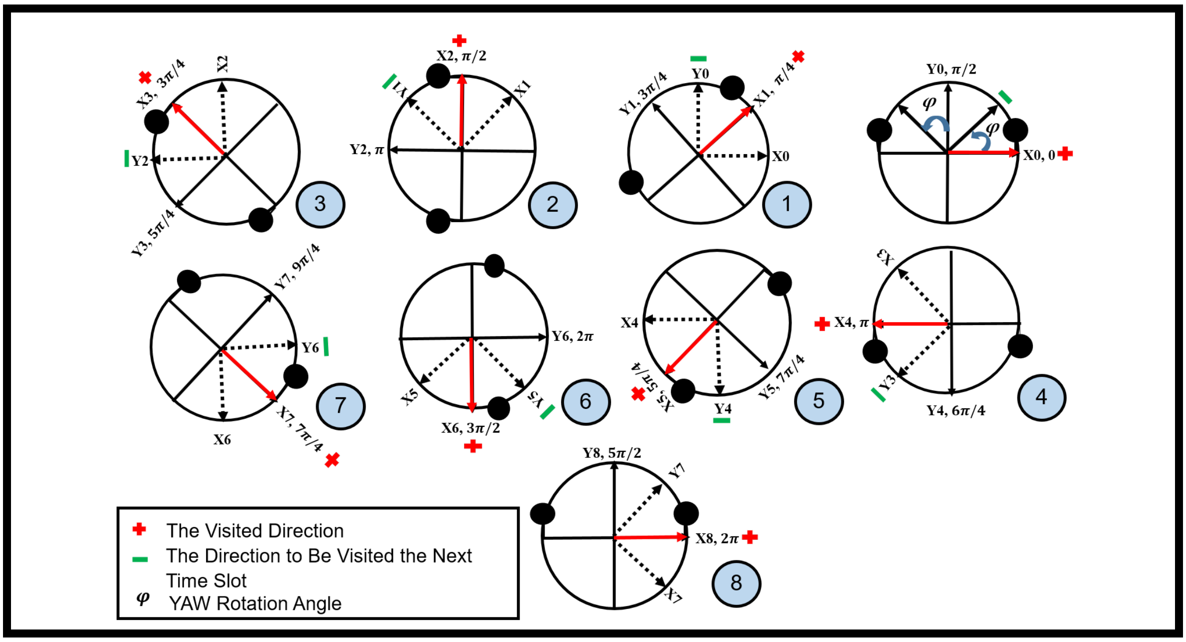


Figure 5.10: *2 π round for each UAV (YAW Angle = $\pi/4$)*

For the entire swarm, in each subarea, the length would be:

$$N\frac{2\pi}{YAWangle}*t*\sqrt{(Speed*\cos(DirectionAngle))^2+(Speed*\sin(DirectionAngle))^2} \tag{5.8}$$

- N: Number of UAVs

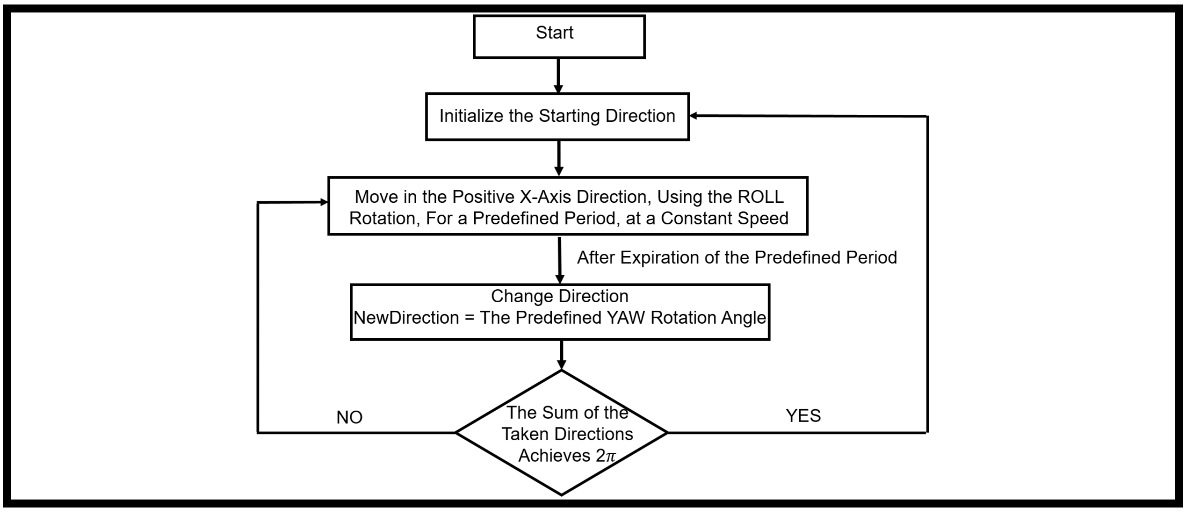


Figure 5.11: *Our mobility model's flowchart*

Algorithm 1 Motion Procedure (ROLL Angle β, YAW Angle φ, Rotating Reference-Frame F (X,Y,Z), EnergyLevel E)

Var Rotating ReferenceFrame G
Begin
if (E > PredefinedThreshold) **then**
  if (($\sum$VisitedDirections = 0) OR ($\sum$VisitedDirections = 2Π)) **then**
    ROLL Rotation (β)
    $\overrightarrow{NewReferenceFrame.X} = \cos(\beta)\overrightarrow{F.X} - \sin(\beta)\overrightarrow{F.Z}$
    $\overrightarrow{NewReferenceFrame.Y} = \overrightarrow{F.Y}$
    $\overrightarrow{NewReferenceFrame.Z} = \sin(\beta)\overrightarrow{F.X} + \cos(\beta)\overrightarrow{F.Z}$
    while (!(Expiration of Predefined Slot of Time)) **do**
      Move Through the Positive X-Axis Using the ROLL Rotation
    end while
    Return To the Former Reference Frame (the Frame Before the ROLL Rotation):
    $\overrightarrow{NewReferenceFrame.X} = \overrightarrow{F.X}$
    $\overrightarrow{NewReferenceFrame.Y} = \overrightarrow{F.Y}$
    $\overrightarrow{NewReferenceFrame.Z} = \overrightarrow{F.Z}$
    E = NewEnergyLevel
  else
    YAW Rotation (φ)
    $\overrightarrow{NewReferenceFrame.X} = \cos(\varphi)\overrightarrow{F.X} + \sin(\varphi)\overrightarrow{F.Y}$
    $\overrightarrow{NewReferenceFrame.Y} = -\sin(\varphi)\overrightarrow{F.X} + \cos(\varphi)\overrightarrow{F.Y}$
    $\overrightarrow{NewReferenceFrame.Z} = \overrightarrow{F.Z}$
    $\overrightarrow{G.X} = \overrightarrow{NewReferenceFrame.X}$
    $\overrightarrow{G.Y} = \overrightarrow{NewReferenceFrame.Y}$
    $\overrightarrow{G.Z} = \overrightarrow{NewReferenceFrame.Z}$
    ROLL Rotation (β)
    $\overrightarrow{NewReferenceFrame.X} = \cos(\beta)\overrightarrow{G.X} - \sin(\beta)\overrightarrow{G.Z}$
    $\overrightarrow{NewReferenceFrame.Y} = \overrightarrow{G.Y}$
    $\overrightarrow{NewReferenceFrame.Z} = \sin(\beta)\overrightarrow{G.X} + \cos(\beta)\overrightarrow{G.Z}$
    while (!(Expiration of Predefined Slot of Time)) **do**
      Move Through the Positive X-Axis Using the ROLL Rotation
    end while
    Return To the Former Reference Frame (the Frame Before the ROLL Rotation):
    $\overrightarrow{NewReferenceFrame.X} = \overrightarrow{G.X}$
    $\overrightarrow{NewReferenceFrame.Y} = \overrightarrow{G.Y}$
    $\overrightarrow{NewReferenceFrame.Z} = \overrightarrow{G.Z}$
    E = NewEnergyLevel
  end if
  Motion Procedure (β, φ, NewReferenceFrame, E)
end if
End

D: Mobility model chart and algorithm

The main instructions of our mobility model are given in Algorithm 1 [130]; also, a flowchart is presented in Fig. 5.11 [130].

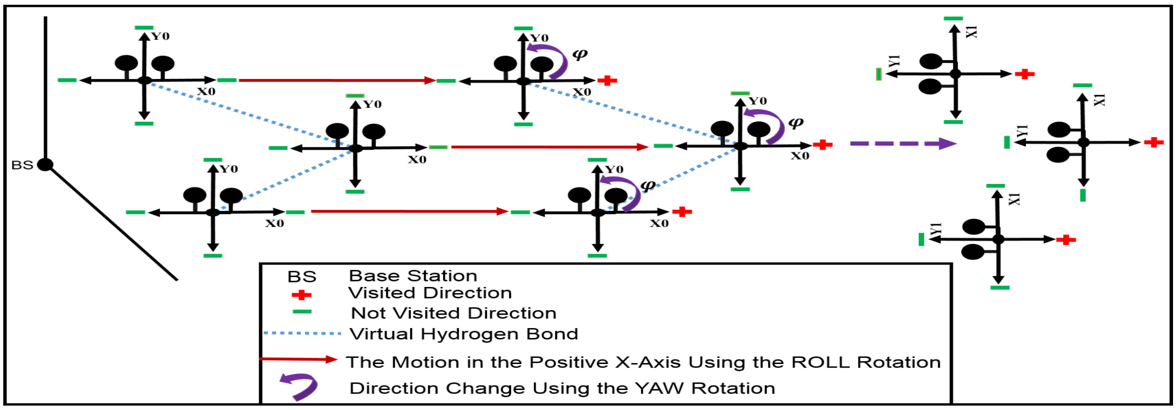


Figure 5.12: *The motion through the positive X-Axis using the ROLL rotation and changing direction using the YAW rotation (actual direction = 0 (starting direction), the next direction = $\pi/2$)*

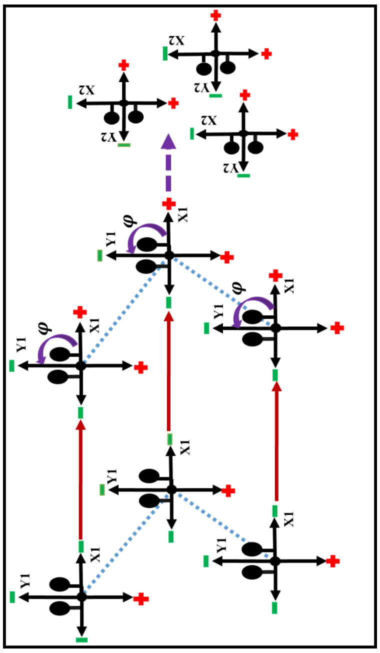


Figure 5.13: *The motion through the positive X-Axis using the ROLL rotation and changing direction using the YAW rotation (actual direction = $\pi/2$, the next direction = π)*

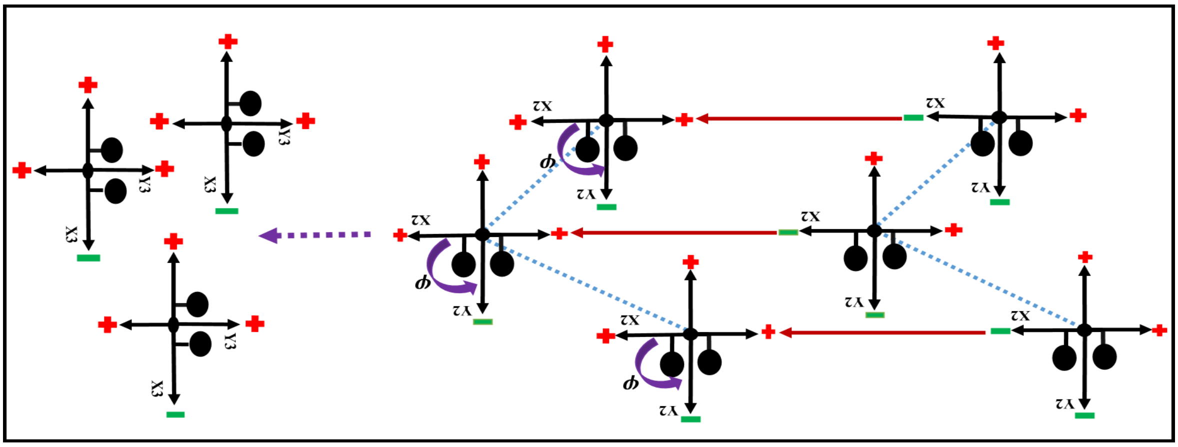


Figure 5.14: *The motion through the positive X-Axis using the ROLL rotation and changing direction using the YAW rotation (actual direction = π, the next direction = $3\pi/2$)*

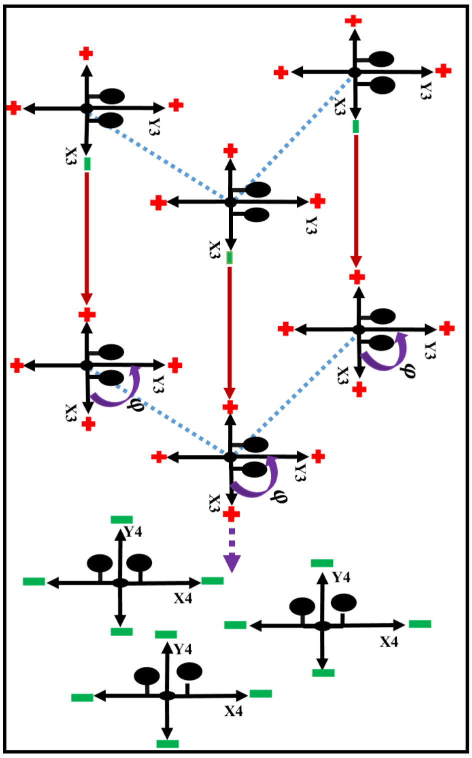


Figure 5.15: *The motion through the positive X-Axis using the ROLL rotation and changing direction using the YAW rotation (actual direction = $3\pi/2$, the next direction = 2π (completed 2π round))*

Furthermore, Fig. 5.12, Fig. 5.13, Fig. 5.14, and Fig. 5.15 [130] present in a more clear way how the ROLL and YAW rotations are used in our mobility algorithm to decide the UAV motion over time within the area of interest. For this example, the adopted YAW angle equals $\pi/2$. Indeed, these figures are a visual presentation of the instructions mentioned in Algorithm 1 and the flowchart, which we explain as follows:

- At the starting stage, all the directions are considered not visited (symbol (-)). In this case, the UAVs go through the starting direction, (Fig. 5.11 (Initialize the starting direction), in our case: starting direction = 0), without performing the YAW rotation (Algorithm 1: Instructions 2-14);
- Each UAV switches to the next direction to be visited using the YAW rotation (Algorithm 1: Instructions 16–19; Fig. 5.11 (NewDirection = The predefined YAW angle));
- After performing the YAW rotation, the gotten direction to be visited corresponds to the positive X-Axis;
- For a predefined period, each UAV should move through the appointed direction using the ROLL rotation (Algorithm 1: Instructions 23–29, Fig. 5.11 (Move in the positive X-axis direction, using the ROLL rotation, for a predefined period at a constant speed));
- After the period of time expires, the actual direction will be considered as visited (Symbol +); the UAV will return back to the previous status (Algorithm 1: Instructions 10–13/30-33) in order to get the previous reference frame to perform the next YAW rotation;
- When the sum of the visited directions gets 2π, each UAV initializes the directions (symbol -) and once again goes through the starting direction (Algorithm 1: Instructions 2–14).

For each UAV, the formed trajectory would be a polygon with sides' number depends on the adopted YAW angle (Equation 5.9). As an example, Fig. 5.16 [130] shows a trajectory of YAW angle equals $\pi/4$.

$$NumberOfSides = \frac{2\pi}{YAWangle} \tag{5.9}$$

5.3.2 Energy-efficient cluster-based communication algorithm

About communication among the network members, we aimed to render it efficient as much as possible. To this end, we have proposed an energy-efficient cluster-based

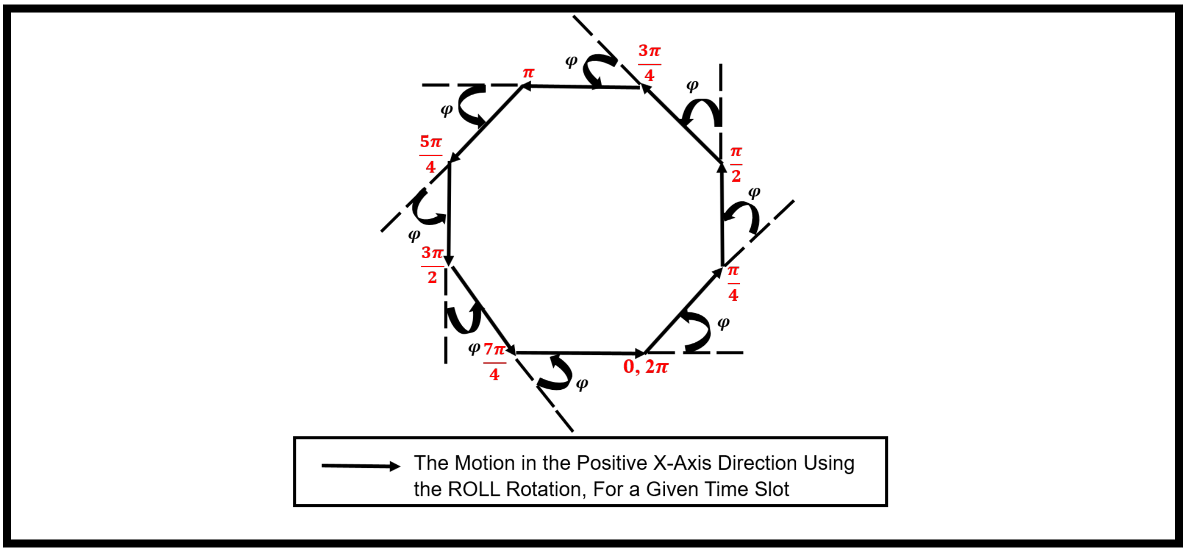


Figure 5.16: *The trajectory formed by each UAV (YAW angle = $\pi/4$)*

communication algorithm to ensure efficient cooperation, boosting productivity. We have adopted a hybrid scheme, where direct and multi-hop communication take place. Indeed, our communication scheme is utterly dependent on the structural aspect of our mobility model, where the communication kind, direct or multi-hop, depends on the level the UAV belongs to. Level 1 nodes use direct communication; on the other hand, multi-hop routes are used in level 2; furthermore, a clustered scheme is used in this level—the clustering is adopted as it boosts energy efficiency according to [136]. Our clustering algorithm brings notable contributions regarding clustering efficiency, energy saving, and overall network performance. Furthermore, the proposed clustering approach aims to balance the tradeoff that could take place between the objective function's parameters. To this end, we have introduced a separated-parameters-based clustering approach, where we separate parameters with a tradeoff to increase clustering efficiency. Besides, our clustering algorithm introduces two kinds of cluster heads, namely: the Main Cluster Head (MCH) and the Helper Cluster Head (HCH), which significantly reinforces energy saving through balancing the load within each cluster and allowing a two-level data aggregation. The nodes in level 2 transmit data to level 1 nodes that will forward them to the base station. The cooperative model among level 1 and level 2 nodes, to successfully transmit data to the base station, mimics the adhesion force between the water molecules and the xylem cells to transport water successfully. As previously mentioned, the adhesion force occurs between dissimilar molecules, where, in this case, the dissimilarity is about nodes' levels (the cooperation takes place between nodes of two different levels: level 1 and level 2). More details about our clustering algorithm and the overall communication scheme, and their contributions are presented below.

A: Proposed clustering algorithm

As we have earlier stated, only level 2 nodes are concerned by the clustering process. The main concepts of our clustering algorithm are presented as follows.

- Each node in level 2 broadcasts a packet containing the energy level and position.
- Each node in level 2 calculates its fitness value "F" as well as neighbors' fitness values using Equation 5.10.

$$F = \alpha 1 Energy + \frac{1}{\beta 1 DistanceToTheFirstLevel} \tag{5.10}$$

$$\alpha 1 + \beta 1 = 1$$

- The node with the highest "F" changes its status to "Main Cluster Head."

Based on Equation 5.10, we have:

$$\lim_{(Energy, DistanceToFirstLevel) \to (\infty, 0)} \alpha 1 Energy + \frac{1}{\beta 1 DistanceToTheFirstLevel} = \infty \tag{5.11}$$

which means that Equation 5.10 helps to choose the appropriate main cluster heads meeting our needs regarding the high energy level and the short distance to level 1 due to the fact that "F" gets maximized when the energy level is high and the distance to level 1 is short.

- The other nodes will turn their status to "Not Main Cluster Head" and select their main cluster head based on the calculated fitness values "F" of their neighbors.
- The main cluster head selection process is modeled as follows:

$$MainClusterHead(F) : \begin{cases} \forall n \in NeighborSet : & \\ F - F_n > 0, & MainClusterHead \\ else, & NotMainClusterHead \end{cases}$$

Indeed, the cluster members in our algorithm are selected with some constraints regarding distance. This constraint aims to reduce the transmission distance inside the cluster. To this end, we define a parameter called distance "d," where:

$$d < TheMainClusterHead'sTransmissionRange.$$

Algorithm 2 The Clustering Algorithm

N: number of neighbors; FitnessVal: The fitness value; MyPos: The current node's position; NeiPos: The neighbor's position; MainCHPos: The main cluster head's position

Begin

if (TheNodeLevel == 2) **then**
    Broadcast (Position, EnergyLevel)
    MyFitnessValue=α1Energy+ $\frac{1}{\beta 1 DistanceToTheFirstLevel}$
    for (i = 1 to N) **do**
        Receive (Position(i), EnergyLevel(i))
        FitnessVal(i) = α1Energy(i) + $\frac{1}{\beta 1 DistanceToTheFirstLevel(i)}$
    end for
    MaxF = Maximum of the Calculated Fitness Values of Neighbors
    if (MyFitnessValue $>$ MaxF) **then**
        MainClusterHead = True
        for (j = 1 to N) **do**
            Distance (j) = CalculateDistance (MyPos,NeiPos(j))
            if Distance (j) $\leq$ d **then**
                Add the Neighbor (j) To the Cluster Members Set
            end if
        end for
    else
        MainClusterHead = False
        MyMainClusterHead = The Node With the Maximum Fitness Value
        Distance = CalculateDistance (MyPos,MainCHPos)
        if (Distance $\leq$d) **then**
            ClusterMember = True
        else
            ClusterMember = False
            MyFitnessValue = α2 Energy + $\frac{1}{\beta 2 AverageDistance}$
            Broadcast (MyFitnessValue)
            MaxF = The Maximum of All Received Fitness Values
            if (MyFitnessValue $>$ MaxF) **then**
                HelperClusterHead = True
            else
                HelperClusterHead = False
                SubClusterMember = True
            end if
        end if
    end if
end if

End

This parameter is used by the main cluster head to select the nodes that will be considered as cluster members. For each neighbor, the main cluster head calculates the separating distance and then decides if that neighbor should be selected as a cluster member. The node will be selected if the separating distance is less than or equals d. On the other hand, each node calculates the distance separating it from the main cluster head and deduce if it has been selected or not. This process is modeled as follows:

$$ClusterMember(d): \begin{cases} \forall n \in NeighborSet: \\ Distance(MCH, node_n) \leq d, & SlectedbytheMCH \\ else, & NotSlectedbytheMCH \end{cases}$$

This process allows eliminating join packets transmission, reducing overhead over the network.

- The nodes not selected by the main cluster head, since they are beyond the distance "d," will form a subcluster with a Helper Cluster Head.
- The helper cluster head will serve as an intermediate between the not-selected nodes and the main cluster head—data will be forwarded by the helper cluster head to the main cluster head. The helper cluster head is selected according to the fitness value "f" calculated as:

$$f = \alpha 2 Energy + \frac{1}{\beta 2 AverageDistance} \tag{5.12}$$

$$\alpha 2 + \beta 2 = 1$$

  - AverageDistance: the average distance separating a given node from its neighbors.

Also, based on the same principle in Equation 5.11, Equation 5.12 helps to select the suitable node as a helper cluster head with a high energy level and a short average distance, where the "f" value is maximized when the energy is high and the average distance is short.

- The process of selecting the helper cluster head is modeled as follows:

$$HelperClusterHead(f): \begin{cases} \forall n \in NotSelectedNodes: \\ f - f_n > 0, & HelperClusterHead. \\ else, & SubClusterMember. \end{cases}$$

Algorithm 2 [130] gives the main instructions of our clustering algorithm.

So that level 2 data reach the base station, level 2 nodes cooperate with nodes in level 1. To this end, some of level 1 nodes are selected based on specific features as relay nodes that take the responsibility to forward level 2 data to the base station, where the selection process is as follows:

- The main cluster heads in level 2 broadcast a relaying request to level 1 nodes to forward their data to the base station—only the main cluster heads close to level 1 will broadcast this request.
- Level 1 nodes receiving the request will broadcast a relaying offer to forward data to the base station.
- Each main cluster head will select the appropriate offer using Equation 5.13.

$$DecisionValue = \alpha3Energy + \frac{1}{\beta3DistanceB + \gamma3DistanceC} \tag{5.13}$$

$$\alpha3 + \beta3 + \gamma3 = 1$$

  - DistanceB: the distance separating the relay node from the base station.
  - DistanceC: the distance separating the relay node from the main cluster head.

The main cluster head will select the node with the highest decision value as a primary relay node; also, a secondary relay node should be selected. Those relay nodes aggregate then forward data to the base station. The main cluster heads divide their transmission rounds between the primary and the secondary relay nodes to balance the load. Furthermore, the nodes in level 2 that receive level 1 relaying offer will transmit their data through relaying nodes in level 1 in case they were with higher energy level and close to them more than their main cluster heads, which saves energy more and decreases delay.

- Each main cluster head broadcasts a level 2 relaying offer for the other main cluster heads that are not accessible from level 1. Hence, those main cluster heads will choose the suitable relaying offer according to the energy level, the distance separating this main cluster head from the one broadcasting the offer, and the distance between the latter and level 1, using Equation 5.13.

Indeed, for accuracy and simplicity, the clustering process is performed while the UAVs are hovering.

- When the main cluster head's energy level gets a specific threshold expressed as follows:

$$EnergyLevel \leq TheAverageEnergyOfTheWholeCluster,$$

it will broadcast a packet containing the identifier of the node that will be the new main cluster head. This new main cluster head is the node with the highest energy level in the whole cluster. Furthermore, the new main cluster head will move to the previous main cluster heads' position to maintain topology and connectivity as much as possible.

- Also, the helper cluster head will plan a reclustering process by notifying the subcluster members when its energy level corresponds to:

$$EnergyLevel \leq TheAverageEnergyOfTheSubCluster$$

Indeed, this process of sharing the role of being a cluster head between the cluster members, through replacing the main and the helper cluster heads, aims to get an equitable energy dissipation within each cluster.

The relay nodes, both primary and secondary, will notify the main cluster heads once they are planning to leave the network if their energy level meets the predefined threshold level as follows:

Energy-Level-Threshold = (The energy needed to broadcast the notification and to stay until the main cluster heads select a new relay node) + (The energy needed to go back to the starting point on the ground)

Hence,

$$EnergyThresholdPercentage = \frac{EnergyThreshold}{InitialEnergy} * 100 \tag{5.14}$$

Notifying the main cluster heads by the relay nodes allows avoiding data loss due to transmitting data to nodes that have already left the network, saving nodes' energy.

Fig. 5.17 [130] shows a clustered network using our clustering approach, where level 2 holds a set of clusters with main cluster heads; in addition, a given cluster may contain a subcluster with a helper cluster head. Furthermore, communication takes place between the main cluster heads and particular nodes in level 1, selected as relay nodes, to transmit data to the base station.

B: Why do we adopt such a clustering approach?

As permanently mentioned in this chapter, we aim to increase energy saving as much as possible. To this end, we tried to maximize our clustering scheme efficiency, which boosts energy saving and improves the overall network performance. For the clustering process, we were interested in selecting cluster heads with high energy level (for long endurance) and close to both the cluster members and level 1 to reduce transmission energy and delay.

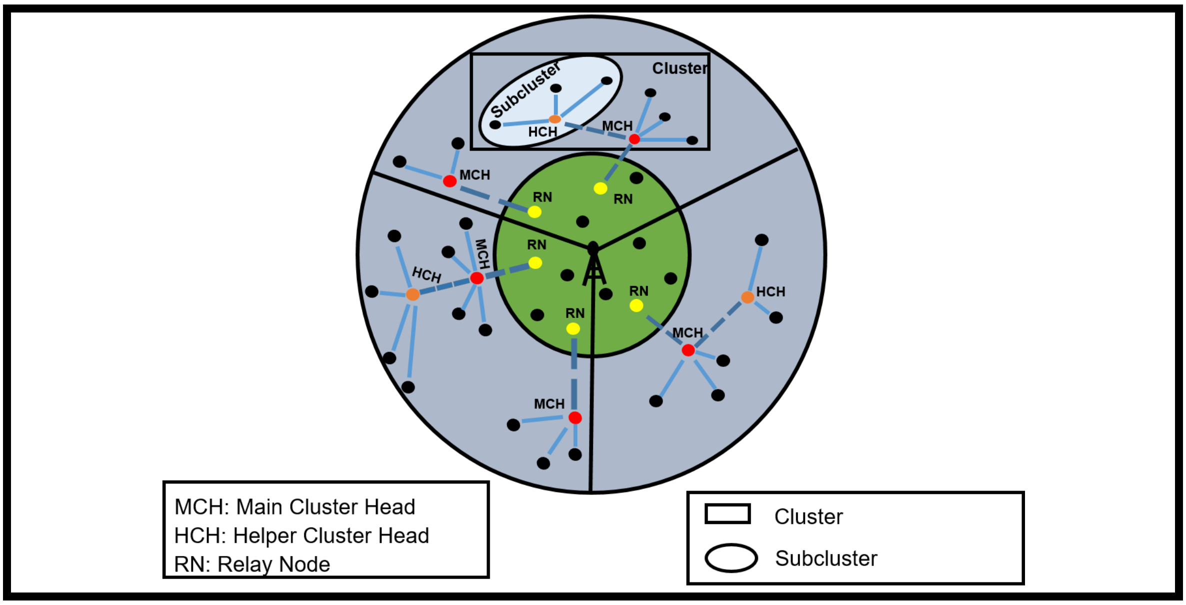


Figure 5.17: *Proposed clustering scheme*

Indeed, including parameters that could present a tradeoff in one objective function could affect the function outputs, which may not meet our needs regarding an efficient clustering scheme. In our case, the parameters that could present a tradeoff are the distance separating the cluster head from the cluster members and level 1. Hence, this tradeoff can hinder getting an efficient clustering scheme with a short transmission distance between the cluster head and the cluster members as well as between the cluster head and level 1. Consequently, the cluster head may be the closest to level 1 but not to the cluster members; on the other hand, the cluster head may be the closest to the cluster members but not to level 1. In the first case, the transmission to level 1 would be with less power and a decreased delay would be achieved, while the cluster members will perform the transmission operations with high power as the cluster head is not the closest to them. On the other hand, in the second case, a short transmission distance is ensured for the cluster members, while the transmission to level 1 would need high power due to the fact that the cluster head is not the closest to level 1. Furthermore, an increased delay would be gotten. Aiming to balance this tradeoff, we proposed a separated-parameters-based clustering approach, where we have separated the parameters that present a tradeoff. To this end, we take advantage of nodes with a high energy level and a short distance to level 1 to ensure long-endurance and low transmission power to level 1 and less delay (these nodes are selected as main cluster heads). Furthermore, the short transmission distance between the main cluster heads and the cluster members is achieved by allowing each main cluster head to choose the cluster members under some constraints about the separating distance (parameter d). On the other hand, for the helper cluster head selection, we considered the energy level for long endurance and the average distance separating the helper cluster head from the other subcluster members to reduce the transmission distance; besides, the short transmission distance to level 1 is ensured by the main cluster head. Using this approach based on separating parameters with a tradeoff, the aim about long endurance, short transmission distance between the cluster head and the cluster members and between the cluster head and level 1 is efficiently ensured, which reinforces energy saving and overall network performance.

Indeed, adopting a helper cluster head significantly boosts energy saving within the network, where it helps to decrease the extensive load on the main cluster head since the latter is responsible for transmitting data of the cluster members as well as other main cluster heads in level 2—if it has been selected as a relay node. Therefore, the helper cluster head would help to increase the main cluster head's endurance and consequently the lifetime. Furthermore, using a helper cluster head reduces the transmission distance within the cluster, saving energy.

This clustering scheme allows a two-level data aggregation inside each cluster, where both the main cluster head and the helper cluster head are concerned by the aggregation process. The two-level data aggregation reinforces energy saving due to reducing the amount of data to be treated and transmitted over the network, which reduces computational and communication energy consumption.

Nodes within level 1 would consume a considerable amount of energy since they are responsible for forwarding the total data of the entire network (levels 1 and 2) to the base station; for that, they have not been involved in the clustering process to save their energy.

To clarify our clustering approach's features and advantages, we have modeled the above-mentioned concepts as depicted in Fig. 5.18 [130]. We have adopted the same nodes group with diverse clustering kinds. In the first case, the node the closest to all neighboring nodes is chosen as a cluster head, which allows a short transmission distance for the cluster members. However, this cluster head is not the closest to level 1, which means a long-range transmission would take place. On the other hand, in the second case, the node the closest to level 1 is designated as a cluster head; hence, the transmission to level 1 would be performed with low power. However, in this case, the cluster head is not the closest to the cluster members. In our case (the third case), our clustering approach allows a short transmission distance between the cluster heads (the main cluster head and helper cluster head) and the other cluster members; furthermore, the main cluster head is the closest to level 1. For cases 1 and 2, a notable overload would take place at the cluster head level; in contrast, in our case, the helper cluster head helps to balance the load. Besides, as previously mentioned, two-level data aggregation is supported using our clustering scheme against one-level for the other cases.

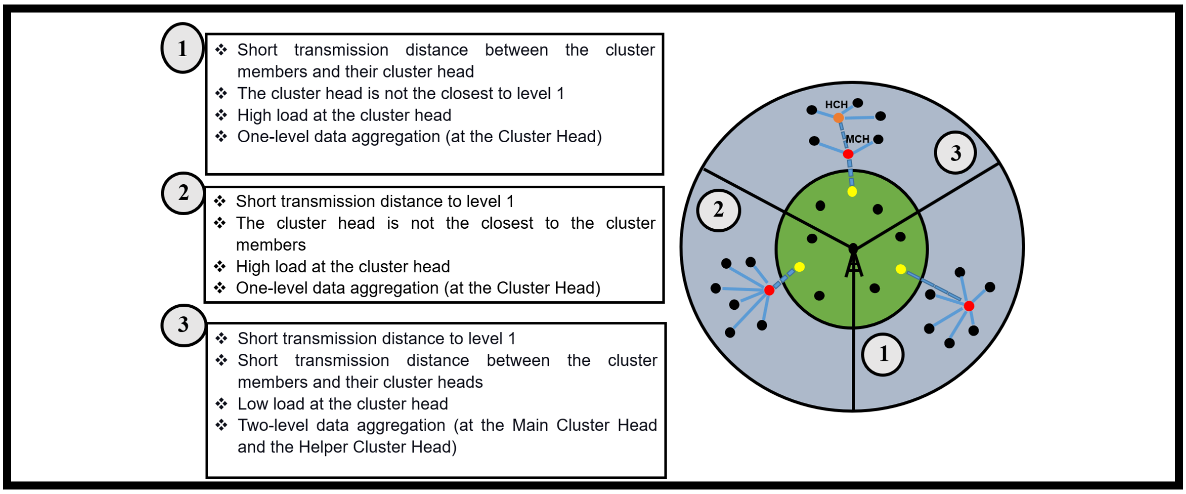


Figure 5.18: *Our clustering approach (SeparatedParameters-based approach) vs. conventional approaches*

C: Total consumed energy

The total energy consumption is modeled as follows:

In level 1:

$$ConsumedEnergy(Level1) = \sum_{i=1}^{N1} \int (Ei_{TX}(t) + Ei_{RX}(t) + Ei_{DA}(t))dt \tag{5.15}$$

- E_{TX}: The energy consumed during transmission
- E_{RX}: The energy consumed during reception
- E_{DA}: The energy consumed during data aggregation
- N1: Number of nodes in level 1

In level 2:

- Cluster Formation (CF):

$$ConsumedEnergy(CF) = \sum_{i=1}^{N2} \int (Ei_{TX}(t) + Ei_{RX}(t))dt \tag{5.16}$$

  – N2: Number of nodes in level 2

- Choice of Relaying Nodes (CRN):

$$ConsumedEnergy(CRN) = \sum_{i=1}^{M} \int (Ei_{TX}(t) + Ei_{RX}(t))dt \tag{5.17}$$

  - M: Number of main cluster heads in level 2

- Data Gathering (DG):

$$ConsumedEnergy(DG) = \sum_{i=1}^{L1} \sum_{j=1}^{L2} \int Eij_{TX}(t)dt + \sum_{k=1}^{L3} \int (Ek_{TX}(t) + Ek_{RX}(t) + Ek_{DA}(t))dt \tag{5.18}$$

  - L1: Number of clusters in level 2
  - L2: Number of nodes in a given cluster
  - L3: Number of cluster heads (Main+Helper) in level 2

$$ConsumedEnergy(Level2) = (5.16) + (5.17) + (5.18) \tag{5.19}$$

Hence,

$$TheTotalConsumedEnergy = (5.15) + (5.19) \tag{5.20}$$

5.4 Key parameters involved in our proposed solution to boost energy saving

In Table 5.2, we give the key parameters that have been involved in our self-organization model to boost energy saving.

5.5 Summary of our self-organization model's prominent contributions

Our self-organization model involves multi-level contributions to increase energy saving, where mobility and communication have been addressed. Contributions into those two aspects are as follows:

5.5.1 Communication aspect

- The clustering process is performed cooperatively, where the cluster head selects the cluster members, and in turn, the cluster members deduce their cluster

Aspect	Parameter	Impact on energy
Communication	Clustering	* Clustering contributes to saving energy due to reduced transmission distance and reduced overhead.
	Ad Hoc mode	* Ad Hoc mode is more efficient regarding energy consumption due to multi-hop communication.
	Data aggregation	* It saves energy since the amount of data to be treated and transmitted over the network is reduced.
Mobility	Stable links	* The stable links maintain connectivity, which reduces data loss ratio, increasing energy saving.
	Eliminate group motion overhead	* Eliminating transmission of packets between nodes will reduce overhead, saving energy.
	Constant speed	* As we have seen in Chapter 3, changing speed affects energy consumption; hence, we adopted a constant value that has been assumed to be energy-efficient.
	Horizontal motion (constant altitude)	* The Motion kind (horizontal/vertical) also has a significant impact on energy consumption (as mentioned in Chapter 3), where the horizontal motion consumes less energy.

Table 5.2: *Prominent concepts increasing energy saving in our proposed self-organization model*

head based on the predefined distance parameter "d"—which reduces overhead due to eliminating join packets.

- The clustering algorithm is based on a separated-parameters approach, where it aims to separate the parameters that could present a tradeoff. Hence, our approach tries to balance that tradeoff to get efficient clustering regarding endurance and transmission distance.
- Our clustering algorithm introduces two kinds of cluster heads (Main Cluster Head and Helper Cluster Head), which increases cluster heads lifetime since the helper cluster head will help to reduce load on the main cluster head that is responsible for the cluster members and other main cluster heads in case it serves as a relay node.
- Our clustering scheme allows a two-level data aggregation within each cluster, boosting energy saving from communication and computation perspectives. Regarding communication, the amount of transmitted data over the network will be reduced; on the other hand, for computation, the amount of data to be treated will also be reduced.
- Our communication architecture is hybrid (multi-hop and direct), where we take advantage of multi-hop communication in level 2 to reduce energy consumption; on the other hand, we adopt direct communication in level 1 to reduce delay.
- Our clustering scheme depends on the structural aspect of the mobility model, which is different from existing works where mobility depends on formed clusters (nodes follow the cluster heads). Hence, in our case, the clusters would be more stable since the clustering depends on the mobility model that allows stable topology.

5.5.2 Mobility model aspect

- Our model contributes to the communication efficiency due to the stable links and stable topology that reduce data loss ratio and consequently retransmission operations, saving energy. Moreover, the stable topology boosts clustering efficiency.
- Eliminate the overhead of mobility models based on group motion through a high level of temporal and spatial correlation.
- Balance the tradeoff between coverage and connectivity, where it is known that the high coverage percentage comes at the cost of connectivity. In our case, the adopted direction change method (the concentration difference principle) allows the UAVs to go through all possible directions (over the 2π directions), increasing the coverage rate. At the same time, the 100% temporal and spatial correlation regarding speed and direction maintain connectivity. Hence, a notable balance regarding coverage and connectivity is achieved.
- Our model is a path-planning-free model, which means no constraints regarding the path are present.

5.6 Simulation and results

5.6.1 Simulation objective

The simulation scenarios aim to investigate how our proposed solution with the different involved concepts can boost energy efficiency and increase network lifetime; also, other network performance parameters were considered, such as data loss ratio and average End-To-End delay. The simulation was about two phases; the first is for exploring the energy efficiency from mobility perspective, where two models and our proposed one were used with our communication algorithm to study how each of them could contribute to the energy efficiency and provide a robust environment for communication. The second phase was dedicated to assessing the efficiency of the proposed communication algorithm, where other pre-existing algorithms were used for performance comparison.

5.6.2 Scenario

The considered application was about monitoring a predefined area of interest, where a set of UAVs forming an Ad Hoc network cooperate in collecting data and transmitting them to the base station. Hence, communication takes place between the UAVs, the UAVs and the base station. The adopted network consists of 60 nodes within the area of interest (simulation area radius is about 1000 m); each node was with an initial energy of 160 Joule. For the MAC layer, the IEEE 802.11 is used. To generate the traffic simulating collected data to be transmitted over the network, we used a traffic generator in the NS-3 environment called "BulkSendApplication," which sends an amount of data up to MaxBytes or started application ended. Table 5.3 [130] gives the main simulation parameters.

Parameter	Value
Simulation platform	NS-3
Network size	60 nodes
Node's initial energy	160 Joule
Simulation time	2670 s
Area radius	1000 m
Distance "d" (Parameter of the clustering algorithm)	Node's transmission range/2
$\alpha 1$, $\beta 1$	0.6, 0.4
$\alpha 2$, $\beta 2$	0.6, 0.4
$\alpha 3$, $\beta 3$, $\gamma 3$	0.4, 0.3, 0.3
UAV speed	20 m/s
Packet Size	1024 Bytes
MAC	IEEE 802.11
Electronics Energy (E_{elec})	10 pJ/bit
Amplifier Energy (Free Space Model) (ϵ_{fs})	105 nJ/bit
Amplifier Energy (Multipath Model) (ϵ_{mp})	120 nJ/bit
Data Aggregation Energy	5 pJ/bit

Table 5.3: *Simulation parameters*

5.6.3 Motion space dimension

Motion space dimension is a vital parameter in UAV-based applications, where the decision about it depends on each application's needs and features. It mainly reflects if the UAVs' altitude would be constant or changing over time. In our case, we consider a 2D space for motion, where a predefined altitude should be maintained. This consideration is a result of two main facts, namely:

- Monitoring applications impose some constraints on spatial resolution, which means that the altitude should be decided taking into account the desired resolution.
- Since we aim to increase energy saving, constant altitude is more appropriate, where changing altitude over time affects energy consumption, as mentioned in [36, 55].

To explain the correlation between the spatial resolution and altitude, we present the example mentioned in [137] and shown in Fig. 5.19 [137]. Main parameters are

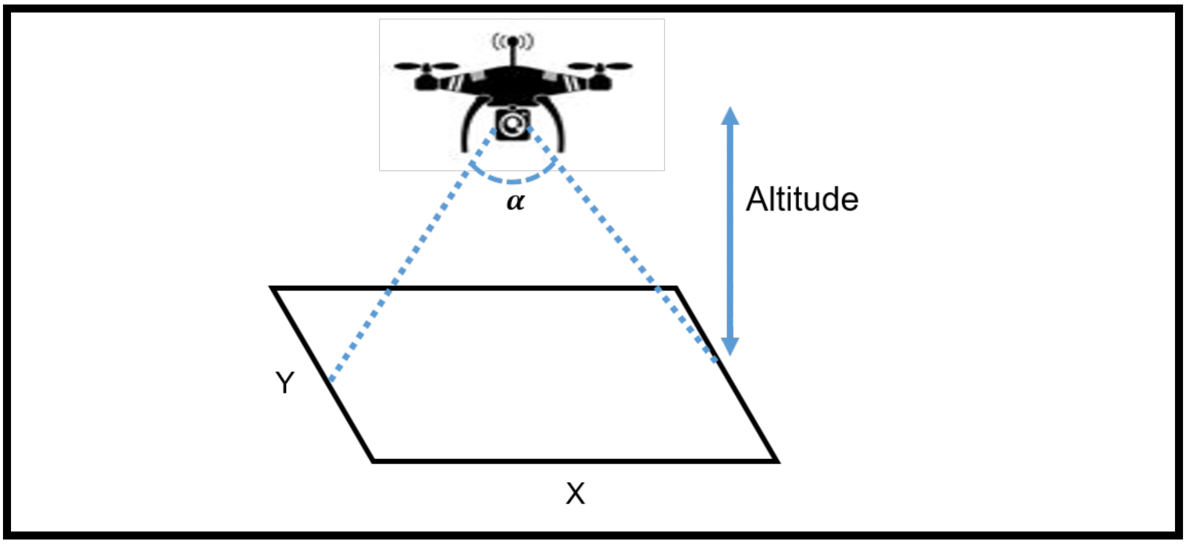


Figure 5.19: *Projected area of a camera with an angle of view α at altitude A*

needed for the calculation process, appointed as follows:

- α: Angle of view (AOV) in radians
- Image resolution (Ix, Iy), in pixels for the image's both sides
- The aspect ratio ρ= Ix/Iy between the image's width and height

The size of the projected area (Lx, Ly) is calculated as:

$$Lx = 2A\tan(\frac{\alpha}{2}) \tag{5.21}$$

$$Ly = \frac{Lx}{\rho} \tag{5.22}$$

The achieved spatial resolution R for a picture taken at altitude A is:

$$R = \frac{Ix}{Lx} = \frac{Ix}{2A\tan(\frac{\alpha}{2})} \tag{5.23}$$

Accordingly, for a predefined desired resolution Rd, it will be:

$$Rd = \frac{Ix}{2A\tan(\frac{\alpha}{2})} \tag{5.24}$$

Consequently, the altitude A must be:

$$A = \frac{Ix}{2Rd\tan(\frac{\alpha}{2})} \tag{5.25}$$

Based on the above considerations regarding resolution calculation, the UAVs must maintain the determined altitude to maintain the desired resolution.

5.6.4 Energy dissipation model

The energy dissipation model estimates the energy consumed by a node in performing a specific task. We have used the model presented in [136], which calculates the amount of energy consumed during transmission and reception operations; electronic energy (E_{elec}) and amplifier energy ($\epsilon_{fs}d^2$ or $\epsilon_{mp}d^4$) are considered. Two impacting parameters are taken into account in this model: length of data and transmission distance. Fig. 5.20 [136] pictures this model's main concepts. For each energy kind (electronics and amplifier), prominent factors are with notable influence. For example, in the electronics energy case, there are digital coding, modulation, filtering, etc. On the other hand, the amplifier energy depends on the distance separating the transmitter and receiver, as well as the acceptable bit-error. For the distance parameter, two situations are possible: if it is less than a predefined threshold d_0, the free space (fs) model is used. Else, the multi-path (mp) is considered. Hence, for data of l-bit and distance "d" between two nodes, the energy consumption will be:

- For transmission (E_{TX}):

$$E_{TX}(l,d) : \begin{cases} lE_{elec} + l\epsilon_{fs}d^2 & d < d_0 \\ lE_{elec} + l\epsilon_{mp}d^4 & d \geq d_0 \end{cases}$$

  - E_{elec}: Electronics energy
  - ϵ: Amplifier energy

- For reception (E_{RX}):

$$E_{RX}(l) = lE_{elec}$$

5.6.5 Tested scenarios and results

A: Mobility model performance

In this scenario, we used three mobility models: our proposed one, Particle Swarm Mobility Model (PSMM) [87], and Distributed Flocking Model (DFM) [88], with

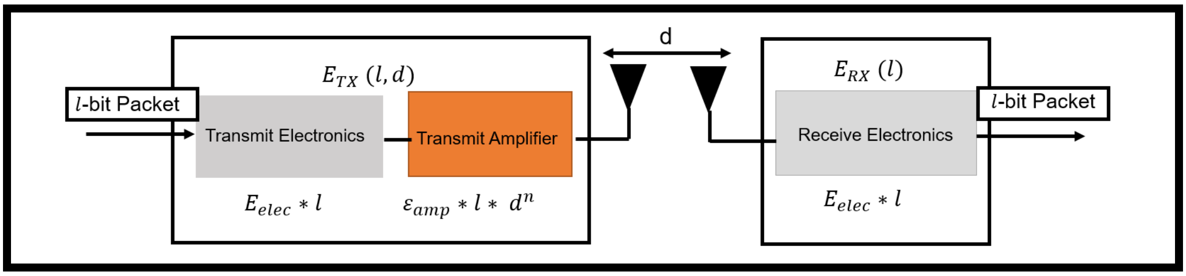


Figure 5.20: *Radio energy dissipation model*

our communication algorithm to investigate network performance with these three models.

As previously mentioned, we boost energy saving through reducing the packet loss ratio as it affects energy consumption due to re-transmission operations. Indeed, this parameter has been highlighted, in our case, from mobility and communication perspectives. The packet loss ratio expresses the percentage of lost packets to the total number of the sent ones (Equation 5.26), given as:

$$PacketLossRatio(\%) = \frac{LostPackets}{TotalSentPackets} * 100 \tag{5.26}$$

The results show how the performance regarding data loss ratio and average en-

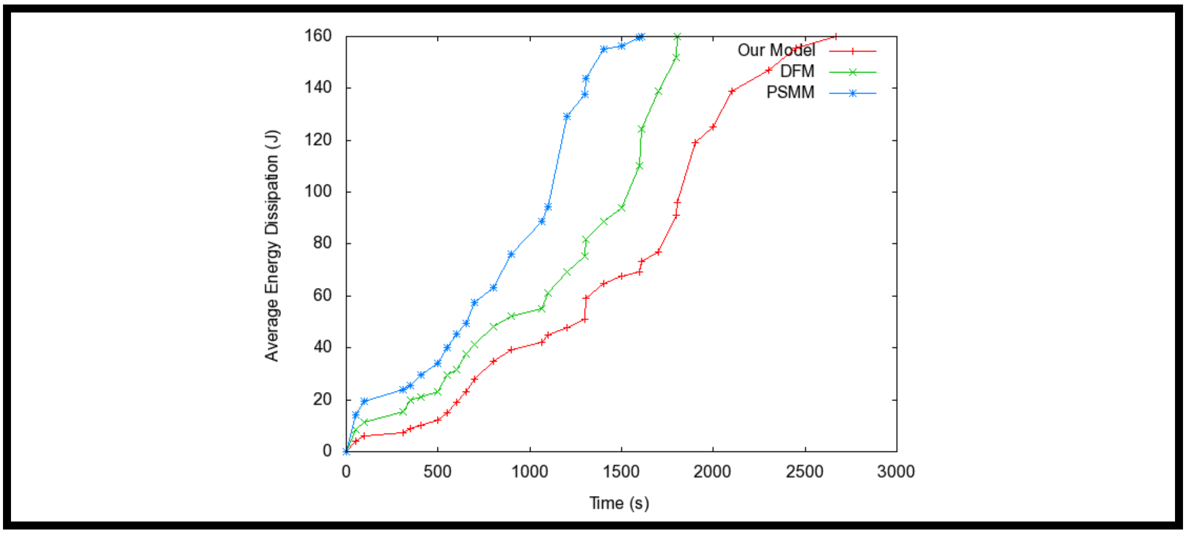


Figure 5.21: *The Average Energy Dissipation (Our Model vs. PSMM and DFM)*

ergy dissipation differs according to the used mobility model. Mainly, that difference is the result of how each model decides speed and direction over time. Indeed, each of these three models implements a group motion for nodes forming a swarm, and connectivity is highly considered for all of them by involving temporal or/and spatial

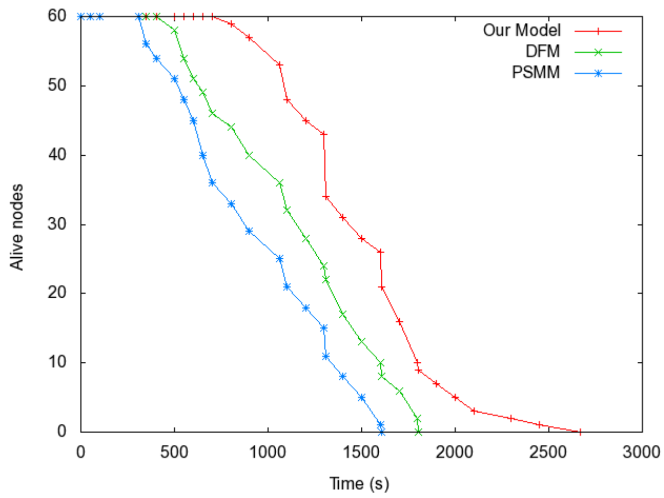


Figure 5.22: *Alive nodes over time (Our Model vs. PSMM and DFM)*

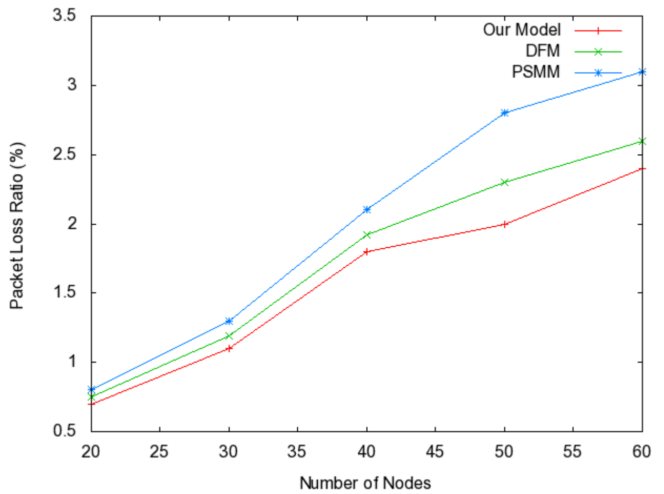


Figure 5.23: *Packet loss ratio (Our Model vs. PSMM and DFM)*

correlation. However, the data loss ratio and average energy dissipation were high when the PSMM is used (Fig. 5.21, Fig. 5.22, Fig. 5.23 [130]) due to the transmitted packets containing nodes' speed and position, leading to more interference and more overhead, giving more data loss more energy consumption. On the other hand, for the DFM, even if packets are also transmitted over the network to inform neighbors about speed and heading, the results were better than the PSMM due to the fact that the DFM restricts the transmission to be only among the leaders and their followers, which reduces interference and overhead. Indeed, the results obtained using our model were better than the other two models due to the high level of temporal and spatial correlation regarding speed and direction change angle, without packet transmission, maintaining connectivity and reducing overhead.

B: Communication algorithm performance

In this phase, we present the results of our proposed clustering algorithm in terms of average energy dissipation, alive nodes over time, cluster heads lifetime, data loss ratio, and average End-to-End delay. We have used two other algorithms for performance comparison. The two algorithms are EALC [79] and CBLADSR [80]; they are also cluster-based algorithms that consider UAVs' limited energy constraint.

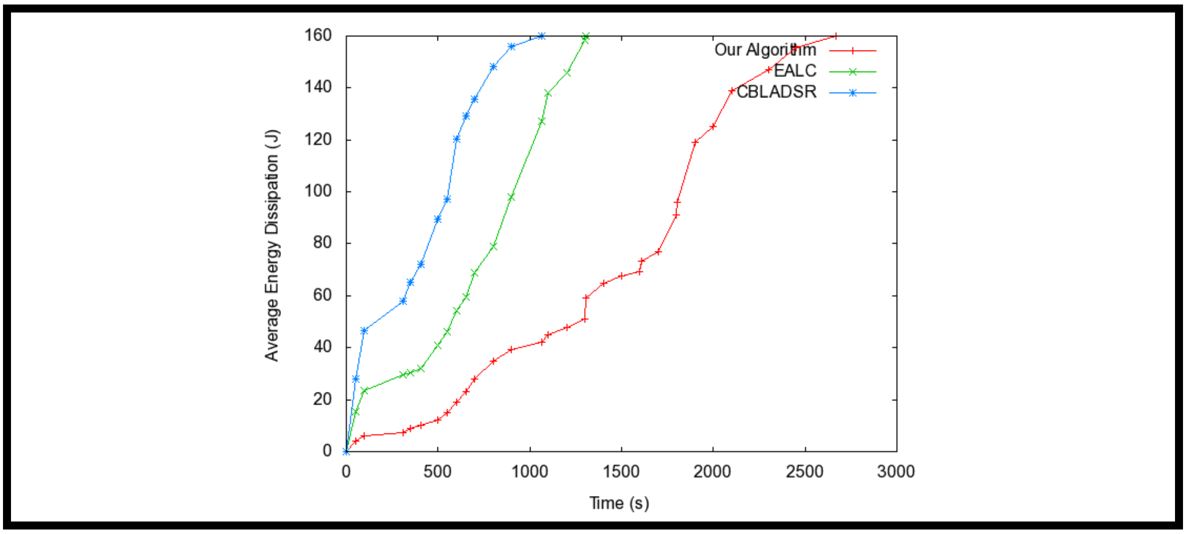


Figure 5.24: *The average energy dissipation (Our algorithm vs. EALC and CBLADSR)*

B1: Average energy dissipation

According to the obtained results, a notable difference occurs because parameters boosting energy efficiency were involved in different forms at different degrees in each of those algorithms. In our algorithm with the best results (Fig. 5.24, Fig. 5.25 [130]) compared to the other two algorithms, energy saving was carefully considered. Transmission distance has been taken into account between the cluster heads (main, helper) and the cluster members; between the main cluster heads in level 2 and relay nodes in level 1; between the relay nodes in level 1 and the base station. About the amount of data transmitted over the network, our clustering scheme allows a two-level data aggregation that significantly reduces data, saving more energy. As a result, our algorithm's average energy dissipation values were lower than the other

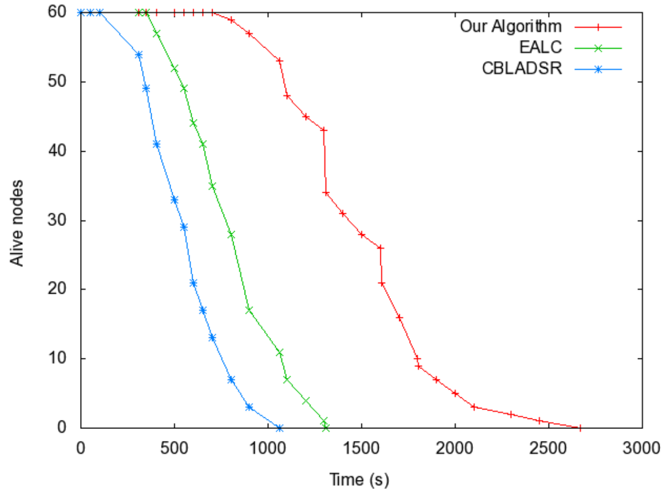


Figure 5.25: *Alive nodes over time (Our algorithm vs. EALC and CBLADSR)*

two algorithm's, giving more network lifetime (enhanced by 104 % compared to EALC and 151 % compared to CBLADSR).

On the other hand, the EALC and CBLADSR also consider the energy level as a selective parameter during the clustering process; however, the EALC achieves better results than CBLADSR since the former takes the distance between the cluster head and cluster members into account, which is not the case for the latter. Furthermore, more overhead would take place in the case of CBLADSR due to the route searching process, where special packets are broadcasted requesting a suitable route to transmit data inter-clusters.

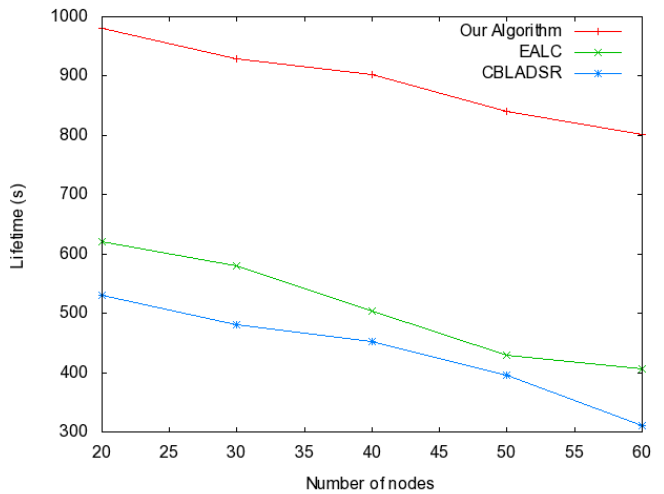


Figure 5.26: *Cluster heads lifetime (Our algorithm vs. EALC and CBLADSR)*

B2: Cluster heads lifetime

Indeed, cluster heads lifetime is a vital parameter since a more lifetime ensures more stable clusters. Increasing such a parameter depends on many factors; outstanding: the proper selection of cluster heads, transmission distance between the cluster heads and the final destination (mostly the base station), as well as the load within the cluster. According to Fig. 5.26, our algorithm allows more lifetime for the cluster heads due to forming a subcluster with a helper cluster head within each cluster, which significantly reduces overload on main cluster heads, increasing their lifetime. Furthermore, multi-hop communication between the main cluster heads and the base station (adoption of relay nodes) boosts energy saving. For EALC, the direct transmission between the cluster heads and the base station does affect energy consumption, affecting cluster heads lifetime due to such long-range transmission. About CBLADSR, the connectivity degree is involved as a selective parameter, where the nodes with more neighbors are the favored to be cluster heads. Such a consideration builds crowded clusters, which increases load on the cluster heads.

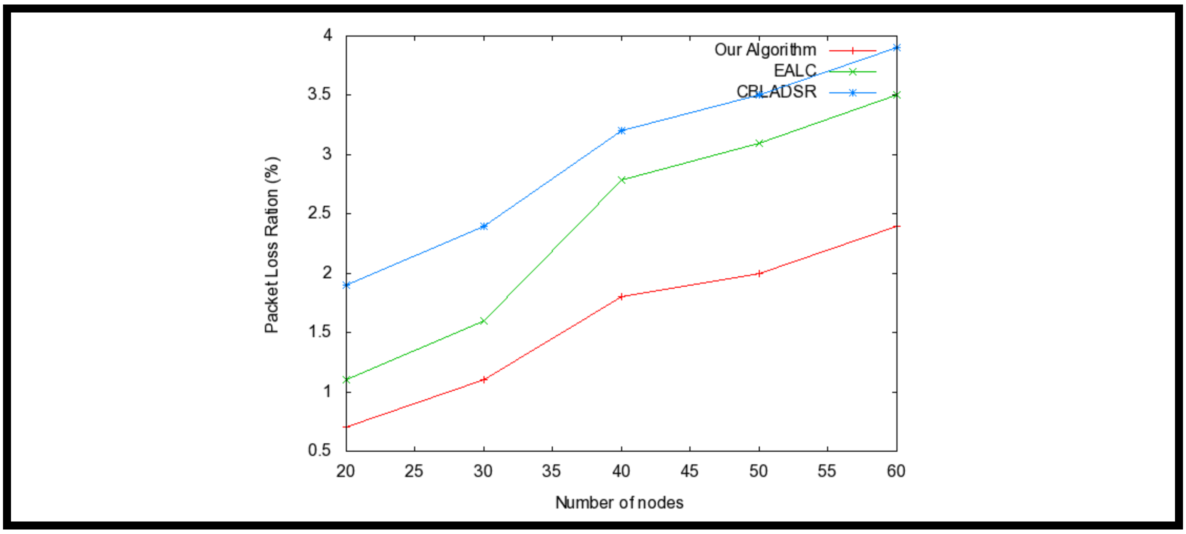


Figure 5.27: *Packet loss ratio (Our algorithm vs. EALC and CBLADSR)*

B3: Packet loss ratio

In this part, we investigated the impact of the clustering algorithm on the packet loss ratio. Indeed, the CBLADSR ratio was the highest (Fig. 5.27 [130]) since it involves connectivity degree, forming crowded clusters where interferences increase, increasing the loss ratio. Also, long-range transmissions significantly affect transmitted signals, which may hinder packets from being received properly as they should be. This fact explains the results achieved by our algorithm that considers ensuring a short transmission distance between the cluster heads and the base station, which is not the case for EALC and CBLADSR.

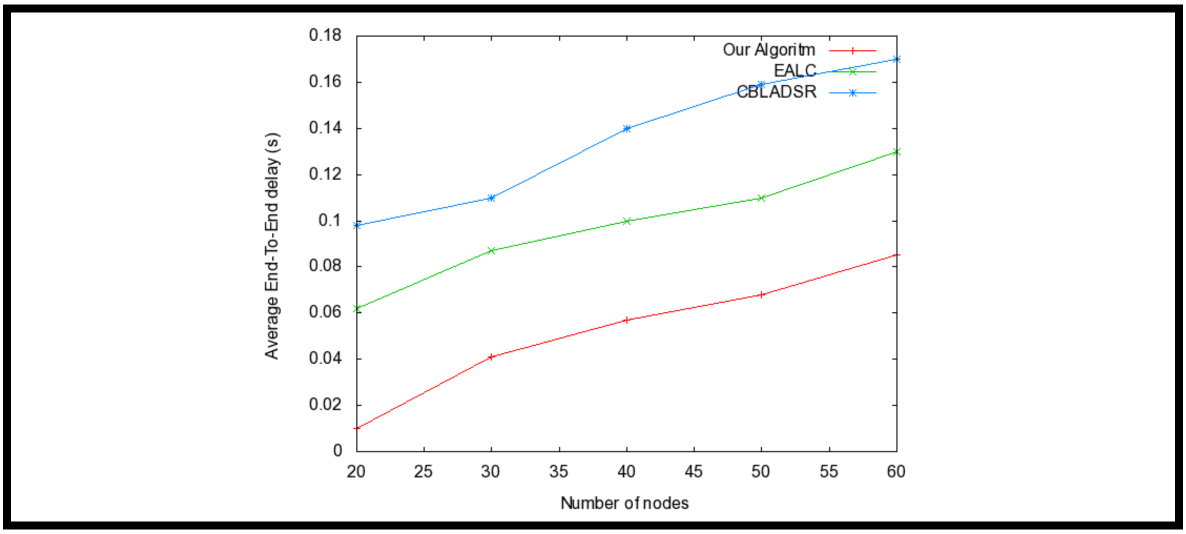


Figure 5.28: *Average End-To-End Delay (Our algorithm vs. EALC and CBLADSR)*

B4: Average End-To-End delay

End-To-End delay (aka OWD: One Way Delay) is about the time a packet takes during its journey from the starting point (transmitter) to the ending point (receiver). Mainly it involves the transmission delay, processing delay, propagation delay, and queuing delay (Equation 5.27).

$$End - To - End - Delay = Transmission + Propagation + Processing + Queuing \tag{5.27}$$

The average End-To-End delay is given as (Equation 5.28):

$$Average - End - To - End - Delay = \frac{\sum_{i=1}^{N} End - To - End - Delay_i}{N} \tag{5.28}$$

- N: Number of nodes

According to Fig. 5.28 [130], the results were better for our algorithm since the distance was carefully considered for the main cluster heads and relay nodes to be those close to the base station, allowing less delay due to decreased propagation delay that mainly depends on distance, which has not been considered in the other two algorithms. Furthermore, the delay increased with the increased number of nodes within the network for all algorithms since the data traffic will be important, which consequently increases queuing delay.

5.7 Conclusion

This chapter paints the full picture of our proposed self-organization model. We have presented the main concepts involved and parameters considered; justified our choice about them; highlighted notable contributions regarding the proposed mobility model and communication algorithm. Also, we showed how those contributions properly meet the stated need about energy efficiency and overall network performance. In the simulation part, we gave the upshots of performed scenarios that aim to present the effectiveness of our contributions numerically. Furthermore, we explained the achieved results depicting how our proposed solution outperforms other algorithms and mobility models in terms of energy consumption, cluster heads lifetime, packet loss ratio, and average End-To-End delay.

Indeed, many aspects could be at the heart of such a treated problem, yet we focus on communication as seen. As previously mentioned, UAVs' energy consumption is subject to several impacting factors. Hence, it will be better if extended considerations about them take place. To this end, we plan to go through other possible contributions in other layers and involve other aspects; then, a combination with the achieved contributions will be the building block of a more robust solution that will allow a high level of energy saving.

General conclusion

Recently, UAV-based applications are getting a great deal of attention in diverse sectors, where applications have become more efficient regarding time, yield, and safety. Moreover, the use rate has gotten higher once the UAANETs are adopted, where more powerful features are acquired, namely, survivability, scalability, extended range, energy efficiency, fault tolerance, etc. Intending to raise UAV-based applications' widespread, literature has pointed out severe challenges, UAVs could face, to be addressed in order to decrease their potential negative impact. As seen, the challenge of the utmost concern is the limited energy due to its significant impact on UAVs' performance and, consequently, the whole network performance. Indeed, such a challenge was our concern as well; it is at the heart of the addressed problematic about optimizing energy saving to overcome the deficiency of limited energy within a UAANET. Hence, the main objective of this thesis is to propose a solution, to be adopted for a UAANET, that would maximize energy saving to extend the network lifetime and enhance performance.

As presented, the literature content regarding the UAVs' limited energy constraint is that blended, where the introduced contributions belong to different fields. Being a part of UAVs' literature, we proposed a new energy-efficient self-organization model, ElectriBio-inspired Energy-Efficient Self-organization model for UAANET, which ensures outstanding contributions in terms of energy saving and overall network performance.

To achieve the thesis aim about energy saving, our proposed model has considered eliminating over-waste of energy related to communication at different levels. The first level is the mobility model that implements a group motion model; it introduces a direction change strategy based on the concentration difference concept. This model involves a high level of temporal and spatial correlation among the UAVs, allowing high connectivity—reduces data loss ratio—and eliminating transmitting information about speed and direction—eliminating overhead. The second level is the communication algorithm, where the proposed one boosts energy efficiency through the adopted clustering scheme with two kinds of cluster heads: the main cluster head and the helper cluster head. The clustering approach also allows to balance the trade-off that could take place between the objective function's parameters. Besides, this clustering scheme allows a two-level data aggregation. Consequently, the proposed self-organization model profoundly contributes to increasing energy saving through reducing communication energy waste in two levels: mobility and communication algorithm, giving a two-level energy-saving solution.

We have performed the simulation scenarios intending to numerically prove the efficiency of our solution contributions regarding the mobility model and communication algorithm; also, other pre-existing mobility models and communication algorithms have been used for performance comparison. The comparison parameters were: the average energy dissipation, alive nodes over time, cluster heads' lifetime, packet loss ratio, and average End-To-End delay. Furthermore, we have given a detailed analysis and justifications of the obtained results, where we have presented the key concepts used in our solution that were the reason behind those results.

The good simulation results do not imply that our proposed solution guarantees the maximum level of energy saving. This statement is a result of two main facts. The first is that the communication involves two main layers: the network and MAC (Medium Access Control). In our case, the MAC layer has not been taken into account. The second is that in UAVs' environment, communication is not the only aspect affecting energy consumption; many other aspects and parameters have a significant impact too (as seen in Chapter 3). Hence, for a more robust solution that will ensure a high level of energy saving, the other communication layer (MAC layer) should be considered due to its significant impact. Furthermore, other aspects with relation to UAVs' energy consumption should be involved.

As a future plan, we intend to go through a real scenario of the adopted application, where a real implementation of the proposed solution takes place for more investigation regarding the efficiency of our contributions for UAV-based monitoring. Furthermore, other UAV-based applications are at the heart of our interests, particularly UAV-based agriculture, which is getting unprecedented attention nowadays.

List of publications

1- A. Bensalem and D. E. Boubiche, "EBEESU: ElectriBio-inspired Energy- Efficient Self-organization Model for Unmanned Aerial Ad-hoc Network," Ad Hoc Networks, vol. 107, no. october, pp. 1–21, 2020.

2- A. Bensalem, D. E. Boubiche, F. Zhou, A. Rachedi, and A. Mellouk, "Impact of Mobility Models on Energy Consumption in Unmanned Aerial Ad-Hoc Network," in Proceedings - IEEE 45th Conference on Local Computer Networks (LCN), vol. 2020-Novem, 2020, pp. 361–364.

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