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MASTER THESIS

Management System for Unmanned Aircraft System Teams

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ABSTRACT

This thesis investigates new schemes to improve the operability of heterogeneous Unmanned Aircraft Systems (UAS) teams through the exploitation of inter-vehicular communications. Releasing ground links from unnecessary data exchanges saves resources (power, bandwidth, etc) and alleviates the inherent scalability problem resulting from the increase in the number of UAS to be controlled simultaneously. In first place, a framework to classify UAS according to their level of autonomy is presented along with efficient methodologies to assess the autonomy level of either individual or multiple UAS. An architecture based on an aerial Mobile Ad-hoc Network (MANET) is proposed for the management of the data exchange among all the vehicles in the team. A performance evaluation of the two most relevant MANET approaches for path discovery (namely, reactive and proactive) has been carried out by means of simulation of two well-known routing protocols: Ad-hoc On-demand Distance Vector (AODV) and Destination Sequenced Distance Vector (DSDV). Several network configurations are generated to emulate different possible contingencies that might occur in real UAS team operations. Network topology evolution, vehicle flight dynamics and data traffic patterns are considered as input parameters to the simulation model. The analysis of the system behaviour for each possible network configuration is used to evaluate the appropriateness of both approaches in different mission scenarios. Alternative network solutions based on Delay Tolerant Networking (DTN) for situations of intermittent connectivity and network partitioning are outlined. Finally, an assessment of the simulation results is presented along with a discussion about further research challenges.

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INTRODUCTION

Currently, Unmanned Aerial Vehicles (UAV) are considered a promising alternative to piloted aircrafts both in civil and military applications. These vehicles are especially useful in dangerous missions where human lives might be put at risk or even in dull tasks where most of the functionalities of a human pilot can be automated. There is a wide range of potential applications in which UAVs can substantially improve the efficiency and costs of the mission such as border surveillance, search and rescue, environmental monitoring and military tactics to name a few. However, a UAV requires an operational environment that includes payload, communications equipment, human operators, etc. All the elements involved in the operation process along with the UAV platform are known as Unmanned Aircraft System (UAS).

Usually, the operation process of most UAV requires some sort of human interaction (either executive or supervisory) during a mission. Humans are prone to error, especially when they are exposed to high workloads and prolonged periods of stress. Therefore, UAS team missions involving multiple UAV which are controlled by a single operator might experience failures as the number of vehicles involved in the mission increases [1].

The accelerating technological evolution occurred in the field of UAS during the last years has led to the progressive automation of tasks requiring human intervention. Consequently, operators' attention can be now directed to analysis and decision tasks facilitating the execution of more complex missions. Such increase in the number of automated functions in a UAS highlights the relevance of the *autonomy* (human independence) of the system. The selection of the most suitable level of autonomy (both for the team as a whole and for each individual UAV) is a crucial aspect for the operability of heterogeneous and collaborative UAV teams.

Operational processes involving autonomous vehicles are evolving towards a growing level of automation either in single or multiple UAS missions [1], [2]. Without some sort of automation, the number of resources involved in the mission would grow geometrically as the number of UAVs increases, resulting in a non-scalable challenge. Automation of the operators' tasks is usually primarily focused upon repetitive or tedious tasks that capture the attention of the operator, thus provoking fatigue and stress. Surprisingly, full automation changes the role of operators and creates some undesired effects such as complacency, loss of situation awareness, overconfidence and low mental workload [3]. Then, an equilibrium between automation and operator's active involvement has to be sought to obtain satisfactory results in systems based on human-machine interfaces [4].

This thesis explores new techniques to increase the level of autonomy of a heterogeneous UAS team up to an optimum level. This autonomy enhancement shall be based on new architectures and support tools for operation and control as well as on the exploitation of flight segment inter-vehicular communications. The interoperability and exchange of information among vehicles would contribute to reduce the data exchange and processing between ground and flight segments, but it would also avoid wasting time and resources in unnecessary uplink and downlink data transfers. Moreover, inter-vehicular communications would eventually lead to an increment of the autonomy of the whole team.

In this work, a new flight segment architecture is proposed based on a mobile ad-hoc network to manage the communications among all members of the team. The simulation of two operational scenarios has been used to assess the validity of the design. Different network topologies, vehicle mobility, routing protocols and data traffic patterns are generated to evaluate the performance of the network and test the integrity of the generated data transactions.

The main topics addressed in this work include:

- Assessment of the most relevant aspects related to **autonomy** of unmanned flights:
    - Selection of the optimum autonomy level
    - Autonomy metrics for UAS classification
    - Impact of the autonomy level on the role of the operator
- Design of a new flight segment architecture based on the exploitation of **inter-vehicular communications**:
    - State-of-the-art of UAS communication technologies
    - Technical requirements for UAS communication links
    - Design and analysis of a mobile aerial network for inter-vehicular communications
- Computer **simulation** of the proposed flight segment model:
    - Definition of operational scenarios that cover most possible use cases in actual UAS collaborative missions
    - Description of the software environment used in the simulations
    - Performance evaluation of a mobile ad-hoc network for UAS operations
    - Analysis of the simulation results to identify the most adequate routing approach for each mission scenario
- Review of related projects and initiatives that might contribute to enhance the capabilities of the systems.

This thesis is organised as follows:

Chapter 1 presents the concept of autonomy and its relevance for simultaneous UAS operation. The effects on the operator generated by the selection of a certain autonomy level are analysed. Moreover, a study of the most remarkable autonomy metrics approaches proposed by the literature is included. A suitable metric that allows the elaboration of a unique taxonomy for all UAS in the team is identified and its usefulness for ground interoperability is also justified.

Chapter 2 introduces the design requirements for the flight segment architecture along with a description of the common UAS communication links. It also includes a technical discussion about the enhancement of autonomy achieved through the exploitation of inter-vehicular communications. An analysis of the limitations in the communication equipment imposed by the vehicle and the communication systems is also exposed. Finally, the chapter includes a review of similar contributions found in the literature and commonalities are compared and assessed.

Chapter 3 assesses the adequacy of an aerial mobile ad-hoc network to accommodate the generated information. An analysis of the challenges faced by this network to overcome the environmental and physical constraints is presented. The relevance of routing algorithms in the scope of this work is highlighted and a discussion about current routing approaches is detailed. Furthermore, network solutions to ensure end-to-end transmissions in situations of intermittent connectivity and long transmission delays are proposed.

The simulations results obtained are presented in Chapter 4. This chapter includes a description of the operational scenarios chosen for the simulation model describing also the network performance achieved in each scenario. The simulation results are analysed to evaluate the validity of the design and the behaviour of two well-known routing approaches for each mission.

Finally, conclusions are detailed in Chapter 5 along with a technical discussion about future work and further research challenges.

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Chapter 1

AUTONOMY IN UNMANNED VEHICLES

1. AUTONOMY IN UNMANNED VEHICLES

1.1. Introduction

During the last century, there has been a remarkable research effort to investigate new ways of endowing UAS with higher levels of autonomy and to properly manage the inevitable changes generated in their operability. This effort has been clearly led by United States with an ambitious investment of money and resources in this technology [5].

The rapid evolution in the performance of unmanned vehicles has not always been accompanied by the required technical analysis of the maturity and efficiency of the algorithms and technologies developed. Therefore, proper test and validation campaigns are necessary to consolidate the latest advances in the field of automation and autonomy.

The literature about autonomy applied to UAS is based upon studies of human-machine (or human-to-robot) interfaces [6], [7], [8], [9]. Due to this generic approach, the studies referenced in most of this work are applicable not only to UAVs but also to Unmanned Ground Vehicles (UGV), Unmanned Underwater Vehicles (UUV), spaceship, etc.

1.2. Autonomy, Automation and Intelligence

The analysed literature highlights that there is not a unique definition of the concept of autonomy applied to unmanned vehicles [10], [9]. Nevertheless, all the definitions found share a common and basic idea, which in the case of UAS can be summarized as follows:

"Autonomy is the ability of an agent to carry out a mission in an independent fashion without requiring human intervention"

Often, the concepts autonomy and automation are used indiscriminately to refer the ability of a system to operate without human supervision. However, there exists a significant difference between both concepts. An automated (or automatic) system executes a set of pre-determined actions in a systematic and deterministic manner. In other words, the system cannot choose freely because all its decisions are previously programmed. On the other hand, an autonomous system is able to make its own decisions so it possesses a certain degree of freedom. An illustrative example of an automated system is an autopilot system that keeps an aircraft within a pre-established course. On the contrary, a collision avoidance system, which is able to resolve air conflict risks by itself, would be considered an autonomous system. In spite of the differences mentioned above, autonomy and automation are tightly related concepts since a variation on the degree of autonomy is inevitably linked to a modification on the automated mechanisms that implement such autonomy.

Similarly, autonomy and intelligence are distinct concepts as well. The latter, is defined as the ability of an entity to learn new concepts and to apply the acquired knowledge to the execution of a new task. This ability has nothing to do with the ability of a system to operate without human intervention. There are many examples in nature (i.e. microorganisms) of autonomous agents with no intelligence. Yet, the characterization of the artificial intelligence of UAS is out of the scope of this thesis since it is a widely studied discipline in the literature nowadays [11].

1.3. General Considerations about Autonomy

There exist different aspects of a mission in which autonomy may be useful to facilitate the role of the operator such as perception of the scenario or decision-making. Since the ultimate goal of autonomy is to aid (or even replace) human actions, it is apparent that further investigation is required about the autonomy concept and its effects on human behaviour.

In particular, studies that analyse the human cognitive process (Figure 1-1) show that according to the current state-of-the-art technology there are four steps of the information processing cycle that are suitable to incorporate a certain form of autonomy or automation [6]. These steps are known as the OODA (Observe, Orient, Decide and Act) cycle. Any kind of autonomy applied to these steps results into a system functionality (or group of them) that is eventually automated [6], [11].

- **Observe**: refers to the process of information acquisition. It is applied to perception and organization activities involved in the processing of the information gathered by the vehicle's onboard sensors. Typical actions in this stage that are suitable to be automated are: filtering the acquired raw data and highlighting the most relevant information to draw the attention of the operator.
- **Orient**: analysis and processing of the acquired (observed) information. This phase of the process is focused on the extraction of information about the tendency of the data in order to elaborate a prediction of its evolution. This step also includes the required data aggregation and integration to enhance the situation awareness of the operator.
- **Decide**: selection of the most appropriate action to execute among all possible alternatives. An automatic decision making process is usually based on the assessment of the outcomes of each possible option and the identification of the optimal choice.
- **Act**: implementation or execution of the selected action. Thus, replacing the physical action of the human operator.

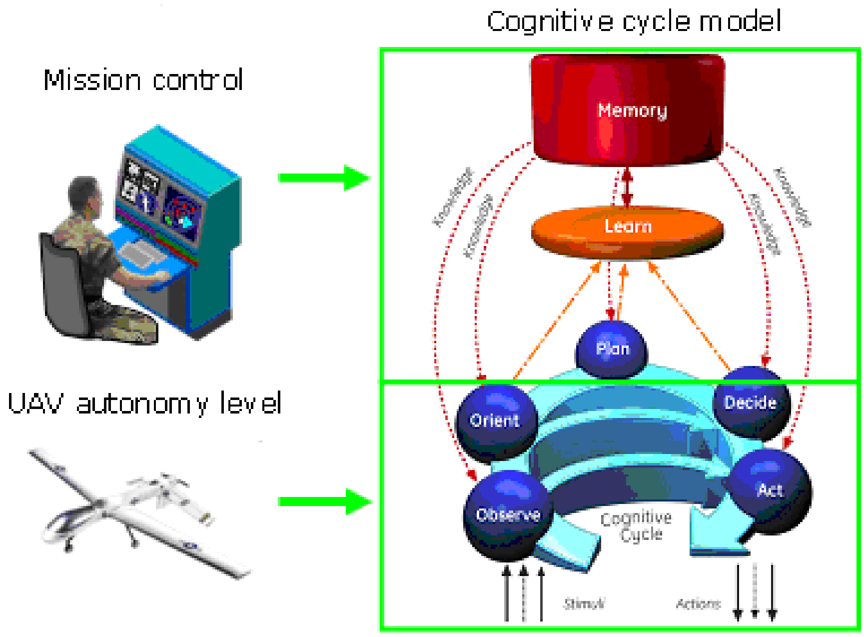


Figure 1-1 Human Cognitive Cycle Model

While the automation of OODA elements usually generates satisfactory results, upper-level processes in the cognitive cycle (i.e. mission planning) or those that require reasoning based on previous experience, intelligence or knowledge, should rely on the operator's judgement [1],[2].

1.4. UAS Taxonomy and Autonomy Metrics

A heterogeneous UAV team includes several types of UAVs with dissimilar levels of autonomy and communications capabilities. Hence, it becomes necessary to define a methodology to group all UAS with similar autonomy characteristics as well as an autonomy **taxonomy** (classification) to improve further analyses. This methodology is known as **metrics** and constitutes a way to assess both quantitatively and qualitatively the amount of autonomy that a vehicle (or a team) possesses.

The reviewed literature indicates that there are certain fundamental requirements that must be fulfilled by any useful autonomy metrics [11]. Metrics must be:

- Intuitive and have a friendly visualization for the end user.
- Sufficiently generic to include in the taxonomy vehicles with different technological features.
- Sufficiently precise to assess the risks and costs of the technological investment in a smooth and practical way.

1.5. Management of Autonomous Teams

1.5.1. Need for Standards and Regulations

The Department of Defence (DoD) of the United States claims that there is a critical need to carry out research activities to examine the human interaction with heterogeneous autonomous vehicles. In particular, the office of the Secretary of Defence states that “the appropriate requirements and conditions under which an operator is able to control a group of unmanned aircraft simultaneously must be investigated” [1], [2].

One of the main conclusions that can be reached after an exhaustive analysis of the literature is that there is not a unanimous definition of metrics to elaborate a taxonomy for UAS [11], [12], [13]. Publications in this field are relatively recent and currently there are several co-existing initiatives (some of them still under development) that are usually supported by independent research institutions, national agencies or military laboratories. However, there is not a consensus on the definition of a standardized procedure for autonomy metrics evaluation or taxonomy elaboration that can be applied systematically to UAS teams.

1.5.2. Autonomy Assignment

It should be mentioned that human interaction is not the only element that determines the design and selection of the systems autonomy. Several factors have to be considered in order to select the optimum level of autonomy for a UAS team in any context. The requirements of the mission (for instance) play a major role in such a selection but there are other relevant aspects such as environment, efficiency or cost. All these factors must also be taken into account in the design a UAS team management system.

There are two types of UAS operational control systems: executive and supervisory depending on the operator's involvement. Most UAS endowed with a minimum degree of autonomy are controlled by at least one operator who plays a supervisory role [7].

Indiscriminately high autonomy levels do not yield satisfactory results in applications or scenarios that are subject to critical time constraints. On the other hand, insufficient levels of autonomy generate an excessive workload that absorbs the operating capacity from the human operator and reduces the efficiency of the mission. Therefore, an equilibrium must be sought between human action and low-level tasks automation to achieve an optimum performance [1], [14].

The level of autonomy selected for a heterogeneous UAS team is strongly related to the characteristics of each vehicle as well as the mission profile. During the analysis phase, the following aspects are of relevance in the assignment of autonomy:

- **Team size**. As the number of UAVs in the team increases, the number of tasks to be executed by the operator augments as well. Thus, a certain degree of autonomy is required to mitigate the induced increment of workload on the operator’s activity. For that reason, the size of the team is considered a key factor to determine the final degree of autonomy of the system [1].
- **Autonomy Levels**. It is essential to figure out how, where, when and how much autonomy will be assigned to the team. An unconditional increment on the level of autonomy does not necessarily lead to satisfactory results. An excess of autonomy may cause over-trust and loss of situation awareness whereas an insufficient autonomy might lead to an excessive pressure over

the human controller. Therefore, as it is shown in [1], [15], a trade-off between direct intervention and supervisory control has to be sought for an optimum mission execution.

- **Automation Reliability**. This is an aspect directly linked to the number of decisions ultimately made in an autonomous way. It is extremely important to estimate beforehand the efficiency of the actions executed autonomously. This estimation permits an assessment of the impact of errors prompted by such decisions (i.e. by means of fault tree and events techniques [6]). This analysis should aid the mission planning and help the authority management process among the different operators.
- **Task Coordination And Allocation**. A certain level of coordination and planning is required within all the agents involved to allocate tasks and define mechanisms to prevent (or fix) potential resource conflicts. Similarly, mission planning and task allocation must be coordinated considering the mission context to obtain an optimum behaviour with no redundancies or shortages [12].
- **Scalability**. The final autonomy level assigned shall take into account the amount of resources available during the system design and mission planning phases. The amount of resources involved in the mission and the complexity of the system should not grow proportionally to the number of UAVs in the team [16].
- **Collateral Factors**. Usually appear during the implementation phase. A few examples of these factors are: human interaction, system efficiency, legal aspects, safety, costs and mission accomplishment (within pre-established margins).

1.5.3. Effects of Automation on the Performance of the Operator

Human behaviour becomes a crucial issue as the level of autonomy of the system increases. The performance of a machine is predictable and stable since its structure and functionalities are well known at all system levels. However, human behaviour is unforeseeable in many senses. The same operation is carried out in different ways by two people and even attention, lucidity and performance of the same person may vary over time given his/her mental condition or other emotional factors.

UAS team management requires a cooperative work from multiple human operators with different responsibilities and degrees of expertise. Hence, personal abilities like experience, team building and training are also relevant aspects in this kind of missions.

The automation of a system replaces the human intervention and at the same time modifies its activity. In order to analyse the most appropriate autonomy level for a system, the changes implied in the role of the operator must also be studied. The most disrupting aspects in the role of the operator created by an inappropriate autonomy are:

- **Mental workload**: ideally, an increment on the level of autonomy leads to a decrease in the operator’s workload. Paradoxically, experimental data shows that a wrong automation approach may even increase such workload, thus generating undesirable situations [3]. An excessive interaction demand, a comprehensive introduction of data or a necessity of operator's attention in inappropriate situations can increase the mental workload excessively given rise to the so-called *clumsy* automation [17].

- **Complacency**: surprisingly, a high number of automated tasks and a low failure rate may have negative effects on the operator's behaviour. The operator might experience complacency (or over-reliance) on the system's autonomous abilities. In other words, the performance of the system is so outstanding that the human operator tends to devote less attention to its behaviour since it unlikely fails. This effect becomes more evident when the operator is executing other tasks simultaneously because complacency can lead him to overlook occasional failures of the system [18]. Although complacency is more frequent in systems with high reliability and low failures rate, it is difficult to predict when and how it will appear.
- **Situation awareness**: this concept was defined in [19] as "the perception of the environment elements within a given time and space, the comprehension of their meaning and the projection of their status in the near future". The operator's situation awareness may not be complete if the human interface has not been properly designed. A situational awareness loss is more likely in autonomous systems in which the operator performs a passive or mainly supervisory task. In general, humans are proven to be less sensitive to environmental changes that have been introduced externally than to such changes that have been produced by them [20].
- **Skill deterioration**: if the decision-making and action processes are fully controlled by an autonomous system, the operator's tends to lose his trained skills since they are not periodically trained. The disuse of certain tasks may lead the operator to forget such tasks or to perform them worse than he used to when he was trained [21].

1.5.4. Responsibility over the Final Decision

In scenarios where multiple human agents interact with multiple robotic agents emulating the human behaviour there appears the possibility of a disagreement between both parties when they have to make a decision. These potential conflicts must be handled by the mission management system in order to solve conflicts occurred between:

- Two human agents
- A human agent and an autonomous system
- Two autonomous systems

Sometimes, a better visibility of the mission parameters (or better situation awareness) may be sufficient to decide among all possible alternatives but this decision might not be always so evident. The conflict resolution criteria in a human-robot interface (HRI) will depend to a great extent upon the level of autonomy selected for the autonomous system. It will also depend on the degree of trust or reliance offered by the autonomous system over time. This is a research field that is gaining much attention given the recent interest in applications involving autonomous systems [8].

1.5.5. Social and Cultural Aspects of Human Machine Interfaces

The optimization of the behaviour of a UAS team requires the knowledge of the motivation and the cognitive process that guides a human brain through a certain action [22]. There are several aspects that influence the human behaviour when controlling an autonomous machine beyond the simple information exchange between both entities. Studies have shown that systems that progressively increment the number of autonomous tasks do not yield satisfactory results necessarily. For example, some aircraft pilots have reported that they do not always rely on cabin navigation aid tools that are intended to increase their situation awareness. Their trust on these instruments is not always complete and they have reported to prefer the manual operation to some extent [1], [4], [23].

The trust on the autonomous system reliability is the key factor to be analysed from a socio-cultural point of view. Trust affects the expectations and the success probability perceived by the observer. Distrust with respect to the performance of the autonomous systems can lead to a misuse or bad use of the automation of the system [3]. Often, one single automation error can permanently influence the operator’s trust and such trust is not easily regained no matter how many successes are achieved afterwards. Studies have shown that it is preferable to decrease the number of automated functions to obtain in return a greater implication and confidence from the operator.

Additionally, there are some individuals who have an inherent predisposition to be more reliant on machines than on humans (and vice versa) either for cultural or social reasons. In some other cases, cultural features lead humans to feel more trust towards certain types of machines according to their operational characteristics. Moreover, studies also show that humans tend to be friendly to machines with anthropomorphic features and to treat them in a similar way as they would with other humans [8].

1.6. Current Trends in the Management of Autonomous Teams

1.6.1. Progressive Increment on the Level of Autonomy

The current tendency in UAS is characterized by the rapid increment of their autonomous functionalities during the last years. Figure 1-2 shows the evolution foreseen by the US government for the levels of autonomy in UAS within the next 20 years [2]. It shows an exponential growth over the next two decades of the autonomy levels for the most popular UAS in the field.

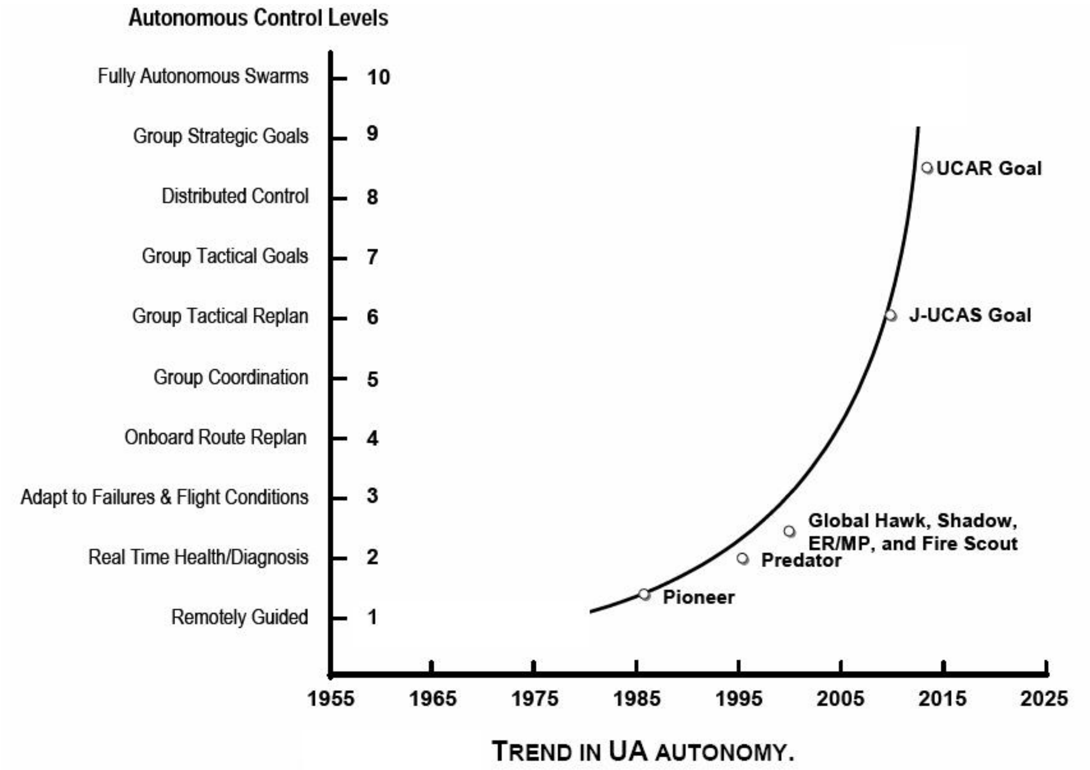


Figure 1-2 Estimation of the autonomy evolution in UAVs, DoD UAS Roadmap 2005-2030

Further literature analysis indicates that such autonomy increase will highlight the necessity to implement new procedures and team management processes to handle the new operational scenarios addressed [6], [15], [24], [25].

1.6.2. Adaptive Automation

As it has already been introduced, an equilibrium between automated and manual control must be sought in order to obtain optimum results. Failure tolerance in critical missions is extremely low so it is necessary to provide the system with enough flexibility to adjust the autonomy levels depending on the evolution of mission. This approach is known as adaptive automation (AA).

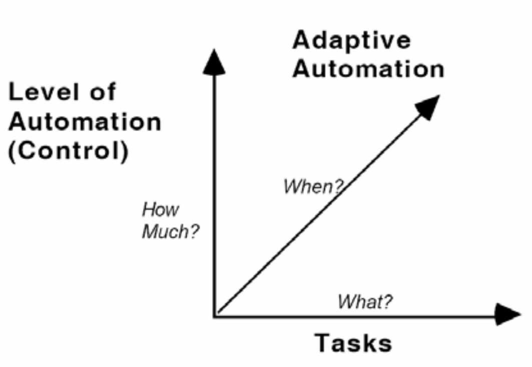


Figure 1-3 Adaptive Automation introduce time variable in the selection of the autonomy levels

The aim of AA is the optimization of the dynamic task allocation by creating mechanisms to determine (in real time) when certain tasks have to be automatically executed [4]. Unlike traditional approaches that implement fixed task allocation, AA aims at optimizing the performance of the operator with systems that continuously adjust their level of automation. These variations are intended to keep the operator in the decision loop at all times. Consequently, this phenomenon is also known as human-in-the-loop (or operator-in-the-loop).

There are two predominant approaches in AA systems. The first approach indicates that autonomy levels must be adjusted according to the changes occurred during the mission execution. In other words, as the mission progresses and some unforeseen events arise, the system should re-calculate and apply the most suitable level of autonomy. The second approach consists of the continuous adjustment of the levels of autonomy depending on the status of the operator. The main objective is to evaluate the physical and psychological status of the individual to extract information about how the generated workload is being processed. Once the human performance is analysed, the system may change (if necessary) the human involvement and replace it by a less attention-demanding task [26].

1.6.3. Distributed Control

Another noticeable tendency in the UAS field is the evolution in the control of UAS teams from the conventional centralized control (usually a single ground control station) to a distributed control among a "network" of control agents [27]. Distributed control offers more versatility and flexibility since it adapts better to occasional and unexpected changes in the mission conditions.

Table 1-1 shows a comparison among different advantages of human operation versus automated machines. A thorough analysis of these characteristics could help to make a decision about what functionalities are suitable to be distributed and therefore moved to the flight segment ultimately [22].

Table 1-1 Comparison of human and machine operation

Human	Machine
Pattern recognition	Fast response to control tasks
Improvisation and use of flexible procedures	Repetitive and monotonous tasks
Recall relevant events at precise instants	Simultaneous management of complex tasks
Inductive Reasoning	Deductive Reasoning
Exert Wisdom	Time invariant behavior

1.6.4. Interoperability Levels Proposed by NATO

This sub-section describes the interoperability levels defined by the North Atlantic Treaty Organization (NATO) in [28] for UAS. These levels indicate the degree of coordinated control that can be exerted by the control segment:

- Level 1: indirect reception of data related to the UAS
- Level 2: direct reception of data (communications in line of sight) from/to the UAS and the Unit Control Segment (UCS).
- Level 3: UAS' payload control and monitoring
- Level 4: UAS monitoring and control except for aircraft launching and recovery functions
- Level 5: UAS monitoring and control (level 4) plus aircraft launching and recovery functions

These interoperability levels are directly linked to the autonomy levels assigned to the team. A high interoperability level facilitates the implementation of high autonomy levels given that it allows the concurrent management of multiple UAVs by a single operator. Nonetheless, the interoperability levels are necessary but not sufficient for the implementation of high levels of autonomy in the team. A level 5 of interoperability does not imply a maximum degree of autonomy unless additional mechanisms and procedures are implemented both in the flight and ground segment in order to ensure its correct integration of such autonomy at individual and collective level.

1.7. Autonomy Metrics for UAS Taxonomy

1.7.1. History

This section reviews the most remarkable contributions to the definition of autonomy metrics for UAS classification according to their level of autonomy. The objective of an autonomy taxonomy is to offer a systematic procedure to classify heterogeneous autonomous vehicles with similar degrees of autonomy and thus, exploit the possible synergies that may be found among the team from an operational point of view. This is a recent research field that has acquired growing interest in the last years as new applications and theories continue to arise. The most relevant contributions identified in the literature are:

- **Sheridan and Verplank** (1978): this is the first consolidated proposal to classify systems according to their autonomy level. It proposes a 10-level scale in which level 1 corresponds to null autonomy (pure remote control or tele-operation) whereas level 10 denotes a completely automated system (no human intervention is required at all) [6].

LEVELS OF AUTOMATION OF DECISION AND ACTION SELECTION

HIGH 10. The computer decides everything, acts autonomously, ignoring the human.

9. informs the human only if it, the computer, decides to

8. informs the human only if asked, or

7. executes automatically, then necessarily informs the human, and

6. allows the human a restricted time to veto before automatic execution, or

5. executes that suggestion if the human approves, or

4. suggests one alternative

3. narrows the selection down to a few, or

2. The computer offers a complete set of decision/action alternatives, or

LOW 1. The computer offers no assistance: human must take all decisions and actions.

Figure 1-4 Sheridan & Verplank, first remarkable autonomy scale

- **Los Alamos and Draper Laboratories** (1995 to 2000): first three-axis map for a spatial representation of robots autonomy. Each axis is further divided into 10 levels so that the three considered magnitudes are weighed for each axis in a separate way. In particular, the three magnitudes considered are: mobility, acquisition and protection [29].

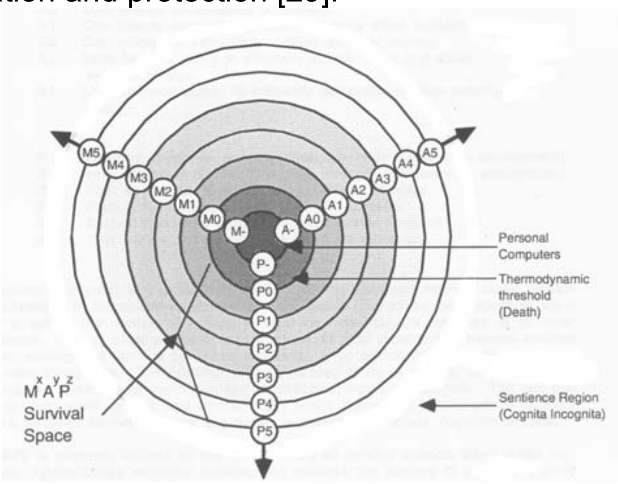


Figure 1-5 First three dimensional taxonomy for autonomous vehicles

- **Air Force Research Laboratory** (2002): this is the most relevant and widespread metrics known to date. It analyses the autonomy of the system according to the four steps of the human cognitive process (OODA) introduced in section 1.3. The resulting metrics are called Autonomous Control Levels (ACL) and they are the result of evaluating the autonomy for each OODA step with a decimal scale (as they have been defined in) [11].

- **COMETS Project** (2004): it defines a matrix-based autonomy metrics relying on four autonomy categories which are graded with a five-level scale value (A to D) ranging from the lowest to the highest possible degrees of autonomy [30].

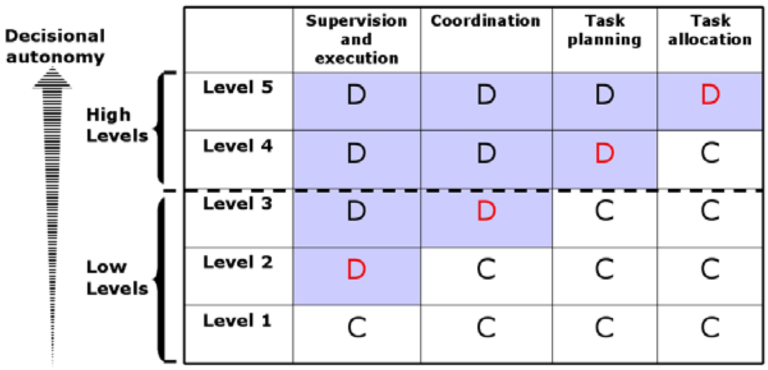


Figure 1-6 Matrix autonomy metrics proposed in COMETS project

- **Autonomous Levels For Unmanned Systems (ALFUS)** (2003 – today): it is a collaboration framework coordinated by means of periodic conferences, workshops and publications which are intended to elaborate autonomy metrics for autonomous systems. The National Institute of Standards and Technology (NIST) promotes this initiative. The innovative approach of this initiative is given by the assumption that the autonomy of a system necessarily depends on three variables: human-machine interface, mission and environment [31].

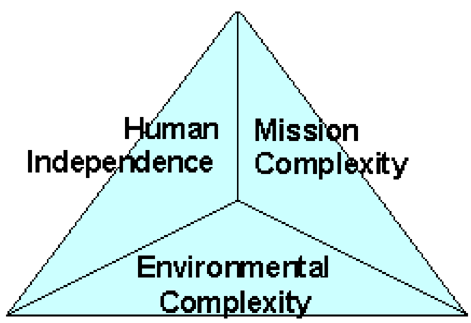


Figure 1-7 Three-axis autonomy map proposed in ALFUS

1.7.2. Current Initiatives

In general, the ACLs defined by the Air Force Research Lab (AFRL) are the most popular autonomy metrics developed to date. However, the international scientific community has not accepted them as a de-facto standard yet. Their major asset resides on their generic approach to the definition of UAS taxonomy.

A commonly adopted alternative for collaborative missions involving autonomous vehicles consists of the implementation of a tailored version of the ACLs depending on the characteristics of each mission [1], [2]. However, a ten-level scale is usually maintained in all the autonomy metrics for the mapping of a certain autonomous vehicle into the taxonomy. Remarkable examples of single axis decimal autonomy metrics can be found in the literature such as the one proposed by the European Technology Acquisition Program (ETAP) [32] or the autonomy scale adopted by the Department of Defence of the United States in one of its latest issued publications [2].

Nevertheless, other initiatives define their own autonomy metrics and either the properties of each level or the number of levels are adapted to the mission characteristics. A significant example of this approach is the SMART program developed by NASA for the design of spacecraft autonomy levels. The metrics created for this project starts from a traditional ten-level scale [6] that is modified later on to an eight-level scale that fits better the project requirements [33].

Many studies indicate that traditional ten-level and single axis scales are insufficient to incorporate all the factors that determine the autonomy of a vehicle. In particular, most metrics consider that autonomy uniquely depends on the vehicle characteristics but the concept of autonomy is much more complex than that. A UAV for instance, could make use of all its autonomous functionalities in a certain mission whereas keeping some of them unused in another mission. Likewise, the level of autonomy possessed by a UAS could also be diminished if unfavourable weather conditions arise at any time (i.e. loss of visibility). Therefore, the autonomy of a UAS (or a team of UAVs) will depend on the characteristics of the vehicle but it will also be influenced by the operational context.

In this sense, the metrics proposed by the collaboration framework ALFUS is the only alternative that takes the mission context into account. ALFUS is a continuously updated effort which studies relevant precedent works and analyses the pros and cons of every autonomy metrics alternative. Moreover, an interesting design characteristic of the ALFUS approach resides in the ability of its methodology to classify both single and multiple autonomous systems at once. This is an essential attribute for the analysis required in this work and the reason that has led us to a detailed study of this contribution in the following section

1.7.3. ALFUS Project

The objective of this initiative (2003) is to join efforts and knowledge to lay the foundations for the evaluation and classification of unmanned (or uninhabited) vehicles according to their autonomy. A number of participants contribute in this project to reach an international consensus in the elaboration of autonomy metrics. Namely, the list of participants includes: government organizations, research laboratories, universities, companies and military institutions.

ALFUS breaks the tendency set by other projects based on a traditional ten-level metrics or an adaptation thereof. Hence, ALFUS is presented here as a meaningful alternative especially adapted to the complexity and the technical advances of modern missions [12], [34].

1.7.3.1. Description

This methodology provides a general approach that offers a multiple-level abstraction layer to assess the autonomy requirements for UAS operations. ALFUS framework allows classifying any type of UAS ranging from fully autonomous platforms to mere remotely controlled vehicles. The main concept behind this approach is the inclusion of a three-dimensional autonomy space that measures: human interface, mission complexity and environmental difficulty as shown in Figure 1-8:

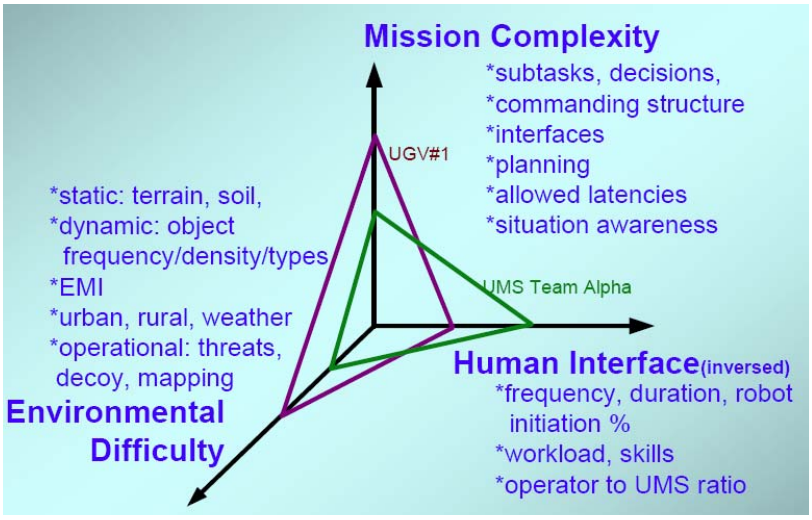


Figure 1-8 ALFUS autonomy metrics based on a three dimensional method

Its range of applicability spans from military, logistics, manufacturing, search and rescue, medicine, services for disabled and elderly people, etc. [31]

1.7.3.2. Advantages and Disadvantages of ALFUS metrics

The following advantages and disadvantages of the described metrics should be taken into account throughout the activities comprised in this work:

Advantages:

- It is the only metrics that takes the context under consideration (unlike traditional metrics which only take into account the vehicle characteristics).
- ALFUS is an important, ambitious and long-term effort for the definition of a common standard for autonomy metrics.
- The metrics proposed considers all relevant aspects of a mission
- The relevance of all participants and the diversity of their area of activity (industry, government, academia, etc.)
- It is the most remarkable on-going research action by the time of writing.

Disadvantages:

- It is an ongoing initiative and thus, the results presented up to now are provisional.
- ALFUS offers a tool to assess the autonomy of a vehicle. However, a homogenous process to map the autonomy capabilities of the system into the taxonomy has not been defined yet. Hence, there is still a subjective component in the decision process.
- The great level of detail provided by ALFUS (up to 1000 different levels of autonomy for any UAS) might be too exhaustive and perhaps excessive for certain applications.

1.7.3.3. Classification Process

The final outcome of the process of autonomy assessment proposed by ALFUS is known as Contextual Autonomous Capabilities (CAC). This result is a weighted average of the three main categories considered by the method as it is shown in Figure 1-9.

Each of these three aspects is further divided into different metrics sub-sets in order to cover all relevant aspects of each category. The aspects considered in the classification depicted in Figure 1-9 include the following abstraction levels:

- High level: provided by the three main axes. The final values given to these levels shall be weighed functions of the low-level measurement averages.
    - Mission complexity (MC)
    - Environment Complexity (EC)
    - Human Independence (HI)
- Low level: sub-categories division to increase the level of detail and the diversity of influencing factors considered within each axis.

These parameters can be summarized in a table that will be used by the user (operator) to map autonomy values for each category and sub-category. Additionally, the scale type and the weighting function to be applied to each parameter under consideration have to be defined on a case-by-case basis. The function should be defined according to the importance given to each parameter and its influence on the mission execution.

Key Definitions	Autonomy, Unmanned System (UMS)		
	Contextual Autonomy Capability (CAC)		
Axes / Aspects	Mission Complexity (MC)	Environmental Complexity (EC)	Human Independence (HI) or Level of Autonomy (LOA)
Metrics			
Scales			

Figure 1-9 ALFUS result table containing the Contextual Autonomous Capabilities (CAC)

1.7.3.4. Study Case

This section describes a study case where the metrics proposed by ALFUS has been applied to assess the level of autonomy of several heterogeneous UGVs [35]. The reasoning applied in this study is mainly focused on autonomy aspects so it could be related to UAVs with no loss of generality. This experiment considers multiple types of vehicles with heterogeneous characteristics namely: road vehicles, cargo transportation vehicles and terrestrial exploration robots. As a result of the autonomy analysis performed, a series of spreadsheets (Figure 1-10) were elaborated containing the autonomy levels elaborated according to the metrics defined by ALFUS.

	MC	ED	HI
10			
9			
8			
7		X	
6			X
5			
4	X		
3			
2			
1			
0			

Figure 1-10 ALFUS study case: weighed autonomy grading assigned to an autonomous vehicle

The obtained score for the different vehicles considered in the experiment enables a quick interpretation of the results and an easy comparison between each UGV's autonomy. Figure 1-11 shows the final outcome of the autonomy evaluation using ALFUS metrics for different UGVs.

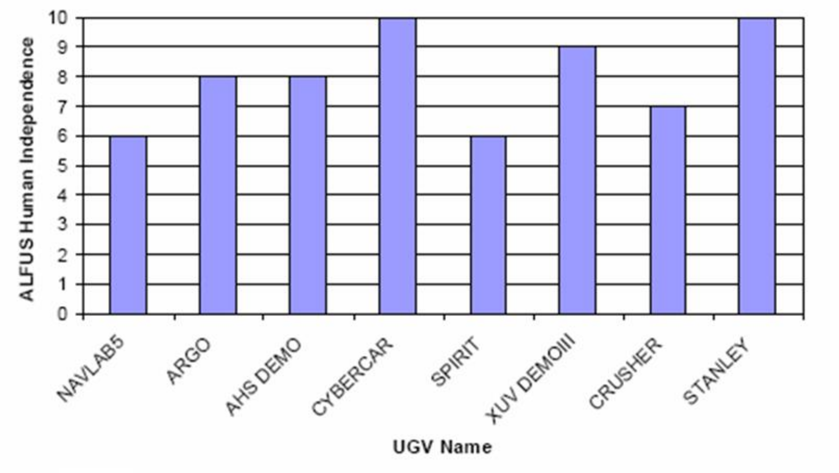


Figure 1-11 ALFUS study case: autonomy levels comparison for different UGVs

1.8. Efficient Evaluation of Autonomous Teams

As it has been previously introduced, human intervention usually improves the efficiency of a mission involving autonomous vehicles. Figure 1-12 shows the evolution of the efficiency of an autonomous system (i.e. a robot) as the time of non-supervised action (neglect time) grows.

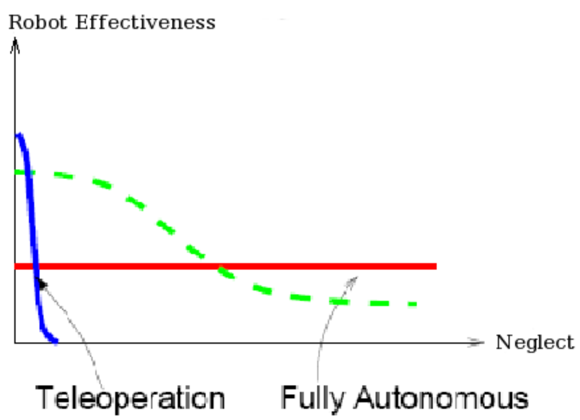


Figure 1-12 Robot efficiency as a function of the neglect time

It can be noticed that tele-operated systems are more sensitive to an absence of supervision. But if the unsupervised periods are short, a non-autonomous system would be more efficient. Therefore it becomes apparent that a trade-off must be found (green dotted line) to reach an optimum efficiency point. The following sections present several methods to assess the efficiency of a UAS team operating under the conditions proposed in this work

1.8.1. Objective Measurements

It is essential to evaluate the efficiency of a human-machine interface from an analytical point of view. A thorough analysis may help to prevent and avoid risky situations originated by a bad use of the available resources. For that reason, there exist different objective variables to quantify the global performance of an autonomous systems team [27], [36], [37].

- **Neglect Time (NT)**: is defined as the time that an autonomous vehicle can be operating without human direct intervention as long as its performance does not go down below a certain threshold.
- **Interaction Time (IT)**: is the time during which the operator's intervention is required to maintain an appropriate operation performance in the system.
- **Fan-Out (FO)**: is number of vehicles (usually homogenous) that can be controlled by a single operator simultaneously. In general, the FO can be interpreted as an upper bound to be considered during the design stage and can be expressed as a function of the previously defined parameters as follows:

$$FO = \frac{NT + IT}{IT} = \frac{NT}{IT} + 1 \tag{1.1}$$

- **Wait Time (WT)**: it is the time passed since the operator's attention is required to carry out a certain task until such an action is executed. This parameter is especially relevant in robot teams management and it includes: (1) waiting time in queue (WTQ) and (2) Waiting Time Situational Awareness (WTSA) and (3) the Waiting Time Idle (WTI):

$$WT = \sum_i WTQ_i + \sum_j WTSA_j + \sum_k WTI_k \tag{1.2}$$

Ideally, these magnitudes should be considered during the system design phase to assess the resource organization and allocation tasks (both in the ground and the flight segment).

1.8.2. Subjective Measurements

This category includes magnitudes related (directly or indirectly) to the operator who controls the vehicle (or the team). In general, subjective categories are grouped into physiological and psychological variables to evaluate the status of the operator [22].

1.8.2.1. Psychological Variables

There are several parameters to measure the mental efficiency of the operator during the execution of a mission [22].

- Efficiency in the assignment of attention
- Efficiency in the processing of information
- Mental Workload

- Situation Awareness
- Self Trust
- Emotional Status

1.8.2.2. Physiological Variables

Systems designers usually are concerned about the psychological (or mental) effects on the operator rather than the physical symptoms. However, the role of the operator also implies certain physical requirements:

- Stress provoked by a high workload
- Fatigue
- Comfort and ergonomics

1.8.3. Accidents Due to Automation Errors

Studies show that the accident rate in unmanned flights is greater than that of manned flights. It has been estimated that up to a 70% of the accidents involving UAVs are due to human errors [2], [38], [39]. Regarding this issue, NATO has recently published a study that recommends a conservative criterion to choose both the in-flight level of autonomy of the aircraft and the operating conditions [40].

It has been proven that in some cases a misuse of automation is due to a lack of user training rather than a bad choice of the automation capabilities of the system [39]. These weaknesses can be improved by means of low-cost solutions like the implementation of computer simulators to optimize the abilities of the operators [2].

Additionally, other studies show that most accidents could be avoided by an exhaustive analysis of the user interfaces employed and the operating procedures. A further analysis of the human errors resulting into accident shows that a 70% of them took place during the most critical flight stages [39], so especial attention should be paid to the automation applied to these phases.

Unfortunately, civil aviation suffers from numerous accidents due to some sort of failure at some stage of the automation process. A few examples of some of these failures are:

- Northwest MD-80 airlines (1987): the aircraft crashed down because the crew did not pay enough attention to an incorrect landing gear deployment since they were experiencing a peak of workload.
- Boeing 737 (1987): one of the automatic warning systems of the aircraft was unnoticed by the cabin crew because they over-trusted the reliability of the system.
- Korean airlines (1983): a Korean aircraft was shot down by USSR missiles since the aircraft flight aid system indicated erroneous coordinates while it was flying over restricted soviet air space.

1.9. Reference Project

A thorough literature review has shown that there are very few projects with similar characteristics to the ones addressed in this work. Despite the increment of the research activities in collaborative UAS, the management of a heterogeneous team constitutes a singular attribute of this thesis. Two projects that share some technological challenges with our approach have been identified: COMETS and SWARMS.

The point in common with COMETS is the management of a heterogeneous team of autonomous vehicles with different levels of autonomy. Likewise, the similarities with SWARM project are focused on formation maintenance and the in-flight intelligence aspects of a mission.

These two projects are summarized in the following subsections as well as several research initiatives that share some research challenges with our project and that can add significant value to this thesis.

1.9.1. COMETS

This project was funded by the European Commission (EC) and its activities lasted from 2002 to 2004. The main objective of the project was to design a distributed control system for detection and monitoring of heterogeneous UAS teams. COMETS proposed a new system architecture and control techniques for a UAS fleet combining all kind of UAS platforms (fixed-wing aircraft, rotor-fixed aircraft, airships, etc).

More specifically, the project investigated distributed detection and control algorithms as well as image processing techniques. The validation process of COMETS was carried out by means of field demonstrations of a support system for wild fire fighting brigades [30].

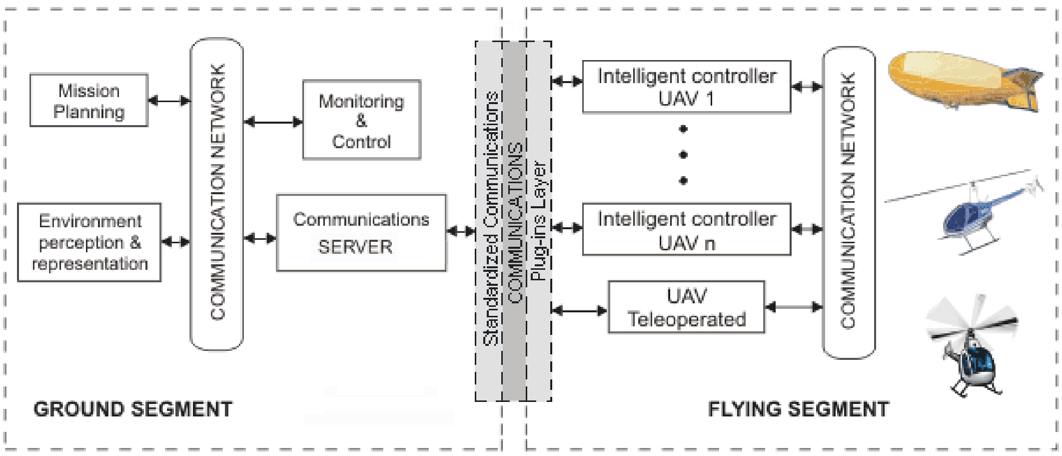


Figure 1-13 Control architecture diagram proposed in COMETS

Regarding the autonomy aspect, COMETS recommended that a single operator controlled every UAV with an adjustable autonomy level depending on the necessities and status of the mission. Five autonomy levels were defined (see Section 1.7.1) and their selection could be also influenced by the type of vehicle and the phase of the mission so that the operator was allowed to switch to manual control at all times if needed

1.9.2. SWARMS

The participants of this project include several prestigious academic and military institutions like Yale University, MIT-CSAIL, University of Pennsylvania, University of California Berkeley, University of California Santa Barbara, Army Research Office and Army Institute of Collaborative Biotechnology. The project started in 2003 and several publications have been issued until 2008.

The main goal of this project is the study of mathematical models that reproduce the behaviour of formation flight (swarms) in nature like the ones produced by some birds or insect species. The practical objective of the project is to apply those analytical models to collaborative autonomous systems like teams of UGVs or UAVs [41].

The approach followed in this project is based on the implementation of a framework of technology and a methodology for the analysis of natural swarms' behaviour. Therefore, this analysis based on biology would be applied to the synthesis of bio-inspired systems answering questions such as:

- Would a group of vehicles deployed in formation be reliable to carry out pre-established missions and response as a team to high-level commands?
- Is it possible for the group to work in challenged environments without a fixed leader in the team and with restricted communication capabilities?
- What can we learn about how these groups get organized in nature (insects, birds, fishes, etc.)?
- Are there hierarchical models to define such behaviour for various levels of resolution (from emerging behavioural characteristics to detailed descriptions that model the individual dynamics of each vehicle)?

1.9.3. Other Initiatives

A number of references can be found in the literature involving homogeneous UAS teams. A selection of the initiatives which have more resemblances with our work are described hereunder:

- **Collaborative Control Centre for Unmanned Vehicles (C3UV**), University of California Berkeley: interdisciplinary research group focused on the operation of homogenous vehicle team with a minimum human intervention. The centre's laboratory has a simulation platform to emulate collaborative missions. Its research areas cover the following topics: detection and control, conflict resolution, communications, task allocation, cooperative execution and information exchange. It is also remarkable the contribution of the centre in the field of flight formation control which is a relevant factor in this project [42]. Another research group from this university is also of interest due to its work: Berkeley Aerobotics (BEAR). This group works in the coordination of reduced UAV platform teams [43].

- **National ICT Australia (NICTA):** is a newly created research centre of excellence devoted to Information and Communication Technologies (ICT) [44]. The scope of its work is oriented to control theory and intelligent systems. The centre participates in the SWARM project doing research in the field of flight formation maintenance.

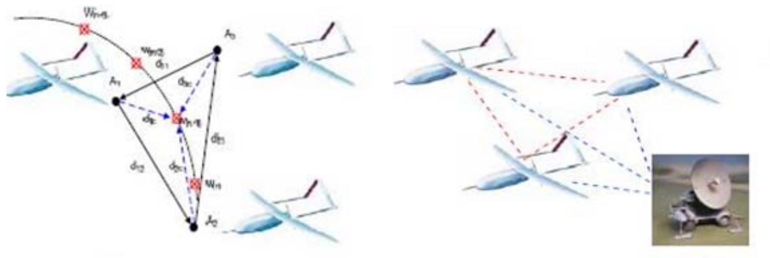


Figure 1-14 NICTA contributes to the field of flight formation control for UAVs

- **Humans and Automation Lab from the Massachusetts Institute of Technology (MIT):** its research activities are focused on human-machine interfaces and the supervision of complex autonomous systems [45]. This institution has a number of publications in the field of automation applied to cooperative (and individual) control and operation of UAS. Namely [27], [36], [22], among others.

- **Aerospace Control Lab (MIT):** its research is oriented to the design of control systems for airships, spacecrafts and terrestrial vehicles. Its main research areas are: decision making under uncertainty conditions, route planning and task allocation. In the framework of the project Real-time Indoor Autonomous Vehicle Test Environment (RAVEN), this laboratory has tested the simultaneous operation of ten small-size UAS controlled by a single operator [46].

Chapter 2

FLIGHT SEGMENT COMMUNICATIONS

2. FLIGHT SEGMENT COMMUNICATIONS

2.1. Communications Architecture

As it was introduced in [47] a UAS consists of: UAV, onboard systems, mission control station and other elements that are necessary for the vehicle airworthiness.

The basic UAS architecture includes the following building blocks (Figure 2-15):

- Flight segment: encompasses the vehicle, the avionics and the onboard payload.
- Mission control segment: includes the services, equipment, staff and tools necessary for the control of the vehicle. This segment can be fixed or mobile, centralized or de-centralized (or both in mixed architectures).
- Communications segment: links and communication systems that implement the connexions between the mission control segment, the flight segment (and Air Traffic Management (ATM) in case of a non-segregated air space).The communications segment of a UAS is characterized by its internal and external links (or interfaces) [28]. As shown in Figure 2-15, the internal links interconnect the own UAS systems (payload, sensors, avionics, etc.) and also establish a communication link between the UAV and the mission control station. The external links allow the interoperability with ATM and with other UAS.

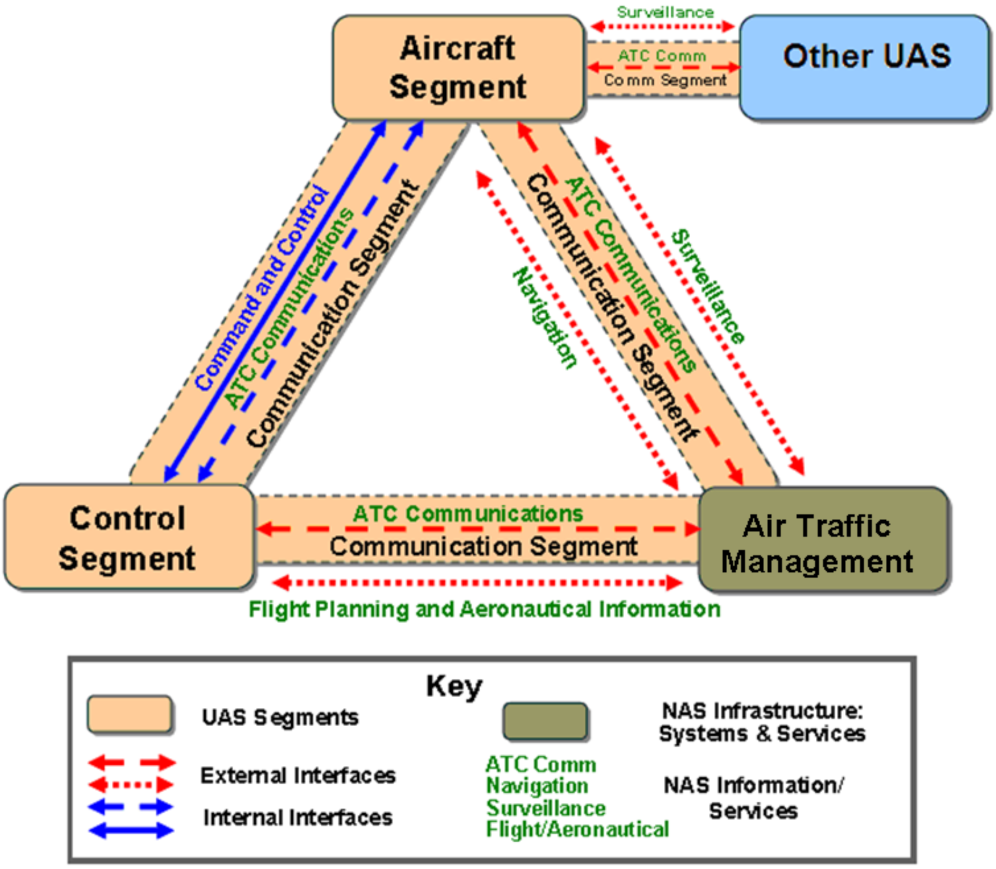


Figure 2-15 UAS Communications Architecture [47]

The main links of the communication segments are:

- Link between flight segment and control segment: this communication link can be a Line Of Sight (LOS) link or a Beyond LOS (BLOS) link. The latter must include redundant communication links to ensure data continuity and integrity. The data transmitted through this link consist mainly of telemetry and telecommand information detailed in Section 2.2.2.
- Link between the control segment and ATM: this link can be implemented by a physical cable, RF terrestrial signals or a satellite. The data exchanged through this link are mainly mission planning information and real time flight management data.
- Link between the flight segment and ATM: this link represents the usual communication link with Air Traffic Control (ATC) for manned aircrafts. The UAS is used as a redundant link between ATC and the control segment in case of emergency or loss of the LOS link.
- Link between the flight segment and other UAS: its functionality consists of the exchange of mission information with other aircrafts sharing the same air space and/or belonging to the same team. This link includes the interfaces UAV-UAV and the air traffic messages (surveillance) exchanged between aircrafts

2.2. UAS Communication Links

2.2.1. Link Characteristics

Table 2-1 shows the data extracted from [48] regarding the taxonomy of several UAS as a function of their communication capabilities such as: type of mission, data transmitted by the payload, characteristics of the communications link (LOS/BLOS, range, bandwidth, and frequency band), etc.

Table 2-1 UAS Classification According to communication capabilities

Application	Military		Civil		
Type Of Mission	Surveillance	Tactic	Surveillance	Emergency	Environmental
Payload	EO/IR ISAR SAR Radar Enlace de red Jammer LTD, ELINT	COMINT MPR EO/IR ISAR SAR Radar Network Link	Spotlight flash EO/IR NBC detectors MTI	NBC detectors EO/IR Radar Localization COMINT ISAR MPR	EO/IR ISAR Radar
Required Bandwidth	5MHz	>5MHz	0.4MHz-5MHz	>5MHz	<1MHz
Range (km)	50-1000	1000-4000	2-300	300-2500	2-100
Autonomy (h)	<24	>24	1-24	>24	<5
Human/Machine Control	Autonomous mission plan and/or human monitoring	Autonomous mission plan and/or automatic monitoring	Autonomous navigation and/or human monitoring	Autonomous mission plan and/or human monitoring	
Telecommand Link (1)	LOS o LOS+BLOS	LOS+BLOS	-	BLOS	RC(72MHz) or Spread Spectrum or LOS
Upload: 10-100Kbps Download: 1-100Bbps	LOS (Redundant)	LOS (Redundant)	-	LOS (Redundant)	
Telemetry Link (1)	LOS	BLOS	LOS	BLOS	Video or Spread Spectrum or LOS
Upload: 10-100Kbps Download: depends on the load	- 1-5 Mbps	- >5Mbps	- <1Mbps	- >5Mbps	- -
Telecommand Link (2)	-	-	GPS backup	GPS backup	Spread Spectrum
Telemetry Ling (2)	-	Yes	-	Yes	None or 2.4GHz
Communications with ATC	VHF	Direct ground link and redundant ATC link V/UHF	On board VHF radio relay through C2 link	On board VHF radio relay through C2 link	Autonomous Navigation
Other links	Transponder IFF, ADS-B	Transponder IFF, ADS-B	Telephone with ATC or Transponder IFF, ADS-B	Transponder IFF, ADS-B	Telephone or Radio or Transponder IFF/ADS-B

2.2.2. Link Functionalities

As it was introduced in the Section 2.1, there are three different types of communication links between the flight segment of a UAS and the other segments. Communications with the Control Segment are oriented to enable GNC (guidance, navigation and control), monitoring and vehicle manipulation functions. Such functionalities are implemented by means of a downlink (telemetry) and an uplink (telecommand). On the other hand, this link supports communications with ATC and with other UAS within the communications range of the transmitter. The following subsections detail the functions of each communication link mentioned before.

2.2.2.1. Telecommand Link

This uplink conveys command and control information sent from the control segment to the UAV [49]. Including:

- Mission plan: definition and detailed description of the mission to be executed by the UAS.
- Task definition: tasks and operations are assigned according to the mission plan defined for each UAS.
- Air Traffic control messages sent from ATC containing information about the status of the air space.
- Hand-over control: status and control of the vehicle and its payload to be delivered to the aircraft.
- Additional Information: support messages required for the mission planning and for a correct execution of the assigned tasks.

2.2.2.2. Telemetry Link

The information regarding the status variables of the UAS are sent through this downlink [49]. The information includes:

- Mission Evolution: current status of the mission scheduled for a certain UAS.
- Resource Availability: status of the payload and avionic systems in terms of resource consumption and endurance.
- Payload Data: information gathered by the UAS onboard sensors.
- Mission Finalization: description of the results of the programmed mission.

2.2.2.3. Link with ATC

The main goals of the link between ATC and a UAS are:

- Allow the monitoring of the UAS status by the air traffic surveillance authorities every time and everywhere.
- Ensure the information exchange between the UAS operator and ATC to allow the execution of the indications, instructions and authorizations sent by ATC that allow the UAS to fly safely within a non-segregated air space.
- Implement distributed mechanism for flight formation maintenance among the UAS team and/or other aircrafts.

- Collaborate with other aircrafts in the air space to carry out coordinated hazard avoidance manoeuvres. Examples of such hazards are: high terrain, severe weather and mid-air collision risks.

The main civil aviation organizations (EUROCONTROL, FAA and ICAO) recommend the assignment of the above-mentioned functionalities to the communication links. The issued recommendations can be summarized in the following quote: "The communication link between ATC and a UAS must ensure the integration of the vehicles in the civil air space without requiring any further modification in the current traffic control systems and without constituting any risk for the safety greater than the one that will be implied by the inclusion of another manned aircraft" [50].

2.2.2.4. Link with Other UAS

The information exchanged by UAS in the team includes basically:
- Data gathered by sensors
- Coordinated execution of navigation and flight control instructions (especially in case of formation-keeping)
- Propagation of data or instructions sent by the control segment such as: task allocation, flight plan updates, etc.

2.3. Design Requirements for a UAS Communications Link

The requirements for the design of a UAS communications link can be classified into:
- Requirements imposed by the communications system
- Requirements imposed by the vehicle
- Safety and Efficiency requirements

2.3.1. Requirements Imposed by the Communications System

For the design of any link of the communications segment, the following basic parameters must be defined beforehand:
- **Transmission rate**: amount of information (bits) transmitted per time unit. Currently, the tendency in UAS is shifting towards the progressive increment in the payload capacity and the number of onboard sensors. Consequently, the transmission rate must be increased accordingly to support real time operations.
- **Bandwidth**: difference between the upper and the lower frequency bounds where the communication system signal is confined.
- **Frequency band**: range of frequencies where the communication system operates.
- **Range:** maximum distance between transmitter and receiver to guarantee reliable communications.

Figure 2-16 shows typical requirements concerning transmission rate and bandwidth for UAS communication segment links.

Communication Stream To & From		Data – Link					
		function	*connection*	*direction*	*application type*	*rate requirement*	*operating frequency*
	The UAV	Flight Control	UCS ↱ Autopilot	up	TC	Low < 30 Kb/s	HF, VHF/UHF
		Task–Payload Control	UCS ↱ Payload	up	TC	Low < 30 Kb/s	HF, VHF/UHF
		Flight Status	Autopilot ↳ UCS	down	TM	High < 1Mb/s	VHF/UHF
		Task–Payload Data	Payload ↳ UCS	down	TM, TV	Broadband > 1Mb/s	L, S, C, X, Ku
		UAV Flight Progress Reporting	UAV ↳ ATC	down	TM	High < 1Mb/s	VHF/UHF, L, S
			UAV ↔ Traffic	two-way		High < 1Mb/s	VHF/UHF, L, S
	The UAV Operator	Traffic Coordination	UAV Operator ↔ ATC	two-way	WM / Voice	Low < 30 Kb/s	HF, VHF/UHF
		Mission Task Coordination	UAV Operator ↔ Command Post	two-way	WM / Voice	Low < 30 Kb/s	HF, VHF/UHF, L, S, C, X, Ku

Legend			
TC	Tele–Command	HF	1–30 MHz
TM	Telemetry	VHF/UHF	30–1000 MHz
TV	Television (Visual & IR Spectrum)	L-, S-Band	1–2 GHz
WM	Written Message	C-Band	5 GHz
		X-Band	10 GHz
		Ku-Band	15 GHz

Figure 2-16 Communication segment link requirements [51]

In general terms, the telecommand link between the Unit Control System (UCS) and the UAS requires a relatively low transmission rate (10 to 100 kbps.) and it operates at HF and VHF/UHF frequency bands. On the other hand, for the telemetry link, transmission rates above 1Mbps are required. The following frequency bands are commonly used for both links: VHF/UHF, L, S, C, X and Ku.

Finally, the link between the control segment and ATC requires low transmission rates (10 to 100 kbps) and it also operates at UHF/VHF and HF frequency bands. Nonetheless, these values may vary depending on the characteristics of each mission.

Currently, the redundant telemetry and telecommand links implementation is usually based on the standards 802.16 (WIMAX) and 802.11 (Wi-Fi) [48]. However, LOS links between a UAV and other manned and unmanned aircrafts usually use dedicated RF links. Occasionally, optical links between two UAVs could also be employed [47].

Table 2.2 summarizes the pros and cons of the most common frequency bands in UAS RF communication links. In particular, it compares UHF and the frequencies from the IEEE standards 802.16 and 802.11.

Table 2-2 UAS communication characteristics [51]

Frequency band	*Advantages*	*Disadvantages*
430MHz (UHF)	▪ multiple channels at one location ▪ little multipath distortion ▪ range less susceptible to weather ▪ signals in VSB modulation can be received by the TV set	▪ does not support broadcast of quality video ▪ legally transmitted power inside band 433,050 - 434,79 MHz restricted to 10mW e.r.p.
900MHz	▪ enables video broadcast ▪ low cost due to the mass production	▪ EU dedicates for GSM - consequently legal transmitting power restricted to 10mW e.r.p. ▪ expected interference in populated areas due to the wide use: cordless phones, spread spectrum wireless LAN
2.4GHz	▪ enables video broadcast ▪ low cost system	▪ expected interference in populated areas due to the wide use: microwave ovens, cordless phones, wireless LAN ▪ line–off–sight operational requirements ▪ range affected by humidity in the air ▪ legal transmitting power restrictions (100mW e.r.p.) for the 802.11.b/g technology
5.8GHz	▪ enables video broadcast ▪ small transmitting antennas ▪ low multipath distortions in spread spectrum OFDM modulation	▪ severe multipath distortion causes very poor performance in FM mode ▪ line–off–sight operational requirements ▪ range affected by humidity in the air ▪ equipment expensiveness

Although it is an external constraint, the spectrum availability and the mitigation of interferences and possible jamming, can be considered as a limitation imposed by the communication system that restricts the communication features of every UAS and that must be considered.

2.3.2. Requirements Imposed by the Vehicle

In a UAV mission the main limitations are: the physical characteristics of the vehicle (size, volume, etc), the battery endurance and the mission duration. Such physical constraints limit the capabilities of the onboard payload (Figure 2-17) that consists of: antennas, transmitters and receivers, electric modules, propulsion, navigation and control systems, sensors and others.

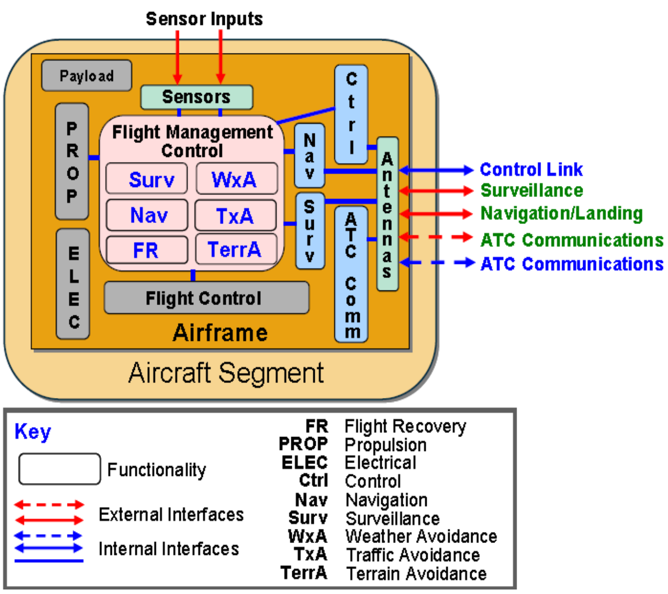


Figure 2-17 UAS basic architecture [47]

These factors along with the duration of the mission determine the design of the battery and all onboard devices (even the flying platform itself). Thus, the amount of energy that can be consumed is limited and consequently, other features of the systems like autonomy and maximum available power become fixed as well.

Other limitations introduced by the vehicle are the performances of the hardware components of the avionics platform used (transmission rate, efficiency, gain of the antenna and sensors, etc).

2.3.3. Efficiency and Safety Requirements

The typical efficiency and safety requirements for the design of the UAS communication links are:

- **Integrity**: measure of the validity of the information received (including navigation and guidance). The integrity includes the ability of the supervisory system to provide on-time alerts indicating when the received data must not be used for the desired operation.
- **Continuity**: system ability to carry out a certain function in the absence of unexpected interruptions.
- **Availability**: probability that the system will be able to provide the desired operation with the required precision (and with adequate values of integrity and continuity). It is defined as a time percentage evaluated over long periods of time in which the service is operating properly both considering expected and unexpected interruptions.
- **Confidentiality**: property of a message that makes it only readable or understandable by certain people or entities.
- **Encryption** of information: guarantees a secure exchange of messages between people or entities.
- **Redundancy**: consists of intensifying or multiplying the number of communication means to prevent occasional failures. The objective is to ensure that the transmitted information reaches the receiver.
- **Interferences**: external processes that alter, modify or destroy the information contained in a message during its transit from the transmitter to the receiver.

2.4. Communication Technologies Employed

Communications between UAV and the control segment generally rely on equipment operating under LOS conditions and supported by a BLOS satellite link. The present section describes the two most employed technologies in UAS communication links: radio frequency and optical communications.

Typically, low power radio links are used for short-range (< 1km.) communications. This type of links can be implemented with the current state-of-the-art Wi-Fi or WiMAX connections. On the other hand, dedicated point-to-point communications with directional antennae are normally employed for long-range (> 1km.) communication links. Due to the limitation on battery endurance UAVs are endowed with pointing systems that permit communication ranges of up to tenths of kilometres in LOS.

2.4.1. Radiofrequency

Wireless communications are based upon non-guided transmission channels, mainly free space. Electromagnetic energy is radiated out by a transmitter antenna which is later received by a receiver antenna placed at a certain distance. There are five possible schemes for the transmission-reception of such energy:

- Simple: for uni-directional point-to-point communication
- Half-duplex: for bi-directional communication with sequential transmission and reception
- Full-duplex: for bi-directional communication with continuous transmission and reception
- Directional: the energy is focused into a beam that is emitted in a certain direction that the receiver must be aligned to.
- Omni-directional: the energy is transmitted in all directions so that multiple antennas can receive it. In the case of high frequency signals transmission, a directional communication is essential to mitigate the efficiency loss occurred when energy is emitted in a direction which is not received by any device.

Table 2.3 shows the radio-frequency bands assigned for civil and military applications. The most frequently used bands in UAS applications are marked in bold:

Table 2.3 Radio frequency bands for UAS communication links

Civil Bands		Radar and Military Bands		Satellite Bands	
1-10KHz	VLF	**1-2GHz**	**L Band**	**1700-3000MHz**	**S Band**
10-100KHz	LF	2-4GHz	S Band	**3700-4200MHz**	**C Band**
100-1000KHz	MF	4-8GHz	C Band	**10.9-11.75GHz**	**Ku1 Band**
1-10MHz	HF	8-12GHz	X Band	11.75-12.5GHz	Ku2 Band
10-100MHz	**VHF**	12-18GHz	Ku Band	12.5-12.75GHz	Ku3 Band
100-1000MHz	**UHF**	18-27GHz	K Band	18-20GHz	K Band
1-10GHz	SHF	27-40GHz	Ka Band		
10-100GHz	EHF	40-75GHz	V Band		
		75-110GHz	W Band		

According to an study carried out by LM Corporation in 2005 [52], the most frequently used frequency bands for the telemetry and tele-command links are the microwave band C and UHF. This study analysed the communication links of more than 40 different UAS in the global market (both civil and military) and its results are shown in Table 2.4.

Table 2.4 Most commonly used frequency bands for UAS telecommand and telemetry links

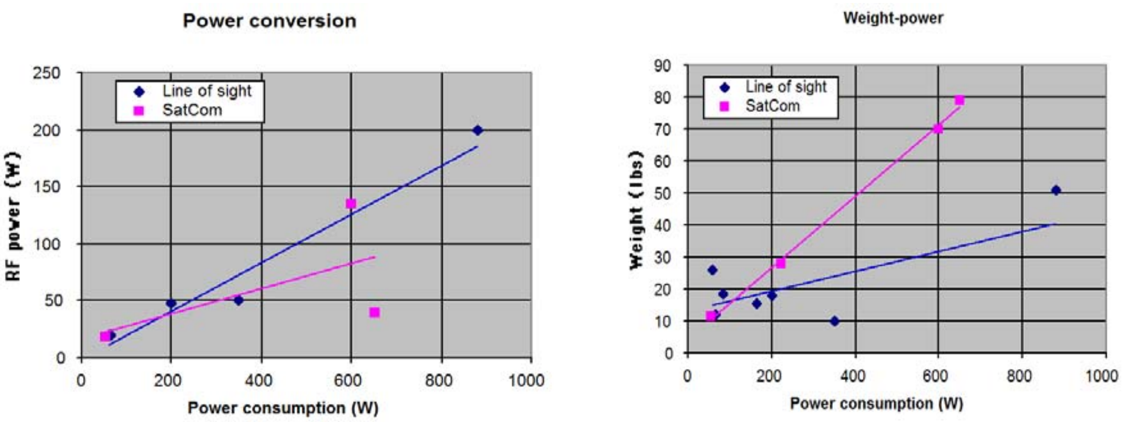
Tele-comand		Telemetry	
UHF	34%	UHF	26%
C Band	21%	C Band	23%
Ku Band	15%	L Band	19%
VHF	13%	Ku Band	17%
S Band	11%	S Band	13%
L Band	06%	VHF	00%

Usually, **satellite** communication links in UAS are used either in LOS (for military applications) or in BLOS mode. The most common frequency bands for this type of links are:

- Ku band: this band has been historically used for high speed links. Due to its short wavelengths and high frequency, this band suffers from more propagation losses. Yet it is also able to trespass most obstacles thus conveying great deals of data.
- K band: possesses a large frequency range which conveys large amounts of data. As a main drawback it should be mentioned that it requires powerful transmitters and it is sensitive to environmental interferences.
- S, L bands: they do not allow data links with transmission speeds above 500 kbps. Their large wavelength signals are able to penetrate into terrestrial infrastructures and the transmitter require less power than in K band.
- C band: it requires a relatively large transmission and reception antenna.
- X band: reserved for military use.

The most typical commercial satellites used for UAS BLOS satellite links are: Inmarsat, Iridium, Globalstar and Intelsat.

In general, as depicted in Figure 2-18, if the transmission rate and bandwidth increase the transmission power and the weight and dimensions of the transmitter-receiver and their antennas increase accordingly. This factor plays an important role since it has a major impact on the selected platform (Section 2.3.2).



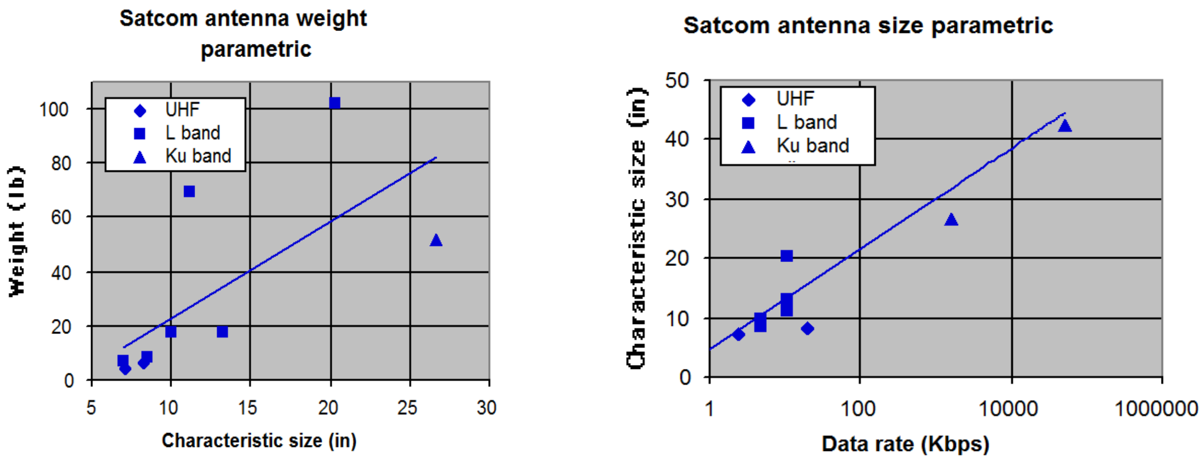


Figure 2-18 Satellite Communication Characteristics [52]

Apart from the technical requirements that can affect the design of the communications system, there are other parameters related to RF satellite communication links that have to be taken into account such as: coverage, deployment cost, complexity, quality of service (QoS), vulnerability, jamming, transmission delays, etc.

End-to-end transmissions for such long distances are also influenced by many environmental factors like atmospheric humidity, solar wind, sun light (or absence of light). The absorption of signal energy from the atmosphere generates a loss of power that attenuates considerably the received signals in satellite-based communication links. The effects of this absorption increase with frequency so a high frequency band (like UHF) will experience lower attenuation than a lower frequency band (VHF).

Terrestrial RF links between UAS usually employ **UHF** and **VHF** frequency bands for telemetry and telecommand links. The UHF band occupies an electromagnetic spectrum range spanning from 100MHz to 1GHz whereas the VHF band ranges from 10MHz to 100MHz. The main advantage of VHF is its shorter wavelength (higher frequency) that allows the implementation of smaller transmission and reception equipment. Table 2.5 shows a comparison between both UHF and VHF frequency bands.

Table 2.5 UHF and VHF comparison

Characteristics	UHF	VHF
Frequencies	100MHz to 1GHz	10MHz to 100MHz
ITU Band	9	8
Wavelength	10 m – 1 m	100 m – 10 m
Applications	- TV - Mobile Telephone - Military Communications	- TV - Amateur Radio

Wireless Fidelity (Wi-Fi) systems are defined according to the IEEE 802.11 standard. It describes the network characteristics for a Wireless Local Area Network

(WLAN). This standard offers transmission rates of 11 to 54 Mbps for short ranges (300m). Its working frequencies are: 2.4 GHz and 5GHz. The 802.11 standard establishes the low-layer level parameters in the Open System Interconnection (OSI) model:

- Physical Layer: defines the radio waves modulation and the signalling characteristics for data transmissions.
- Link Layer: defines the interface between the equipment bus and the physical layer as well as the communication rules for each network station. It can be further divided into the Link Layer Control (LLC) and the Medium Access Control (MAC).

The basic standard has been modified to optimize the used bandwidth and more specific standards have been created such as: 802.11a, 802.11b and 802.11g.

Currently, the market offers interesting commercial off-the-shelf (COTS) solutions that can be easily mounted on a UAV platform, offering quick and reliable RF links for many practical operations with acceptable data rates.

Wideband Interoperability for Microwave Access (WIMAX) systems implement the IEEE 802.16 standard to offer high bit rate and long range transmissions for WLAN communications. The service is provided either by big sector antennas or by adaptive antennas and flexible modulations which allow a variation in the bandwidth according to the distance to the transmitting source.

The WiMAX technology mitigates (or even solves) some of the most common drawbacks found in NLOS (No-LOS) and BLOS transmissions by means of the:

- Implementation of multi-carrier modulations like Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA). This modulation schemes (the same as modern Wi-Fi scheme) employs a number of frequency sub-carriers (256 and 2024 respectively) which are orthogonally spaced in frequency so that no Inter-Channel Interference (ICI) occurs. This modulation is quite robust against narrow-band interference and selective fading that can occur regularly in UAS mission.
- Incorporates support for smart antennas that improve the efficiency and coverage.
- Includes adaptive modulation mechanisms by means of which a base station and an end user establish communication using the best possible modulation scheme. The available modulations for WiMAX systems are: QPSK, 16-QAM and 64-QAM.
- Supports Frequency Division Duplex (FDD) and Time Division Duplex (TDD) to allow the interoperability with cellular networks and other wireless systems.
- Supports hundredths of end users per channel with an acceptable bandwidth and it is adequate both for continuous traffic and data bursts. Moreover, it supports multiple simultaneous services with Quality Of Service (QoS), thus resulting a suitable solution for Voice Over IP (VoIP) and multimedia data exchanges.
- As indicated in the 802.16 standard, inherent privacy and cryptography measures are included in the WiMAX protocols.
- It operates both in licensed and non-licensed frequency bands.

- It supports transmission rates up to 75 Mbps and its working frequency ranges and more detailed performance features are shown in Table 2.6

Table 2.6 Summary of WiMAX and Wi-Fi communication features

	802.16	802.16a	802.16e
Spectrum	10 - 66GHz	< 11GHz	< 6GHz
Operation	LOS only	NLOS	NLOS
Transmission Rate	32-134Mbps	Up to 75Mbps	Up to 15Mbps
Channels	28MHz	20MHz	5MHz
Modulation	QPSK, 16QAM and 64QAM	OFDM 256 sub-carriers QPSK, 16QAM, 64QAM	OFDM 256 sub-carriers QPSK, 16QAM, 64QAM
Mobility	Fixed system	Fixed System	Pedestrian Mobility
Bandwidth	20, 25 and 28MHz	1,25 to 20MHz	1,25 to 20MHz
Typical Cell Radius	2 - 5km	5 - 10km	2 - 5km

The following table offers a comparison of the two introduced standards (802.11 and 802.16) that might be useful for the design of the telemetry and tele-command links in the application considered in this work.

Table 2.7 Comparative Analysis of WiMAX and Wi-Fi standards

	802.11	802.16
Range	Optimized for radii of 100m	Optimized for cell sizes from 7 to 10Km Up to 50km
Coverage	Optimized for indoor environments	Optimized for outdoor environments
Scalability	Per-channel bandwidth of 20MHz (fixed)	Flexible bandwidth from 1.5MHz a 20MHz
Data rate	2.7bps/Hz up to 54Mbps - 20MHz	3.8bps/Hz up to 75Mbps - 20MHz. 5bps/Hz up to 100Mbps - 20MHz
QoS	Does not support QoS	Supports QoS for voice and video

2.4.2. Free Space Optic Communications

Radio frequency signals are the most typical technology employed traditionally for UAS communication links. However, there are a number of limitations that anticipate that presumably, a technological evolution will be necessary in the forthcoming years to cope with the growing demand of enhanced communication capabilities. The most remarkable limitations of RF communication systems in UAS missions are [53], [54]:

- **High relative speed** of vehicles: UAVs can reach high velocities (typically hundredths of km/h) relative to the ground (or to other UAVs) that may degrade the communication link performance. Such a high speed may cause a reduction of the coherency time and a spread of the frequency range due to the Doppler effect. This fact can be critical in the case OFDM transmissions since the orthogonality between sub-carriers would be lost, thus worsening the performance of the system.
- **Spectrum Unavailability**: currently, spectrum saturation is one of the most critical issues for the design of any communication system. Free Space Optics

(FSO) systems usually operate in the near infra-red (NIR) frequency band where a licensed use of the spectrum is not necessary.

- **Limited Transmission Rate**: it is especially critical in communications within a swarm of UAS. In this case, it is required a real-time exchange of large amounts of data (i.e. imagery or video measured by the payload cameras) among the members of the team in a short time.
- **Security**: it is necessary to implement information encryption mechanisms to prevent undesired agents to have access to private and confidential information or to replace the actual entity. Even if such mechanisms are implemented, there is always a risk of intrusion in RF-based systems that should not be ignored.
- **Interferences**: any RF channel can be affected by external interferences (signals emitted from a transmitter within the same frequency band) or by electromagnetic interference (EMI) generated by internal electronic devices.

These limitations can be overcome to a large extent employing FSO systems. Currently, low-cost FSO systems offer high transmission rates (up to 2.5 Gbps), interference immunity and inherent protection against external intrusions or jamming. An enemy agent would not be able to interrupt the data flow without being detected given that it would imply interrupting the light beam to access such data.

The main drawbacks of this technology are: the necessity of permanent LOS, atmospheric losses (especially clouds and fog), and geometric losses due to beam divergences. Altogether, it requires that the requirements of the three-fold Position-Acquisition-Tracking (PAT) grow dramatically with the length of the communication link. Consequently, FSO-based solutions for inter-vehicular communications between UAS are mainly conceived for short-distance links (up to 1 km). Precisely, for this reason, it is an interesting alternative for UAV-to-UAV swarm communications.

A possible solution provided for the permanent LOS maintenance is the use of high-speed gimbals. However, these devices are usually high-cost solutions and might be prohibitive for some applications. A less costly alternative is the use of omni-directional spherical emitters that radiate light beams in multiple directions. By means of these on-board devices, it will be possible to establish UAV-to-UAV communications from different angles (which would also favour the implementation of a UAS network). Some studies highlight the scalable nature of FSO systems and their suitability of ad-hoc UAS networks [55].

Figure 2-19 Omni-directional spherical transmitters for optic UAV-to-UAV communications

2.4.3. Comparative Analysis

Table 2.8 summarizes a comparison between RF and FSO technologies that might guide the system designers throughout the design process by stressing the advantages and disadvantages of both systems:

Table 2.8 Comparative summary of RF vs. Optical links for inter-vehicular communications.

RF Link	Optical Link
Consolidated technology. Widely tested and validated.	Non-consolidated technology. Still in research phase
Security issues. Vulnerable to Interceptions and Replacements.	Reliable and Safe. Intrusions are easily detected
It can be affected by interferences (other wireless systems, EMI, etc.)	Not affected by interferences from other systems
Saturated Spectrum	Available Spectrum
Not affected by meteorology	Strongly limited by meteorology
Doppler effect because of UAV high relative speed	Not affected by UAV high relative speed.
Omni-directional	Directional (require permanent LOS)
Low scalability in ad-hoc networks	Good scalability

Chapter 3

AERIAL NETWORK

3. Aerial Network

3.1. Rationale

This work proposes the implementation of a mobile wireless network to manage the exchange of information among all UAS integrating the team. This modification gives rise to a new architecture for the flight segment that accommodates the new network functionalities. To that end, this work proposed a new flight segment UAS architecture based upon an evolution of the UAS control architecture proposed by NATO in [28]. Such architecture is mainly oriented to single UAV operations and the operator interacts directly with the common Unit Control System (UCS) to manage any UAV involved in the mission. The UCS communicates with each UAS via a Data Link Interface (DLI). Then transmission messages are adapted to the aircraft-specific protocol and format by the Vehicle Specific Module (VSM), thus accommodating heterogeneous UAVs scenarios..

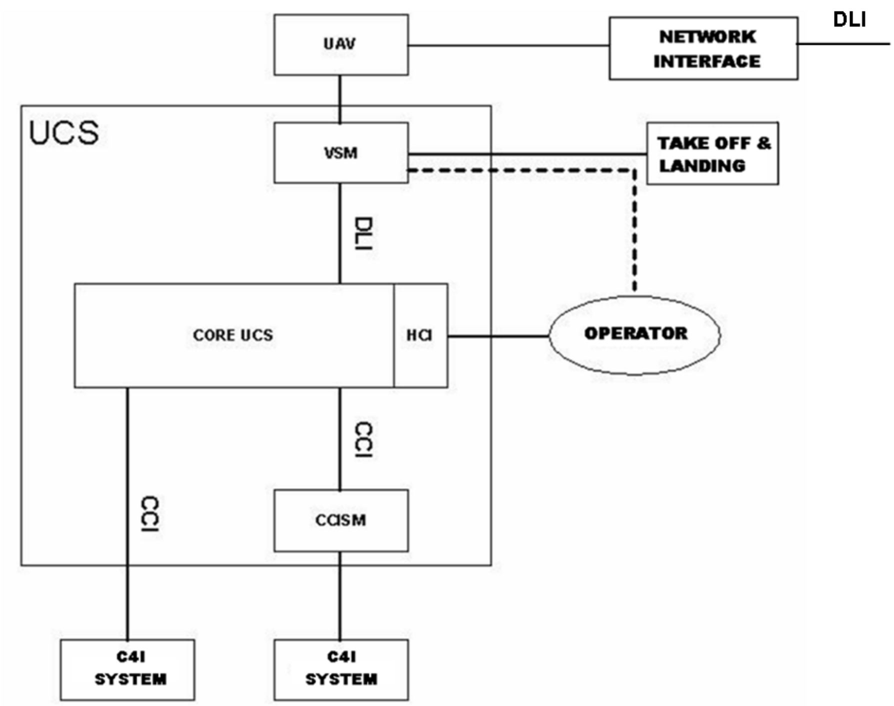


Figure 3-20 Flight segment architecture extended from [28]

An additional communication module has been added to the UCS as a Network Interface (NI) that implements the inter-vehicular communication link as depicted in

Figure 3-20. The aim of this new module is to provide an alternative communication link that allows a decentralization of the UAV control in the network and a release of the UCS from part of its workload. Usually, the information exchanged between UAVs in the team consists of data measured by the onboard sensors, and commands or other information sent from the mission control segment to be executed in a coordinated way [56].

Current state-of-the-art technologies make it possible to implement low-cost, small, high-bandwidth and short-range communication links [57]. An approach based on WLAN systems has been systematically followed as an optimum solution for UAS communication. In particular, WLAN, Wireless MAN and HyperLAN II standards have been used yielding successfully results. The main reason behind the selection of this alternative is the great and well-known performance obtained with such systems since their appearance in the 70's. WLAN-based systems are able to cope with high data rates providing a low Bit Error Rate (BER) and an excellent spectral efficiency [58], [59].

Nevertheless, this kind of network requires an infrastructure of fixed base stations to operate. In the operational scenarios contemplated in this work, it will be assumed that such infrastructures will not necessarily be available. This hypothesis guarantees the versatility and efficiency of the network and its operation in any challenged scenario.

Furthermore, the characteristics of the communication links in an ad-hoc network of UAVs are significantly different to those of the conventional WLAN links. Commonly, one communication terminals in a wireless network remain still whereas the other terminal might move at speeds of up to 150 km/h. On the contrary, two UAVs with heterogeneous capabilities may experience much higher relative speeds (up to 1000 km/h! [58]). Some studies show the negative impact on a typical wireless modulation caused by such effects [58].

- Reduction of coherence time
- Intensification of the Doppler effect and multi-path propagation
- Lost of orthogonality between sub-carriers (in the case of multi-carrier systems) giving rise to ICI.

Finally, the topology of an ad-hoc network needs a high degree of flexibility and dynamic adaptation since it can vary permanently due to the relative movement of the UAVs.

Therefore, it is necessary to develop a flexible wireless network applicable to a heterogeneous UAS team (or fleet) that does not require any infrastructure to operate. This kind of infrastructure-less network oriented to collaboration is known as Mobile Ad-hoc Networks (MANET) [60]. MANETs are self-organized networks where the different wireless links (nodes) cooperate to provide network connectivity.

In MANETS, every node acts as a communication repeater (or relay), forwarding information to the destination node. It is foreseen that during the next years, these networks will be extensively used in civil and military applications involving communication equipment for collaborative missions [61], [62], [56], [58], [59].

3.2. Topology

There are several topologies that model the geographical distribution of a UAV team. In the scope of this work, such topologies will evolve dynamically depending on the mission requirements. According to the operational conditions the topology will be stable (i.e. formation flight) or totally varying.

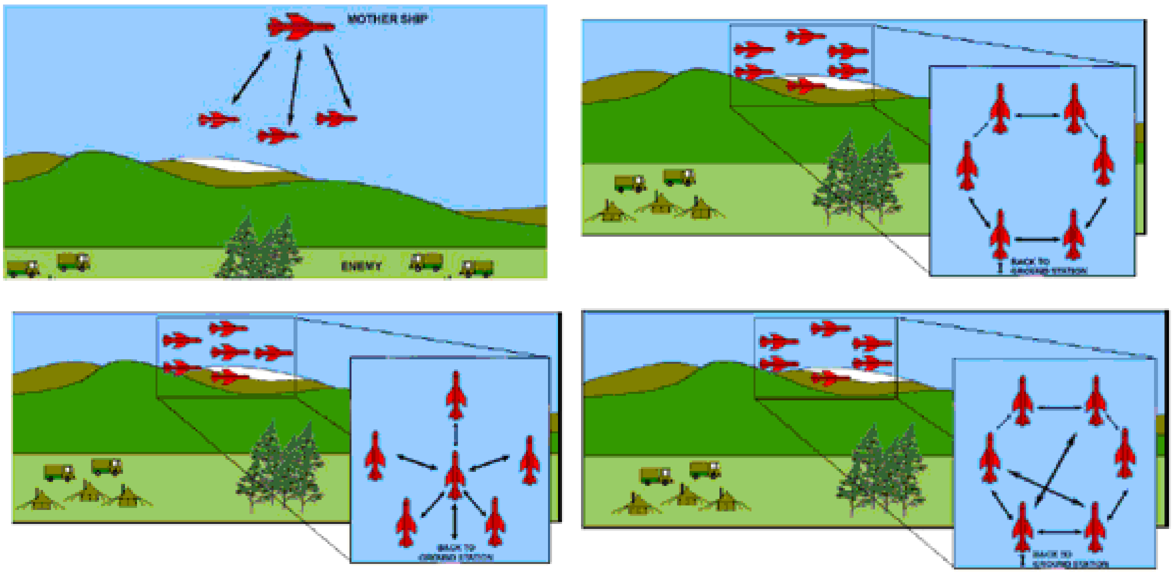


Figure 3-21 Possible network topologies for heterogeneous UAV teams

The most common topologies (Figure 3-21), an assessment of their advantages and disadvantages and the most representative use cases are described hereunder [53], [54], [63]:

- **Tree topology** (upper left hand corner of Figure 3-21): nodes only establish vertical communications with their upper or lower hierarchical level. Tree topology is especially suitable for supervision and control tasks where a UAS with a greater level of autonomy can be able to command a sub-group of vehicles with lower autonomy capabilities (i.e. a homogeneous secondary team flying in formation).
- **Ring topology** (upper right hand corner of Figure 3-21): each UAS is able to communicate only with adjacent UAVs placed within the communications range. If the receiver UAV is the destination node of the information, then it is processed. If not, the information is forwarded to the next node in the chain that performs the same checking. This operation is repeated until the destination node is reached. This topology is applicable in cases of short-range UAV since communications are restricted to neighbour (and thus closer) nodes. The main drawback of this topology is the accumulation of delays in the circulation of the information along the ring. The analysed studies recommend the use of bi-directional redundant links in this kind of topology.

This will allow changing the direction of the circulation in case of link failure (counter-clockwise vs. clock-wise).

- **Star topology** (lower left hand corner of Figure 3-21): the central vehicle acts as a Multi-point Unit (MU) that receives information from the peripheral vehicles. The main advantage of this centralized topology is a shorter inter-vehicular distance since communications are basically single-hop links, thus the required range is reduced. However, star topologies have an inherent risk of link failure on the MU that would eventually turn into a total network failure.
- **Mesh topology** (upper right hand corner of Figure 3-21): unlike the previous cases, this category encloses all unstructured topologies that have a generic arrangement pattern. In a mesh network, a node can establish a communication link with any other node in the network. The number of interconnections will be determined to a great extent by the degree of redundancy in the network and such redundancy is tightly coupled to the robustness in the communications. An increase in the number of redundant links would improve the reliability, robustness and failure tolerance of the network but would decrease the scalability, efficiency, complexity and costs.

3.3. Mobile Ad-hoc Networks

A basic service required for every network is the ability to route messages from a source node to a destination node. In wired networks (like Internet) the routing process is carried out by means of dedicated terminals that exchange messages to build and end-to-end link path. This links remain valid as long as such links remain stable and does not change. This fact will rarely occur in MANET networks because of their node mobility, interferences and signal fading.

3.3.1. Mobility Patterns

The mobility pattern of all UAS in the team influences directly in the routing process and consequently, determines the overall performance of the aerial network. In general, the performance of the network decays as the number of nodes and their mobility increase. Both facts hinder the routing process and increase the amount of control traffic (overhead) [57], [64]. For that reason, analytically elaborated mobility patterns are often used to predict the most probable node movements and therefore assist the routing algorithms. Relying on such predictions, improbable (or impossible) node trajectories and movements are discarded reducing the routing complexity. Each mobility pattern has a different impact on the routing algorithm. Studies can be found in the literature proposing general mobility patterns customarily used for mobile networks such as random walk and random waypoint models. However, these models do not reproduce the mobility characteristics of a generic collaborative UAS team so they are not suitable for this work [65]. There is another category of mobility patterns known as Mobility Vector Models (MVM) that are perfectly applicable to heterogeneous UAS teams. These MVM models are based on the estimation of the mobility vector (position, speed and acceleration) for each agent [66]. The most significant examples are:

- **Gravitational Model**: nodes tend to move towards the signal source to achieve an optimum reception. In order to reproduce this behaviour, the model assigns a potential force to each node that can be positive (repulsion) or negative (attraction).

- **Dependent Localization Model**: this model represents collective and homogeneous mobility patterns (i.e. automobiles in a highway)
- **Target Model**: nodes move towards a target (mission goal). Knowing the position of the target and the dynamics of the vehicles allows predicting the position of the nodes.
- **Group Movement Model**: this model is applicable to those sub-groups of an ad-hoc network that move jointly (i.e. swarms). A good knowledge of the formation maintenance algorithm can be helpful not only to determine the entire group movement but also the individual deviations with respect to the planned trajectory.

3.3.2. Routing

Given the limitations in the available power and spectrum, a high efficiency of the routing protocol is essential for an efficient network performance. That implies a low-level of control traffic generated. In a MANET, each node must act as a router. Unlike traditional static networks, the assignment of IP addresses is a difficult task since they should indicate the position of the node. Given the mobility of the nodes and the variability of the network topology, each MANET node should register periodically all possible routes in the network. These constraints would increase the complexity of the network and decrease its scalability. Therefore, alternative routing schemes are necessary in MANETs that can cope with high mobility dynamics and topology variations without penalizing the scalability and the efficiency,

In general, routing protocols are classified in:

- **Proactive**: all the route tables between nodes are periodically calculated (and even exchanged) regardless the traffic demands in the network. The most remarkable proactive routing protocols are: Optimized Link-State Route (OLSR) [67], Topology dissemination Based on Reverse path Forwarding (TBRF) [68] and Destination Sequenced Distance Vector (DSDV) [69].
  Proactive protocols are an efficient routing solution in small and low-mobility networks given the amount of resources used to permanently calculate and transmit updated routes. Hence, these protocols are strongly conditioned by the number of nodes in the network. However, their performance improves (even in large networks) if the traffic load is big or the number of interconnections (mesh) is high. In these cases, an upgraded technology is necessary to be able to manage the large amounts of traffic supported by the network.

- **Reactive**: the routing tables are only computed on traffic demand when they are really necessary. The most popular reactive protocols are: Ad-hoc On-demand Distance Vector (AODV) [70], Optimized Link State Routing (OLSR) [67] and el Dynamic Source Routing (DSR) [71]. Reactive protocols show a better performance than proactive protocols in terms of scalability and data management. Hence, they are a good choice for large networks with low traffic loads and few topology changes. Similarly, as the mobility of the networks increases, the discovery of new routes becomes too frequent and the overall efficiency of the protocol diminishes. Besides, reactive protocols experience higher initial delays (latency) since the route must be calculated before the information is sent.

In conclusion, as the size of the network increases and it becomes more heterogeneous, reactive routing schemes are the most suitable approach. However, if the traffic is too intense and a greater level of interconnections is required, a proactive routing approach would be the reasonable alternative.

A midway solution for those protocol categories are the so-called **hybrid protocols.** They constitute an intermediate solution to the previously presented schemes and combine features from both proactive and reactive approaches. The most relevant algorithms in this category are the Zone Routing Protocol (ZRP) [72] and the Hybrid Wireless Mesh Protocol (HWMP) [73].

In spite of their drawbacks, MANET routing protocols can be an interesting routing alternative for situations of link failure or frequent topology change since the provide a new set of routes to reach the destination node or at least a set of possible nodes for the next hop.

There are alternative classifications for MANET routing protocols according to other factors like:

- Node geographical distribution_
  - Topological Algorithms: they constitute a network perspective based on how nodes can communicate between each other.
  - Geographical Algorithms: the routing information is based on the geographical position of the nodes.
- Last packet destination
  - By source: the whole route that must be followed by a packet is calculated at the source node and is codified in the message somehow.
  - By hop: the route is calculated at each node as the message progresses through the network.

An especial case of MANET protocols is the Landmark protocol. Due to its characteristics, this protocol is especially suitable for aerial networks like the ones set out in this work. The main quality of this protocol is the aggregation of all vehicles with similar dynamics in a sub-network or cluster to speed up the routing process.[61], [59]. Each cluster has a cluster leader that is in change of the coordination with other clusters and distributing the information within its own cluster [74]. This layout could easily correspond to groups of homogeneous UAVs that operate at the same hierarchical level along with more autonomous UAVs (cluster leaders) that would operate at a higher level in the mission hierarchy. Therefore, Landmark protocol is an interesting alternative that should be taken into account in posterior phases of the project.

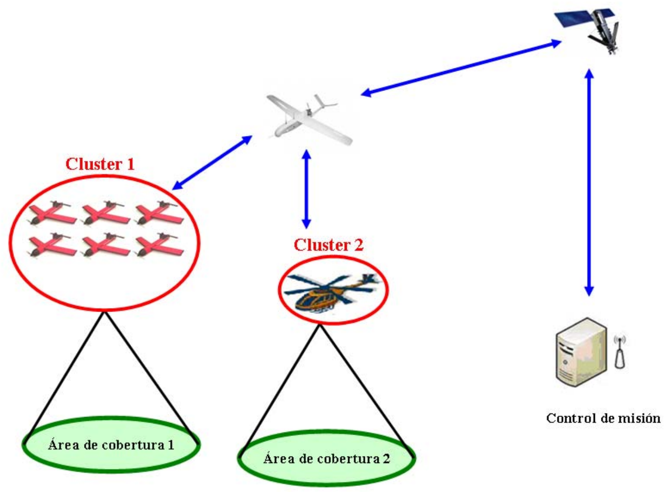


Figure 3-22 MANET Routing protocols might benefit from UAV grouping

The main inconvenient of MANET routing algorithms proposed so far is that they have been designed for contexts where there will always be a possible route that can be found to the destination node. There are some likely situations that may occur in the scope of this work that would lead to errors in most MANET routing protocols. For example, a temporary link loss due to a UAS that moves away from its neighbouring UAS. This will prompt a failure in the route discovery algorithms since no route can be found to the deviated UAS that has gone out of reach. Some intelligent mechanisms have to be implemented in these situations if transmission continuity and integrity are required so that no information is lost or corrupted. A logical solution to this problem can be achieved by the implementation of Delay and Disruption Tolerant Networks (DTN) algorithms described in the next section.

3.4. Delay and Disruption Tolerant Networks (DTN)

Delay (or Disruption) Tolerant Networks (DTN) [75] are a particular case of mobile networks that can be applied in some operational scenarios defined in this project. These networks are especially suitable for scenarios where network communications experience any of the following impairments:

- Long and variable propagation delays.
- Intermittent connectivity between nodes. Parts of the network (partitions) can be temporarily isolated from the rest of the network for long periods of time. It must be taken into account that system disconnections are usual in UAVs since communication equipments are frequently disconnected to save energy.
- High error rates and packets losses.
- Asymmetric communications between nodes. This is especially important taking into account the heterogeneous nature of the team.

DTNs are basically a solution to ensure data integrity in scenarios where traditional Internet protocols (TCP/IP suite) would fail.

3.4.1. Store and Forward Concept

In order to overcome the limitations of ad-hoc mobile networks, DTN propose a mechanism for temporary information storage in case the information can not be delivered to its destination. This storage is carried out at the node itself until a new transmission window allows the transfer of the information (forward). On the other hand, since DTNs are mobile networks, they may have a twofold function: store the information so that no data is lost and conveying it to its destination. This process is known as data ferrying and it is especially useful to inter-connect vehicles (or sub-teams) within the fleet. This case is referred as Store-Carry-Forward scheme.

3.4.2. Node Connectivity

The links (contacts) used to connect a source node A and a destination node B in a DTN can be classified according to the nature of the link or to the time when the transmission is issued.

According to the type of link:

- **Direct Contact**: the information is transmitted from node A to node B directly without third parties.
- **Relay Contact**: the link between node A and node B is not established within LOS and a third party is used as a repeater to bridge the information from source to destination.
- **Ferry Contact:** the repeater (or relay) node conveys the information from node A to a neighbouring area of node B where the information is ultimately transmitted.

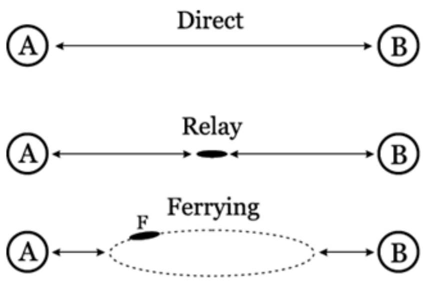


Figure 3-23 Types of node connectivity in DTNs

According to the time of transmission:

- **Opportunistic Contacts:** those contacts whose transmission takes place as long as two nodes are able to establish a direct communication link. An example of this type of contact is the download of information from a ferry node to one (or more) vehicle in the team once the ferry node flies at a sufficiently short distance.
- **Scheduled Contacts**: those whose transmission time is known beforehand and hence, it is carried out at deterministic time instants. An illustrative

example of this case is a communication link with a Low Earth Orbit (LEO) satellite at a certain time of the day which the satellite is known to fly over a control ground station.

3.4.3. DTN Protocols

The two most relevant DTN protocols found in the literature are [75]:

- **Bundle Protocol**: this protocol has many similarities with the e-mail service but is mainly oriented to be integrated into other applications rather than being an application itself. Each node stores the information when it cannot be delivered along with other relevant control messages into what is called a bundle. Information bundles are store and transported by intermediate nodes during variable periods of time and finally delivered. This protocol highlights the concept of an overlay network that can run on top of traditional Internet protocol suites or above any other customized protocol.

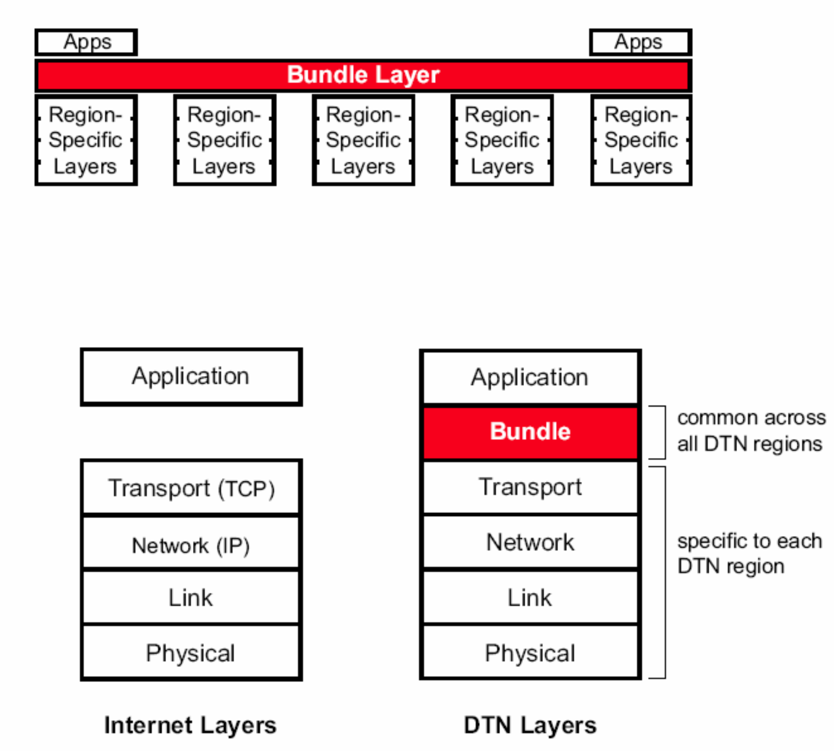


Figure 3-24 DTN protocol stack

- **Licklider** Transmission Protocol (LTP): sometimes, DTN mechanisms are required at lower network layers. For example if the propagation delay is so long that not even a single data exchange can be completed (i.e. space communications) the protocol must be able to fragment and forward parts of such information. Therefore, LTP protocol can be considered as a DTN end-to-end protocol.

3.5. Network Efficiency Metrics

There exist several metrics to evaluate the efficiency of a mobile network (MANET, DTN, etc). These metrics are necessary to analyse the validity of the design assessing the main performance parameters of the network [74], [76]. Basically, these metrics evaluate the routing efficiency the way data traffic is managed:

- **Overhead**: traffic that does not correspond to useful information. Control messages include route requests, route replies, transmission acknowledgements and error messages among others.
- **Latency**: time lasted since the packet generation until packet delivery at the destination node. Usually, the computed value is the maximum value or the mean value of the latency.
- **Throughput**: ratio between the number of successfully delivered packets and the total number of packets generated by the source node.
- **Mean point-to-point delay**: average time that a packet spends in the network before it is delivered. This delay includes the waiting times (buffering) while a route is being calculated, waiting time in the interface queue, transmission delay at physical layer and transference time.
- **Routing Load**: number of routing packets sent and delivered to its destination. Each hop is considered as a newly transmitted packet. While the previous metrics are oriented to assess the fluentness of the traffic through the network, this metrics is very useful to evaluate the efficiency of the routing protocols since it shows how much routing overhead (no real data) is being generated.
- **Link status changes:** thus metrics measures changes on the direction of the links that correspond to an alteration in the situation of the nodes due to a node movement. When a node moves away from the transmitter the line of sight is lost and it forces the protocol to find a new link (deactivation change). On the contrary, when a node comes close to a transmitter, a new channel becomes available (activation. This link alternation is considered an indicator of how the node mobility affects the network routing. Figure 3-25 shows a change rate for different mobility pattern and transmission ranges.

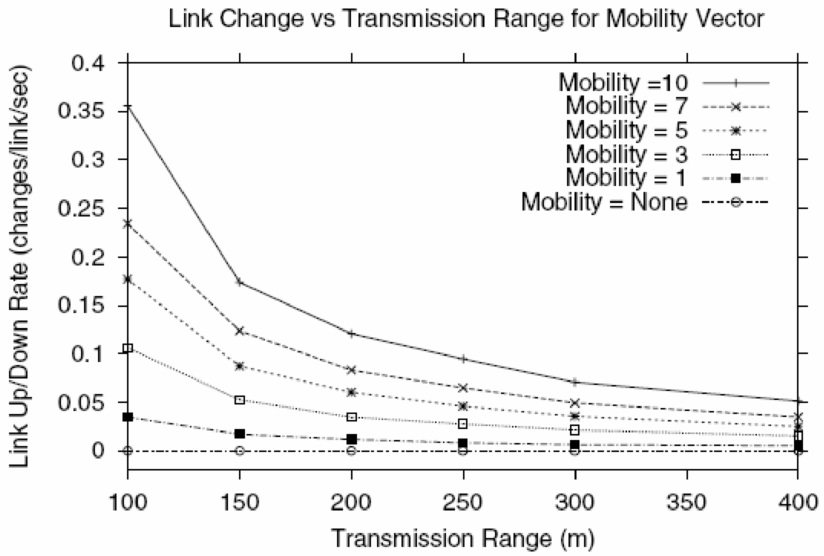


Figure 3-25 Link status changes for different mobility patterns

3.6. Reference Projects

3.6.1. Common Data Link (CDL)

The military program called Common Data Link (CDL), has the objective of achieving interoperability in the data link and to provide transparent communications among multiple heterogeneous UAS. This program establishes norms and specifications starting from the necessary requirements that are specified to allow aircraft inter-operability.

3.6.2. Airshield

Airborne Remote Sensing for Hazard Inspection by Network-Enabled Lightweight Drones (AirShield), is a research project whose objective is the study of new intelligent and autonomous systems, creation of ad-hoc networks and geographic information systems applied to UAV fleets. It is a three-year project coordinated by the Dortmund Technical University with a total of 9 German institution participants and it started in 2008.

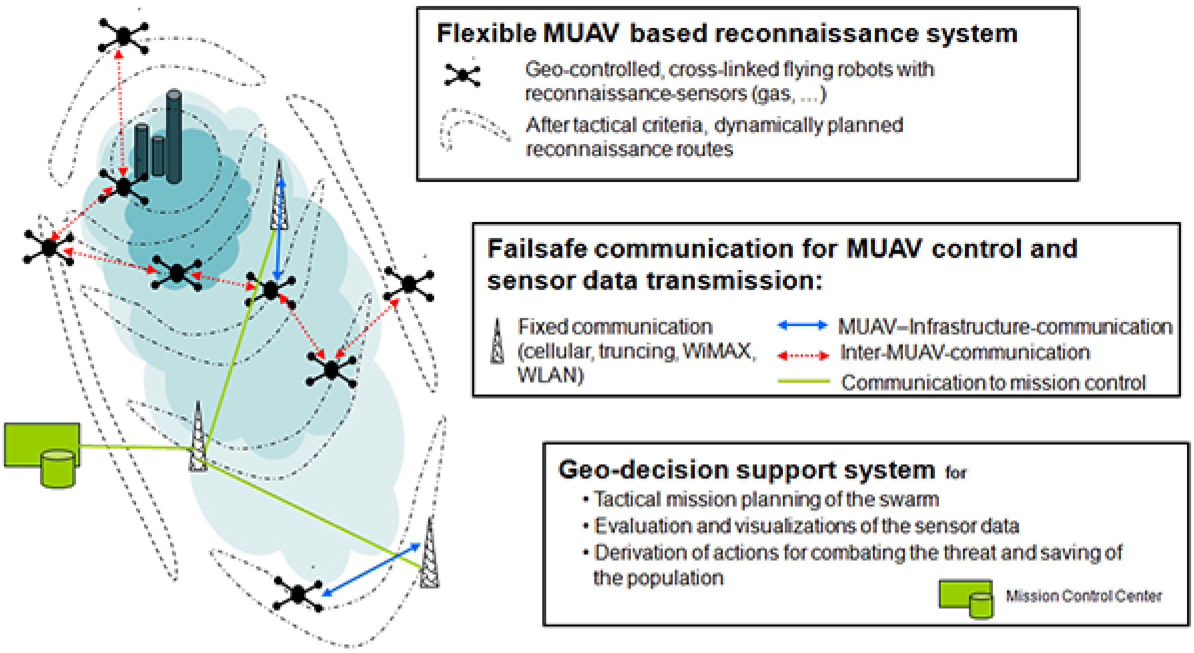


Figure 3-26 AirShield project overview

3.6.3. AUGNET

Ad-Hoc UAV-Ground NETwork (AUGNET) is an initiative from the University of Colorado that aims at solving the problem of communications in collaborative UAV teams by using Wi-FI (802.11) links. To that end, the project proposes an implementation based on a MANET that combines mobile nodes (UAV) and static terrestrial nodes. This research group uses light and low-cost COTS equipment for transmitters and receivers for an easy implementation in small UAV swarms. The project consists of several stages including intelligent network management algorithms and field tests. The most remarkable goals of the project are:

- Implement an application manage the routing process in a mobile network.
- Integration of COTS communications hardware.
- Assembly of the different electronic devices on the UAV platform.
- Field tests and demonstrations.

The interest of this project resides in the fact that it uses several of the techniques and technologies proposed in this work such as: MANETs, relay UAVs wireless COTS communication links etc.[77]

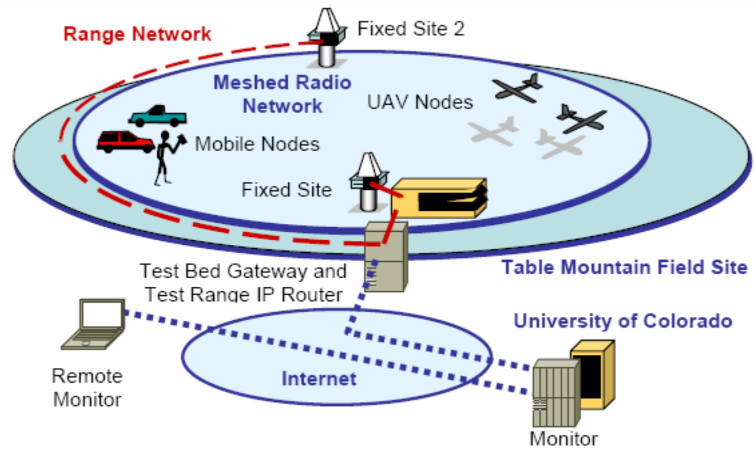


Figure 3-27 System Architecture proposed by the AUGNET initiative

3.6.4. John Hopkins University

The Applied Physics Laboratory of the John Hopkins University has studied in the last years techniques to increase the autonomy of UAS to eliminate the human factor from the vehicle operation process. This research line was initiated in 2001 and has been useful to endow UAS with control systems that are able to operate in collaborative environments at a moderate cost. The main objectives of its research activity are:

- Demonstration of multi-vehicular cooperative autonomy for UAS teams.
- Development of new architecture for single and simple vehicles.
- System integration demonstrations

Currently, the research activity of the laboratory is ongoing and preliminary flight tests have been performed for a coordinated mission for location and search tasks by means of radio beacons with the scheme depicted in Figure 3-28.

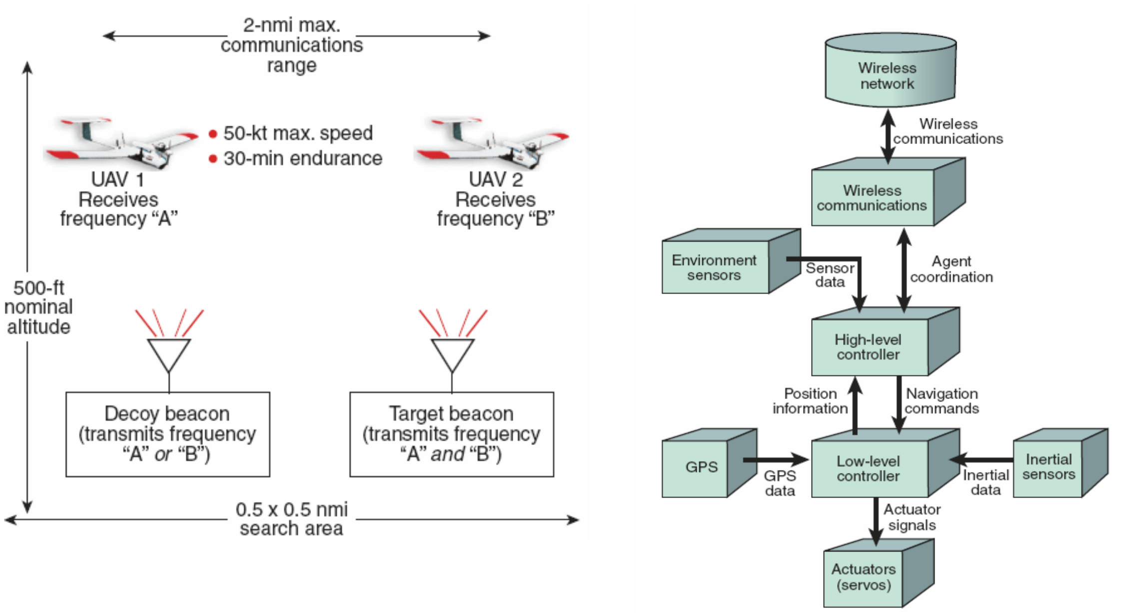


Figure 3-28 UAV team control architecture proposed by APL

Applied Physics Laboratory (APL) also employs onboard COTS products for communications offering a routing scheme with permanent LOS connectivity between nodes and a routing scheme based on message exchange between neighbour nodes.

Chapter 4

PERFORMANCE ANALYSIS

4. PERFORMANCE ANALYSIS

4.1. Introduction

The objective of this section is to describe the computer simulations carried out as a proof-of-concept for the flight segment architecture proposed for the management of heterogeneous UAS teams. This performance evaluation is mainly focused on the routing algorithms given that finding an optimum path through relay nodes becomes a crucial issue as the number of vehicles in the team increases. The literature analysed has shown that there is no de-facto standard routing protocol for MANET that can be applied in all possible scenarios. On the contrary, there are multiple research contributions with variable levels of applicability and which are in fact ad-hoc solutions for specific problems. Therefore, this performance analysis aims at figuring out the best routing scheme for any potential UAS collaborative mission.

4.2. Scenario Description

Network statistics have been calculated and analysed in the scenarios presented below for different routing protocols, traffic patterns and flight plans. In order to add more relevance to this work we have selected two complementary routing protocols: one reactive (AODV) and the other proactive (DSDV). Both protocols have a solid and stable software implementation and have been widely studied in the literature.

Two different scenarios have been considered in this work. They reproduce complementary mission profiles in terms of flight patterns for each UAV in the team. This dual approach enables an analysis based on the ability of the network to cope with the generated traffic in every type of environment. For the elaboration of this flight patterns, the mobility models introduced in Section 3.3.1 has been taken as a reference.

4.2.1. Scenario 1

The first scenario (Figure 4-29) includes two types of UAV platforms: fixed-wing and hovering aircrafts. Each type of UAV will carry out a different mission task and will follow a completely different flight pattern since its physical flight performance will be determined by the aircraft platform selected for each vehicle and its payload.

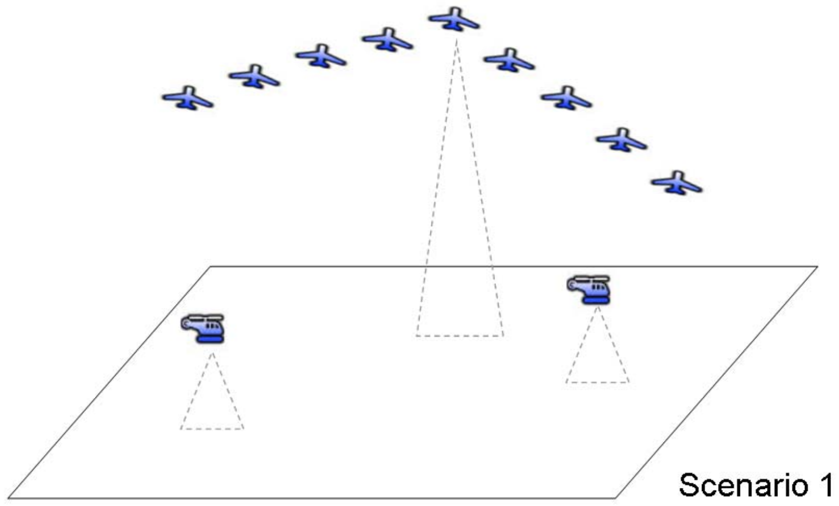


Figure 4-29 Scenario 1- Emulation of Search and Rescue operations.

The fixed-wing platform selected is the SIG Rascal 110 model aircraft depicted in Figure 4-30 [78]. This small-size aircraft is an easily configurable platform that has already been used for UAS teams forming mobile ad-hoc networks by the C3UV centre introduced in section 1.9.3. Moreover, this UAV has been successfully tested by C3UV in real UAV collaborative missions with the inclusion of off-the-shelf RF communications equipment based on the 802.11 standard.

Figure 4-30 SIG Rascal 110 UAV selected to model fixed-wing aircrafts

Fixed-wing aircrafts are assumed to fly at higher speed (25 m/s) and double altitude (200m.) than rotor aircrafts. Flight plans are intended to emulate a search and rescue mission over a bounded area. A total of nine fixed-wing aircrafts fly in V-shape formation over the available terrain repeatedly as they scan the area of interest.

On the other hand, rotor-fixed aircrafts are programmed to hover almost statically at a lower altitude to obtain high-resolution imagery or other data. The UAV platform selected for the rotor aircrafts is the Draganflyer X6 Helicopter shown in Figure 4-31

[79]. This platform has comparable dimensions to the SIG Rascal 110 platform and similar communication capabilities (802.11 links) so they can be seamlessly included to the aerial MANET simulation.

Figure 4-31 Drafanflyer X6 Helicopter UAV selected to model rotor-fixed aircrafts

Additionally, in order to test the versatility of the network when facing an unexpected contingency, one fixed-wing aircraft is forced to exit the formation and returns to base at some point of the mission. These kind of events can happen in actual missions in situations such as: the UAV requires a battery re-charge, there has been any mechanical problem or if mission control segment decides that the UAV is no longer necessary for the mission. Simulations will show whether the ad-hoc network is able to adapt to this gap created in the formation by the missing aircraft and ensure end-to-end communications among the remaining team members.

4.2.2. Scenario 2

The second scenario (Figure 4-32) includes a team of 15 homogeneous UAVs flying in pyramidal formation at constant speed (40m/s) and steady altitude (400m). This scenario aims at reproducing a perimeter surveillance mission (e.g. border surveillance). At a certain instant, one UAV experiences a trajectory deviation that takes it away from the initial flight plan. This unforeseen event may be originated by an instrument inaccuracy or external disturbances such as sudden wind gusts. The main objective of this simulation is to prove that the shifted UAV will be able to re-calculate a new route (as it is flying away from the swarm) that that would let the formation control algorithm apply the necessary corrections for a return to the swarm at its former position.

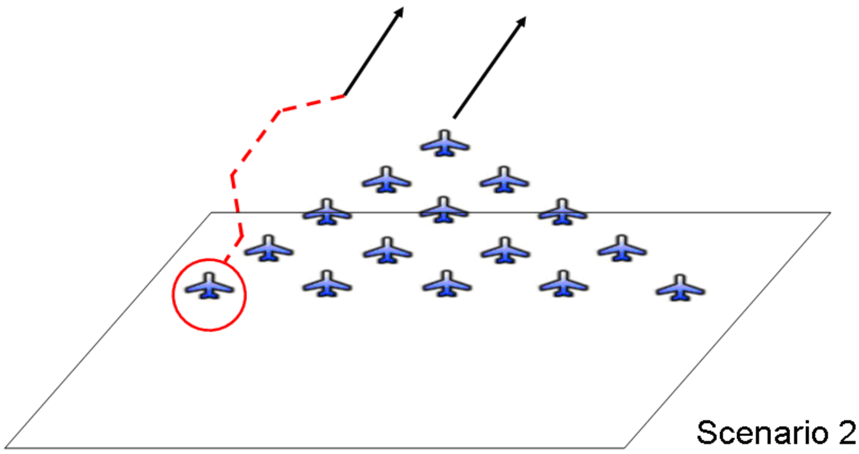


Figure 4-32. Scenario 2 – Emulation of Border Surveillance operations.

Furthermore, each protocol has been simulated for two types of traffic pattern. The first traffic mode consists of a periodic transmission of small-size information packets (100 kilobytes in intervals of 5 seconds) from a source node/UAV to a destination node/UAV. This traffic pattern aims at emulate data transfers for command and control information exchange, flight plan modifications or propagation of control segment messages. The second traffic mode corresponds to a single big file transmission (10 megabytes). This second pattern aims to reflect the exchange of large amounts of data among UAVs for coordinated processing or data aggregation. These large files may model terrain imagery or video transactions that require long transmission times and a steady link status. The total duration of all simulations is limited to 1000 seconds and the area of interest is a squared region of 3km × 3km.

In each scenario, our objective is to analyse how an aerial network could help to mitigate and/or prevent undesirable situations by providing robust data links and end-to-end connectivity.

4.3. Simulations

4.3.1. Network Simulator Tool Selection

The selection of the optimal software simulator tool for the simulation of MANET protocols was the result of a thorough review of many publications related to wireless ad-hoc network with especial focus on those works addressing routing issues and autonomous vehicles. Figure. 4-4 shows a comparative study on the different existing tools in the market for MANET simulations [80]. This study, (Figure 4-33) analysed a total of 114 full papers published in international ACM Symposium on Mobile Ad Hoc Networking and Computing (Mobi-Hoc) from 2000-2005. The study considered either open source tools (like ns2 or GloMoSim) or commercial tools (QualNet, OPNET, etc) and it highlights that ns2 has been the main software tool used by researchers up to now. What is more, other studies indicate that the average use of ns2 tool in the international research community is actually higher than 50% [81].

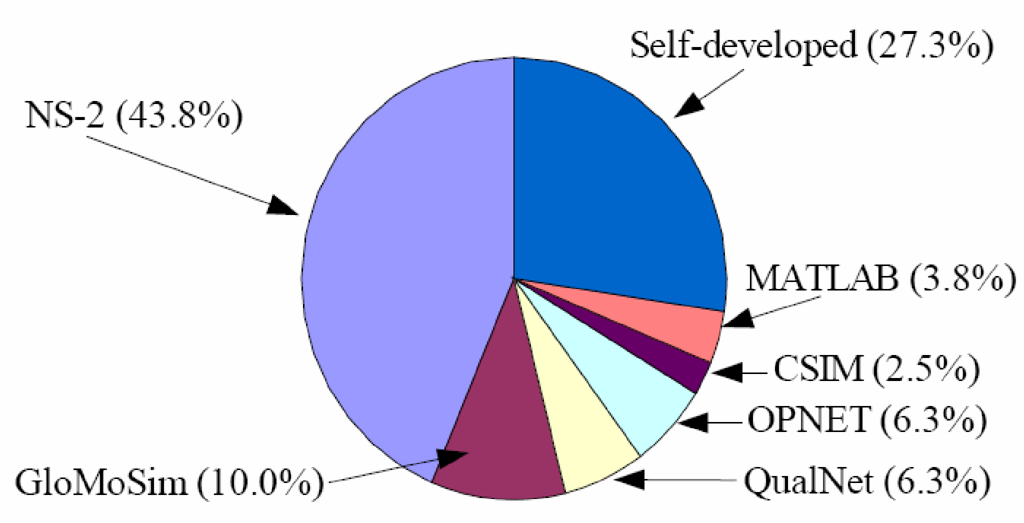


Figure 4-33 Network simulation tools commonly used for MANETs

However, the popularity of ns2 as a principal MANET tool has not been the only attribute that has been taken into account in our selection. We identified a number of characteristics of ns2 that make a suitable and attractive tool for the application described in this thesis. Table 4-1 summarizes a comparison of the most relevant features of the most used network simulation tools. It can be noticed that ns2 tool offers the highest degree of granularity (level of detail) for the simulation and besides, it is an open source tool so that no commercial license was required. Furthermore, the widespread use of ns2 ensures a sufficiently exhaustive online documentation and support material that would help us in case that any problem could arise during the simulations.

Table 4-1 Summary of the main features of MANET simulation tools

Tool	Granularity	Mobility Support	Parallelism	License	Interface
ns-2	Finest	Yes	No	Open source	C++/OTcl
GloMoSim.	Fine (Medium)	Yes	SMP/Beowulf	Academic License	Parsec C
OPNET	Fine	Yes	Yes	Commercial	C
QualNet (commercial version of GloMoSim)	Fine (High)	Yes	SMP/Beowulf	Commercial	Parsec C
OMNet++	Fine (Medium)	No	MPI/PVM	Free Academic License	C++
NAB	Fine (Medium)	Native	No	Open Source	Ocaml

Nevertheless, there are some drawbacks in the use of ns2 for our scenarios. It makes use of flat earth model in which it assumes that the environment is flat without any elevations or depressions which is not completely realistic. Likewise, even though it performs three-dimension network simulations, it does not allow vertical node movement. Therefore, all the flight plans and mobility patterns described in this work are confined into a two-dimensional space.

Therefore, analysing the advantages and disadvantages of all the alternatives, ns2 has turned out to be the most sensible choice in the scope of this thesis. Apart from its technical interest (given its efficient computation of node activity up to physical level), ns2 has been found an ideal selection because of its availability, widely use and abundant reference documentation.

4.3.2. Software Environment

As it has been introduced in the previous section, the software tool used for the core of our simulations is the open source network simulator **ns2** [82]. Ns2 is a discrete event simulator targeted at networking research that runs over Unix operating system. Ns2 provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks [83]. The simulator covers a very large number of applications, protocols, network types, network elements and traffic models. It is internally built in C++ and it provides a simulation interface through OTcl, which is an object-oriented version of Tcl. A number of mission parameters are introduced as inputs to the simulation engine by means of an OTcl script. The list of parameters introduced by the mission designer includes:

- Flight plan for each of each UAV, including the list of waypoints, cruise speeds, timestamps and all the required in-flight information.
- Traffic pattern of each UAV, including the message scheduling, network protocols, packets definition, antenna type, channel model, etc.
- Node topology and communication capabilities.

The ns2 tool has a network visualization software tool called **nam** that provides visualisation of the continuous evolution of the simulation. This tool is useful to verify the overall network performance and especially the routing algorithms evolution over time. In order to perform a comparative analysis of the network performance, we have developed a prototype tool in MATLAB for data post-processing that deals with the trace files generated by ns2, in order to extract and plot relevant network statistics used for benchmarking. Figure 4-34 shows the high-level software architecture for the simulator developed in this project.

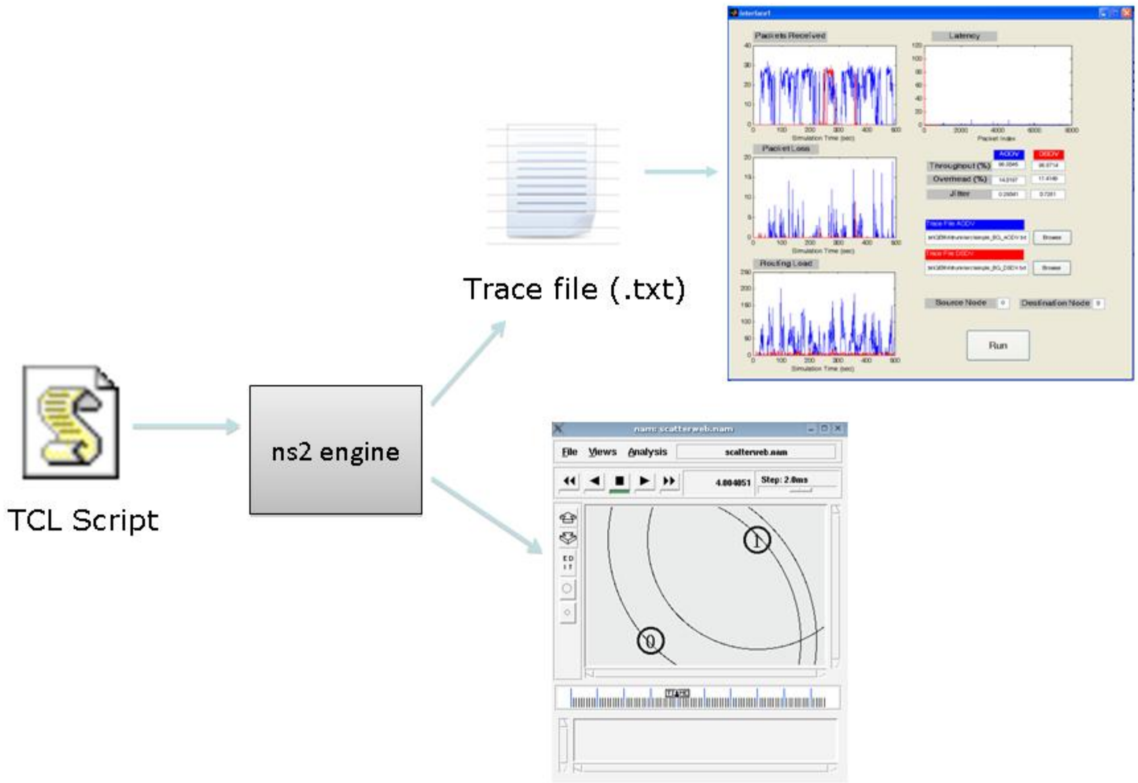


Figure 4-34 Simulation software environment

4.3.3. Simulation Procedural Description

This section describes the steps followed in the simulation of each scenario described in Section 4.2 and how all the blocks in the diagram depicted in Figure 4-34 interact. First of all, the user defines a mission scenario (node topology, node evolution, communication capabilities of each node, scheduling, etc) by writing an OTcl input script. Then, the main program (ns2 core) launches a simulation of the introduced scenario with the specified parameters. Additionally, other simulation parameters are also configured by the user before the simulation is started. Namely: channel model, propagation channel, physical and MAC layer models, queue type and length, geographic area of the simulation, routing protocol, among others. A screenshot depicting the main static configuration parameters is shown in Figure 4-35.

```
####################################
#
# Wireless Network Scenario
#
####################################


# ======================================================================
# Define options
# ======================================================================

set val(chan)        Channel/WirelessChannel
set val(prop)        Propagation/TwoRayGround
set val(netif)       Phy/WirelessPhy
set val(mac)         Mac/802_11
set val(ifq)         Queue/DropTail/PriQueue
set val(ll)          LL
set val(ant)         Antenna/OmniAntenna
set val(ifqlen)          50            ;# max packet in ifq
set val(nn)              11            ;# how many nodes are simulated
set val(nh)              2               ;#number of hovering nodes
set val(rp)              DSDV
set val(x)               3000   ;# X dimension of the topography
set val(y)               3000   ;# Y dimension of the topography
set val(stop)            1000.0          ;# total simulation time

set ns [new Simulator]

#Open the trace file
set tracefd [open GEMA_Scenario1_DSDV_longTx.tr w]
#trafficModel=1 indicates longTx mode
#trafficModel=0 indicates shortTx mode
$ns trace-all $tracefd

#Open the NAM trace file
set namtrace [open simwrls.nam w]
$ns namtrace-all-wireless $namtrace $val(x) $val(y)

set windowVsTime2 [open win.tr w]

# set up topography object
set topo       [new Topography]

$topo load_flatgrid $val(x) $val(y)
```

Figure 4-35 Static parameters configuration in an OTcl script

Once the general configuration parameters of the simulation have been defined, the OTcl script must detail the initial topology distribution, the topology evolution (flight plan of each node/UAV) and the scheduled contacts (transmission/reception events). To that end, each node that participates in a data exchange must be tagged as source (transmitter) or sink (receiver) of information. The user can also specify the parameters of the type of connection that will be established (TCP, FTP, MAC packets, etc).

The OTcl script must also include node movement and message scheduling and it has to be defined individually for each node in the network. Figure 4-36 shows a piece of OTcl code extracted from the routine that generates node mobility patterns that are compatible with OTcl format. It has been extracted from a real UAV flight plan and it models the node movement according to the waypoints specified there.

```
for {set i 0} {$i < [expr $val(nn)-$val(nh)]} {incr i} {
        $ns at [expr $timeOrigin] "$node_($i) setdest [expr $horizontalInit + $i *
$horizontalSeparation] [expr $verticalInit+$travelDistance] $speed"
}

while {$travelCounter < $totalTravels} {
        if {[expr {fmod($travelCounter,2)}] == 1 } {
                for {set i 0} {$i < [expr $val(nn)-$val(nh)]} {incr i} {
                        if {$travelCounter >= $travelFailure} {
                                #Force node failure
                                if {$i == $failedNodeIndex} {
                                        #This is the case of the failed node -> Put the
node to rest
                                        if {$stopNodeFlag == 0} {
                                                $ns at [expr $timeOrigin +
$travelCounter*$turnTime - $i*$timeSeparation] "$node_($i) setdest [expr $horizontalInit
+ $i *$horizontalSeparation] 0.1 $speed"
                                                set stopNodeFlag
1
                                        }

continue
                                }
                        }
                        #Normal movement
                        if {$i < 5} {
                                $ns at [expr $timeOrigin + $travelCounter*$turnTime - $i*
$timeSeparation] "$node_($i) setdest [expr $horizontalInit + $i*$horizontalSeparation]
0.1 $speed"
                        } else {
                                $ns at [expr $timeOrigin + $travelCounter*$turnTime -
($val(nn)-$val(nh)-$i-1)*$timeSeparation] "$node_($i) setdest [expr $horizontalInit + $i
*$horizontalSeparation] 0.1 $speed"
                        }
                }
        } else {
                for {set i 0} {$i < [expr $val(nn)-$val(nh)]} {incr i} {
```

Figure 4-36 Screenshot from the UAV mobility generation routine

Individual UAV flight plans are provided to the simulator in the form of XML files (Figure 4-37) containing all the necessary flight information. The waypoints, timestamps, cruise speeds and other flight data provided by the XML files is translated into OTcl code by a parser function and added to the input simulation script.

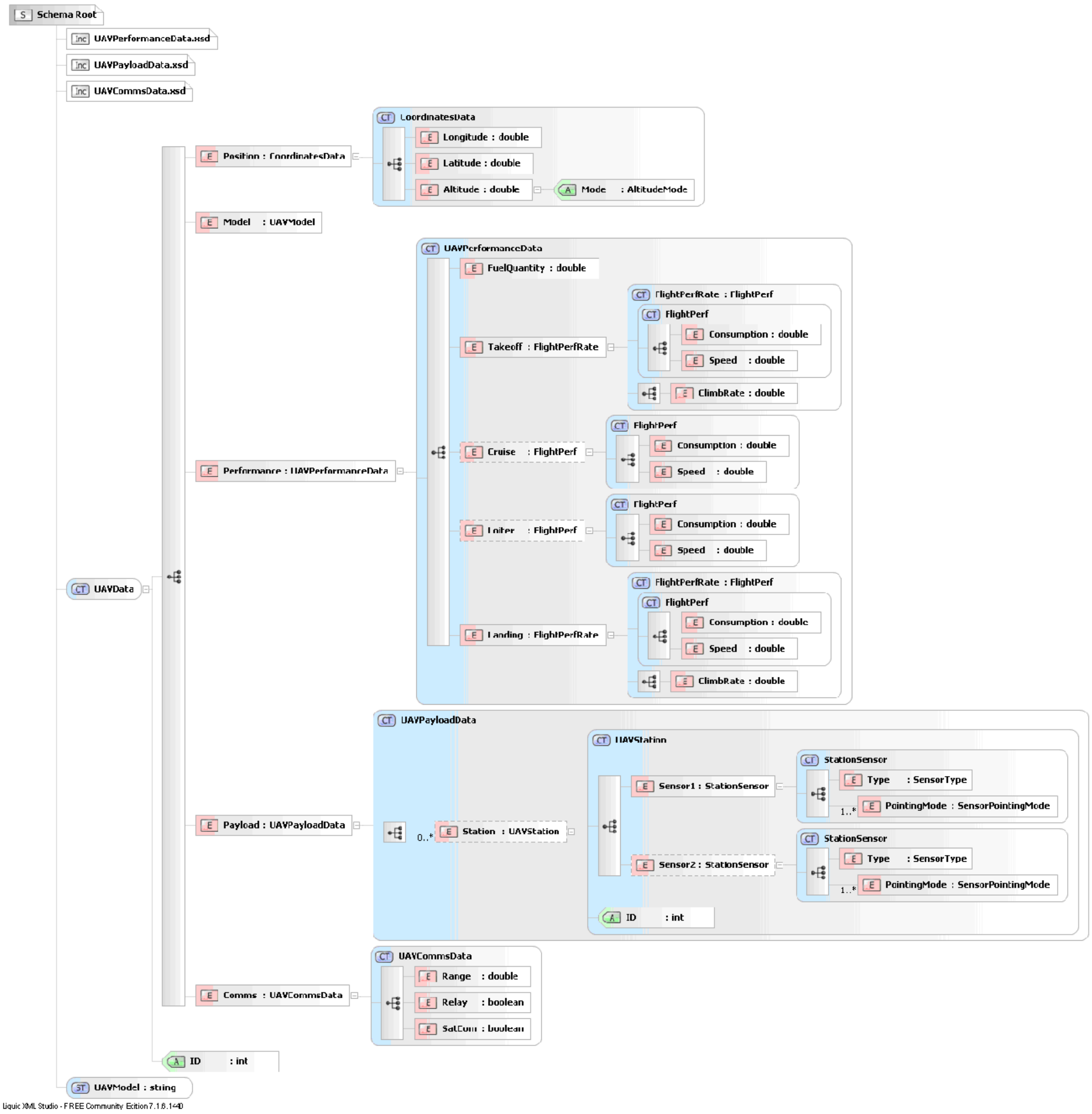


Figure 4-37 XML file containing the actual UAV flight plan

Finally, the communication parameters (file size, traffic model, routing protocol, etc) are set up and ns2 simulation engine is launched and produces an output trace file. This text file contains a log-like report detailing all the communication transactions occurred during the simulation time. The trace file register every packet sent/received by each node, the transmission and reception times with a resolution of up to 10^{-9} seconds, the network layer (OSI) which the packet corresponds to and other relevant information. Figure 4-38 depicts a sample of a piece of trace file generated by our simulator.

```
s 11.015626571 _10_ RTR  --- 0 AODV 48 [0 ffffffff 9 800] ------- [10:255 -1:255 28 0] [0x2 3 3 [8 0] [0 8]] (REQUEST
r 11.017666689 _2_ RTR  --- 0 AODV 48 [0 ffffffff 3 800] ------- [3:255 -1:255 29 0] [0x2 2 3 [8 0] [0 8]] (REQUEST)
r 11.017666689 _4_ RTR  --- 0 AODV 48 [0 ffffffff 3 800] ------- [3:255 -1:255 29 0] [0x2 2 3 [8 0] [0 8]] (REQUEST)
r 11.017666742 _9_ RTR  --- 0 AODV 48 [0 ffffffff 3 800] ------- [3:255 -1:255 29 0] [0x2 2 3 [8 0] [0 8]] (REQUEST)
r 11.017666885 _5_ RTR  --- 0 AODV 48 [0 ffffffff 3 800] ------- [3:255 -1:255 29 0] [0x2 2 3 [8 0] [0 8]] (REQUEST)
r 11.017667161 _1_ RTR  --- 0 AODV 48 [0 ffffffff 3 800] ------- [3:255 -1:255 29 0] [0x2 2 3 [8 0] [0 8]] (REQUEST)
r 11.017667272 _6_ RTR  --- 0 AODV 48 [0 ffffffff 3 800] ------- [3:255 -1:255 29 0] [0x2 2 3 [8 0] [0 8]] (REQUEST)
r 11.017667632 _0_ RTR  --- 0 AODV 48 [0 ffffffff 3 800] ------- [3:255 -1:255 29 0] [0x2 2 3 [8 0] [0 8]] (REQUEST)
r 11.017667709 _7_ RTR  --- 0 AODV 48 [0 ffffffff 3 800] ------- [3:255 -1:255 29 0] [0x2 2 3 [8 0] [0 8]] (REQUEST)
r 11.017668162 _8_ RTR  --- 0 AODV 48 [0 ffffffff 3 800] ------- [3:255 -1:255 29 0] [0x2 2 3 [8 0] [0 8]] (REQUEST)
r 11.018605743 _5_ RTR  --- 0 AODV 48 [0 ffffffff 6 800] ------- [6:255 -1:255 28 0] [0x2 3 3 [8 0] [0 8]] (REQUEST)
r 11.018605743 _7_ RTR  --- 0 AODV 48 [0 ffffffff 6 800] ------- [6:255 -1:255 28 0] [0x2 3 3 [8 0] [0 8]] (REQUEST)
r 11.018606206 _9_ RTR  --- 0 AODV 48 [0 ffffffff 6 800] ------- [6:255 -1:255 28 0] [0x2 3 3 [8 0] [0 8]] (REQUEST)
r 11.018606215 _4_ RTR  --- 0 AODV 48 [0 ffffffff 6 800] ------- [6:255 -1:255 28 0] [0x2 3 3 [8 0] [0 8]] (REQUEST)
r 11.018606215 _8_ RTR  --- 0 AODV 48 [0 ffffffff 6 800] ------- [6:255 -1:255 28 0] [0x2 3 3 [8 0] [0 8]] (REQUEST)
r 11.018606326 _3_ RTR  --- 0 AODV 48 [0 ffffffff 6 800] ------- [6:255 -1:255 28 0] [0x2 3 3 [8 0] [0 8]] (REQUEST)
r 11.018606605 _2_ RTR  --- 0 AODV 48 [0 ffffffff 6 800] ------- [6:255 -1:255 28 0] [0x2 3 3 [8 0] [0 8]] (REQUEST)
r 11.018606972 _1_ RTR  --- 0 AODV 48 [0 ffffffff 6 800] ------- [6:255 -1:255 28 0] [0x2 3 3 [8 0] [0 8]] (REQUEST)
r 11.022026803 _2_ RTR  --- 0 AODV 44 [13a 2 7 800] ------- [8:255 0:255 29 2] [0x4 2 [8 8] 10.000000] (REPLY)
f 11.022026803 _2_ RTR  --- 0 AODV 44 [13a 2 7 800] ------- [8:255 0:255 28 0] [0x4 3 [8 8] 10.000000] (REPLY)
r 11.027200403 _0_ RTR  --- 0 AODV 44 [13a 0 2 800] ------- [8:255 0:255 28 0] [0x4 3 [8 8] 10.000000] (REPLY)
s 11.027200403 _0_ RTR  --- 0 tcp 60 [0 0 0 0] ------- [0:0 8:0 30 2] [0 0] 0 0
r 11.029287232 _2_ RTR  --- 0 tcp 60 [13a 2 0 800] ------- [0:0 8:0 30 2] [0 0] 1 0
f 11.029287232 _2_ RTR  --- 0 tcp 60 [13a 2 0 800] ------- [0:0 8:0 29 7] [0 0] 1 0
r 11.031616331 _7_ RTR  --- 0 tcp 60 [13a 7 2 800] ------- [0:0 8:0 29 7] [0 0] 2 0
f 11.031616331 _7_ RTR  --- 0 tcp 60 [13a 7 2 800] ------- [0:0 8:0 28 8] [0 0] 2 0
r 11.033621745 _8_ AGT  --- 0 tcp 60 [13a 8 7 800] ------- [0:0 8:0 28 8] [0 0] 3 0
s 11.033621745 _8_ AGT  --- 2 ack 40 [0 0 0 0] ------- [8:0 0:0 32 0] [0 0] 0 0
r 11.033621745 _8_ RTR  --- 2 ack 40 [0 0 0 0] ------- [8:0 0:0 32 0] [0 0] 0 0
s 11.033621745 _8_ RTR  --- 2 ack 60 [0 0 0 0] ------- [8:0 0:0 30 7] [0 0] 0 0
r 11.035867159 _7_ RTR  --- 2 ack 60 [13a 7 8 800] ------- [8:0 0:0 30 7] [0 0] 1 0
f 11.035867159 _7_ RTR  --- 2 ack 60 [13a 7 8 800] ------- [8:0 0:0 29 2] [0 0] 1 0
s 11.037200403 _0_ RTR  --- 1 tcp 60 [0 0 0 0] ------- [0:0 8:0 30 2] [0 0] 0 0
r 11.037876258 _2_ RTR  --- 2 ack 60 [13a 2 7 800] ------- [8:0 0:0 29 2] [0 0] 2 0
f 11.037876258 _2_ RTR  --- 2 ack 60 [13a 2 7 800] ------- [8:0 0:0 28 0] [0 0] 2 0
r 11.040243086 _0_ AGT  --- 2 ack 60 [13a 0 2 800] ------- [8:0 0:0 28 0] [0 0] 3 0
```

Figure 4-38 Trace file generated by ns2 simulator

Along with the trace file, the ns2 visualization tool **nam**, produces a simplified animation file that allows a quick checking of the network behaviour. It illustrates the node evolution during the mission and the packet transmission as they travel from the source node to the destination node which is especially useful when analyzing routing performance. A screenshot of the animation for Scenario 1 is shown in Figure 4-39. The figure shows a single data exchange between node 0 and 10.

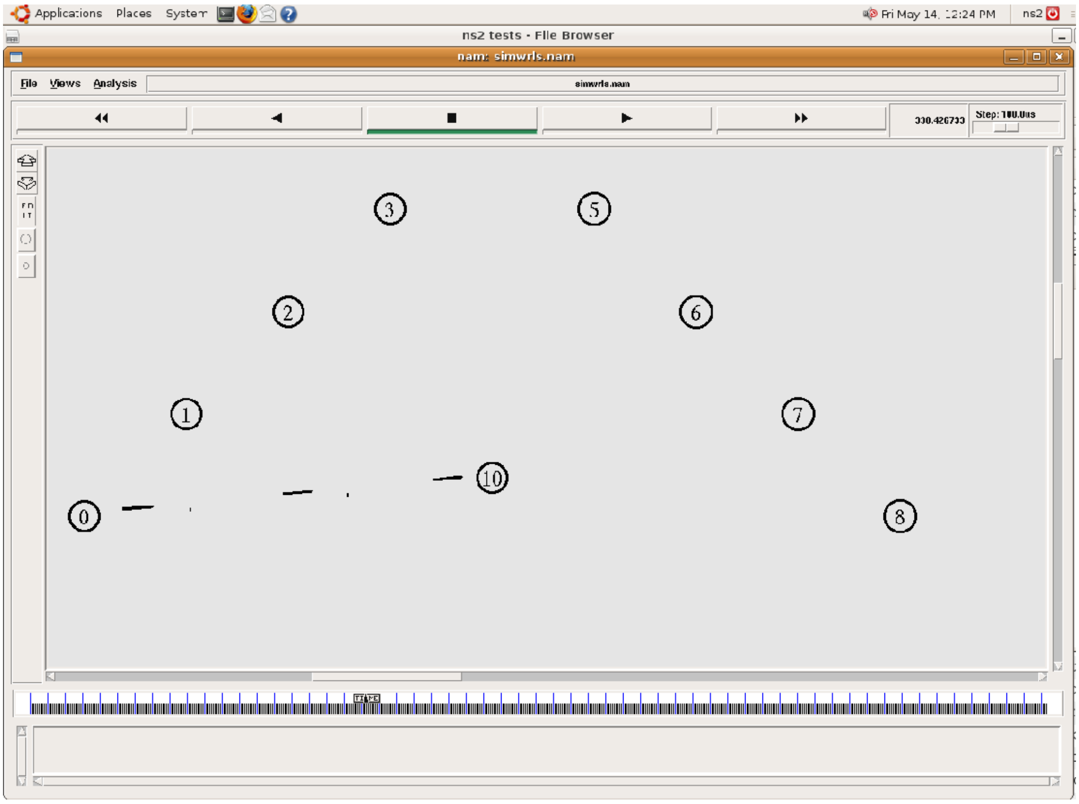


Figure 4-39 Visualization tool (nam) for network communications monitoring

4.4. Statistical Analysis

The last step required to carry out a performance analysis of the UAV MANET defined in this thesis is to process the comprehensive amount of data of the trace file generated by ns2. A MATLAB Graphic User Interface (GUI) has been developed in this thesis. This application allows the user to configure all necessary information and to easily compare the performance of both protocols. The trace files from both protocols generated by ns2 are introduced to the application along with the source and the destination node identifiers in the network. Then, the application plots the evolution of the number of packets received, packets lost, routing load and latency. Additionally, mean values of throughput, routing overhead and jitter are also computed for each protocol as illustrated in Figure 4-40.

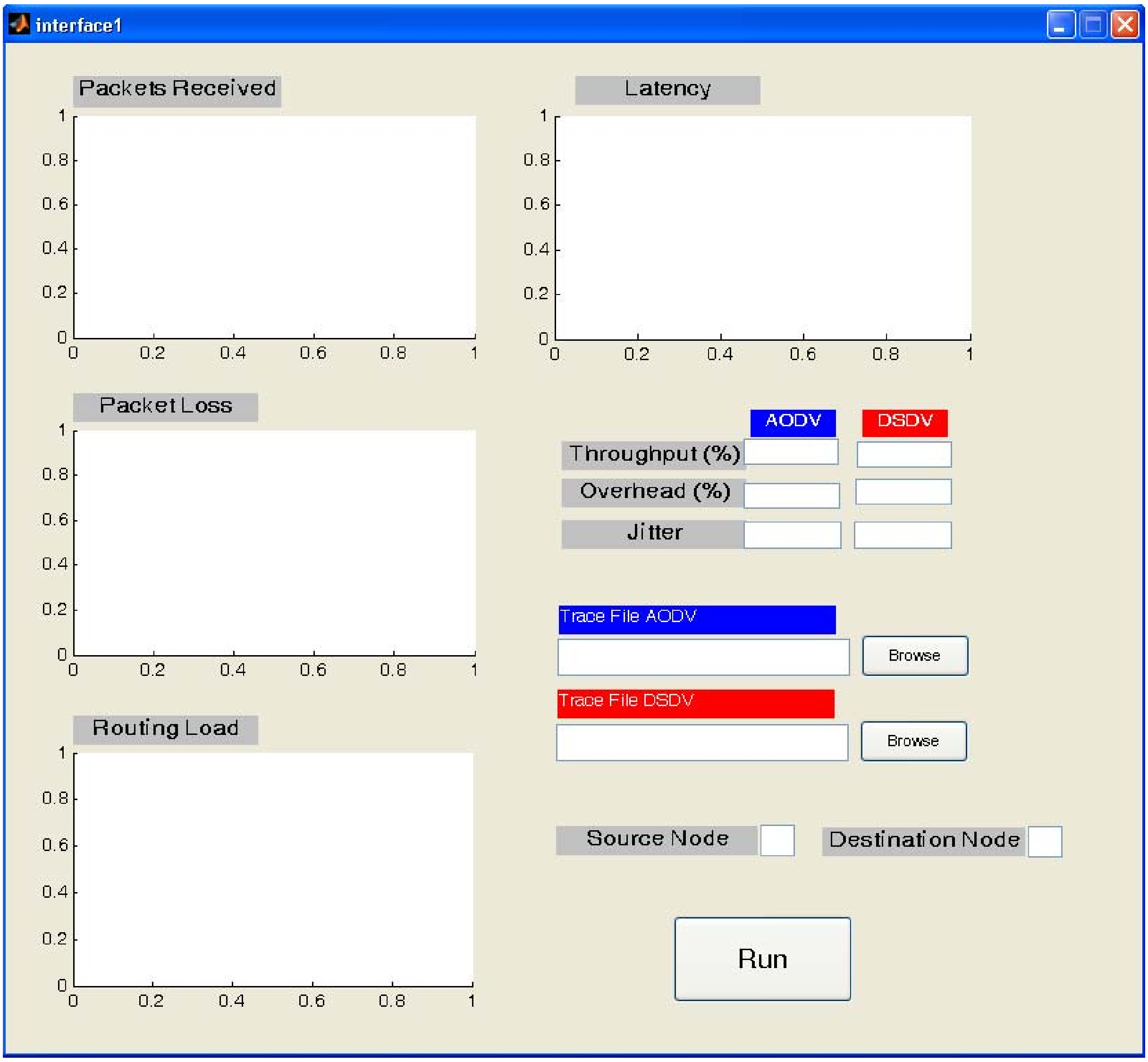


Figure 4-40 A Graphic User Interface has been developed in MATLAB for network statistical analysis

4.5. Simulation Results

The following parameters have been considered in the simulation to compare the performance of AODV and DSDV protocols: the number of packets successfully acknowledged by the destination node, the amount of routing information generated by the routing protocol (*overhead*) and the time elapsed since the packet is generated at the source node until it is received by the destination node (*latency*) and its standard deviation (*jitter*).

4.5.1. Scenario 1

The first scenario aims at testing the network behaviour in situations of rapid topology variation and heterogeneous UAV in the team. This scenario is highly influenced by the topography dynamics of the network since it forces the routing protocol to re-calculate routes very often. Besides, the sudden departure of a UAV from the team (in particular the leading UAV in the V-shaped formation) adds more complexity to the scenario and obliges the network to reconfigure its routes to bridge the newly created gap in the network. The source and the destination nodes are two UAVs placed at the tips of the V-shaped formation. Such condition has been imposed in order to test the routing protocols in the worst possible case that is when the number of hops required for an end-to-end path is maximum.

Figure 4-41 and Figure 4-42 show a comparison between the evolutions of the number of successfully received packets for both protocols at network level. In the case of a single big file transmission (Figure 4-41) a steady data flow is obtained with AODV protocol whereas DSDV presents a more variable behaviour even with periods of no transmission at all. Additionally, these idle periods increase the total transmission time in the case of a single long transmission using DSDV. This effect yields a total transmission time which is 180 seconds longer than the case of AODV. This is an especially critical issue in actual missions where efficiency and short transmissions are a must. The reason for the difference in the performance of both protocols resides on their intrinsic behaviour. Proactive protocols are less sensitive to topology changes than reactive protocols and routes become outdated as soon as the relative position of the UAV changes. In other words, the route discovery process has to be executed continuously and proactive protocols cannot take advantage of the permanent route availability that characterises their approach. For this reason, DSDV has more difficulties to maintain a high throughput when the topology is varying. This variation is emphasized when the UAVs in the formation are scanning the area of interest back and forth and their relative position changes every time they turn around to carry out a new scan.

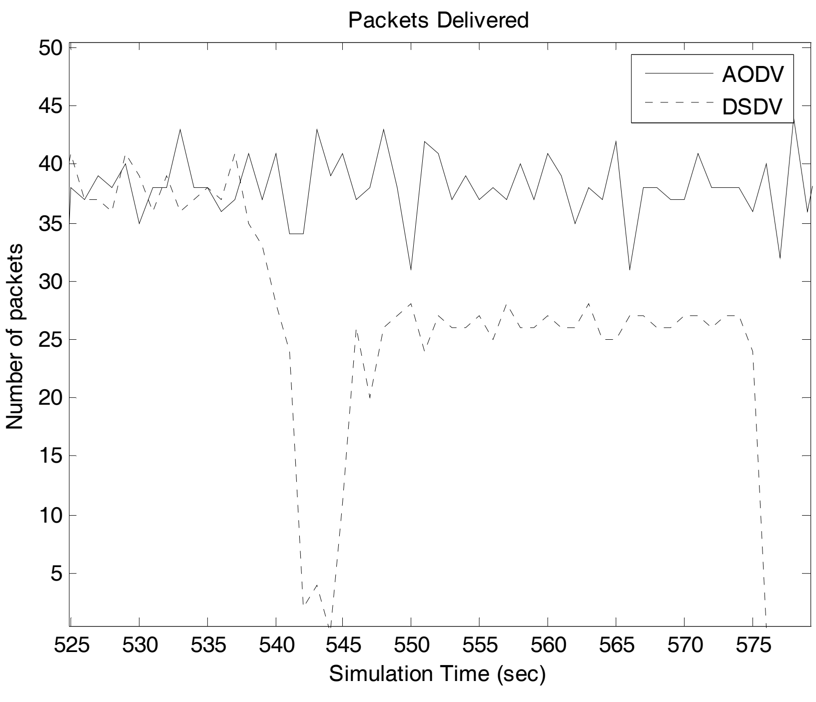


Figure 4-41 Successfully delivered packets evolution in Scenario 1 for long file transmission

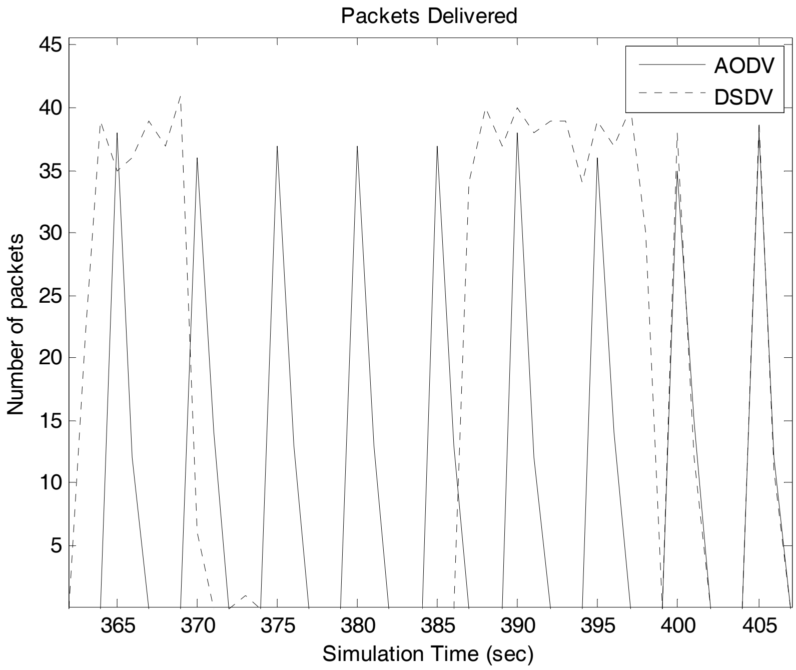


Figure 4-42. Successfully delivered packets evolution in Scenario 1 for a single periodic short file transmission

Analogously, in the case of periodic small-file transmissions (Figure 4-42), file transferences every 5 seconds are only possible using a reactive protocol. In the case of a proactive protocol, only burst transmissions occur when the network topology is arranged favourably, in such a way that an actual path can be found and maintained.

In terms of routing overhead, DSDV protocol generates constant low-level traffic in the case of long file transmission (Figure 4-43). This traffic is independent of the actual data traffic in the network. Meanwhile, AODV shows a complementary performance with respect to DSDV. It experiences no routing overhead when the network remains silent but, once the communications are initiated, it requires a large number of routing messages to cope with the rapidly changing topology. In the case of periodic short transmissions (Figure 4-44), AODV accumulates a lot of routing overhead at the beginning of the mission (first route discovery) but it rapidly decays and it is reduced to minor data transfers during the rest of the mission as long as the routes remain valid.

The conclusion that can be obtained in terms of routing is the following: whereas DSDV overhead does not depend on the topology variation, AODV is rather sensitive to the size of the file to be transmitted (the performance is worse in the case of big files) but it also depends on whether there are previously stored routes to the destination node or not. If the new route has to be discovered from scratch a burst of high routing load is likely to happen at the beginning of the transmission.

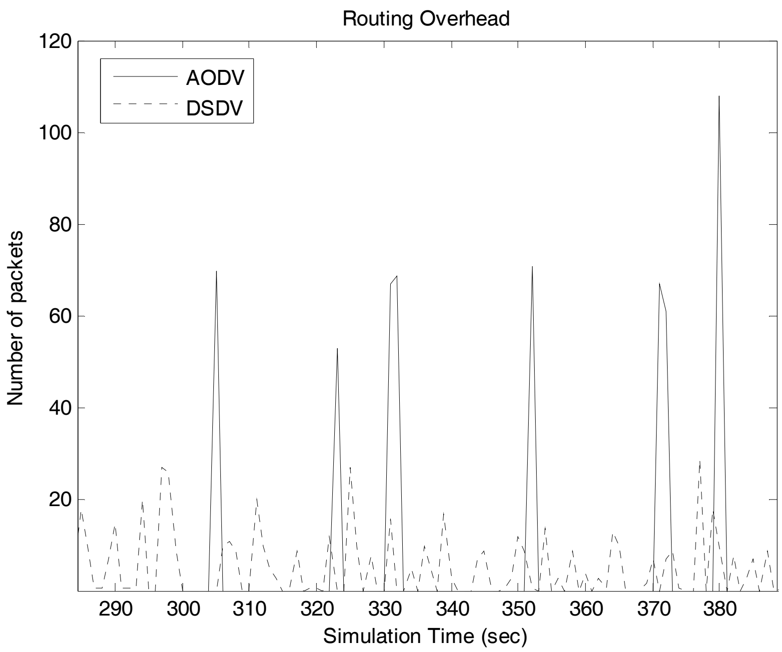


Figure 4-43 Routing overhead in Scenario 1 for a single long file transmission.

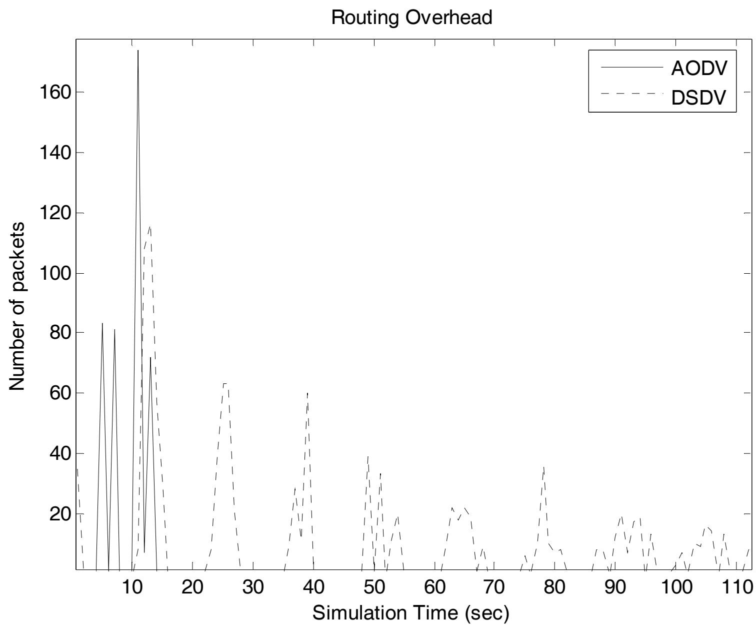


Figure 4-44 Routing overhead in Scenario 1 for periodic short transmissions.

Another interesting performance indicator to be considered is the packet end-to-end delay. As it is depicted in Figure 4-45 for the case of long file transmissions, there is no significant difference between both protocols once the route has been discovered. To find a fine difference between them we have to resort to average values that will be exposed later on. This similitude indicates that the quality of the routes found by both protocols is similar in terms of number of hops and latency.

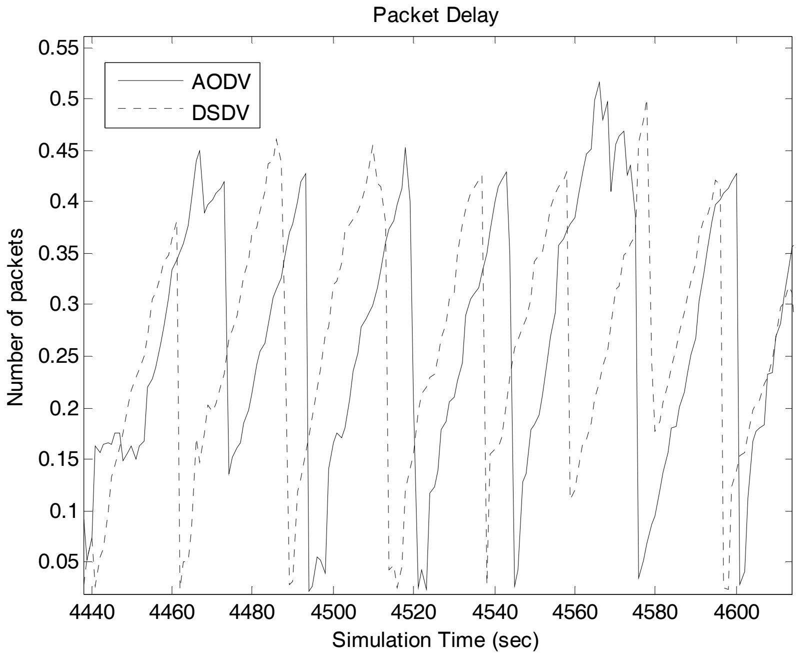


Figure 4-45 Packet Delay evolution in Scenario 1 for a single long file transmission

Therefore, AODV achieves a better performance than DSDV in terms of throughput given its greater flexibility and fast re-calculation of new routes under rapid topology variation conditions. Moreover, AODV presents routing overhead peaks at certain points if the traffic load is high or if the topology changes frequently. Conversely, DSDV protocol generates a quasi-steady and low routing overhead regardless of the traffic demand and/or the node movement. Both protocols are comparable in terms of end-to-end latency.

Simulations also showed that when one of the fixed-wing aircraft abandons the formation in Scenario 1, both routing algorithms calculate a new path that includes a hovering aircraft as an intermediate node. This feature highlights how the network is able to exploit the heterogeneity of the team and the inter-link communications to workaround a link failure.

4.5.2. Scenario 2

Scenario 2 presents some relative movement among nodes but it has a static topology (flight in pyramidal formation). The aim of this scenario is to test the ability of the mobile network to adapt to a formation perturbation caused by a UAV that moves away from its correct position for a short period. In particular, the node trajectory is corrected from t_1=160 to t_2=320 s. during the simulation time. The network should be able to overcome this disruption by creating new paths/routes between the formation leader (in our case the central UAV in the pyramid) and the deviated vehicle.

In the case of a large file transmission (Figure 4-46) both protocols present a similar performance since the transmission starts (t=100 sec.) until the destination node starts to deviate from its correct position in the swarm (t_1). Inter-link communications with other UAVs help to coordinate the return of the displaced node to its original position after 300 seconds. It is also surprising that the throughput of both protocols varies after the return of the displaced node. Once routes are calculated, they remain valid until there is a link failure. In our example, this failure has been caused by the node deviation, thus forcing the routing protocols to re-calculate new routes. Since the initial conditions have changed and the node that re-enters the formation has a slightly different position, protocols find new paths with higher throughputs which are not the same as the former routes.

Unlike the first scenario in the case of short periodic transmissions both protocols can sustain periodic short transmissions since there are not major topological changes in the network as shown in Figure 4-47.

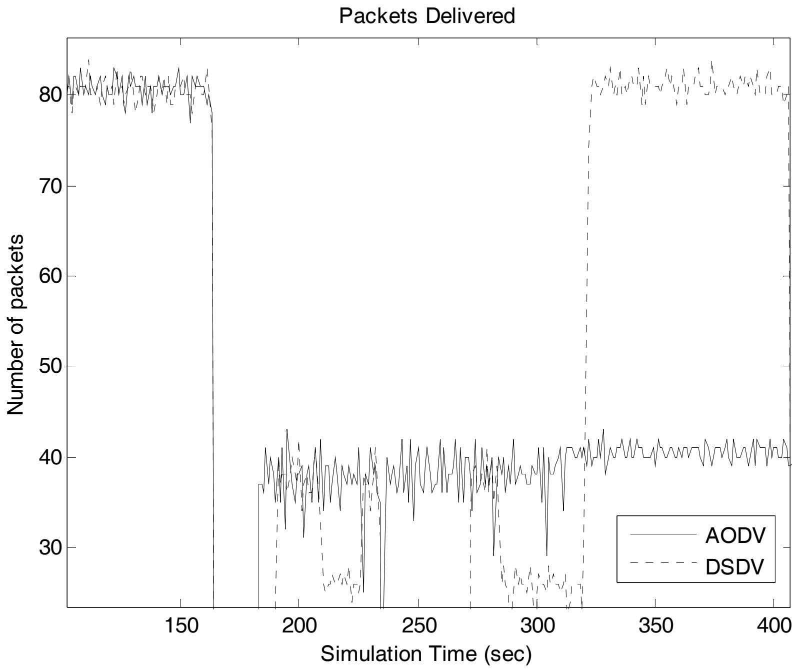


Figure 4-46. Successfully delivered packets evolution in Scenario 2 for a single long file transmission.

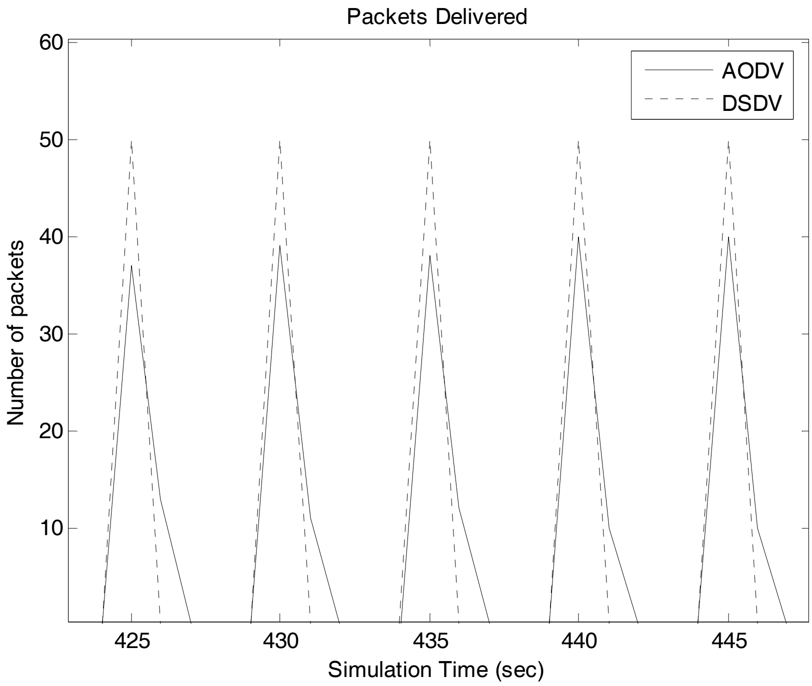


Figure 4-47. Successfully delivered packets evolution in Scenario 2 for periodic short transmissions.

An interesting observation to be made in the case of short periodic transmissions is that during the period of time while the shifted node is out of its correct position the total throughput for each individual transmission is lower than during the nominal throughput in formation (Figure 4-48). Moreover, it can be observed that once the new routes are re-established (after the node re-entry) the throughput of both protocols varies over time. As in the case of long file transmissions, while the AODV protocol has a quasi-steady throughput during the deviated UAV re-positioning (from t_1 to t_2), DSDV protocol has a more variant behaviour with a throughput peak at the re-entry point (t_2=320 sec.).

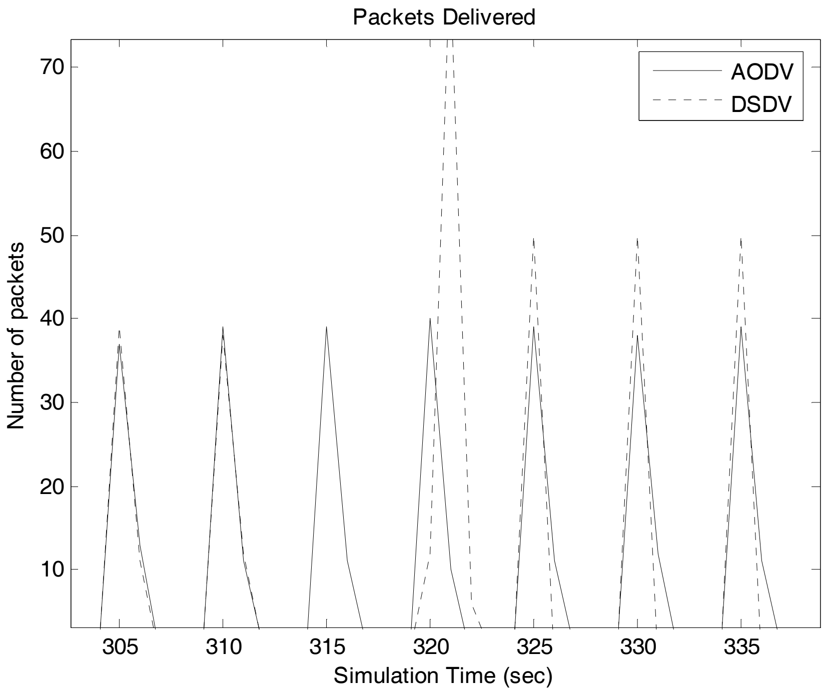


Figure 4-48 Successfully delivered packets evolution in Scenario 2 for periodic short transmissions (transition due to node re-entry).

In terms of routing load, it can be observed that both protocols have a consistent performance. In the case of long file transmissions (Figure 4-49), AODV generates a high routing load during the network disruption (160 to 320s.) whereas DSDV produces a steady traffic level during the whole simulation. However, in the case of short periodic transmissions (Figure 4-50), AODV generates less traffic during the network disruption and almost no traffic during most of the mission time, which means that the disruption has a minor impact on the protocol performance for such short data exchanges.

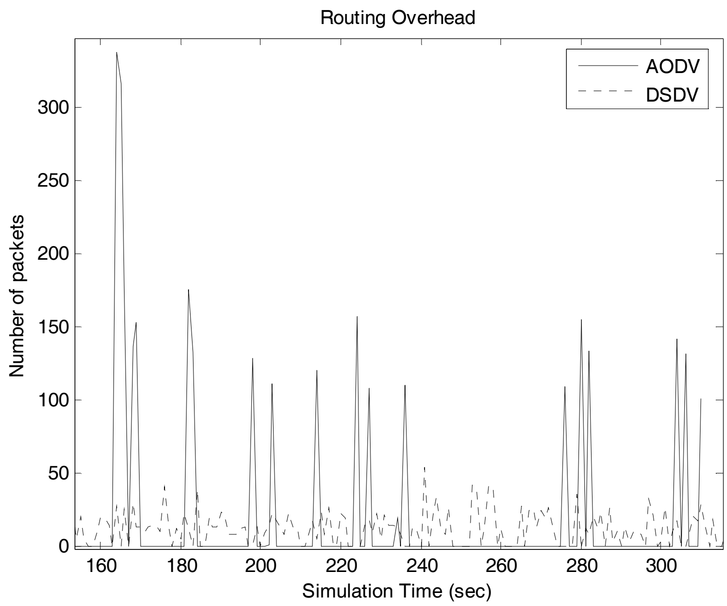


Figure 4-49 Routing overhead in Scenario2 for a single long file transmissions

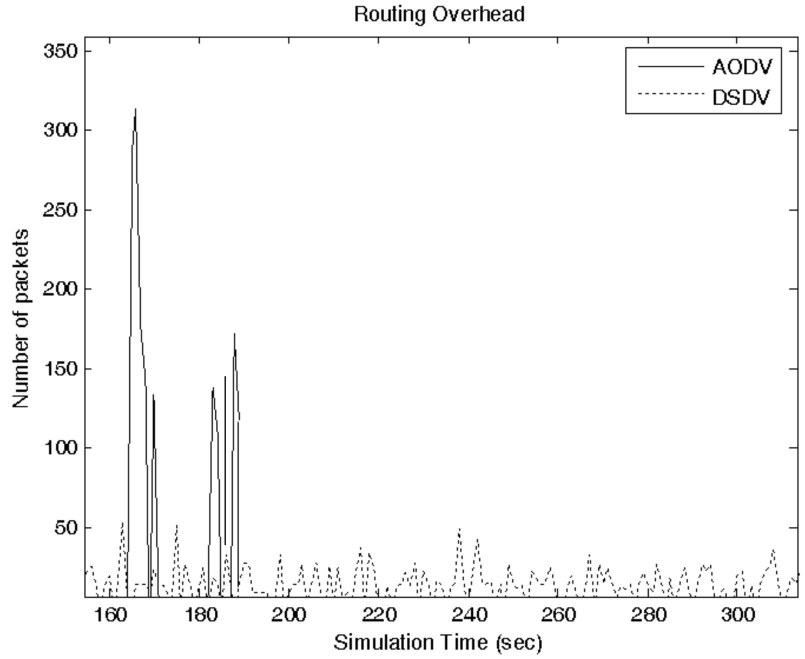


Figure 4-50 Routing overhead in Scenario 2 for periodic short transmissions

Again, both protocols present a comparable behaviour in terms of packet delay evolution (Figure 4-51). The posterior analysis of the mean values will reveal if there is any significant difference between both routing alternatives.

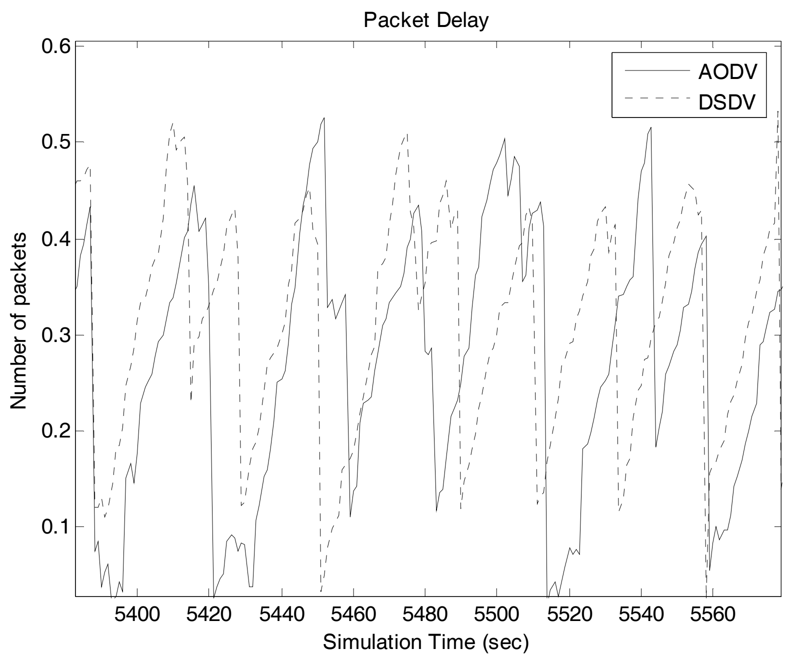


Figure 4-51 Packet Delay evolution in Scenario 1 for a single long file transmission

Table 4-2 and Table 4-3 show the numerical results obtained in all the study cases described previously for Scenario 1 and Scenario 2 respectively. All the values displayed in these tables are mean values averaged for the whole transmission time. Although both protocols have a similar performance in terms of jitter, it can be observed that DSDV exhibits lower mean latency than AODV except in the case of short periodic transmission in Scenario 1 which corresponds to the case with maximum topology variation. In this case, the accumulated delay resulting from a permanent route re-calculation increases the end-to-end delay. This is one of the main drawbacks identified in reactive routing. However, AODV presents a better routing efficiency which results into a lower routing overhead in all cases despite of occasional routing peaks triggered by topology re-arrangements.

Table 4-2 Comparative Analysis of network statistics for Scenario 1

	Scenario 1			
Traffic *Mode*	**Long Tx**		**Short-Periodic Tx**	
Routing	AODV	DSDV	AODV	DSDV
Latency (sec.)	0.264	0.177	0.089	0.12
Jitter (sec.)	0.14	0.13	0.08	0.1
Overhead (%)	2.24	4.23	0.79	7.18

Table 4-3 Comparative Analysis of network statistics for Scenario 2

	Scenario 2			
Traffic Mode	**Long Tx**		**Short-Periodic Tx**	
Routing	AODV	DSDV	AODV	DSDV
Latency (sec.)	0.21	0.16	0.12	0.07
Jitter (sec.)	0.12	0.09	0.09	0.07
Overhead (%)	3.02	16.37	2.31	24.56

In summary, simulations show that there is not a unique routing solution that can meet the communications requirements for all types of UAS mission in an optimal way. The complementariness of current routing approaches makes each protocol a suitable alternative for certain communication aspects while impacting negatively upon others aspects.

Chapter 5

CONCLUSIONS AND FUTURE WORK

This work has investigated new technologies for the management of large UAS teams. The current overhead and the amount of resources required by the state-of-the art technologies to operate a single UAV safely imply an insurmountable obstacle for a scalable and efficient operation of multiple UAV in collaborative missions. In a first step, a taxonomy of the UAS according to their level of autonomy has been presented as a tool for the control segment to share resources among UAVs. Given the heterogeneous nature of the UAS teams considered in this work, the elaboration of proper autonomy metrics and taxonomies is essential to operate UAS with similar autonomy capabilities in an analogous way.

A step beyond this previous analysis, has been the exploitation of inter-vehicular communications to release part of the ground resources necessary to control a single UAS. Ground communication links as well as the control segment infrastructure and logistics will increase its workload and become more constrained as the number of UAS in the fleet increases. Therefore, UAV-to-UAV data exchanges may be useful in terms of communication links efficiency but also will allow implementing more complex distributed algorithms and eventually increasing the level of autonomy of the entire team. To that end, we have proposed an aerial mobile ad-hoc network as a complementary solution to offer and manage inter-vehicular communications in flight segment for a collaborative UAS mission. The implementation of this infrastructure is proposed as an extension to the system architecture defined in NATO STANAG 4586 standard. This work aimed at analysing this recommendation, by performing an evaluation of inter-vehicular communication links.
The availability of this infrastructure and interoperability through a standard would offer a reduced ground segment dependency, more efficient mission control, optimised data-links and flight endurance.

Finally, this work has focused on analysing the performance of the network at routing level measuring: the evolution of the number of successfully received packets, latency, jitter and overhead parameters, in order to assess the vehicle-to-vehicle connectivity. These parameters are investigated in two scenarios under different conditions. Results show that the selection of an optimal routing algorithm is tightly constrained by the characteristics of the traffic load and the topology dynamics of the network. In conclusion, there is no optimal routing solution for all scenario cases presented. The selection of routing algorithm must consider the scenario characteristics such as traffic, network size and topology evolution over the mission. Nevertheless, such selection must also take into account the performance requirements that the mission objectives impose over the communication system and prioritise those features that are more relevant for the success of the mission.

Future research steps should be focused on the implementation of additional mechanisms to ensure the reliability of the communications and to increase the robustness of the network in those cases where MANET protocols have proven to fail or at least to provide non-satisfactory results. Hence, the integration of DTN protocols on top of the most suitable MANET algorithm for each mission scenario would be an interesting experiment that would allow verifying the applicability of this type of network in terrestrial challenged environments. Moreover, an inclusion of a third routing protocol (i.e. hybrid between proactive and reactive routing) would also be worthwhile. This approach would explore the usefulness of an intermediate routing protocol and to evaluate its performance compared with the other two classical methods.

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