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COMPREHENSIVE STUDY ON UNMANNED AERIAL VEHICLES (UAVs)

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Abstract. Recently, the cooperation scenario among multiple unmanned aerial vehicles (UAVs) has gained a great amount of interests because it's associate UAV members either to coordinate simultaneous coverage of large areas or to cooperate to achieve common goals/targets. These coordination and cooperation need a reliable communication with an appropriate network architecture to ensure exchange of both control and data packets among UAVs. Such network models should provide all-time connectivity to avoid unintended consequences in addition to serious failures. In this area, the flying ad hoc network (FANET), a new paradigm of wireless communication, is emerging. Along with the FANET unique features, challenges and open issues are also discussed especially in the networking approach. So as to spur further research in those outstanding issues relating to the UAVs system, our paper try to surveys most of the work done toward them. This system has gained popularity around the world in recent years, and thus it is important to characterize it not to understand its nature only, but also to obtain knowledge on its constraints and possibilities. However, after analyzing the existing works it has been seen that there are still several fields where the researchers can give more focus on them in the future.

Keywords: Unmanned aerial vehicles (UAV), single and multi-UAVs system, cooperation and coordination, flying ad hoc network (FANET).

AMS Subject Classification: 68M10.

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1 Introduction

In recent years, various types of low-cost UAVs (Unmanned Air Vehicle) have been produced thanks to technological advances in electronic sensors, robotic systems, and telecommunications techniques Maza et al. (2009). UAV is a flying device that does not require on-board pilots and equipped with radio communication modules. This device either is controlled in a manual way by an operator at a ground control station (GCS) or in an autonomous manner by a flight program. The progress on miniaturization technologies and the development in embedded systems have paved the way for reducing the physical size of the UAV such as the mini quadrotor. Consequently, UAVs have emerged as an alternative means of providing diverse applications in not only the military areas, but also in civilian fields such as surveillance, radio source localization,the 3-dimensional aerial mapping for earthwork projects, transportation of suspended loads Palunko et al. (2012), disaster Scenarios, relaying for ad hoc networks, persuading pollution-free area, search and destroy missions George et al. (2011), reconnaissance and surveillance, maintaining of the weapon systems network, combat support. In the last decade, single-UAV systems have been utilized in different fields. With the progress of time and the increasing complexity of the tasks and applications in which a single-UAV system is used, the design of efficient network architecture becomes a vital issue. By means of the technological advancement in avionics and micro-electromechanical systems, the utilization of the multi-UAV system to perform complicated missions has been emerged Singh et al. (2015).Many reasons such as the easy installation, flexibility and also relatively small operating expenses of UAVs made the large scale of UAV applications have proliferated widely within the last few years. It's worth noting that the size, type and configuration of UAV are altered based on the applications nature Pastor et al. (2006). Using multiple UAVs instead of a single-UAV systems yields a wide range of advantages, which we will try to summarize them as follows Valavanis and Vachtsevanos (2015):

- Multiple simultaneous interventions.
- Greater efficiency.
- High Reliability.
- Complementarities of team members.
- Low Cost.
- Increasing accuracy.
- High Scalability.
- Low Detectability.

Accordingly, groups of UAVs are of special interest due to their ability of coordination and cooperation Ryan et al. (2004). The concept of coordination and cooperation plays an important role in any system that comprises multiple autonomous vehicles. Regarding to the coordination, there are two main types of it, i.e., spatial and temporal coordination. The coordination that deals with the idea of sharing the space among multiple UAVs to ensure safe performance for each UAV called spatial coordination. Sharing resources is therefore the main issue in order to ensure safe performance for each UAV and coherent with respect to each of the potential obstacles in addition to the plans of other UAVs. However, temporal coordination means that UAVs are synchronized among each other, and it is required in a wide range of applications such as object monitoring.

The cooperation concept emerges when a group of homogeneous or heterogeneous UAVs can interact with each other and execute the missions as a single entity. Thus, a Cooperation means provision common collaborative behaviors by using centralized or decentralized (distributed) architectures in order to produce a coordinated mission Butenko et al. (2013). It is worth noting that one main requirement to ensure a global coherence within the whole system is having a successful coordination and cooperation by sharing information as mentioned in Kumar et al. (2004).

Typically, two types of information are shared by a multi-UAV system: mission data and control messages. The mission data remotely sensed and gathered by the airborne sensors on UAVs and then transmitted to fusion centers Christmann and Johnson (2007). For effective team coordination, the second type of information is created by the controller and must be exchanged with minimal delay and error. With the emergence of smart and converged services for these autonomous UAVs, there has been a rapid increase in the need for reliable connections among UAVs and control centers. This a stable communication will guarantee that UAVs are in communication most of the time during the mission and readily sharing the information. Accordingly, the network and telecommunication systems are the fundamental components of this system that needs a vast interest by researchers. Moreover, the communication environment of a multi-UAV system deviates significantly from traditional wireless networks regarding mobility degree, networking models and communication requirements.

The main objective of this paper is to provide a comprehensive study on the multi-UAV system and the critical issues that related to it. Our paper is organized as follows. In Section 2, we present coupling and networking in a multi-UAV system. In Section 3, the challenges and open issues of this system are discussed. The last sections are devoted to the Conclusions and References.

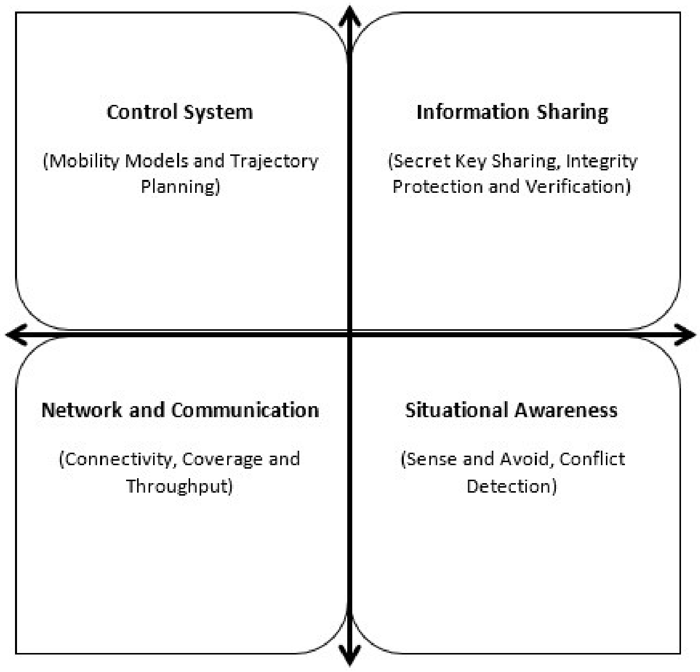


Figure 1: Design principles of network with flying nodes

2 Coupling and Networking in a Multi-UAV System

The unprecedented recent advances in unmanned aerial systems technology make it possible to widely deploy UAVs, such as drones, small aircrafts, balloons, and airships for using them in carrying loads, sensing, and other use into the sky. The world scientific community has been investigating four design-principles dimensions use for bringing group of UAVs into a team and creating network among them. As depicted in Fig.1, the post mentioned design principles are network & communication, control system, information sharing and situational awareness Namuduri et al. (2012). Indeed, work UAVs as a team requires significant coordination efforts in order to guarantee that UAVs to be placed appropriately with respect not only to its neighbors but also to its tasks within mission plan. There are two important concepts in the multi-UAV system are presented in this section: coupling and networking. The existed relationship among UAVs is represent the coupling, while the networking readily characterizes the communication status among UAVs.

2.1 Coupling in a Multi-UAV System

As shown in Fig.2, there are four types of coupling in a multi-UAV system: *physical coupling*, *Formations coupling*, *Swarm coupling* and *Intentional Cooperation coupling*. In what follows, the details of all coupling types in addition to their possible applications are presented.

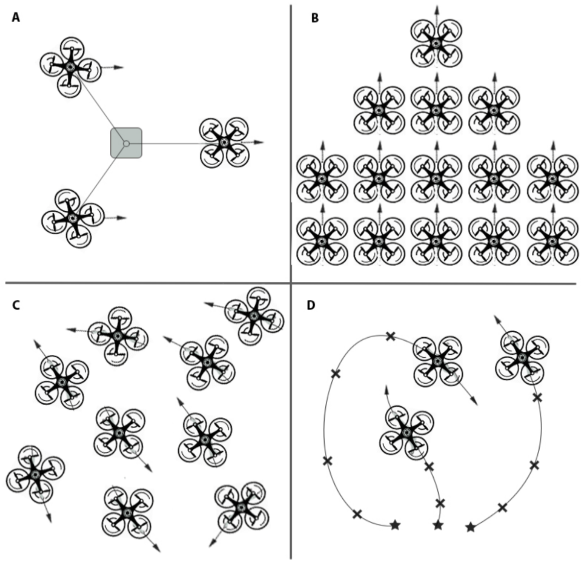


Figure 2: Coupling types in multi-UAV system,(A) Physical coupling, (B) Formations, (C)Swarms, (D) Intentional cooperation

2.1.1 Physical Coupling

Within this kind of coupling, there are physical links that connect the UAVs to each other. The motion of an UAV is constrained by forces that are originated as a result of motion of the other UAVs in system, which remains an open problem for researchers. One of the applications of this type of coupling is to cooperatively lift & transport suspended loads using multiple UAVs. In more details, it is a nature extension of collaborative behavior of several persons to move an object that is too heavy to be carried by a single person. The UAVs take into account not only the consideration of physical interactions between them, but also the involved forces induced by the suspended payload. Flying with a suspended load is a challenging and, sometimes hazard task. Thus, not only designing of a control system that considers the effects of the suspended load on the flight characteristics but also providing the stability of the vehicle-load system remain an open problem for researchers and practitioners Palunko et al. (2012). Moreover, the motion-coordinated control is considered the main issue for design and implementation such this application Maza et al. (2009). The both centralized and decentralized control architectures can be applied in physical coupling, especially when the number of vehicles is low. Note that Fig.3 shows load transportation using three autonomous small size helicopters, which was experimented by department of computer science in Technische Universität Berlin.

2.1.2 Logical Coupling

This type of coupling is grouped into three sub-types as follows.

1. *Formations*: UAVs perform a cooperative task by flying in a formation as a group, where a formation flight means that the members of the UAV group must keep a fixed distance among themselves within other group and thus whole group moves as a rigid entity in a desired shape Blondel et al. (2008). It can be seen as a control problem in which the goal is to compute the inputs that drive the UAVs along certain trajectories. In this type of coupling, the decentralized control is usually preferred. Note that the control of UAV formation flight must consider three important issues: how to come together, how maintain a formation and How to achieve collision/obstacles avoidance.

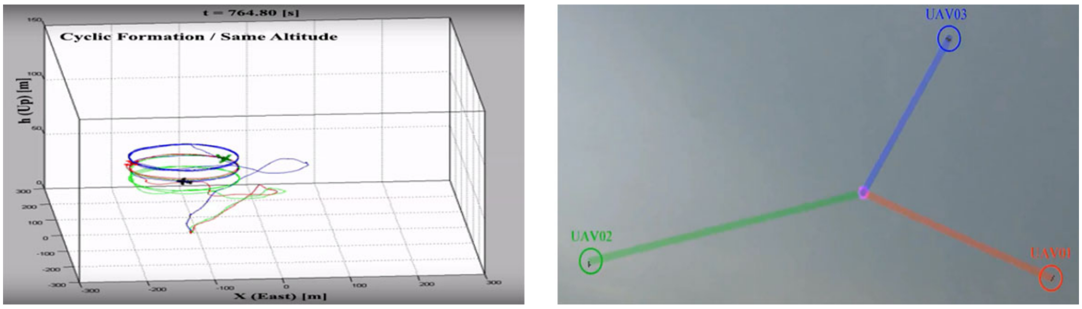
   At the present time, many formation control strategies are proposed; however, there are mainly three approaches are used, namely, leader-follower, virtual leader, and behavioral

Figure 3: Load Transportation Using Three UAVs (mbernard79, 2007).

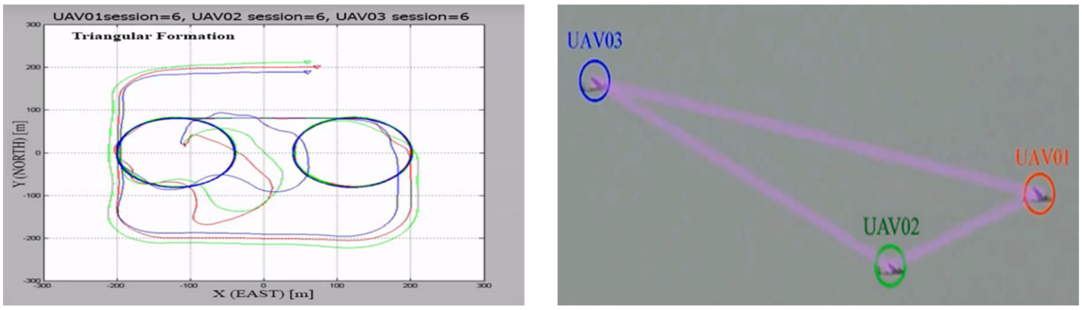
approach. Each formation has many applications such as surveillance, radar deception, and surface-to-air missile jamming. Indeed, how to define the practical architectures for formation in addition to the signal flows that associated with communications, sensing and control are crucial issues that need a vast interest by researchers. Fig.4 shows a flight experiment of three-fixed wing UAVs flying in many formation models via decentralized communication, which was experimented by Seoul National University and Korea Aerospace University as a study on distribution system of multiple UAVs.

2. *Swarm*: In these days, the current technology enables us to mimic the behaviors of varied types of insects (or birds). Indeed, we are able to create accurate artificial simulations for their interactions not only among each other, but also with their surrounding environment Sharkey (2006). One of these emerging behaviors that can be used in the multi-UAV system is a swarm. UAVs swarm means forming of teams of homogeneous UAV interacting with each other to generate complex collective global behaviors; nevertheless, it does not necessarily mean that the resulting motion leads to a formation. Swarm cooperation involves many repetitions of the same activity over a large area. Moreover, a member within a swarm commonly moves in random depending on the movement of others to generate the corresponding action. While the multiple UAVs are organized into a swarm, the new challenges such as providing a robust local communication and proposing an effective control mechanisms that collectively achieve goals without a collision need to be addressed by researchers in order to obtain effective swarm management. Different control techniques are proposed for swarm approach, for example, agent-based control framework, rule-decentralized control algorithm. Artificial potential functions and sliding-mode control technique. The swarm of multiple UAVs is practical for many applications, for instance, the assessment of forest environments, and coordinated search Waharte et al. (2009). Now, a swarm of drones gained considerable attention by the military sector. Based on "scout warrior" site, Air Force in U.S army seeks to use mini-drone swarms to overwhelm enemy radar or to function as small bombs to attack a target. Furthermore, "military.com" stated that NAVY launched its first at-sea "air show" of dozens of drones that are flying themselves in swarm formations. Fig.5 shows the NAVY demo test.

3. *Intentional Cooperation*: In this type of coupling, the global mission of a multi-UAV system is performed according to particular planning strategies by which a set of tasks



(a) Cyclic Formation and its Data Version



(b) Triangle Formation and its Data Version

Figure 4: Many Formation Flight Models Of Multiple UAVs (Park., 2015a,0).

Figure 5: Dozens Of Drones In Navy Demo Test.

(sub-goals) are explicitly allocated to each UAV. Consequently, UAVs of the team move along specific trajectories in order to execute these individual tasks. However, the UAV trajectories are not geometrically related as mentioned in the case of formation coupling. Therefore, the overall goal of the multi-UAV system will be achieved in an intentional cooperation scheme. It is however worth noting that in the intentional coupling, different issues and considerations such as multi-UAV task allocation, communication guarantee, conflict-resolution, plan decomposition and UAVs heterogeneity has to be taken into account when implementing the global mission Valavanis and Vachtsevanos (2015). Recently, intentional cooperation scheme is used in many civil applications, for instance, fire confirmation, extinguishing, and monitoring. Recently, intentional cooperation scheme are used in many civil applications, for instance, fire confirmation, extinguishing, and monitoring. In addition, this coupling was the main principle of "COMETS" project Merino et al. (2005), which examined a distributed control system for cooperative detection and monitoring using two autonomous helicopters and one an airship, as shown in Fig.6.

(a) autonomous helicopters **(b)** an airship

Figure 6: Heterogeneous UAVS In Comets Project (Technology., 2004).

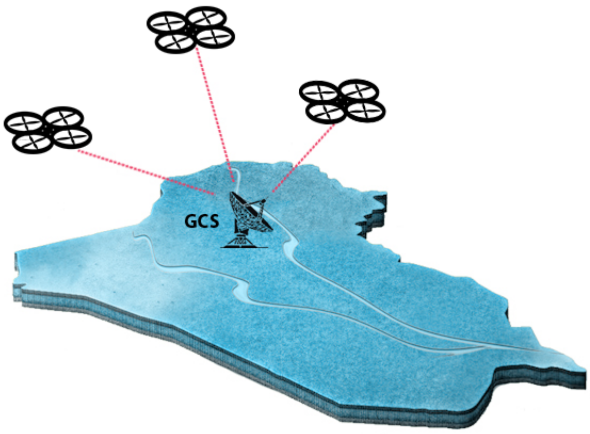
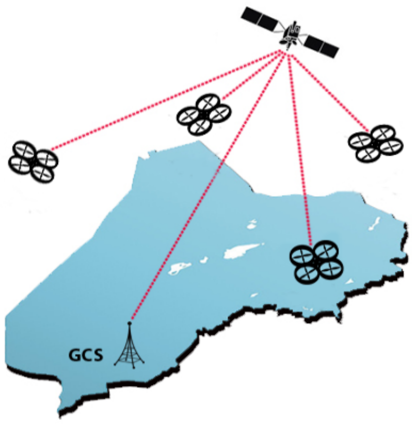


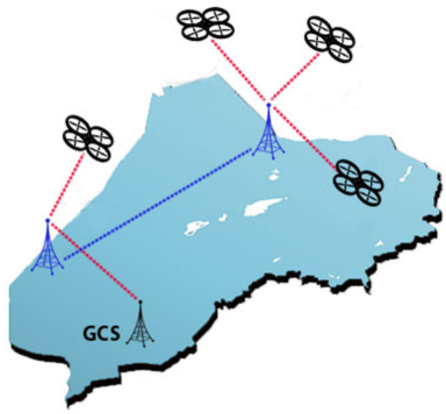
Figure 7: Direct Communication Architecture.

2.2 Networking in a Multi-UAV System

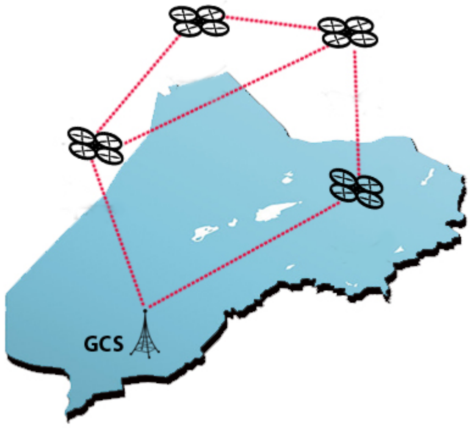
Describing the characteristics of the data transmission over the entire multi-UAV system plays an important role in selecting a networking architecture for the best performance. Therefore, there exist different networking architectures proposed and emerged Bekmezci et al. (2015). As shown in Fig.7, the simplest one is to have a ground station that is simply responsible for creating the communication between these UAVs as well as coordination their motions (direct communication). The other network architectures are *satellite*, *cellular* and *flying ad hoc network (FANET)* as depicted in Fig.8. In satellite architecture, the UAVs connect to a satellite instead of a single ground station, and thus the deterioration effects on communication links will be decreased. However, UAVs-to-satellite connections need to mount heavy and expensive airborne satellite communication hardware on each UAV Frew and Brown (2009). For providing a good level of network connectivity and reliable data delivery, the Cellular architecture has been suggested. It is worth noting that during the flight, UAVs can do a handover between different base stations scattered on the ground. However, the multiple ground station architecture is an expensive network because of the high cost of each tower and its equipment Valavanis and Vachtsevanos (2015). In the last type FANET, all UAVs could work as a relay node in order to forward the data until it reaches the destination. This type of communication is called UAV-to-UAV communication.



(a) Satellite Communication Architecture



(b) Cellular Communication Architecture



(c) FANET Communication Architecture

Figure 8: Basic Communication Architecture

3 The Concept, Challenges and Open Issues in FANET

It is important to emphasize that changing in the orientation from using one UAV to use several small UAVs needs to develop new networking technologies among UAVs. FANET is within that context considered as a popular technology for a communication networking among multi UAVs as a result of not only extending the operational scope and ranging but also enabling quick and reliable response time. However, setting up an ad hoc network among UAVs imposes challenging issues and needs some additional requirements different from those a traditional network needs. In this section, the concepts of FANET and its open issues and challenges are presented.

3.1 Concept and Unique Features

Recently, one of the most prestigious technologies in the communication and networking is FANET. It is a kind of self-organized wireless network carried by a group of UAVs each of which is a small flying robot Gurdan et al. (2007). It is worth mentioning that FANET is a very attractive technology for many applications, especially in the case of the calamitous events where the infrastructure operation mode is not available. The construction of self-managed wireless ad hoc network by using a group of small and rapidly deployable UAVs will be a feasible solution on these events. In addition, FANET has many usage scenarios which lead not only to increase both reliability and collaborative actions to perform complex tasks but also reduce payload and cost Bekmezci et al. (2015). Thus, FANET significantly outperforms on the other communication structures of multi-UAV system.

As shown in Fig.9, FANET can be considered as a special form of mobile ad hoc network (MANET). Moreover, it can also be considered as a subgroup of vehicular ad hoc network (VANET). In spite of fact that FANET has common features with MANET and VANET, it apparently possesses unique features distinguished from their features. For example, when FANET is considered three dimensions span in location of UAVs, the MANET considered two dimensions in location of nodes (e.g. Mobile users in area), while VANET generally considered single dimension span in location of vehicles (e.g. The vehicles on the road). These main differences between FANET and the current ad hoc networks are listed as follows:

- *High Mobility* Rosati et al. (2016): Each UAV in a FANET considered as a node in the ad hoc network, where node mobility issues are considered the most prominent difference between FANET and other ad hoc networks. For example, while the nodes in FANET are UAVs with a typical speed of 30-460 km/h, the nodes in VANET and MANET are cars and humans respectively. In this situation, there are a relatively higher mobility degree in FANET than VANET and MANET, which results in several communication design problems.

- *Rapid Topology Changes* Zhang et al. (2008): The topology changes in FANET are more frequently than that either in typical MANET or VANET. It is also more dynamic due to the high mobility degree, which causes maintaining the communication links between UAVs are one of the hardest challenging tasks. In fact, rapid topology changes plays important role in comprehending the nature of an ad hoc network. Analyzing the network topology provides useful insights on how information propagates throughout the network in addition to how the UAV team reaches consensus on quantities of interest such as parameters, situational awareness, and plans.

- *Long Distance* Tareque et al. (2015): The mobility and speeds of UAVs, as mentioned before, is higher than those of VANET and MANET, which causes the average distance among nodes in FANET is also higher than those in VANET and MANET. Therefore, the communication between UAVs is required to have the longest range and thus may not be robust against to channel fading conditions.

- *Low Node density* Frew and Brown (2009): The node density can be defined by calculating the average number of nodes (UAVs) in a unit area. Accordingly and because of the long distance in FANET, the reader can be realized that the node density in FANET will be less than its counterpart in the VANET and MANET.

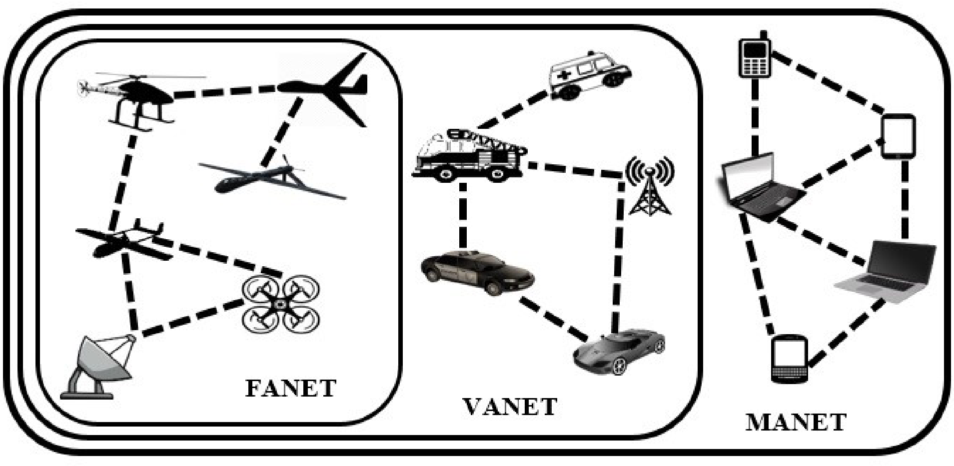


Figure 9: MANET, VANET, and FANET

- *More Flexibility* Kellerer et al. (2015): One of the other essential measure units in network is the flexibility. The term flexibility is commonly defined as the ability to adapt the available network resources to changes of design requirement. Because of not only the unique features of FANET (e.g. highly dynamic nature) and the higher impact of weather conditions on it but also the nature of mission and its updates make the several parameters in FANET are changeable during the operation of multiple UAVs system. Thus, FANET design needs to be more adaptable than the other current ad hoc networks.
- *Minimal Latency* Bekmezci et al. (2013): In addition to both collision avoidance and coordination among high mobility UAVs, most of the FANET applications require delay-bounded data delivery in order to produce the efficient and reliable communications. Therefore, the minimal latency is considered vital issue in FANET more than VANET and MANET.

Consequently, these vital issues impose another constraints and challenges that must be taken into account by any researcher work in this area. For instance, a high mobility and rapid topology changes have a main effect on the mobility model design. In addition, the long distance and low density require a good study on the RF propagation and antenna design in FANET. Moreover, the routing strategies and its information updating mechanisms need to be more flexibility to keep pace the latency constraint.

3.2 Open Issues and Challenges

The distinct characteristics of FANET-based multi UAV systems promise a vast usage for both military and civilian spaces because of not only its versatility and flexibility but also the capacity of its UAVs to be deployed as a communication relay. However, it also brought the new challenging issues and additional burdens on the physical, Medium Access Control (MAC) and network layer designs. In this section, we review the researches, which have been performed to address with these challenges in addition to some of open issues for future works.

3.2.1 UAV Airframe Constraints

The space of UAV airframe is considered one of the challenging issues in FANET design. In FANET, UAVs are usually a small size and their airframes actually have a limited space Pastor et al. (2006). The UAV payload and communication hardware should be contained within this airframe. Consequently, the space limitation of airframe plays important role in determining the size, weight, and power (SWAP) of the onboard hardware and thus their performance. Using of lightweight payload and communication hardware provide an opportunity for extension of UAVs endurance. In addition, the small hardware will be fit for carrying in an internal payload bay and thus they do not cause a deterioration of the aerodynamic properties for UAV Sahingoz (2014). However, SWAP constraints limits onboard computing capability that used for processing the complex algorithms in the planning strategies and networking.

Through this, it is clear that space limitation is another issue related to constraints for FANET design especially for mini UAV. It is important to note that when the FANET network is designed taking into consideration trade-off between payload and communication hardware size to be fitted into the UAV airframe commensurate with the desired missions. In addition, attempt designing an UAV from lightweight materials will help to mitigate this problem Purohit et al. (2012).

3.2.2 Mobility Models

The mobility models are one of the simulation environment features, which are designed to describe the movement patterns of mobile nodes, and how their location, velocity and acceleration change over time. They play a significant role in determining the ad hoc network performance. Mobility model has to be matched to the expected real environment by capturing a realistic mobility pattern in which one wants to operate the network. It is therefore necessary to choose a proper underlying mobility model appropriate for each ad hoc network design characteristics. Based on geographical scope of interest, the mobility models in a VANET can be classified into two levels Santi (2012): macroscopic and microscopic. However, MANET and FANET mobility models are microscopic level only. As stated in Bai and Helmy (2004), there are two groups of mobility models in MANET. The first group involves memoryless (random) mobility models (e.g., random walk, random direction, and random waypoint) while the second group involves four sub-groups, which are listed as follows:

- Temporal dependency mobility model, such as Gaussian-Markov model (GMM),
- Graphical restriction mobility model such as CosMos model,
- Hybrid characteristics model such as disaster-area model (DAM),
- Spatial dependency mobility model, such as reference point group model (RPGM).

At the present time, numerous of wireless ad hoc mobility models with random and simple straight line movement are proposed. However, the direct use of these models for FANET may not describe the actual movement of UAVs, and thus they will lead to unrealistic FANET scenarios. In fact, the mobility models of FANET must be able to capture the trails, speed deviation and the other UAV specifications. Due to the different specifications of UAV models, the mobility model that is feasible in some FANET scenario will not be feasible in another. For example, random way point model (RWPM) is appropriate to describe the movement of rotary-wing UAVs while it is not appropriate for fixed-wing UAVs. The reasons behind this are the lack of ability for rapidly changing in direction and speed of the fixed-wing UAVs. In addition, fixed-wing UAVs cannot stay for a while at the same point.

Some FANET applications prefer using global path plans. In this approach, the UAVs move on a predetermined path and thus mobility model will be regular. However, the flight plan in autonomous multi-UAV system is not predetermined because of environmental changes or the mission updates even if there are a predefined flight plans are used. In Kuiper and Nadjm-Tehrani (2006), Kuiper et al. defined and compared between two mobility models for reconnaissance application (random and distributed pheromone repel mobility model). The comparison results showed that the pheromone model has a much higher coverage rate and it can maintain a higher steady state level than the random model. Moreover, their study showed that continuous communication and area coverage are goals that work in opposite directions. Thus, the mobility models should be optimized to choose one of them as a primary criterion.

A novel mobility model based on semi-random circular movement (SRCM) is presented in Wang et al. (2010). In this model, UAVs rotate clockwise (or anticlockwise) along a predefined circle with a velocity and a central angle chosen uniformly at random in the certain interval. The SRCM model is suitable for simulating UAVs in quite a number of movement scenarios requiring circular movement such as gathering information from specific locations. In addition, SRCM ensures that UAVs have the adaptability to adjust their movement parameters to dynamic targets in realistic movement scenarios. Thus, the simulation results showed that the SRCM outperforms the existing mobility models for the curved movement scenarios of UAVs.

Bouachir et al. presented in Bouachir et al. (2014)) a mobility model called paparazzi mobility model (PPRZM). PPRZM is a realistic model designed for UAV ad hoc networks based on the five possible movements of Paparazzi UAV (Stay-At, Way-Point, Eight, Scan and Oval). These movements have different probabilities to occur. In PPRZM, each UAV chooses a movement type and fixes its characteristics (Location and Speed). Thus, UAVs are assigned a specific position and follows a well-defined path according to the movement chosen. The results of both geometric and network performance metrics show that PPRZM has a closer behavior to the Paparazzi real traces. The mobility model in multi-UAV swarms represents another approach. In Danoy et al. (2015), the authors proposed a scenario consist of two levels of UAV swarms, one is fixed-wing UAVs swarm with high altitude (the backbone network) and the other is rotary-wing UAVs swarm with low altitude. In addition, the mobility of a low-level swarm system is divided into two types of mobility models that are the pheromone mobility model and the other is a mobility model with k-hop clustering algorithm (KHOPCA) that aims at keeping a stable and connected network. At the end, the final results show the validity of the KHOPCA-based model in improving the network stability in multi-level UAV swarms. Accordingly, the proposed mobility models have great effects on the accuracy of FANET simulation outcomes. As a result, these models should be representative of reality with respect to the intended real application. Thus, the designing of FANET mobility models will become the vital issue that needs a big interest by researchers.

3.2.3 Physical Layer

The physical layer coordinates the functions required to carry a data bit sequence over a transmission medium. It also defines the procedures and functions that physical devices and interfaces have to perform for transmission such as modulation and signal coding. In the case of FANET, the transmission mediums are wireless channels, and thus the data bits are modulated to the different sinusoidal waveforms by varying the amplitude, frequency, and phase of a signal. Finally, these signals are transmitted into air and received by utilizing antennas Sarkar et al. (2003).

Since FANET is considered as a special case of MANET, it is highly dependent on its physical layer of communication. Therefore, the quite high mobility in FANET will add extra challenges and issues that must be solved Bekmezci et al. (2013). In fact, obtaining a robust and consistent data communication architecture, the physical layer conditions have to be well defined and understood. In this section the radio propagation model and antenna structure are investigated as the key factors on the physical layer design.

1. Radio propagation model: The initial understanding of radio wave propagation goes back to the great efforts made by both James Clerk Maxwell who formulated the electromagnetic theory of light and predicted the existence of radio waves in 1864 and Heinrich Hertz who demonstrated the physical existence of these waves. Radio waves radiate from the transmitter antenna and then propagate through environments where they are reflected, scattered, and diffracted by walls, terrain, buildings, and other objects. This dictates that the characteristics of the radio waves change as they travel to the receiver antenna. In fact, these characteristics depend upon the distance between the two antennas, the path(s) taken by the signal, and the environment (buildings and other objects) around the path. The radio wave propagation and its characteristics can be expressed as mathematical functions that are called radio propagation modeling. In comparison with the other types of wireless networks, FANET has several unique features in terms of radio propagation, which are summarized as:

   - Interferences and jamming,
   - Shadowing caused by UAV platform and its equipment,
   - Environmental effects,
   - Effects of ground reflection,
   - High mobility that causes variations in communication distance,
   - The effect of UAV attitude and speed motion (Doppler Effect) on the link quality.

   Accordingly, the quality of wireless communication links varies over time in FANET Motlagh et al. (2016). There are indeed many researchers investigating a wireless technology for communication in FANET. For that reason, modeling (i.e., statistically characterizing) the fading conditions in wireless communication requires more attention for a feasible FANET network. In the state of UAV-to-UAV communication, the channel-modeling problem has been investigated in Zhou et al. (2012). They proposed a two-state Markov model to incorporate the effects of Rician fading, depending on the changes of the distance between UAVs. The simulation results showed that the errors statistics are non-stationary of the wireless channels between UAVs. The characterization of ground-to-UAV, UAV-to-UAV, and UAV-to-ground communication links are studied in Ahmed et al. (2011). In this study, the comparison of each link type was done in both free space and two-ray ground approximation models. The authors of this study observed gray regions that was existed when the UAVs are close to the ground. These gray regions showed that each of the UAV-to-UAV links and two-ray ground model are similar in the radio propagation model. As a result, FANET protocol designers must have an awareness of the presence of gray zones due fading. For a feasible cooperative UAV network, the analysis of output probability over what is called the Nakagami-m fading channel has been presented in Abualhaol and Matalgah (2006). The received signal strength in a multi-path fading environment is estimated in this model, and it is simply defined as a function of two parameters: Fading Intensity and Average Received Radio Signal Strength. It is proposed that the fading conditions in the radio propagation in FANET communication is modeled by Nakagami-m fading distribution.

2. Antenna structure: Antennas transform wire-propagated waves into space-propagated waves. They receive electromagnetic waves and pass them onto a receiver or they transmit electromagnetic waves produced by a transmitter. Indeed, antenna structure can be considered as a crucial factor for an efficient FANET communication. Actually, the distance between UAVs in FANET is longer than the typical distance in other wireless ad hoc networks. This long distance has the direct effect on the FANET antenna structure. One of the solutions to overcome this problem is the use of high transmission power. However, FANET may face not only the high interference, but also the high variation and link loss could still arise because of this higher transmission power. In order to overcome this phenomenon, Kung et al. proposed in Kung et al. (2010) exploiting the channel's spatial / temporal diversity by using a multiple transmitter and receiver nodes that cooperate to improve overall packet reception. They showed that at small time scales the correlation between receiver nodes on the UAV is poor and thus using several receivers and transmitter will lead to boost packet delivery rates substantially.

   Another factor that affects the FANET performance is antenna type. Indeed, there are two types of antennas are utilized in FANET applications: Omnidirectional antenna that radiates the electromagnetic waves in all directions, and Directional antenna that directs a wave power to a desired direction. It is worth mentioning that node location information is not needed in the state of the omnidirectional antenna. Accordingly, it feasibly use in high mobility environments because of their natural advantage to transmit and receive signals. However, the directional antennas also have many advantages when compared to omnidirectional antennas. These advantages are summarized as following:

   - Long transmission range,
   - Decreasing hop count and thus enhancing the latency performance,
   - Handling the communication range and spatial reuse problem of omnidirectional antenna,
   - Enhance security, in fact the systems with directed antenna are less prone to jamming than the systems with omnidirectional antenna.

Accordingly, we can understand that the characteristics of the physical layer affect the overall FANET performance as a result of its effect on the design of the other layers. For this, the researchers should investigate the accuracy on their studies for the physical layer. Moreover, the performance analysis of the physical layer must be done in 3D environment instead of 2D as is the case in most of the current studies.

3.2.4 MAC Layer

One of the most significant topics in wireless ad hoc networks is the medium access control (MAC) layer. In these networks, the limited wireless spectrum, low complexity, time-varying propagation characteristics, energy constraints, and distributed multiple access control impose considerable challenges for MAC protocol design to provide reliable wireless communications with high data rates. Basically, FANET is a novel and upcoming mobile wireless ad hoc network. In this sense, the first examples of FANET use IEEE 802.11 MAC layer that is a random medium access control (MAC) with omnidirectional antenna and four way handshake procedures (i.e., RTS/CTS/DATA/ACK). These procedures are used to avoid collisions with long data packets in addition to handling the hidden node problem. However, the distinctive features of FANET such as its high mobility, variable link quality, and varying distances between UAVs impose new challenges on the FANET MAC design that need to be thoroughly studied by researchers. In addition, in some FANET applications such as the real time applications, the packet latency is considered another important design problem that must be bounded to ensure the accurate performance. Two promising technological advancements can be used to handle these problems: directional antenna and full-duplex radio circuits.

In Temel and Bekmezci (2015), Temel and Bekmezci proposed a Location Oriented Directional MAC (LODMAC) for FANETS that incorporates the location estimation of the neighboring nodes and directional antennas within the MAC layer. This study showed that LODMAC increases the spatial reuse and overall network capacity of FANETs in 3D space. In addition, the simulation results show that LODMAC outperforms on both DCF and DMAC protocols. In the same orientation, Alshbatat and Dong proposed Adaptive MAC protocol for UAVs (AMUAV) Alshbatat and Dong (2010). AMUAV is a directed antenna-based MAC protocol that uses omnidirectional antenna to send the control packets (RTS, CTS, and ACK) while using a directional antenna for sending data packets. Their simulation showed that the directed antenna based AMUAV protocol capable to improve the bit error rate, end-to-end delay and throughput for multi-UAV system.

Wireless nodes cannot transmit and receive data packets at the same time on the same channel for a long time, and also these nodes are incapable of receiving multiple packets simultaneously. However, with the current enhancements in communication technology, the full-duplex scheme of wireless communication became available. In this scheme, wireless nodes are able to exchange their data over the same frequency band and but without any discontinuities in time. Moreover, by using multiple packet reception (MPR), it makes each node capable of receiving multiple packets simultaneously.

In Cai et al. (2012),), the authors proposed a new token-based MAC layer for FANET with multipacket reception (MPR) radios in full-duplex mode, and frequent update of Channel state information (CSI), and thus UAVs can have the latest CSI information at any time. Even if the resulting channel knowledge is imperfect, the performance results have shown the effectiveness of the mentioned MAC layer.

It is accordingly obvious that one of the promising technologies for creating powerful MAC protocol is to use of the directed antenna. However, sharing the estimated location information among UAVs is considered as a crucial issue of this type of MAC protocols, which needs to be investigated and solved by the researchers.

3.2.5 Network Layer

As a result of the advancement in wireless communications, wireless networks can operate cost-effectively in both Ad hoc and infrastructure modes. In Ad hoc mode, nodes are self-organized and self-configured; accordingly saying how to route messages efficiently within the network has turned into a crucial issue. The primary purpose of a wireless ad hoc network routing protocol is to implement a correct and efficient route establishment between a pair of wireless nodes such as UAV, so that messages could be delivered in a timely manner. Routing protocols play a dominating role in enhancing the performance of the ad hoc networks **?**. For operating in Ad hoc mode, there exist different types of routing protocols proposed in literature Goyal and Tripathy (2012). Each routing protocol has its own advantages and disadvantages from the view of operational and information-theoretical characteristics. Routing protocols can be classified by different ways depending on various criteria. Such classification makes it easy to comprehend and contemplate the operational and information-theoretical characteristics in order to design some hybrid solutions to get composite advantages. The routing protocols classification on this paper will be as follows.

1. Classification Based on Updating Routing Information.
2. Classification Based on UAV-Role Information.
3. Classification Based on Message Transmission Awareness.
4. Classification Based on Energy Awareness.
5. Classification Based on Location.

In wireless routing protocols, there exist different types of measurements that include the key factors involved in the design of routing metrics. It is important to analyze these measurements to get a good knowledge about how the routing metrics are implemented in practice. There are various methods enable the metrics from obtaining the measurements they need **?**, which are listed as follows:

- *UAV-related*: The measurements for the metric are obtained from a UAV and have fixed, variable, or configured values, such as the number of UAV's interfaces, input and output queue's length, and financial communication respectively.
- *Passive monitoring*: In this case, the observation of the traffic coming in and going out of a UAV will be the method by which the measurements are gathered for the metric. Traffic load and interferences are considered examples of the measurements that can be obtained by this method.
- *Piggy-back probing*: By inserting probing information into the data or routing protocol messages, this method will be able to acquire the measurements for metric without creating and injecting a special probe packet into the wireless multihop network. In fact, the piggy-back probing is a common method to measure the delay.
- *Active probing*: With this method, special packets are inserted into the network in order to monitor and measure the link characteristics. It is worth mentioning that this method has some drawbacks such as increase the overhead, overestimation of the link quality because of loss the probe packets, and inaccurate measurements due to the intermittent nature of wireless links. However, it is considered a good solution to overcome the inability of some network card drivers to participate useful measurements such as the transmission rate.

As a result of the different characteristics and goals of the wireless multihop network systems and their applications, five major categories of measurements must be considered in the design of routing metrics. These categories are traffic-based, topology-based, radio-related, geography-based, and energy-related. In recent years, significant changes have been occurred for the network structure. Since 40 years ago, the only known and available network was the wired networks. However, as the wireless techniques continue to grow, the wireless multihop networks have been emerged as an efficient solution to meet the growing service requirements. However, these networks face several types of vital issues that influence on their performance and need to optimal solutions such as bandwidth constraints, power restrictions, high topology changes, etc. Andrews et al. (2008). One of the key solutions for these issues is to use of appropriate routing protocols in order to provide the optimal paths for directing of the traffic within the network. However, the routing protocol functions is affected by the pace of network topology changes. The routing protocols must be able to update routing tables or cashes dynamically based on these changes on topology. The dynamic nature of FANET results in frequent changes in the network topology and thus makes the routing process among UAVs in FANET a daunting task that needs to be addressed by researchers. Therefore, the data routing between UAVs undergoes a serious challenge or issue. In spite of FANET is a subcategory of MANET or VANET, Most of their protocols is not directly applicable for FANET Sahingoz (2014). In fact, some specific ad-hoc networking protocols have been implemented and some of the previous ones have been modified in order to be feasible in FANET. The design of effective routing metrics depends on the specific characteristics of a target network in addition to the measurements that set out in the previous sub-section. Accordingly, the routing metrics for wireless multihop networks have followed four main trends: Basic Metrics, Interference-Aware Metrics, Load-Aware Metrics and Hybrid Metrics.

Each metric can be readily considered as a set of measurements that are contributed into the route computation algorithms to estimate new weights for each hop / link in the routes. The weights, once aggregated, discourage selecting a route going through heavily loaded regions of the network topology. In this context for delivering messages successfully, the quality-aware routing (QAR) protocols utilize the quality metrics to select the most reliable route among all available routes (from the source node to the destination node). Although different link-quality routing metrics have been proposed, there have been only a few of them implemented and practically evaluated in real network. Implementing new quality metrics for wireless routing protocols involves with that adaptation of protocols and / or metrics, which is not straightforward. To improve the hop count metric, the expected transmission count (ETX) metric is proposed in De Couto et al. (2003). The ETX of a single hop path considers only the delivery ratios (message delivery probabilities) while the ETX of a multihop path considers not only the number of hops but also the delivery ratios of each hop; the summation of the ETXs along the multihop route path will give a selection cost of that route path. Similarly, the minimum loss (ML) is the other metric based on the delivery ratios. ML selects the route having the lowest overall loss probability by multiplying forward and backward delivery ratios of each hop through the route path. In wireless multihop networks, not only the message size but also the bandwidth of each hop is different. To adopt these two characteristics in route selection, the expected transmission time (ETT) metric is proposed in Draves et al. (2004). ETT is simply a delay-based routing metric that represents the time that the message requires to be transmitted successfully.

It is worth mentioning that there exists different delay-based routing metrics (such as improve expected transmission time (iETT), minimum delay (MD), and per-hop round trip time (RTT)) each of which has the same shortcomings identified by ETT. In the case of wireless multihop networks with fast link quality variation, the quality metrics that based on average values computed on a time-window interval may not be able to follow the link-quality variations or may produce expensive control overhead. To deal with this problem, Koksal, C.E. et al. Koksal and Balakrishnan (2006) proposed using the modified ETX (mETX) metrics. The mETX is able to capture the time-varying properties of a wireless hop/link in a way that could be directly translated into network and application layer quality constraints. Actually, the above metrics can be named as the basic routing metrics. Note that utilizing the usage of multi-channel instead of a single one can significantly improve the throughput of the wireless multihop network. In a multi-channel technique, the nodes can simultaneously transmit the messages to their neighborhood as long as they work in different channels. However, this technique must deal with two critical issues namely, intra-flow and inter-flow interference. As a matter of fact, the interferences have significant impacts not only on the throughput but also on the amount of delay in the network, and thus on the overall networks performance **?**. In order to deal with these two types of interferences, there are available in the literature different types of interference-aware routing metrics; such as weighted cumulative ETT (WCETT), metric of interference and channel-switching (MIC), interference aware routing metric (iAWARE), sum of motivated expected transmission time (SMETT), exclusive expected transmission time (EETT), interferer neighbors count (INX) , and interference and bandwidth adjusted ETX (IBETX).

Although both the interference and transmission rate affect the network performance, the traffic load on nodes is the other phenomena that should be participated in the route selection. By considering the remaining capacity on each hop as a load-sensitive metric, the routing protocols can adapt better to the actual available resources in the overall network, especially by avoiding the congestion of resource usages. Thus, considering a load balancing in the routing protocols can enhance the route decision in network. Currently, the load aware ETT (LAETT) metric and weighted cumulative expected transmission time with load balancing (WCETT-LB) metric are just variant types of the load-aware routing metrics proposed in the literature.

4 Conclusion

Unmanned aerial vehicles (UAVs) have already been applied to solve problems in a variety of applications in military and civilian domains. Indeed, complex tasks can be readily performed by using UAVs especially those in areas that are relatively inaccessible from the ground. As the UAV application range constantly expands, its working condition is getting more complex, and is always unknown and dynamic. Accordingly, the multi-UAV system has been emerged that can complete some tasks that cannot be completed by a single UAV system. Many advantages beyond a single UAV system are mentioned in the paper (such as coordination and cooperation, controller design and collaborative mission requirements), need to be investigated by the researchers. UAVs need to maintain communication links between themselves in order to accomplish their mission cooperatively. Thus, one of the most challenging design issues in the multi-UAV system is the communication. In literature there are lots of communication architectures such as satellite, cellular and flying ad hoc network (FANET). FANET has been proposed as the best solution to overcome these problems on the other types such as a limited communication range and the scalability. Within that context, a comprehensive review of the recent literature on flying ad hoc network (FANET) in terms to its unique features, challenges and open issues are presented. A detailed information is displayed about the measurements, metrics, and the currently available routing protocols for FANET. Accordingly, FANET represents a new era of ad hoc networks, which will offer a wide range of future applications to the community. It is worth to say that, lots of researchers and practitioners should study this type of ad hoc network to find solutions for the most challenging problems mentioned in the paper.

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