SWARM-BASED UNMANNED AERIAL VEHICLES – ROLES AND FUTURE POTENTIALS

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KEYWORDS: UAVs, Swarm, FANETs, VANETs, MANETs

ABSTRACT: Unmanned Aerial Vehicles (UAVs) have promising role to accomplish the complex tasks, particularly for the region that are inaccessible on the ground. The use of multi-UAVs requires cooperation with each-other UAVs and need a quick & easy deploying network system. Swarm-UAV system, consists of a number of flying devices connected with each other, and reduces the operation time and increase reliability of the system as compared to a single-UAV system. Communication is one of the most challenging issues for swarm UAV systems. To apply networking in non-line of sight, urban, aggressive and noisy environment, swarm UAVs is very effective and accurate. With the rapid development in wireless adhoc networks that do not rely on any pre-existing infrastructure, swarm UAVs provide efficient communication capabilities. Swarm-UAV system forms an ad-hoc network, called Flying Ad-hoc Network (FANET). The FANET is basically a special form of MANET/VANET. The Mobile Adhoc Network (MANET) consists of a number of mobile devices (i.e., laptops, cellular phones, sensors etc.) that together form a network as needed, without any support from any existing internet infrastructure or any other kind of fixed ground stations. The Vehicle Adhoc Networks (VANET) is composed of terrestrial vehicles as mobile nodes. Mobility degree of FANET nodes is much higher than that of MANET or VANET nodes. The FANETs have recently captured the attention of researchers due to the nature of entities in the flying network. This paper discusses the role of swarm-UAVs in various scenarios (FANET, MANET and VANET), including their future potentials in various applications.

1.1 Introduction

Unmanned Aerial Vehicles (UAVs) or Drones are flown autonomously or guided remotely without a human controlling these. The UAV is defined as "*an aircraft that can be remotely controlled or fly autonomously through software-controlled flight plans in their embedded systems*". Both the private and public sectors are deploying the UAVs as useful tools to provide required solutions as well as value-added services to users. The UAVs are typically used with Line of Sight (LoS) concept, i.e., the pilot can command and control the UAV from the ground without losing the sight (Garg, 2020). The number of application of UAVs is rapidly increasing, such as power line inspection, monitoring of traffic, environmental, disaster, fire and gas detection, healthcare, precision agriculture, etc., (Akram et. al., 2017). The low cost and fast mobilisation time of UAVs are main advantages for their main adoption in these applications. The traditional operation of UAVs has limitations as they have a limited payload and flight time, and are operated through a handheld transmitter or computer controlled software.

In many applications, UAVs would not operate individually but as a fleet of UAVs. Large number of UAVs/drones flying similar to flock of birds in order to perform coordinated tasks is known as swarm

UAVs/drones. Reliable communication amongst swarm UAVs is most essential to achieve the coordination (Garg, 2020). The utility of UAVs in swarming is that they add more functionality and perform tasks addressing the limitations of single UAV (Campion et. al., 2018). Some important features of a single UAV and multi-UAVs are presented in Table 1. Swarms give rise to a collective behavior distributed across many UAVs, and are capable of solving complex problems, resulting in a whole system greater than the sum of its parts. Advantages to swarm include time-savings, reduction in man-hours, reduction in labor, and a reduction in other costs. Swarm intelligent systems are robust, scalable, adaptable, and efficient problem solvers for several applications (Akram et. al., 2017).

Table 1. Features of single UAV multi-UAV (modified from Aljehani et. al., 2018)

S.No	Features	Single UAV	Multi-UAV system
1.	Failure of work completion	High	Low
2.	Speed of finishing work	Low	High
3.	Survivability	Poor	High
4.	Multitasks capability	Poor	High
5.	Reconfiguration	Low	High
6.	Ad-Hoc networks	Not possible	Optimal
7.	Heterogeneous	Not possible	Possible
8.	Complexity	Low	High

Swarm is not a new technology, as its applications and development has been proposed for military applications in early 1990s. There are several applications of UAV swarm system; entertainment, hobbyist, search and rescue, spot spraying during fire outbreaks, hunting thieves, providing Wifi coverage, national security, delivery of goods, etc. A single operator from the ground control station (GCS) can control large number of UAVs. The common natural flocking phenomenon/behaviour which has been observed in birds, fishes, insects etc., without losing direction and without hitting obstacles or each other, is explored for the development of UAV swarm system.

The UAV fleets may be behave like swarms, where artificial intelligence (AI) algorithms designed for the swarm intelligence paradigm can be applied. swarm intelligence takes inspiration from the collective behaviour of natural systems, such as swarms of ants (Akram et. al., 2017). These are inherently decentralized systems, having the ability to self-organise. The swarm's behaviour is often optimised using evolutionary algorithms based on swarm intelligence principles, such as (i.e., ant colony optimisation, bee-inspired algorithms and particle-swarm optimization). Autonomous swarm of UAVs may operate in remote locations with little or no control by a human operator but with communication capabilities. In autonomous UAVs swarm, multiple tasks can be performed simultaneously, and the workload can be distributed across the swarms.

Types of Swarm UAVs

A swarm is "*a set of aerial robots that are capable to perform a collective task for a specific goal that is created from interactions between unmanned aircraft and their environment*". The UAV swarm system can be either remotely controlled or controlled by automation algorithm. For certain applications, UAV fleets are likely to act autonomously and can make in-flight decisions without requiring instructions from the GCS (Garg, 2020). For some applications, all decisions might be taken by the GCS, which require UAVs to communicate information in real-time to the ground, and to quickly respond to any received instructions.

The swarm classification can be further sub-divided as (i) single-layered swarms with every UAV being its own leader, and (ii) multi-layered swarms with dedicated leader UAV at every layer, which report to their leader UAV at a higher layer; a ground control station (GCS) is the highest layer in this hierarchy (Tahir et. al., 2019). In each layered-swarm, every UAV will have dedicated data collection and processing with sufficient computing capability to perform these tasks in real-time. Its central processing takes place at the GCS or even in the cloud.

The swarm could be static or dynamic, depending on the applications (Figure 1). The static swarm is the most basic type, where the members of the swarm are pre-selected at the pre-mission stage. During the flight operation, no new drone can be added into the swarm as the collective mission is locked at the mission center. It provides secure communication, mutual-trust and collaboration. Dynamic swarm has the flexibility to add or remove a drone along with the existing group, at any time: pre-mission and/or during the mission. Such a system can either be a closed dynamic that only allows addition of new drones from the same organisation, or an open dynamic allowing addition of drones from a third-party organisations. The challenges of secure communication, mutual trust and collaboration are unique in comparison to static swarm.

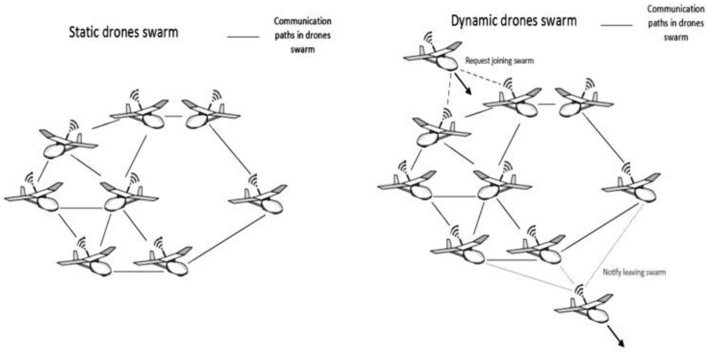

Figure 1 Static swarm and dynamic swarm of drones (Akram et. al., 2017)

Remotely controlled system requires monitoring and control of UAVs using either GCS or remote controller device, and UAVs communicate information to the ground system, potentially in real-time, and to quickly react to any received instructions. The transceiver sends and receives telemetry data from swarm UAVs. Telemetry data normally includes ground speed, and other parameters collected from payload sensors, including GPS.

The automated UAV systems adopt themselves based on complex algorithms, where each UAV is separately programmed to follow the specific flight path. There are varying levels of autonomy of UAVs which are based the number of tasks, coordination, or decision making of a UAV without input from an operator (Campion et. al., 2018). In such system, UAVs can self-organize based on the designed algorithm and communications from other UAVs, and based on communication during flight, they can respond to changing conditions automatically. Thus, they can exhibit flocking behavior, like birds or insects. The swarm of UAVs can also take advantage of the network they form to continue communication with the GCS, particularly when there are obstacles in the path between some UAVs and GCS, by simply relying messages to neighbouring UAVs to establish communication with the GCS.

A conceptual model is shown in Figure 2, where the process of fleet construction consists of two parts: pre-mission and post-mission. The model begins with the formulation of a mission with its objectives where the mission control center generates a mission brief that may include mission objectives, airspace regulations, ethical principles, security and privacy policies, organization commitments, baseline configuration, and collaborative knowledge (Akram et. al., 2017). The mission brief is then communicated to the ground flight management system (GFMS) that would select the drones participating in the mission, based on the mission requirements, drone availability and organisation preferences. The GFMS would then upload the mission brief to the selected drones. The selected drones would establish secure communication channel among themselves, before start of the swarm. After the completion of the mission, the swarm of drones returns back, where the GFMS communicates with each drone to download the mission logs, learning/evaluation matrix and other data that can contribute to the collaborative knowledge. The GFMS communicates this information to the mission control centre that would analyse the mission information and improves the collaborative knowledge.

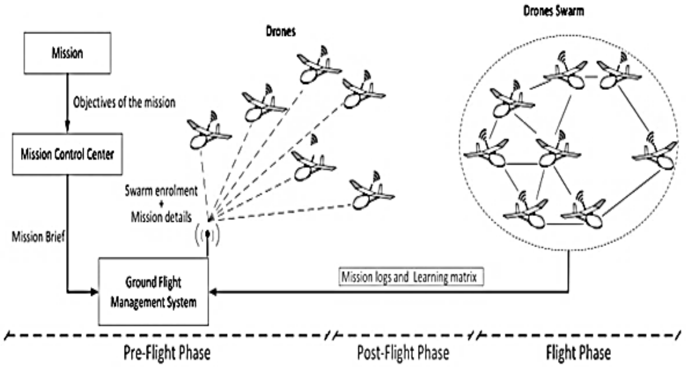

Figure 2 Two types of drones swarms (https://www.rfwireless-world.com/Terminology/How-Drone-Swarm-System-Works.html)

Advantages and Disadvantages of Swarm UAVs

The UAVs have several advantages in civilian applications, such as providing accessibility to hilly and difficult sites, availability of data from various sensors, continuous monitoring the region, quick real-time data acquisition, and many more. For example, the use of UAVs is found to be economical, quicker, and safer for inspection of structures (Gupta et. al., 2018). The biggest benefit of UAVs system is the acquisition of high spatial resolution images at desired frequency, and dense point cloud laser data, which could be used for planning relief in emergent situations. The advantages of the swarm UAV systems can be summarized as follows (Bekmezci et. al., 2013, Shakhatreh et. al., 2016, Garg, 2020):

1. The acquisition and maintenance cost of small UAVs is much lower than the cost of a large UAV.
2. They are more stealthy, and less noisy than a big UAV.
3. Being smaller in their weight, they are safer in the event of a crash for civilian applications.
4. The swarm behavior of multi-UAV can accomplish complex missions.
5. The usage of multi-UAV systems can extend the scalability of the operation easily, as compared to single UAV covering only limited area.
6. If the UAV fails in a mission operated by single UAV, the mission cannot proceed, whereas if a UAV fails in a multi-UAV system, the operation can still continue with the other UAVs.

7. UAV(s) can be added or removed from a swarm in order to better adapt to changing conditions or to replace the UAVs malfunctioning or having low battery.
8. The work in a mission can be completed faster with swarm UAVs.
9. Instead of one large radar cross-section, multi-UAV systems produce very small radar cross-sections that are difficult to see and hard to catch on radar, which is crucial for military applications.
10. UAVs swarm can also be linked to a GCS or to a satellite system. While some UAVs communicate with a GCS, while others can communicate with the satellite.
11. Swarms UAVs are cost effective to complete the task of a large area.
12. Military drone swarm system is equipped with anti-jamming and anti-radiation weapons in order to block hypersonic missiles, thus helps in providing security to war fighters and nation.
13. They can easily detect enemy targets and strike them down with smaller weapon loads.

There are some disadvantages, as listed below;

1. Small UAVs are very light and can carry only limited payload capacity.
2. One of the most prominent challenge is communication. As the number of UAVs increases, designing efficient network architecture is a challenging issue.
3. Militants and enemies can misuse the technology creating a threat to country.
4. Present UAV swarm system generates considerable noise, and also they are equipped with short range communication devices. These challenges are being analyzed to make UAV swarm system more robust in the future.
5. Designing UAV swarm system to cover greater distances is also a challenge issue.
6. Text based communication as compared to speech based communication between the GCS and UAVs is considered as difficult control option in time sensitive application/use.

The Swarm Architecture

A Flying Ad-hoc Network (FANET) is composed of network of nodes that fly at high altitude platforms, such as balloons, UAVs/drones (Garg, 2020). Traditionally, the software at the GCS controls each of the UAV in a swarm. In FANET, the UAVs is able to transfer the data to GCS individually, if they are within the influence range of existing ground infrastructure. As soon as a UAV is outside the range of coverage area of the GCS, it gets disconnected and no data can be made available. The effective design of network architecture for communication becomes a challenging issue as the number of UAVs increases. The UAVs perform a distributed task to send a continuous flow of information required to support the desired applications. The FANETs have gained commercial & industrial popularity in applications, such as surveillance, search & rescue, agriculture, journalism & media, etc. A FANET owns several unique characteristics that make it different from other systems, e.g., the possibility to extend enormously the operation coverage using ad-hoc communication.

The autonomous UAVs, on the other hand, make informed decisions using on-board hardware and processing software. The instant communication between the UAVs allows the swarm to adjust its configuration, as per the need. Real-time data/information collection and its real-time processing capabilities make UAVs swarm well-suited and demanding for applications, such as making a search over large areas in emergent situations (Kallenborn and Bleek, 2019). As the mobility level of swarm UAVs is high, the routing becomes one of the most important and critical to allow such cooperation (Bujari et. al., 2017). Present applications of UAVs swarm may utilize two main forms of architecture; (i) Infrastructure-based swarm architecture, and (ii) FANET-based architecture (Campion et. al., 2019).

Infrastructure-based swarm architecture

It is the most commonly used architecture so far (Chandrasekharan, 2016), and the UAV swarms in this architecture are directed and guided from a central GCS to accomplish the task. The software at GCS receives the signal/command from swarm UAVs, and sends signals/information to individual UAV independently (Shakhatreh, et. al., 2016). The main advantage of infrastructure-based UAVs swarm is that a GCS can perform computations in real-time using a high end computer. The UAVs in the architecture are however fully dependent on the directions received from the GCS for their effective and efficient coordination. The main disadvantage is that the entire swarm becomes inoperative in case of an attack or non-functional of the UAV. Moreover, the infrastructure-based approach works only if all the UAVs fly within range of the GCS. As the small UAVs can carry light payloads, the hardware required to establish the reliable communication with GCS would also pose the limitation on the utility of infrastructure-based swarms. With the infrastructure-based approach using FANETs, there might be several design limitations and issues (Tareque et. al., 2015), as individual UAV possesses an exclusive hardware to effectively communicate with a GCS or a satellite. The lack of distributed decision-making by the GCS algorithm makes this structure less demanding (Chandrasekharan, 2016).

FANET-based swarm architecture

This method uses multi-UAV systems for creating an ad-hoc network, popularly known as FANET, which minimizes the need of large infrastructure on the ground. In FANET network, a small number of UAVs communicate with the GCS or the satellite while all other remaining UAVs communicate between UAV-to-UAV (Garg, 202). Small UAVs, being economical, have applications in several businesses, including civil and military applications. The FANETs are also being deployed in areas, such as traffic management, security & surveillance, precision agricultural, forest fire, and relay networks (Bekmezci et. al., 2016). These swarm UAVs offer several advantages, such as faster exchange of information, less time to complete work, cost-effective, reliability of data, and greater possibility for scalability (Guillen-Perez and Cano, 2018).

The biggest issue for FANET is to provide all-time access to network resources at any given location. In several critical applications, such as disaster recovery operations due to an earthquake or flood, the use of FANETs becomes even much more challenging, where real-time data/information transmission is essential all the day. Thus, advanced technology related to wireless communication are required to be developed that is not only economical but also can be adopted for faster data communication with UAV-to-UAV and/or UAV-to-GCS. With the development in ICT, faster wireless communication technologies are also being developed; thus enhancing the potentials of smaller-sized UAVs for FANET-based applications in future (Khan et. al., 2019).

The FANETs can also communicate with other networks, e.g., *via* satellite or cellular system. The FANETs, mainly due to their greater mobility, minimum central control required, and flexibility of structure, can be used to enhance the connectivity and communication range in those areas that have limited or poor cellular infrastructure (Zafar and Khan, 2016). A relaying network of FANETs can be used to maintain a reliable connection between remote transmitters and receivers that are not able to directly communicate either due to larger distance or obstacles present between them. This technology, therefore, is expected to play an important role in the upcoming cellular networks, i.e., 5G networks (Mozaffari et. al., 2018) to provide higher speed and smaller latency. The FANETs would offer an economical solution for easy maintenance and further expansion of internet infrastructure world-wide (Azevedo et. al., 2019).

The FANET can be considered as another form of Mobile Adhoc Network (MANET) and/or Vehicle Adhoc Networks (VANET). The FANET, VANET and MANET are interlinked together, as FANET is a part of VANET, which is also a subpart of MANET (Zafar and Khan, 2016), as presented in Figure 3. The MANET consists of mobile nodes, such as laptops, cellular phones, tablets, wearables sensors, etc., that can form a network together as and when needed, without requiring any support from existing infrastructure or GCSs (Garg, 2020). The MANETs can be used for connectivity applications, node mobility models, routing processes, services, etc. The VANET is composed of vehicles, cars, buses, ambulances, van, trucks etc., which act as mobile nodes as they have onboard communication devices. Even though, the FANET has some common features with MANET and VANET, but still many features differentiate it with the remaining two, such as, mobility, topology changes, better connectivity, more application areas, and energy constraints (Guillen-Perez and Cano, 2018), as presented in Table 2.

Table 2 A comparison of three ad-hoc networks

Criteria	Ad-hoc networks		
	FANET	VANET	MANET
Mobility	Nodes mobility is high in 3D space	Nodes mobility is medium in 2D space	Nodes mobility is low in 2D space
Speed	Nodes speed is high, typically between 50-100 km/h	Nodes speed is medium, typically between 20-100 km/h	Nodes speed is lower, typically 6 km/h
Mobility model	Usually pre-determined models are used, but specific models incorporate independent UAV in multi-UAVs	Steady types model is used	Random types model is used
Node density	It has low thickness density	It has medium thickness density	It has low thickness density
Topology change	It is highly varying	It is medium change	It is slow change
Energy constrains	Medium to high	Low	Medium
Wave propagation model	It is above the ground in air, and LoS is available for all the cases	It is near ground, and LoS may not be there for all the cases	It is closes to ground, and LoS may not be there for all the cases
Power requirement	It is not required for small UAVs, but required for mini UAVs	It is not required separately.	It requires energy efficient protocols
Computational capabilities	It is large	It is average	It is very limited
Location	Uses GPS, DGPS, IMU	Uses GPS, DGPS	Uses GPS

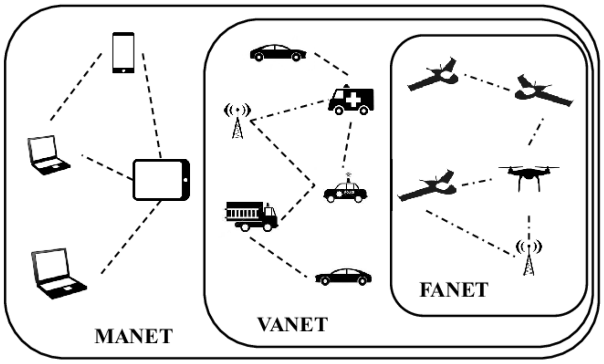

Figure 3 The FANET, VANET and MANET structures

Mobility of MANET or VANET nodes is very low as compared to the mobility of FANET nodes. Another major difference is that the FANET nodes are flying in the space/air, whereas typical MANET and VANET nodes are generally moving nodes on the ground. The FANET can be used to generalize and interpolate from 2D to 3D, because of the flexibility of UAVs to fly independently in 3D space (Souza et. al., 2019). The FANET nodes can move at varying speed, from static (e.g., in case of aerial coverage or relaying network-nodes) to flying between 50-100 km/h speed (e.g. in case of search and rescue work). In VANET, ground vehicle nodes are assumed to move at an average 100 km/h speed on highways and 50 km/h on urban roads in 2D plane. The MANET nodes generally have a very low mobility around 6 km/h (e.g., walking). In FANET, since the distances amongst the nodes are greater than in MANETs or VANETs nodes; so it requires higher communication range (Tareque et. al., 2015). In FANET, as the nodes fly high, there is no possibility of reflections received from the ground, buildings, or obstacles. In addition, the LoS is clearly seen between the inter-connected FANET nodes.

Market Potential of UAVs

Globally, some countries have taken a big lead to derive maximum benefits from the applications of UAVs, and they are driving the innovation in this market. The global UAV market offers several opportunities from flying UAVs to electronics, communications, sensors, scanners, cameras, and software. Figure 4 shows that for the year 2019, the market volume was 392,000 drones sold worth US$ 1.6 billion. Sales and revenue have been predicted up to year 2025. It was observed that the North America is by far the largest market for commercial drones, followed by Asia and Europe (Buchholz, 2019).

The market of UAVs/drones is growing at a fast rate in various sectors, such as consumer, commercial, and military. According to recent research PwC (2018), the UAV market globally is estimated to grow to US$ 19.85 billion by 2021, with a Compound Annual Growth Rate (CAGR) of 13% during 1997-2023. Thus, in future the drones will be used in a large number of applications, such as communication, construction, security & surveillance, search and rescue, precision agriculture, insurance sector, oil & gas, mining, traffic & transportation, mapping hazardous sites, military surveillance, weather & climate monitoring, photography and journalism, logistics, delivery of medicines and goods services and many more.

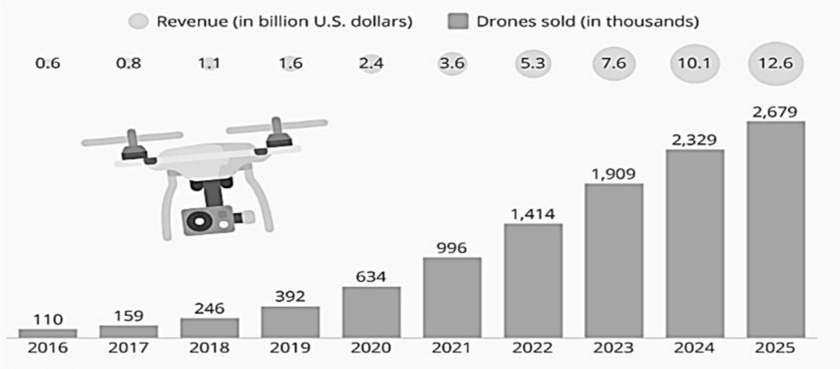

Figure 4 Drones market (Buchholz, 2019).

Conclusion

The UAVs/swarm UAVs are at present being used for applications, such as disaster, surveillance, healthcare, journalism, photography, movies, sports, real-estate, early warning system, emergency services, business, monitoring traffic, agriculture, military and spy, communication work, and many more. The use of UAVs in communication requires greater attention, such as an excellent coordination among the UAVs; an efficient control system; safe actions; and faster communication between UAV-to-UAV and/or UAV-to-GCS. Effective and reliable communication is the foundation for swarm-based applications (Campion et. al., 2019). The most notable application of UAV swarm is delivery services. Amazon and United Postal Service have indicated interest using UAVs for package delivery.

The swarm UAV-based communication provides promising application to wireless connectivity in mountainous terrain, remote locations, or areas having constant damages by recurring natural disasters. The use of multiple networked UAVs as relay nodes can enhance spectral and link connectivity and maintain reliable wireless communication links between users in an obstructed line-of-sight (LOS) environment. Despite the dynamic nature of UAV applications, the actions of UAVs operating together need to be coordinated in order to improve UAV-to-UAV and UAV-to-GCS communications (Tuna et. al., 2014). Several problems, such as control, cooperation and path planning need to be handled by swarm UAVs.

The FANETs, unlike the wired networks and MANETs, have highly mobile nodes and wireless communication links. They have recurring communication link disruptions depending upon the positions of UAVs and GCS. Therefore, new transport layer solution is required to be developed to have a reliable communication for different FANET applications. The 5G communication systems are expected to boast download speeds and will allow for additional data streaming including data types, such as video from payload cameras or data from payload light detection and ranging (LiDAR) systems. The ability to achieve low latency is important for UAV swarm communication. Another objective to 5G communications is machine to machine (M2M) communications that would provide a natural backbone for UAV swarm environments.

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