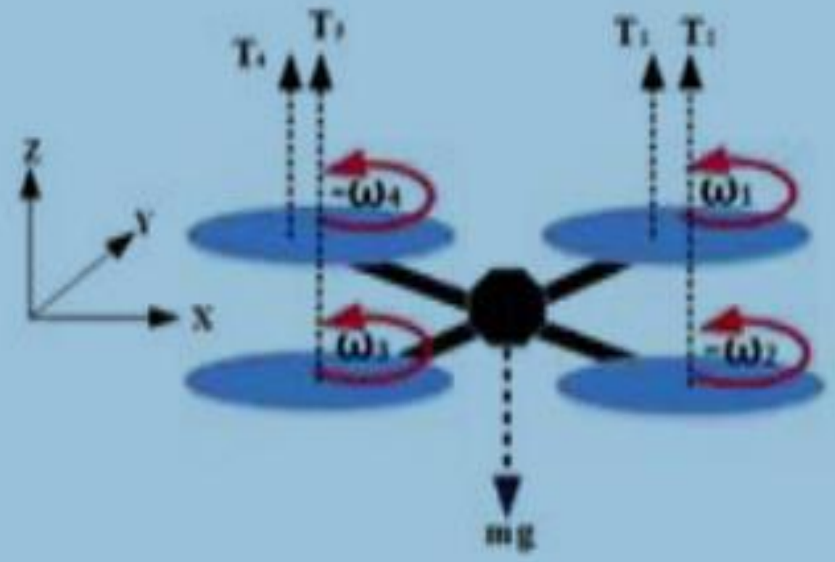
UAV NETWORKS

UAV: An unmanned aerial vehicle (also known as a drone) refers to a pilotless aircraft, a flying machine without an onboard human pilot or passengers.

- The FAA(Federal Aviation Administration) has defined an Unmanned Aircraft or UA as “A device used or intended to be used for flight in the air that has no onboard pilot”.
- This includes all classes of airplanes, helicopters, airships, and translational lift aircraft that have no onboard pilot.
- Unmanned aircraft are understood to include only those aircraft controllable in three axes and therefore, exclude traditional balloons.
- Control functions for unmanned aircraft may be either onboard or off-board (remote control).

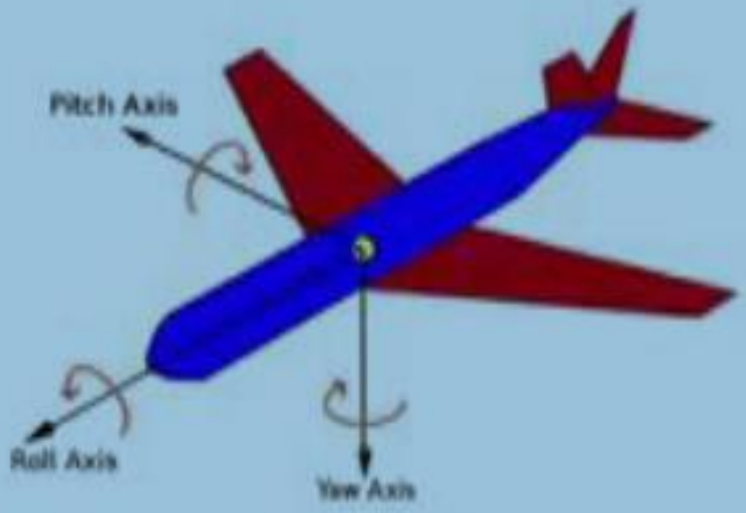
Basics of Aerial Systems



$$T = T1 + T2 + T3 + T4$$

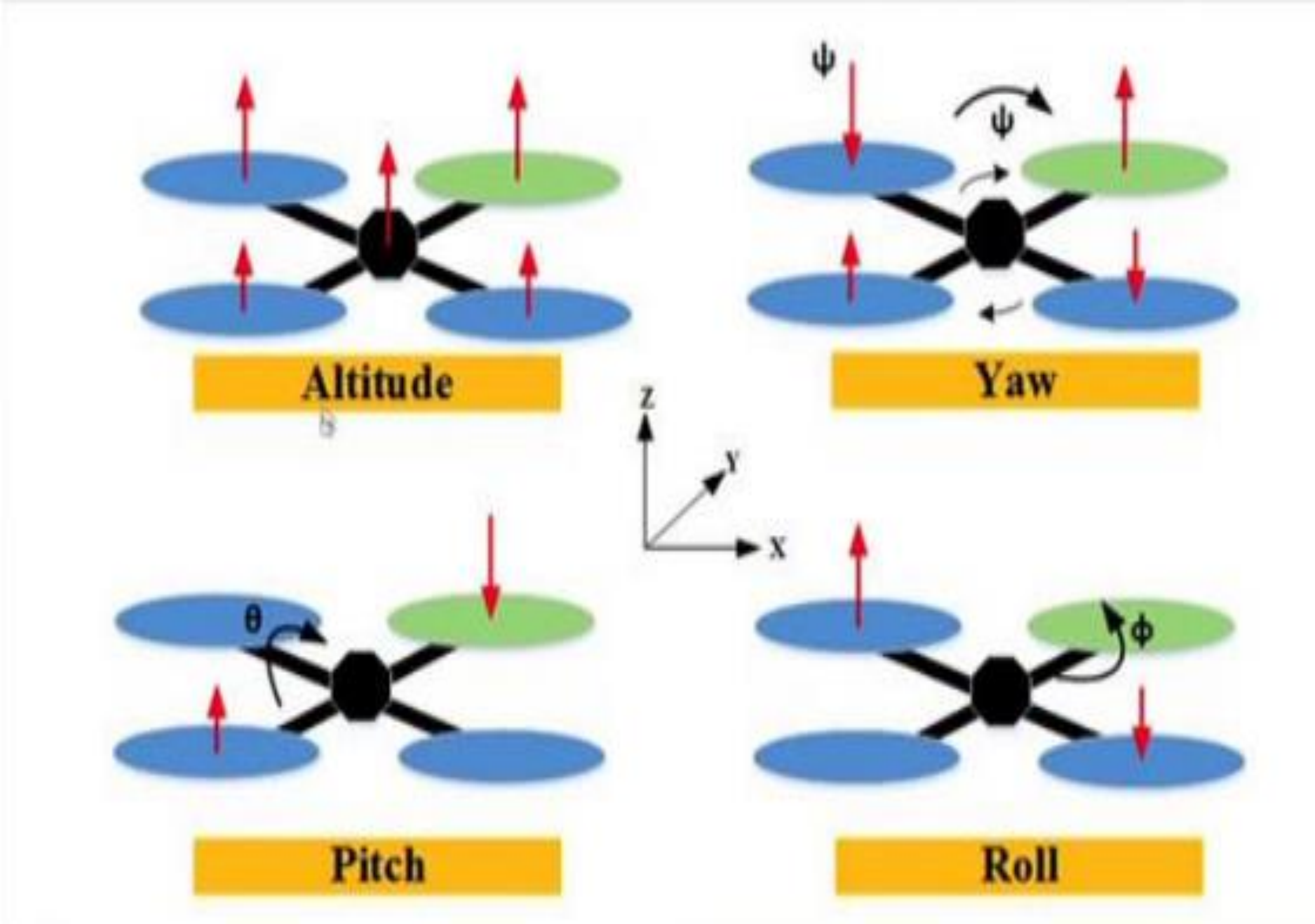
$$T > mg$$

- Forces:-
  - Thrust (T)
  - Angular velocity of motors (ω)



- Actions:
  - Yaw (along z-axis): ψ
  - Pitch (along y-axis): θ
  - Roll (along x-axis): ϕ

Aerial Systems: Actions



The Customisable Hex Copter

Ready to Fly Quad Copter

UAV

- Unmanned Aerial Vehicles
- Aircraft without an on-board human pilot or controller.
- May have various degrees of autonomy.
- Operated-
  - Remotely by a human operator Manual
  - Autonomously to achieve a defined mission- Autonomous
  - Autonomously, with minor human interventions - Hybrid

UAV Applications

- Unmanned aerial vehicles (UAVs), commonly known as drones, have been the subject of concerted research over the past few years, owing to their autonomy, flexibility, and broad range of application domains.

- UAVs are an emerging technology that can be harnessed for military, public and civil applications.

- Military use of UAVs is more than 25 years old primarily consisting of border surveillance, reconnaissance and strike.

- Public use is by the public agencies such as police, public safety and transportation management. They are likely to become invaluable inclusions in the operations of police departments, fire brigades and other homeland security organizations in the near future.

UAV Applications

- UAVs can provide timely disaster warnings and assist in speeding up rescue and recovery operations when the public communication network gets crippled.

- They can carry medical supplies to areas rendered inaccessible.

- In situations like poisonous gas infiltration, wildfires and wild animal tracking UAVs could be used to quickly envelope a large area without risking the safety of the personnel involved.

- Besides, advances in electronics and sensor technology have widened the scope of UAVs to include applications as diverse as traffic monitoring, wind estimation, powerline and pipeline inspection as well as remote sensing.

CASE STUDIES

3D View of Landslide

Mapping of Landslide Affected Area in **Meghalaya**

Infested Fields in Naramari Village, Morigaon District, Assam

Categorisation of BPH Infested Rice Fields

Infested Crop Damage Assessment

3D Reconstruction: MUDA Shopping Complex, Nongpoh

3-Dimensioinal Terrain Model Construction in Nongpoh, NE

UAV Classification

- **Classification based on MTOW:**

MTOW(Mean TakeOff Weight) is a good metric to classify aircraft for regulatory purposes since it correlates well with the expected kinetic energy imparted at impact, which in turn is considered to be the primary factor affecting safety of operations.

Class	MTOW (kg)	Range category	Typical max altitude (ft)
0	<25	Close range	1,000 ft
1	25–500	Short range	15,000 ft
2	501–2,000	Medium range	30,000 ft
3	>2,000	Long range	Above 30,000 ft

- **Classification based on Autonomy:**

ACL	Level descriptor
0	Remotely piloted vehicle
1	Execute preplanned mission
2	Changeable mission
3	Robust response to real-time faults/events
4	Fault/event adaptive vehicle
5	Real-time multi-vehicle coordination
6	Real-time multi-vehicle cooperation
7	Battlespace knowledge
8	Battlespace cognizance
9	Battlespace swarm cognizance
10	Fully autonomous

ACL: Autonomous control level

- **Classification based on function**

- Target and decoy – providing ground and aerial gunnery a target that simulates an enemy aircraft or missile
- Reconnaissance – providing battlefield intelligence
- Combat – providing attack capability for high-risk missions
- Logistics – delivering cargo
- Research and development – improve UAV technologies
- Civil and commercial UAVs – agriculture, aerial photography, data collection

- **NASA UAS Classification**

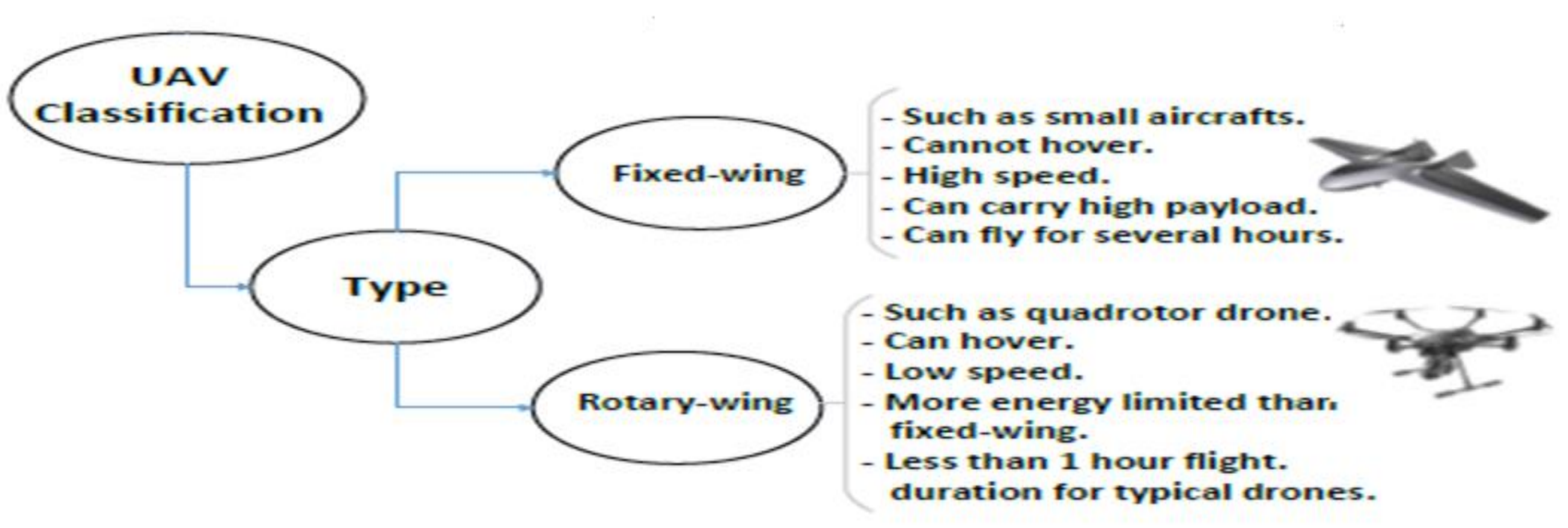
Category	I	II	III
Weight	< 55 lb (25 kg)	55-330 lb (25-150 kg)	> 330 lb (150 kg)
Airspeed (kt)	≤ 70	≤ 200	> 200
Type	Model or sUAS	sUAS	UAS

- **Classification based on weight, altitude and endurance**

	Mass (kg)	Range (km)	Flight alt. (m)	Endurance (h)
Micro	<5	<10	250	1
Mini	<20/25/30/150[a]	<10	150/250/300	<2
Tactical				
Close range (CR)	25–150	10–30	3.000	2–4
Short range (SR)	50–250	30–70	3.000	3–6
Medium range (MR)	150–500	70–200	5.000	6–10
MR endurance (MRE)	500–1500	>500	8.000	10–18
Low altitude deep penetration (LADP)	250–2500	>250	50–9.000	0.5–1
Low altitude long endurance (LALE)	15–25	>500	3.000	>24
Medium altitude long endurance (MALE)	1000–1500	>500	3.000	24–48
Strategic				
High altitude long endurance (HALE)	2500–5000	>2.000	20.000	24–48
Stratospheric (Strato)	>2.500	>2.000	>20.000	>48
Exo-stratospheric (EXO)	TBD	TBD	>30.500	TBD
Special task				
Unmanned combat AV (UCAV)	>1.000	1.500	12.000	2
Lethal (LET)	TBD	300	4.000	3–4
Decoys (DEC)	150–250	0–500	50–5.000	<4

- **Classification Based on Ownership:**
-
- **Public/State: O**wned and operated by public entities like federal agencies or local law enforcement agencies.
- **Civil: O**wned by industry or private parties.

- **Classification Based on Type:**



Federal Aviation Authority(FAA) guidelines on UAV Operations (2015, for a govt. public safety agency)

- Weight must be 4.4 pounds or less.
- Must be within the line of sight of the operator.
- Must fly less than 400 feet above the ground, during daylight conditions.
- Must be outside of 5 statute miles from any airport, heliport, seaplane base, spaceport, or other location.
- Should be flown a sufficient distance from populated areas and full scale aircraft.
- Must not be used for business purposes.

History of UAVs

- The earliest recorded use of UAV was in 1849 when Austria attacked Venice using UAVs.

- However the idea of building “flying machines” was first conceived close to 2,500 years ago, in ancient Greece and China!

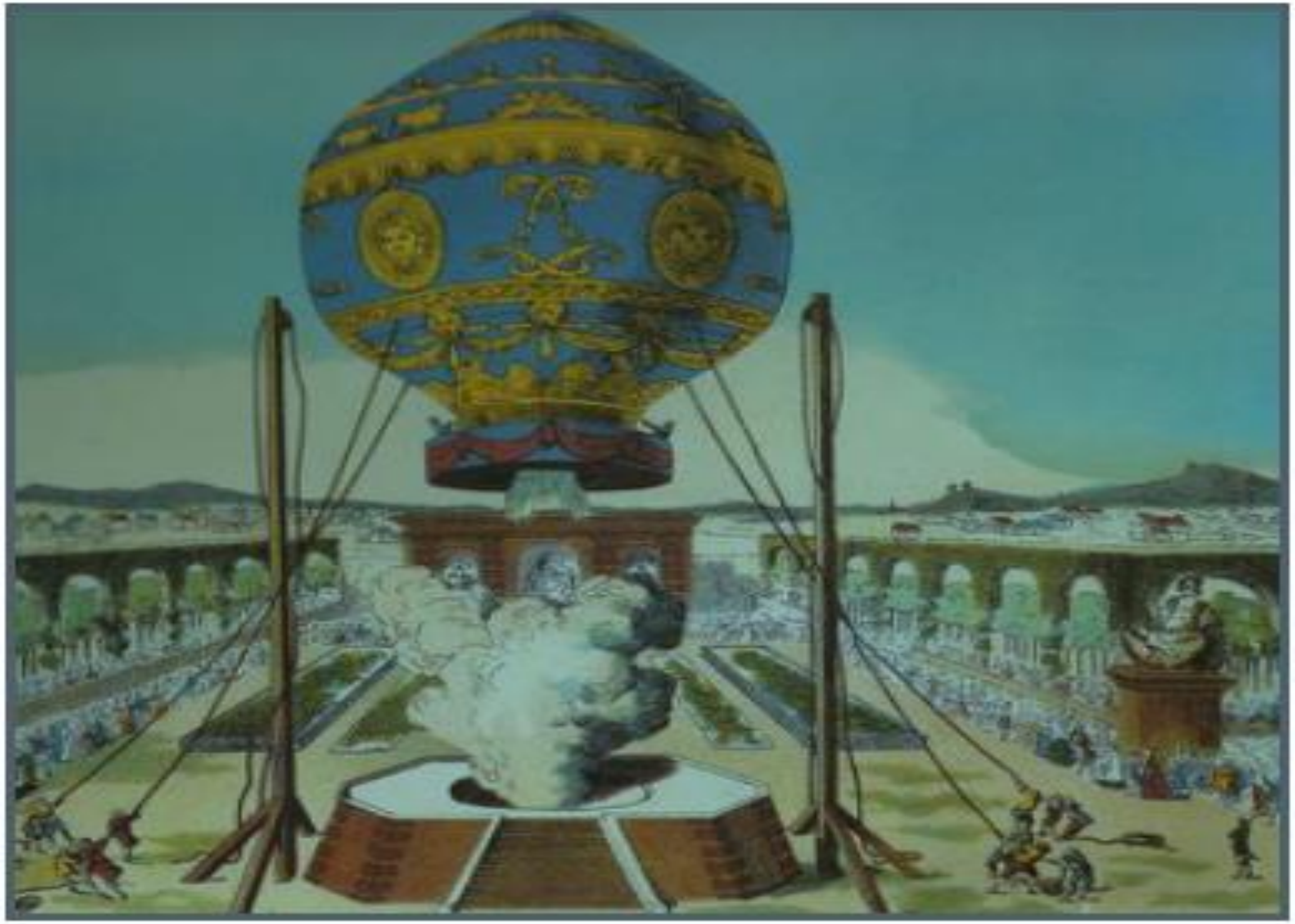
- In 425 BC Archytas built a mechanical bird called “the pigeon” which flew for about 200m.

History of UAVs

- During and after World War I, UAVs were used by US Army.
- In World War II Nazi Germany produced and used various UAVs.
- The V-1 flying bomb was the first cruise missile ever built. It was first tested in 1942. The V-1 was intended to target London and was massively fired, achieving more than one hundred launches a day.
- Target drones evolved post World War II.
- The use of drones as decoys goes back to at least 1950s.
- In 1946, eight B-17 Flying Fortresses were transformed by American airmen into drones for collecting radioactive data from the radioactive cloud.

History of UAVs

- During 1960s both USA and USSR developed reconnaissance drones.
- UAVs were used in Vietnam War during1966-1971.
- On August 21, 1998, *Laima* becomes the first Endurance UAV to cross the Atlantic Ocean, completing the flight in 26 hours.
- During 1980s solar powered UAVs were popular.
- As of 2012: US army employed 7494 UAVs.
- Recreational drones became popular in the United States in 2015.



The first manned flight using a hot air balloon in 1783 in France

History of UAVs

The SD-1, also known as the MQM-57 Falconer, was the first reconnaissance drone of the US Army and remained in service until the 1970s (Photo Credit: National Museum of the USAF)

The Neptune, a reconnaissance UAV capable of water landings (Photo Credit: US Navy)

Fig. The Helios UAV developed by NASA and AeroVironment. During its second high-altitude flight, it reached 96,863 ft, shattering the existing world altitude record for sustained level flight for both propeller and jet-powered aircraft (Photo Credit: NASA)

- World War I: Hewitt-Sperry Automatic Airplane
- 1935: The first scaled remote pilot vehicle was developed
- World War II: Nazi Germany produced and used various UAVs
- 1959: US Air Force began planning use of UAVs to reduce pilot loss
- 1964: UAVs were used for combat missions in Vietnam War

UAV NETWORKS

A network of UAVs can be viewed as a flying wireless network in which each UAV serves as a node transmitting its own information to other nodes or receiving the information intended for it or relaying information meant for others in the network.

The network could be ad hoc without any supporting infrastructure or it could be supported by ground-based and/or satellite-based communication infrastructures.

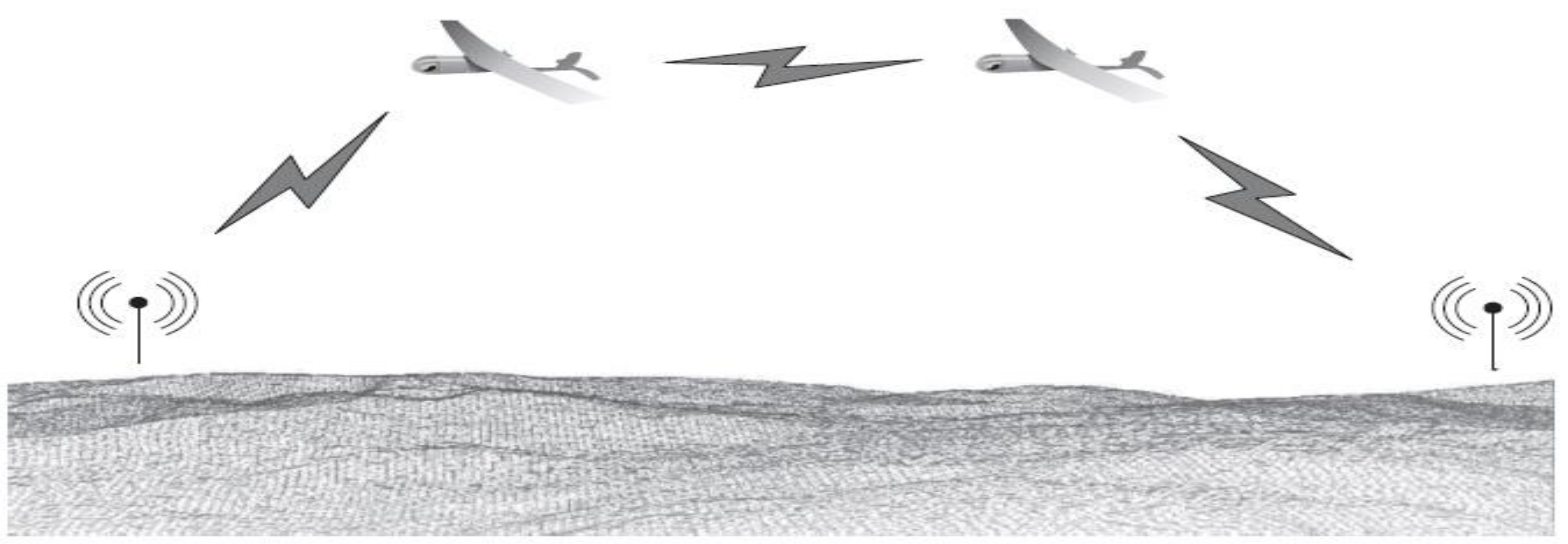


Figure Two UAVs working together as a simple relay network extending the range of coverage on the ground

UAV networks are basically not about single UAVs, but multiple UAVs which can communicate with one another.

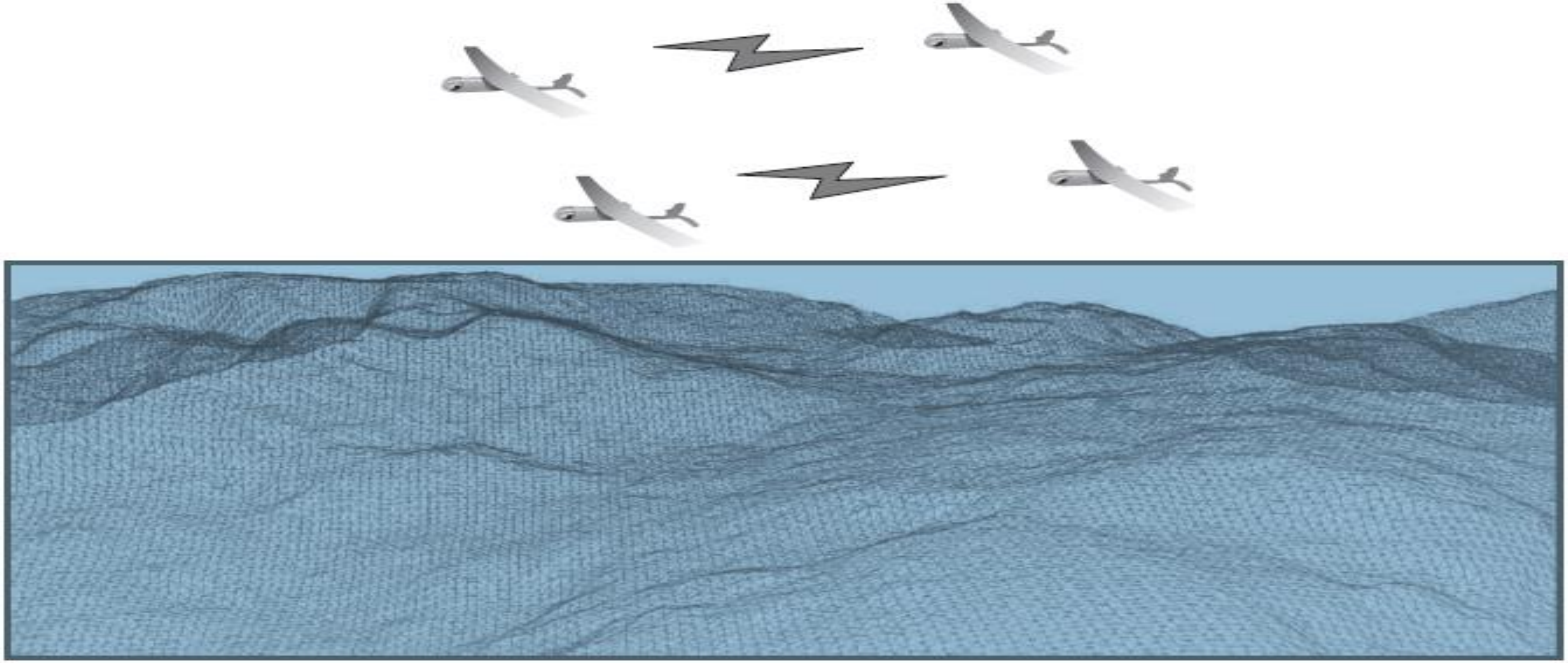


Figure Multiple UAVs forming an aerial mobile ad hoc network

Multi-UAV Network

- More than one UAV associated with the network
- UAVs are smaller and less expensive.
- Communication between UAVs and between ground node is important.
- Co-operation of UAVs.
- Degree of mobility

The topology or configuration of the UAV network: Mesh, star, or even a straight line. It primarily depends on the application and use case scenario.

A UAV enabled communication infrastructure provides a better alternative to ground based infrastructure, especially when a clear line of sight between a transmitter and receiver is not available due to uneven terrain or cluttered environment.

An aerial MANET is a multi-hop networking solution for delivering information over long distances.

Each node in the aerial MANET acts as a terminal as well as a relay node or router carrying information within the network.

In an ad hoc configuration, there is no need for any other infrastructure such as satellites or centralized servers to support the UAV swarm.

Global Positioning System (GPS) sensor helps to estimate and exchange geolocation information among the UAVs.

A UAV network with ground- and satellite-based communication infrastructure is commonly known as an airborne network.

Since aerial nodes move much faster than nodes on the ground, the topology of an aerial network will be very dynamic.

The extremely changing dynamics require specific protocols for routing and secure information exchange.

In addition, sense-and-avoid and situational awareness strategies are necessary to make sure that the nodes maintain a minimum safe distance during their flight.

Airborne networks are unique and significantly different from vehicular networks involving only ground vehicles in many perspectives.

Classical mobility models and security strategies designed for MANETs and ground vehicular networks are not suitable for airborne networks.

An airborne network is a cyber physical system (CPS) in which there is an intense interaction between its physical and cyber components.

The fundamental challenge for airborne networks is to bring the synergistic interactivity between its cyber and physical components.

Mobility Models in MANET

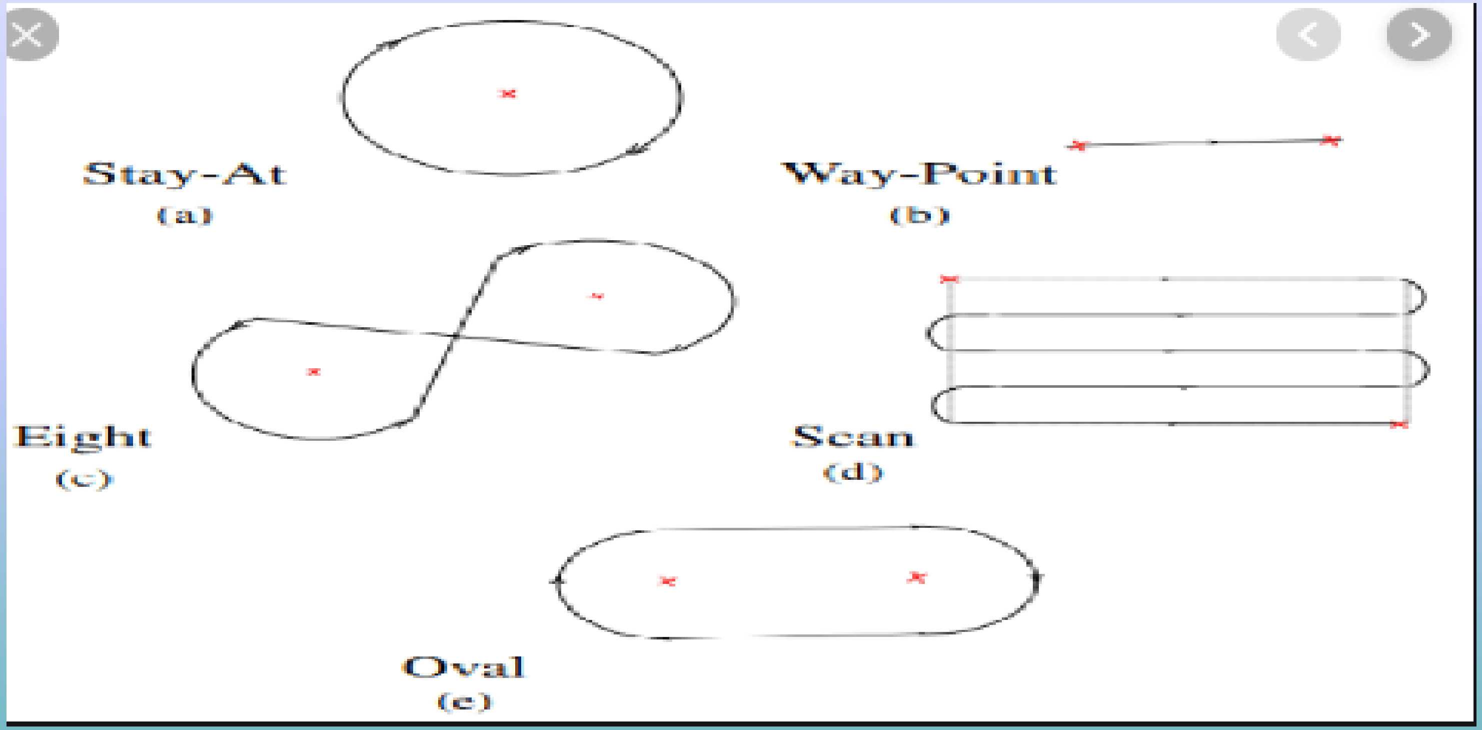
- Random Walk Mobility Model
- Random Waypoint Mobility Model
- Random Direction Mobility Model
- A Boundless Simulation Area Mobility Model
- Gauss-Markov Mobility Model
- A Probabilistic version Random Walk Mobility Model

Mobility Models in UAV Networks

- 3D Gauss Markov Mobility Model
- Semi-Random Circular Movement Mobility Model
- Smooth Turn Mobility Model
- 3-Way Random Mobility Model
- Flight –Plan Based Mobility Model
- Multi-Tier Mobility Model.

Mobility Models in UAV Networks

- **Pheromone Mobility Model**
- **Paparazzi Mobility Model**



5 movements in Paparazzi Mobility Model

UAV Systems: Features

Feature	Single UAV System	Multi-UAV System
Failures	High	Low
Scalability	Limited	High
Survivability	Poor	High
Speed of Mission	Slow	Fast
Cost	Medium	Low
Bandwidth required	High	Medium
Antenna	Omni-directional	Directional
Complexity of Control	Low	High
Failure to coordinate	Low	Present

Features of the UAV Networks

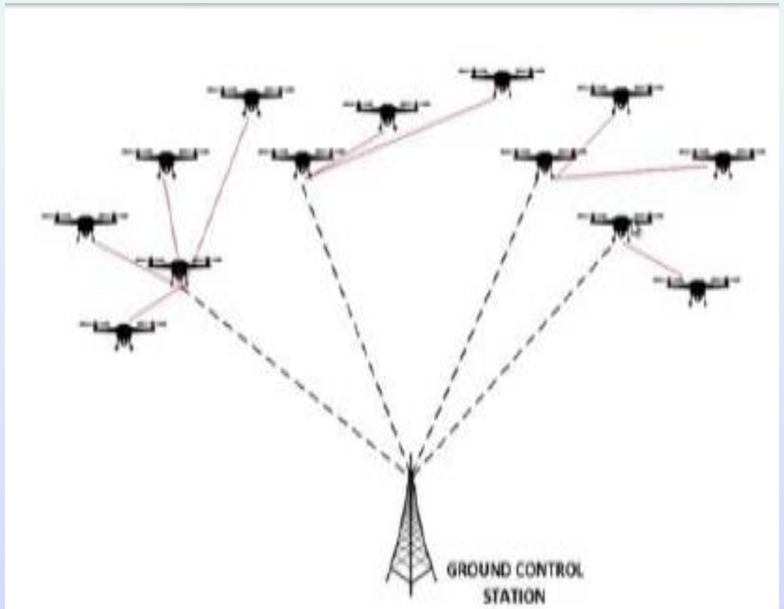
- Infrastructure-based or Ad Hoc?
  - Constant inter network with UAVs and a control center may be treated as infrastructure based network
  - Highly mobile nodes change their position and communicate, co-operate and establish the network dynamically in Ad Hoc manner.

- Server or client?
  - Usually server.
  - Routing packets for clients.
  - Relaying sensor data to control centers.

Star or Mesh?

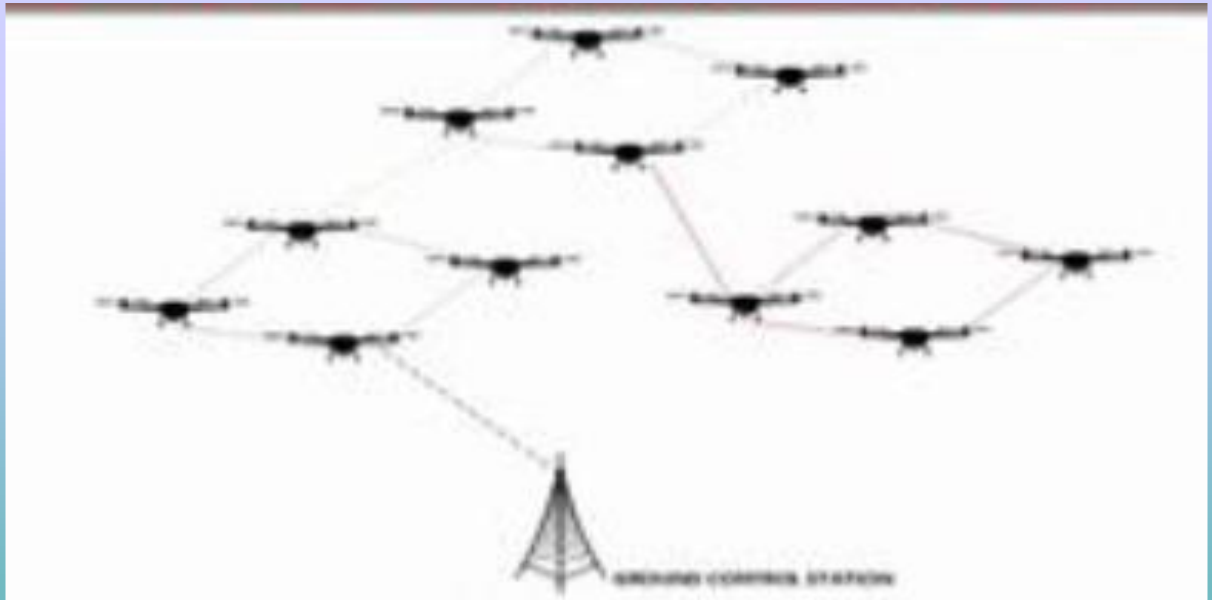
- Star :
  - Typically two types –
    - Star Configuration,
    - Multi-star Configuration .
  - In Star Configuration, UAV is directly connected to the ground station.
  - In Multi-star Configuration, UAVs form multiple star topology. One node from each group connects to the ground station.
  - High latency.
  - Highly dependent on ground station.

Star Configuration



Multi-star Configuration

Flat Mesh Network



Hierarchical Mesh Network

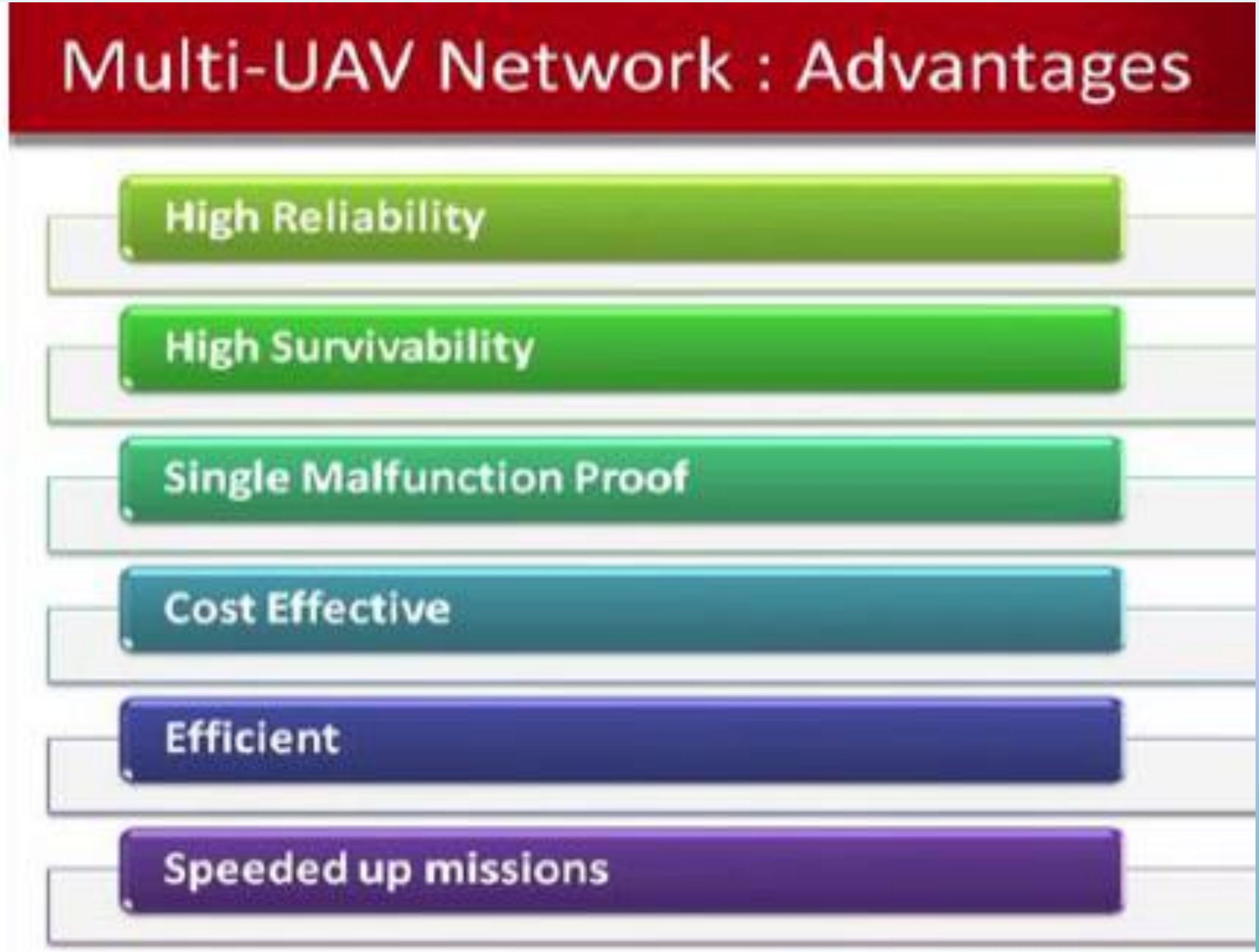
Star Network	Mesh Network
Point-to-point	Multi-point to multi-point
Central control point present	Infrastructure based may have a control center, Ad hoc has no central control center
Infrastructure based	Infrastructure based or Ad hoc
Not self configuring	Self configuring
Single hop from node to central point	Multi-hop communication
Devices cannot move freely	In ad hoc devices are autonomous and free to move. In infrastructure based movement is restricted around the control center
Links between nodes and central points are configured	Inter node links are intermittent
Nodes communicated through central controller	Nodes relay traffic for other nodes

UAV Topologies are prone to different types of disruptions and Delays.

- Disruptions depend on mobility, power transmission, inter-UAV distances, extraneous noise.
- Delay depends on poor link quality, end-to-end path not being available.

Multi-UAV Network : Constraints

- Frequent link breakages
- Prone to malfunction
- Huge power requirements
- Very complex
- Physically prone to environmental effects: winds, rain, etc.


Multi-UAV Network : Advantages
High Reliability
High Survivability
Single Malfunction Proof
Cost Effective
Efficient
Speeded up missions

Challenges in UAV Networks

- UAV networks remain fluid: Topology, number of nodes, links, etc change fast.
- Challenges for simple proactive or a reactive routing scheme.
- Conserving energy.
- Prone to environmental disturbances such as winds, rain, birds, animals, etc.
- Localization
- Maintaining coverage
- Path planning

COMPARATIVE STUDY

	MANET	VANET	UAV Networks
Description	Mobile wireless nodes connect with other nodes within communication range in an ad-hoc manner(No centralized infrastructure required)	Ad-hoc networks in which vehicles are the mobile nodes. Communication is among vehicles and between vehicles and road side units.	Ad-hoc or infrastructure based networks of airborne nodes. Communication among UAVs and with the control station
Mobility	Slow. Typical speeds 2 m/sec. Random movement. Varying density, higher at some popular places	High-speed,typically 20-30 m/s on highways, 6-10 m/s in urban areas. Predictable, limited by road layout,traffic and traffic rules	Speeds from 0 to typically as high as 100 m/s. Movement could be in 2 or 3 dimensions, usually controlled according to mission
Topology	Random, ad-hoc	Star with roadside infrastructure and ad-hoc among vehicles	Star with control center, ad-hoc/mesh among UAVs.

COMPARATIVE STUDY

	MANET	VANET	UAV Networks
Topology Changes	Dynamic - nodes join and leave unpredictably. Network prone to partitioning.	More dynamic than MANETs. Movement linear. Partitioning common.	Stationary, slow or fast. May be flown in controlled swarms. Network prone to partitioning
Energy Constraints	Most nodes are battery powered so energy needs to be conserved.	Devices may be car battery powered or own battery powered.	Small UAVs are energy constrained. Batteries affect weight and flying time
Typical use cases in public and Civil domains	Information distribution (emergencies,advertising,shopping, events) Internet hot spots	Traffic & weather info, emergency warnings, location based services, infotainment	Rescue operations, Agriculture-crop survey , Wildlife search, Oil rig surveillance

COMPARATIVE STUDY

Characteristics	MANETs	VANETs	UAV Networks
Density	High	High	Low
Network connectivity	High	Medium	Low
Energy autonomy	Low	High	High (Depends on UAV kind)
Topology variation	Occasionally	Frequently	Very frequently
Scalability	Medium	High	Low
QoS	Low	High (Depends on the application)	High (Depends on the application)
Mobility models	Random	Restricted through roads pattern	Predefined by mobility models
Node speed	Medium	High	Very high

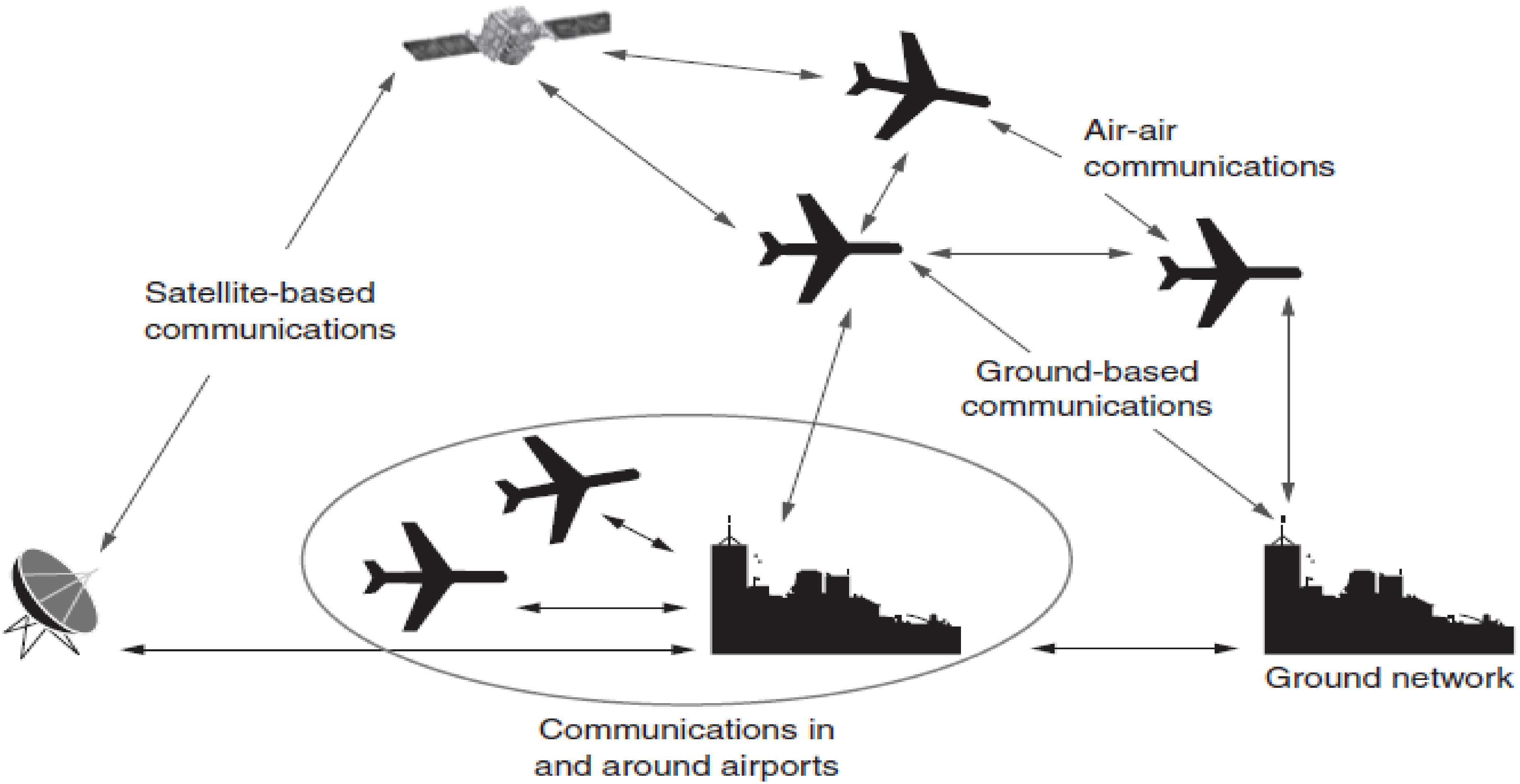


Figure A real-world airborne network consisting of unmanned aerial systems as well as the satellite- and ground-based communication infrastructure

Categorization of UAV Networks

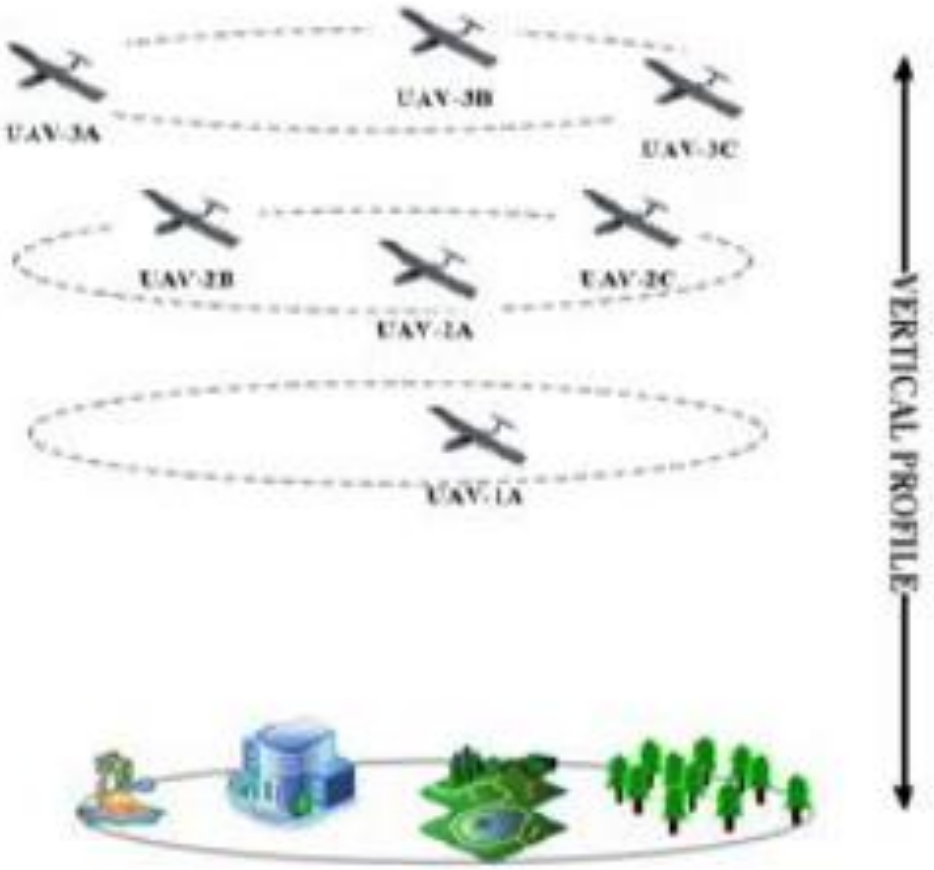
- Internet delivery
- Sensing
- Attack

- Internet Delivery :
  - Application: Disaster communication , Oil exploration , Remote health etc.
  - Network : Infrastructure based, base station in the sky.
  - Topology : Star/Mesh.
  - Control (communication) : Centralized (position control based).
  - Client or Server: Server (routes communication and control).
  - Routing: Through server

- Sensing :
  - Application : Reconnaissance, search, detecting forest fires, tracking wild animals etc.
  - Network : Infrastructure based.
  - Topology : Mesh.
  - Control (communication) : Centralized (task control based).
  - Client or Server: Server (when receiving from sensors) / client(when carrying sensors)
  - Routing: Central or mesh (control from central data to central, also data among UAVs)

- Attack :
  - Application : War Multi-UAV attack
  - Network : Infrastructure based/Infrastructure less, Ad-hoc
  - Topology : Mesh.
  - Control (communication) : Distributed (task control based),Individuals controlling each UAV.
  - Client or Server: Server (delivering info to formations) /client (for attack).
  - Routing: Mesh routing (control from central, data among UAVs).

FANETs: Flying Ad Hoc Networks

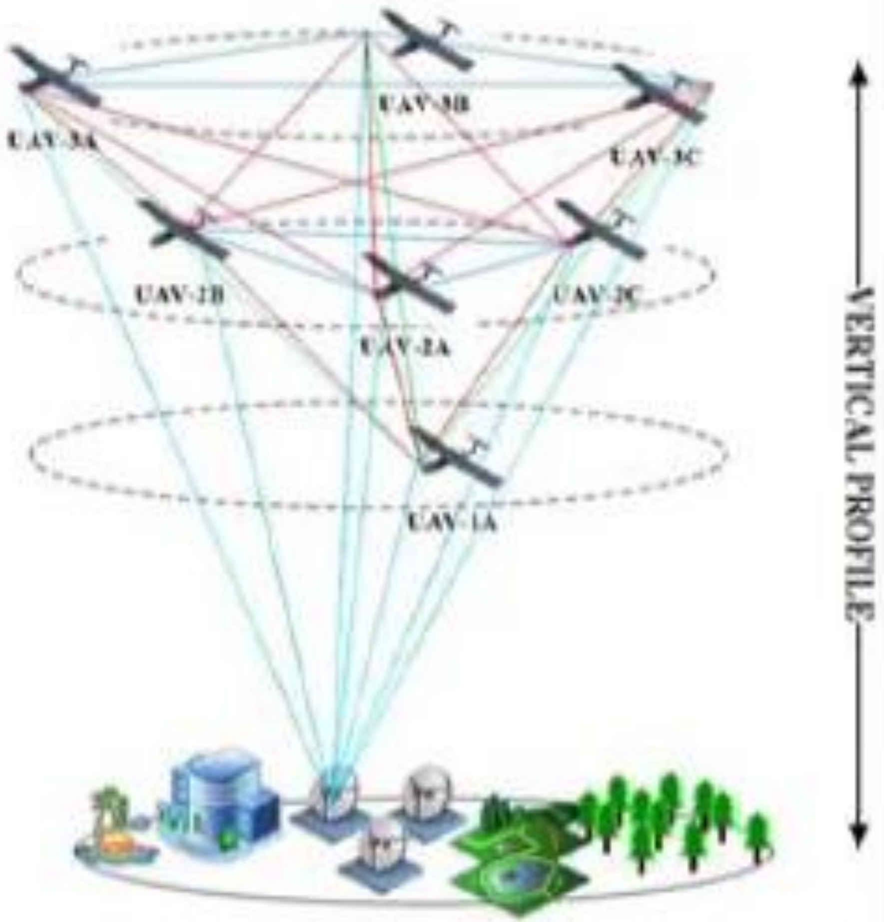


- Network formation using UAVs which ensures longer range, clearer line of sight propagation and environment-resilient communication.
- UAVs may be in same plane or organized at varying altitudes.
- Besides self-control, each UAV must be aware of the other flying nodes of the FANET to avoid collision.
- Popular for disaster-time and post-disaster emergency establishment.

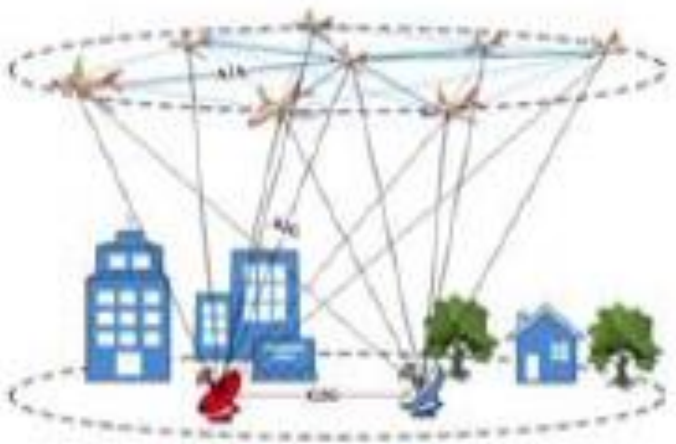
FANETs: Flying Ad Hoc Networks (Contd...)

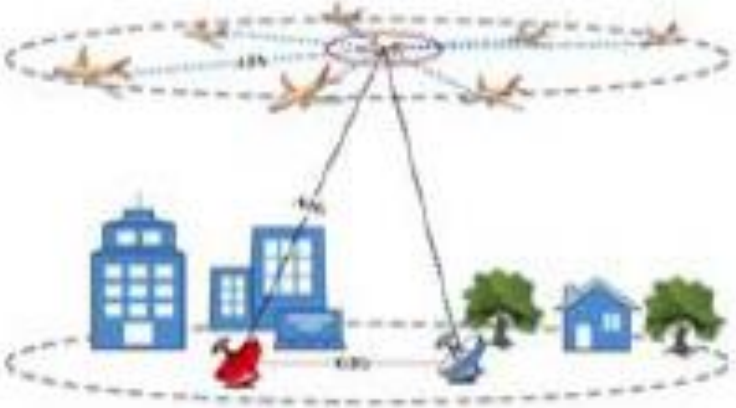
Features:

- FANET Inter-plane communication
- FANET Intra-plane communication
- FANET- Ground Station communication
- FANET- Ground Sensor communication
- FANET-VANET communication



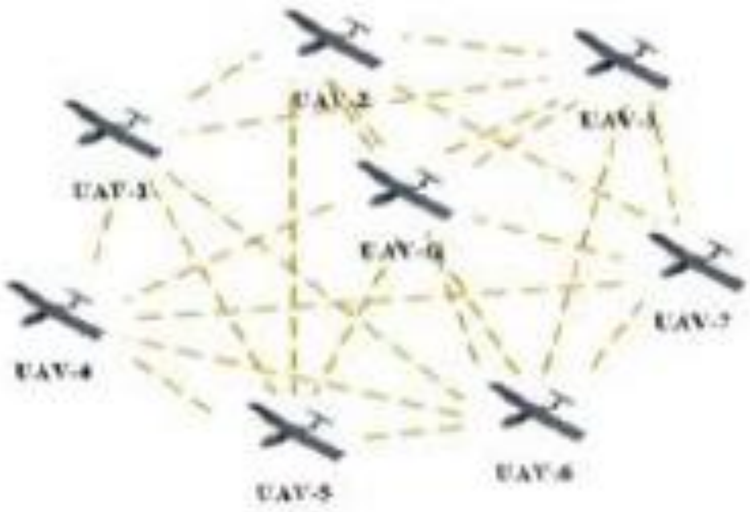
FANET & Ad Hoc Networks





- A2A links for data delivery among UAVs.
- Heterogeneous radio interfaces can be considered in A2A links, such as XBee-PRO (IEEE 802.15.4) and Wi-Fi (IEEE 802.11).
- Ground networks may be stationary WSNs or VANETS or Control stations.
- UAV-WSN link-up may be used for collaborative sensing as well as data-muling.
- UAV-VANETS link-up may be used for visual guidance, data-muling and coverage enhancement.

Distributed Gateway Selection



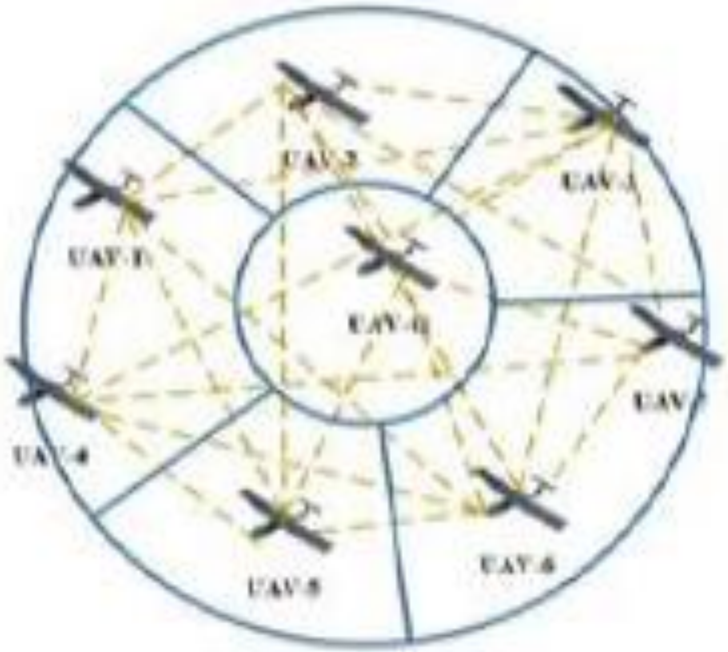
Main communication requirements of UAV networks are:

- Sending back the sensor data.
- Receiving the control commands.
- Cooperative trajectory planning.
- Dynamic task assignments.

Number of UAV-ground remote connections should be controlled to avoid interference.

Reduced nodes in the UAV network should act as gateways, to allow communication between all UAV and the ground

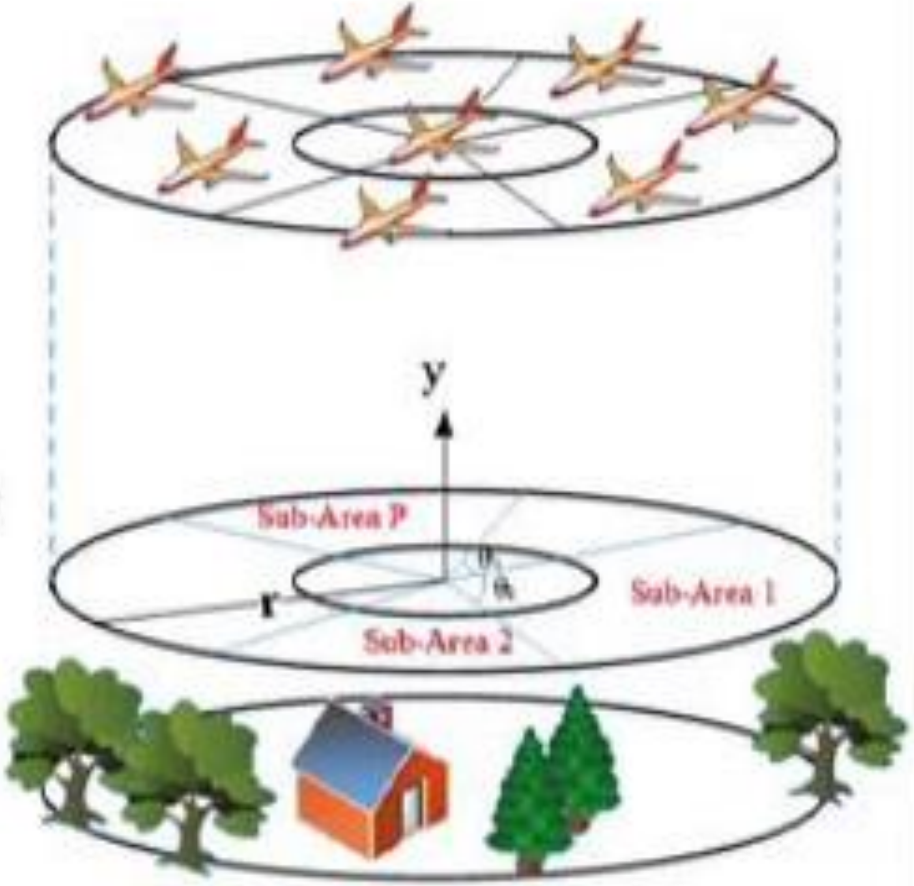
Distributed Gateway Selection



- Entire UAV network coverage area divided into sub-areas.
- Sub-areas collectively cover the entire communication area.
- Size of sub-area to be controlled and adjusted dynamically.
- Adjustments based on UAV-interconnections and derived metrics.
- The derived metrics are optimized for several iterations till optimum state is achieved.

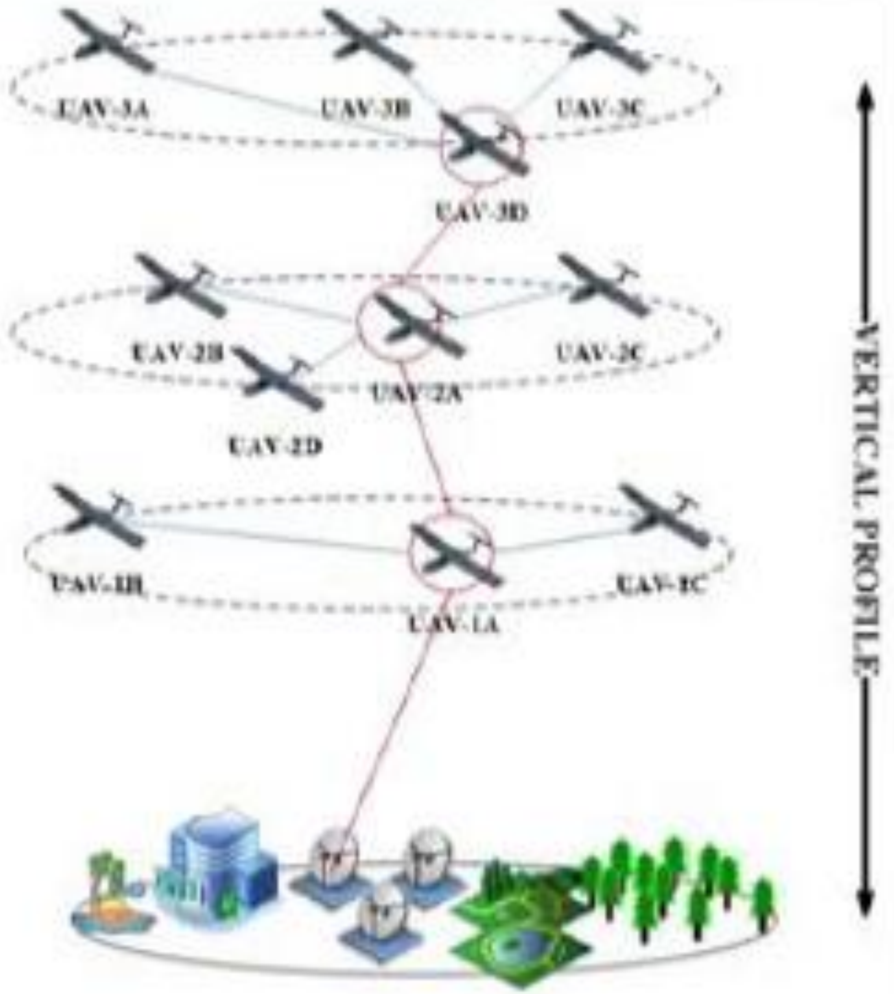
Distributed Gateway Selection

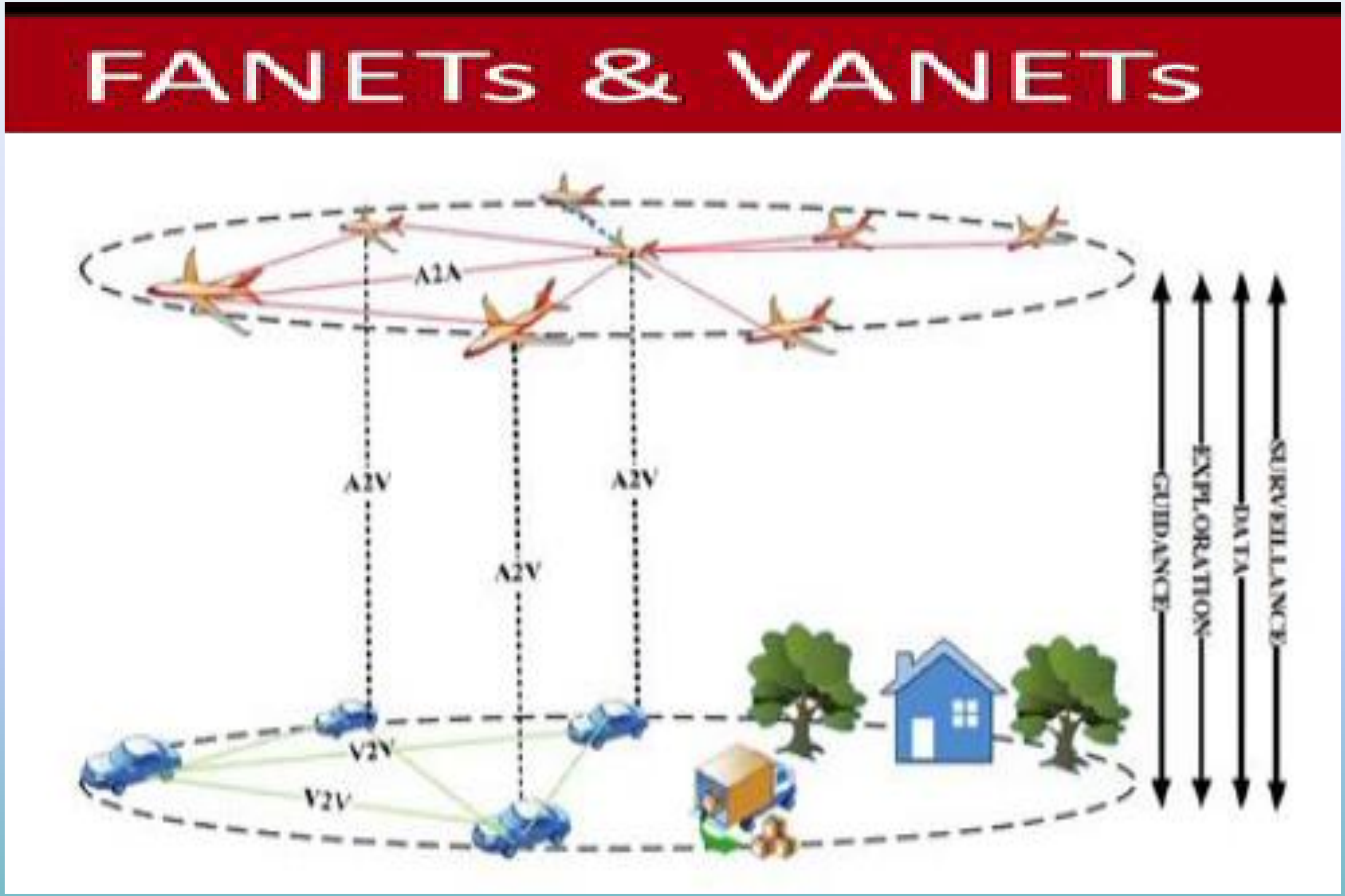
- Gateway selection initiated by selection of the most stable node in the sub-area.
- Consecutively, the partition parameters are optimized according to topology.
- Each UAV acquires the information of all UAVs within its 2 hops.



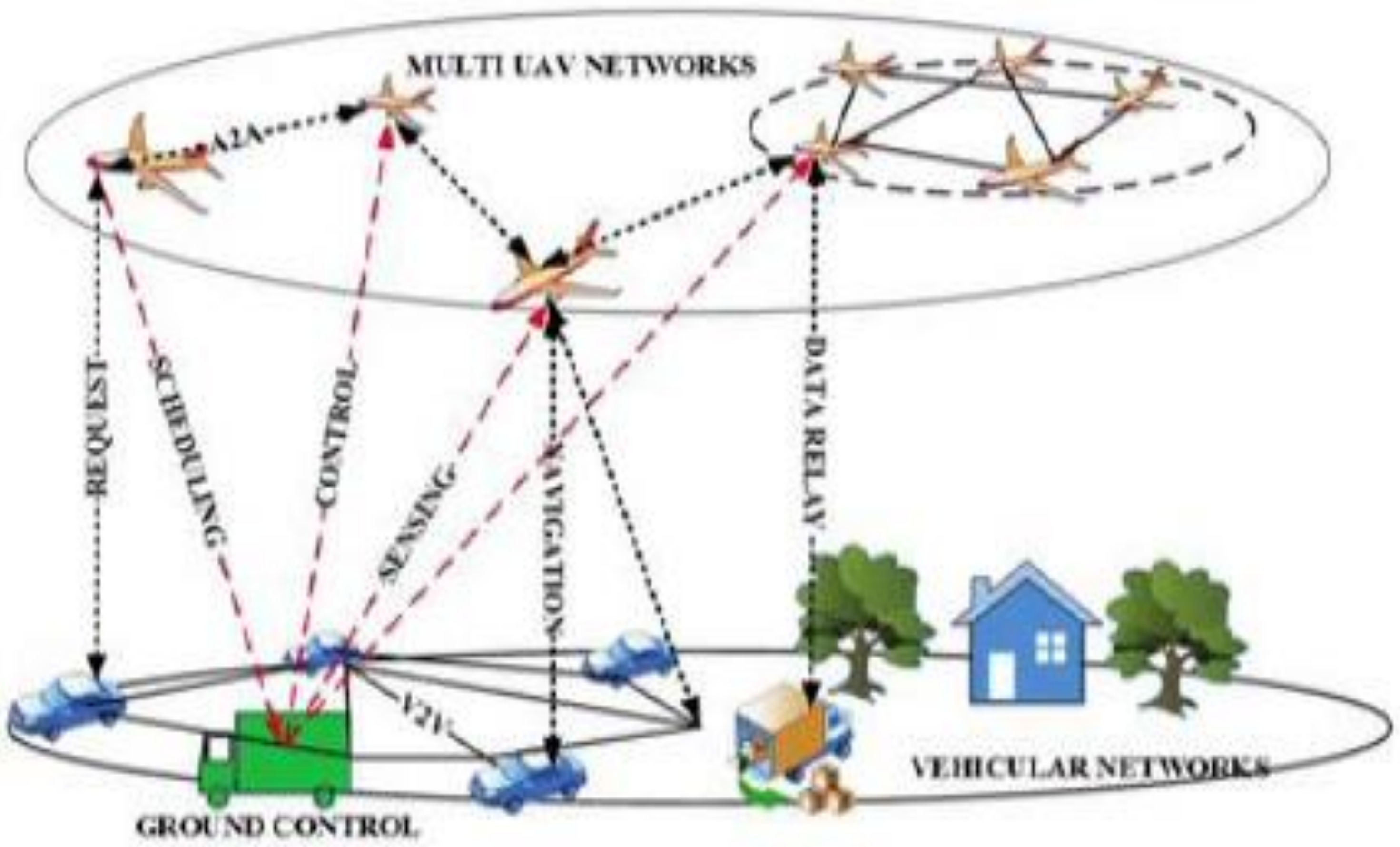
Layered Gateway In FANETs

- Multi-layered UAV topologies select one gateway.
- The gateways from each layer communicate to forward information between layers, as well as from ground control.
- Will increase the delay between ground control and higher layers.
- Not suitable for time-critical relaying tasks.

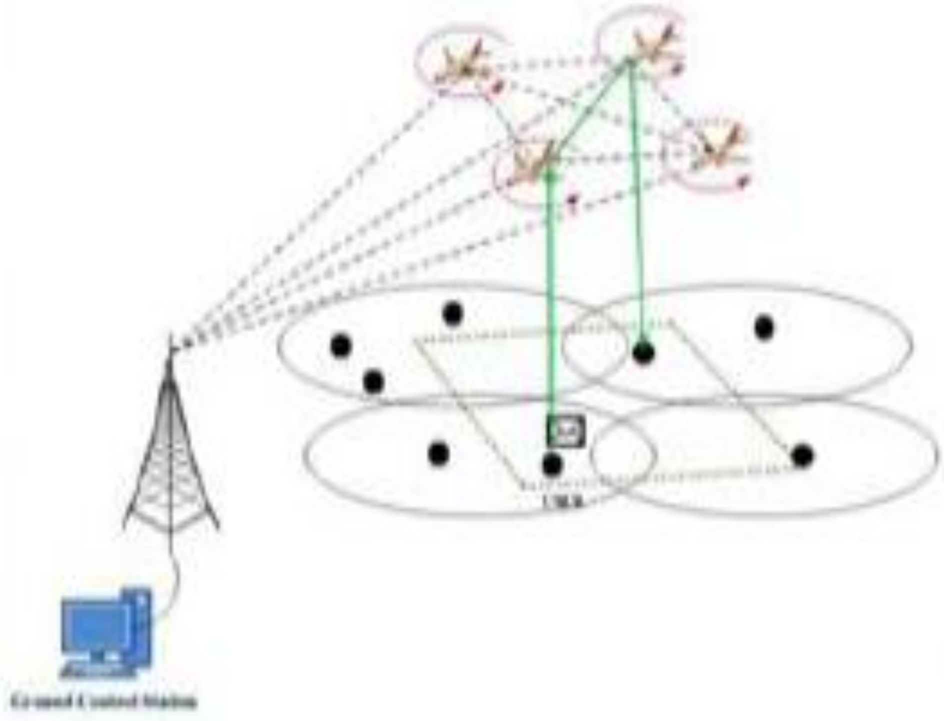



FANETs & VANETs
A2A
A2V
A2V
A2V
V2V
V2V
GUIDANCE
EXPLORATION
DATA
SURVEILLANCE

FANETs & VANETs

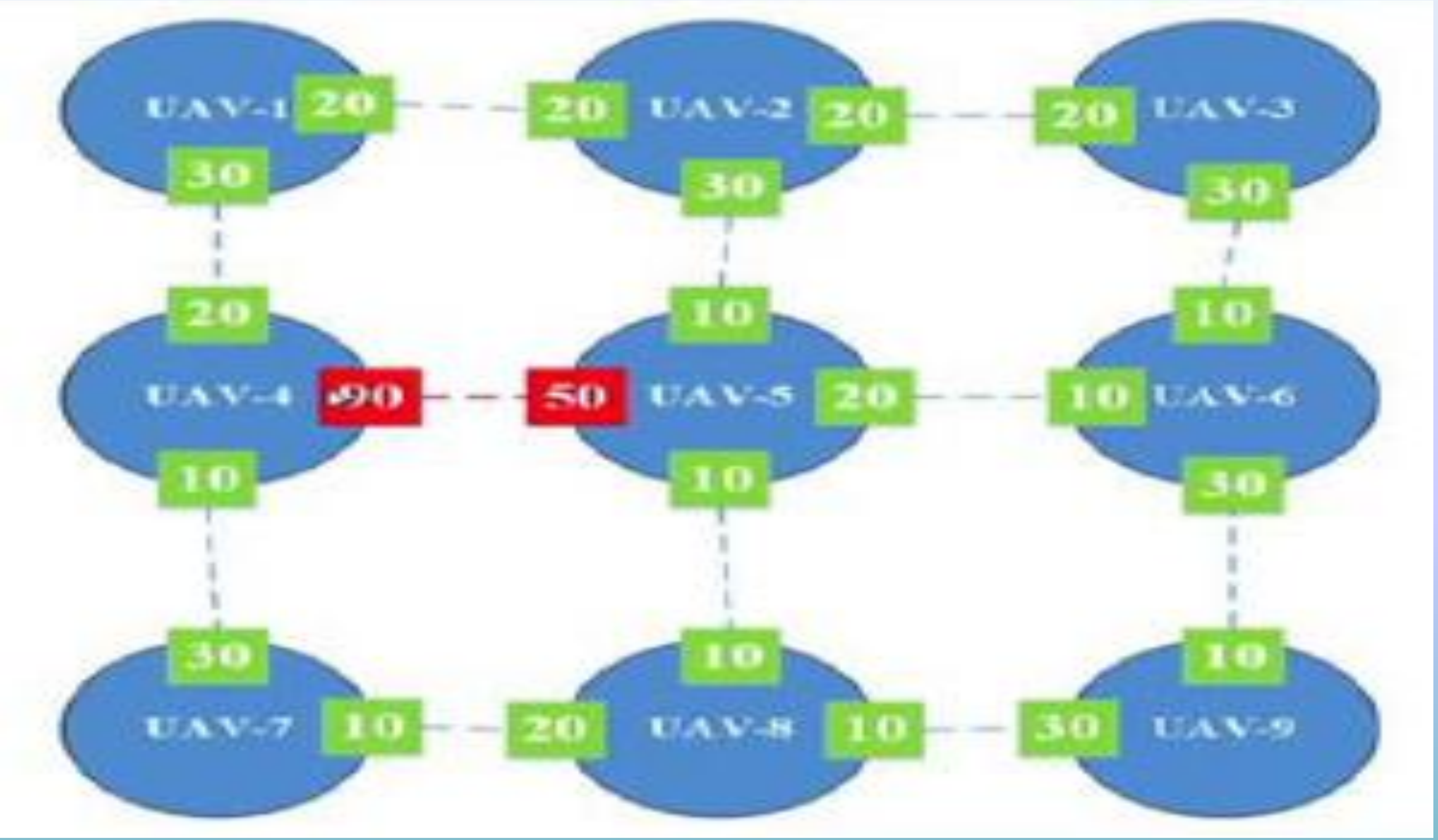


Trajectory Control for Improving Throughput

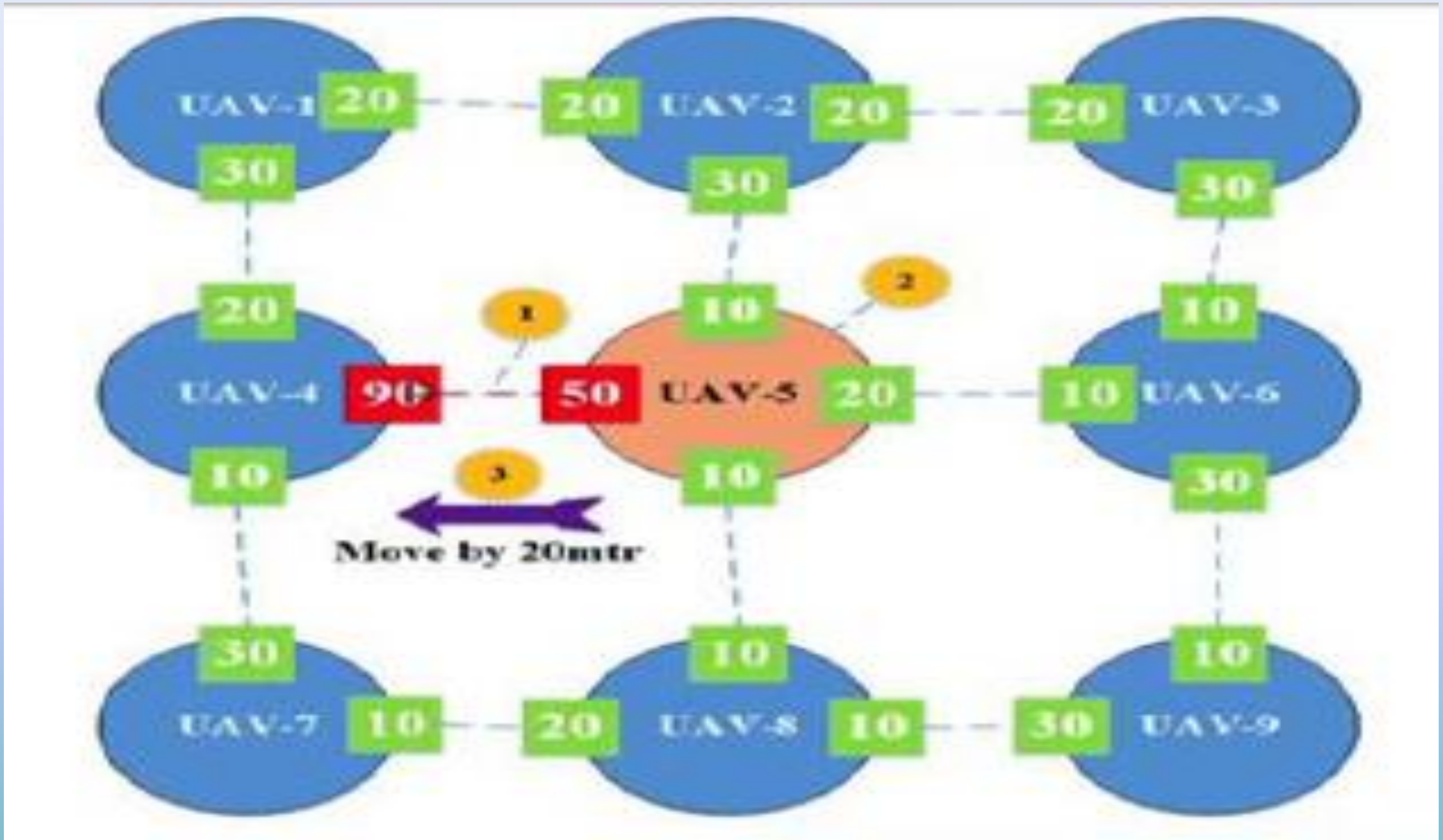


- UAVs with queue occupancy above a threshold experience congestion resulting in communication delay.
- Control station instructs UAVs to change centers of trajectory.
- Command given based on traffic at "busy" communication link.
- To provide enhanced coverage, UAVs may be commanded to change radius of their trajectories.

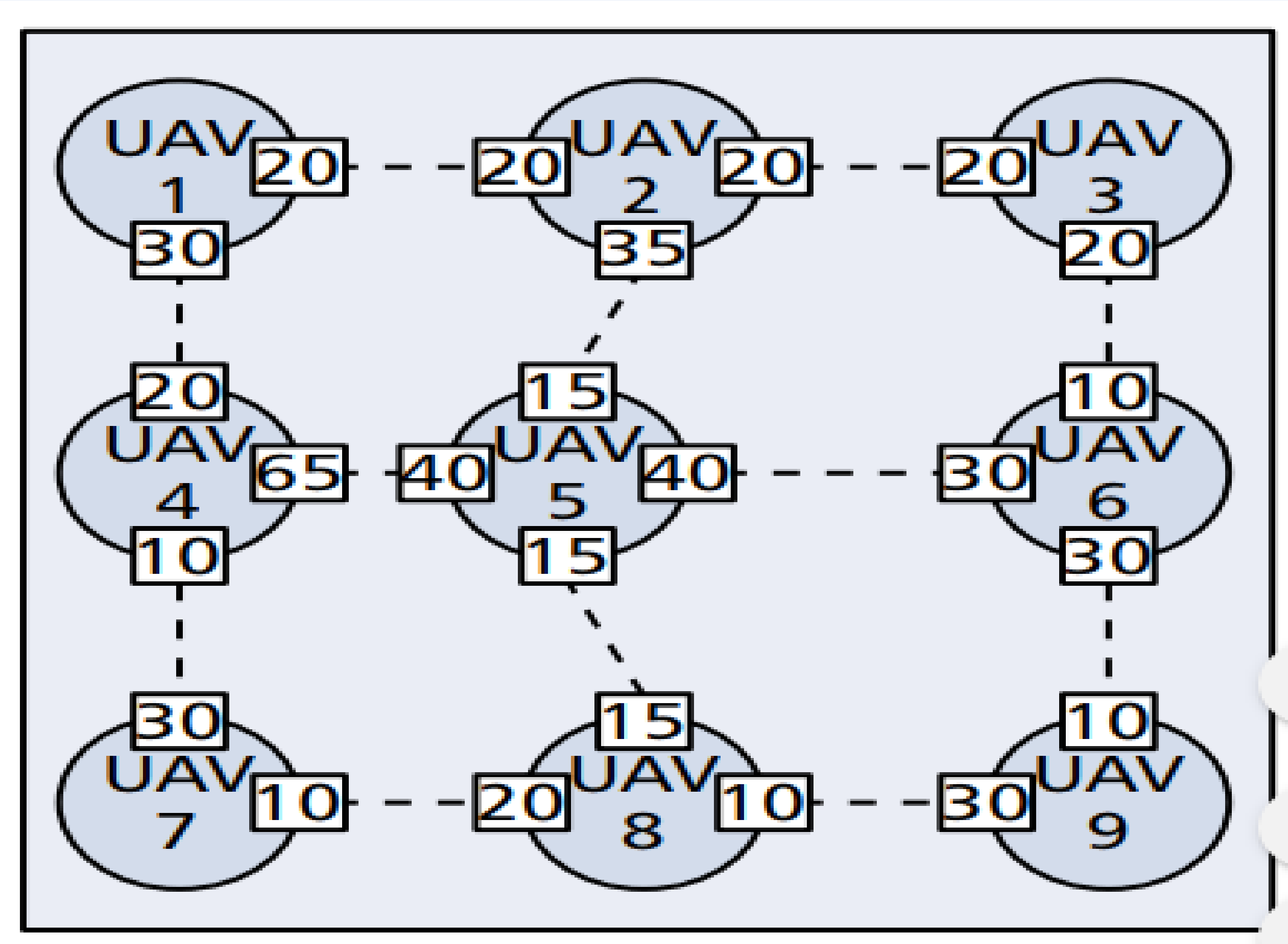
Trajectory Control for Improving Throughput



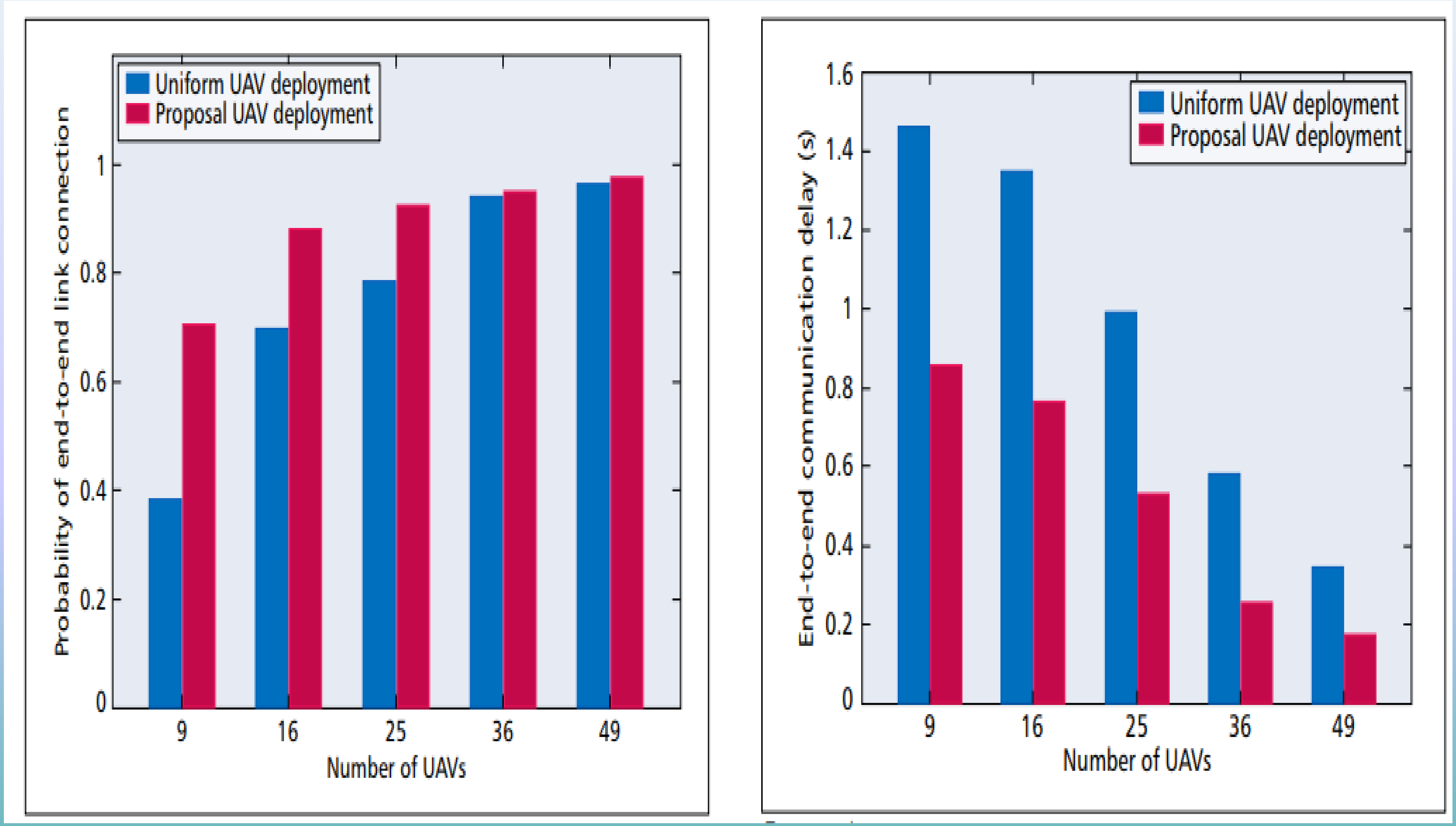
Trajectory Control for Improving Throughput



Trajectory Control for Improving Throughput



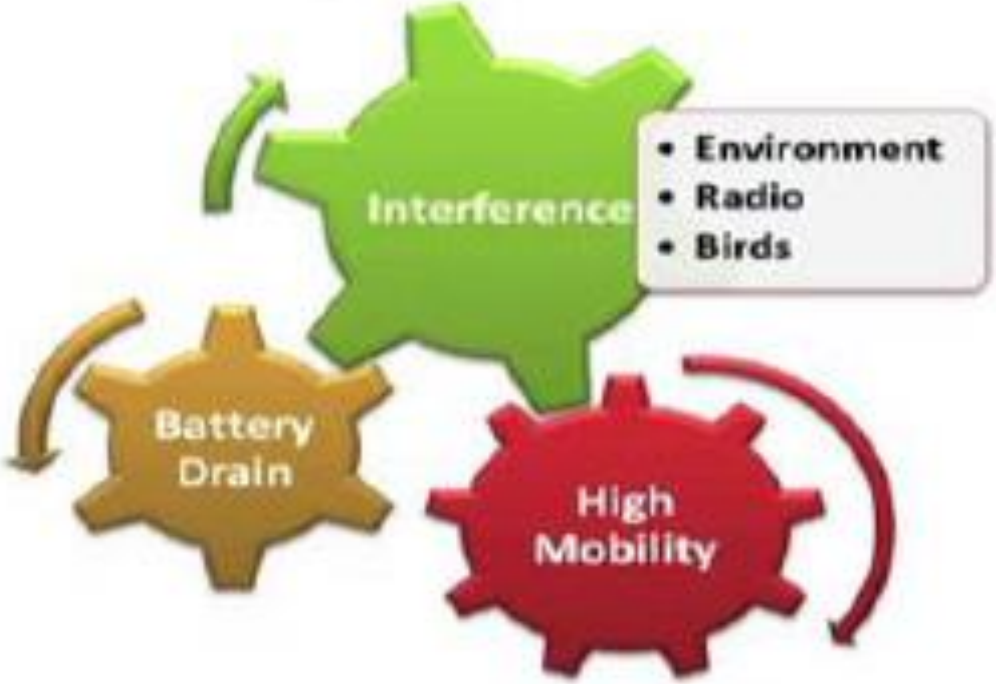
Trajectory Control for Improving Throughput



Self-Organization in UAV Networks

- Why ?

Links can be broken frequently because of :

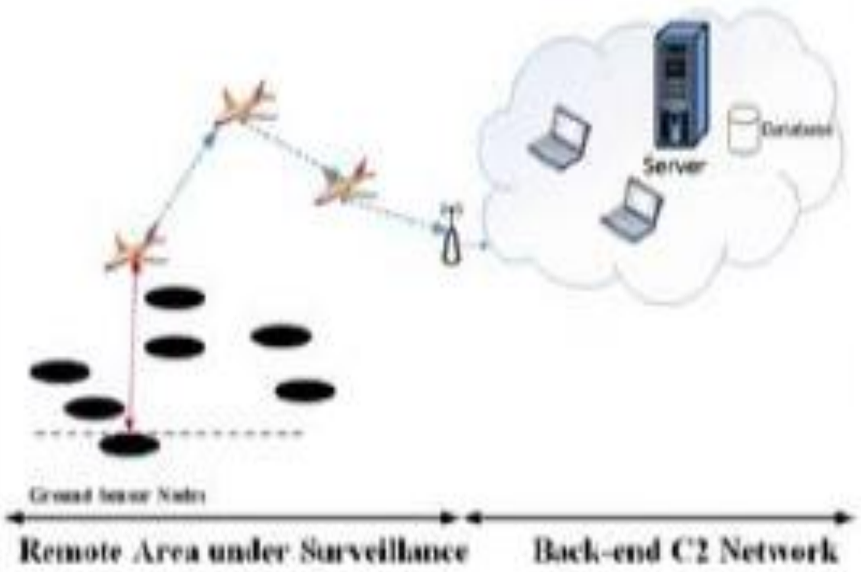


This translates into utilization challenges in planning and allocation of resources.

Self-Organization in UAV Networks :

- Steps of Self-organization :

Self Organizing FANETs



- Unpredictability of motion for military applications can be achieved through:
  - Embedding randomness into the UAVs behavior,
  - Minimizing the number of UAVs needed for a mission, as well as
  - Minimizing the total number of conducted missions by combining them into a single multi-goal mission.

UAV Network Protocols

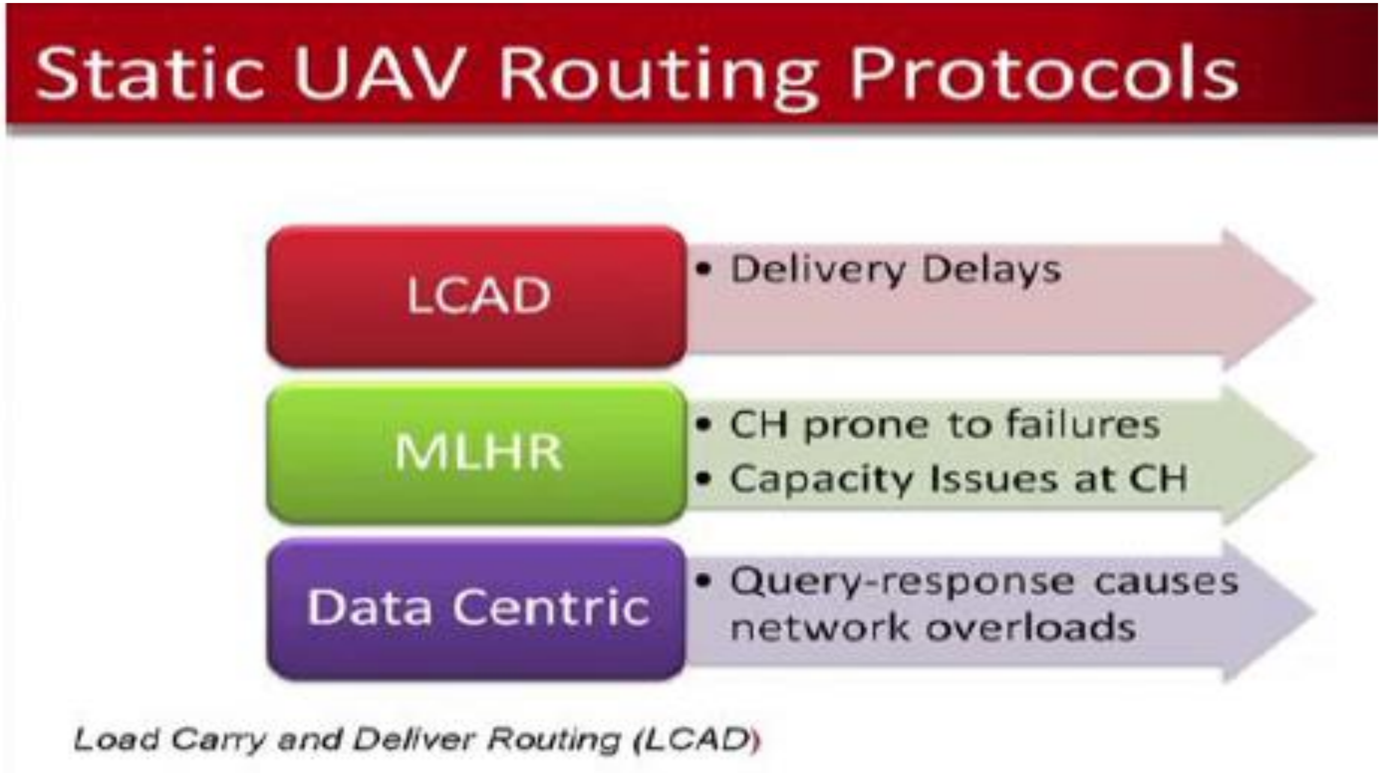
Static
- Fixed Tables, Not for Dynamic topology, Not scalable, High error

Poactive
- Large overhead for maintaining tables, not for bandwidth constrained networks, slow reaction to topology changes causing delays

On-demand
- High latency in route finding, source routing does not scale well for large network , overheads may increase because of large header size.

Hybrid
- Hard to implement for dynamic systems

Geographic 3D
- Location information may not be always available


Static UAV Routing Protocols
LCAD
• Delivery Delays
MLHR
• CH prone to failures
• Capacity Issues at CH
Data Centric
• Query-response causes network overloads
Load Carry and Deliver Routing (LCAD)

Load Carry and Deliver Routing (LCAD)

One of the most popular secure routing protocols. In this model, communication between UAVs does not occur.

This protocol is used to transfer data from a ground base to a ground base using flying UAVs with single hop communication; it is useful to transfer images or videos.

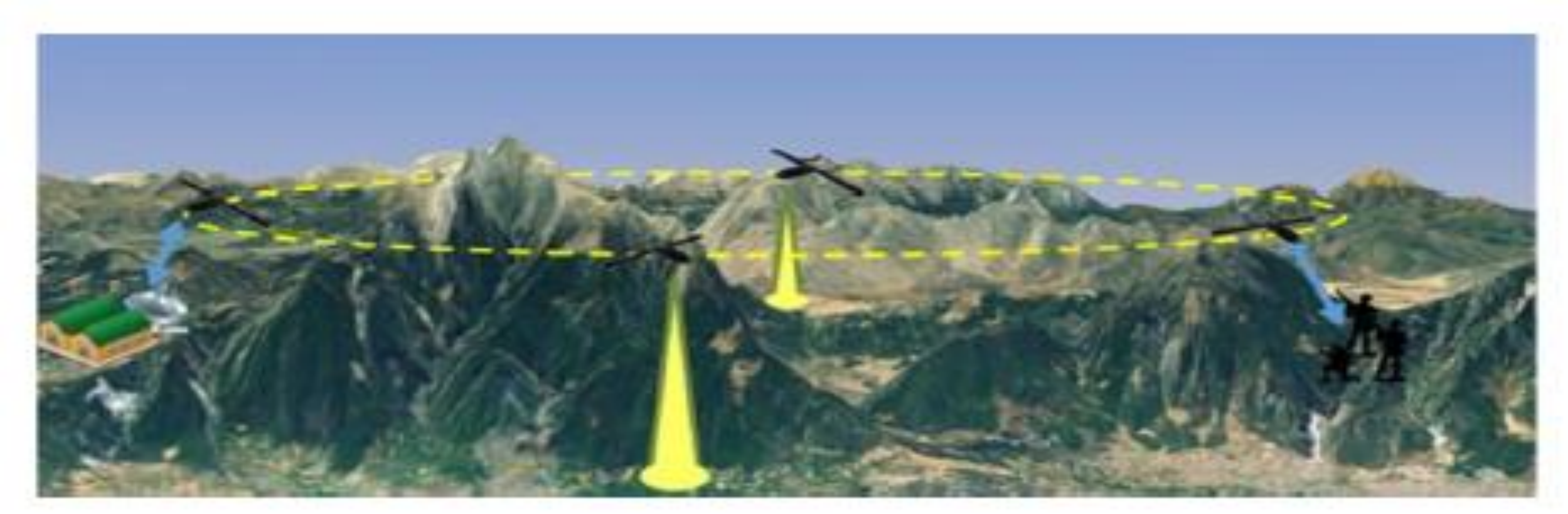
Firstly, the data is loaded from a source access point to the UAV and the UAV moves to the destination access point to deliver the data.

The main objectives of load carry and deliver routing is to maximize throughput and increase the security. In terms of security, this model is secure; because there are no hops during the transfer of data.

The time needed to deliver the data from the source ground base to the destination ground base depends on the speed of UAV and the distance between the source and destination access points.

To decrease the transfer time more than one UAV can be used for the same source and destination, or increase the speed of UAVs, or divide the network into smaller LCAD sub-networks.

Load Carry and Deliver Routing (LCAD)



Multi-Level Hierarchical Routing(MLHR)

Used when UAV networks are organized hierarchically into a number of clusters that need to operate in different mission areas.

Each cluster has a cluster head (CH), which will represent the whole cluster; this separate cluster can perform different activities.

Each CH is in connection with the upper/lower layers (ground stations, UAVs, satellites, etc.) directly or indirectly.

To broadcast data and control info to other UAVs in the cluster, CH should be in direct communication range of other UAVs in the cluster.

This model is better if UAVs are controlled in changed swarms, the mission area is huge, and several UAVs are used in the network.

Multi-Level Hierarchical Routing(MLHR)