Towards Networked Airborne Computing in Uncertain Airspace: A Control and Networking Facilitated Distributed Computing Framework

Poznan Workshop, October 2024

General introduction to the project

Poznan University of Technology

Towards Networked Airborne Computing in Uncertain Airspace: A Control and Networking Facilitated Distributed Computing Framework

Poznan Workshop, October 2024

AGENDA

1. UAVs classification.
2. UAVs applications.
3. Networking requirements and architecture.
4. Selected routing protocols.
5. Security – selected vulnerabilities, threats and countermeasures.

WHAT IS DRONE?

- Unmanned Aerial Vehicle (UAV)
  - aircraft designed to fly without pilot on-board,
  - controlled remotely or able to fly autonomously thanks to embedded systems, software, sensors and GPS,
- Unmanned Ground Vehicle (UGV),
- Unmanned Underwater Vehicle (UUV);

https://www.wired.com/2017/05/the-physics-of-drones/

UAV TYPES – DESIGN

- Rotor-based
- Fixed-wing
- Hybrid

https://geo-jobe.com/drones-uav/multi-rotor-vs-fixed-wing-uav-platforms-considerations-for-evaluating-capabilities-and-limitations/

https://www.researchgate.net/figure/Fixed-wing-UAS-image-source-authors_fig2_318437446

https://www.jouav.com/blog/drone-types.html

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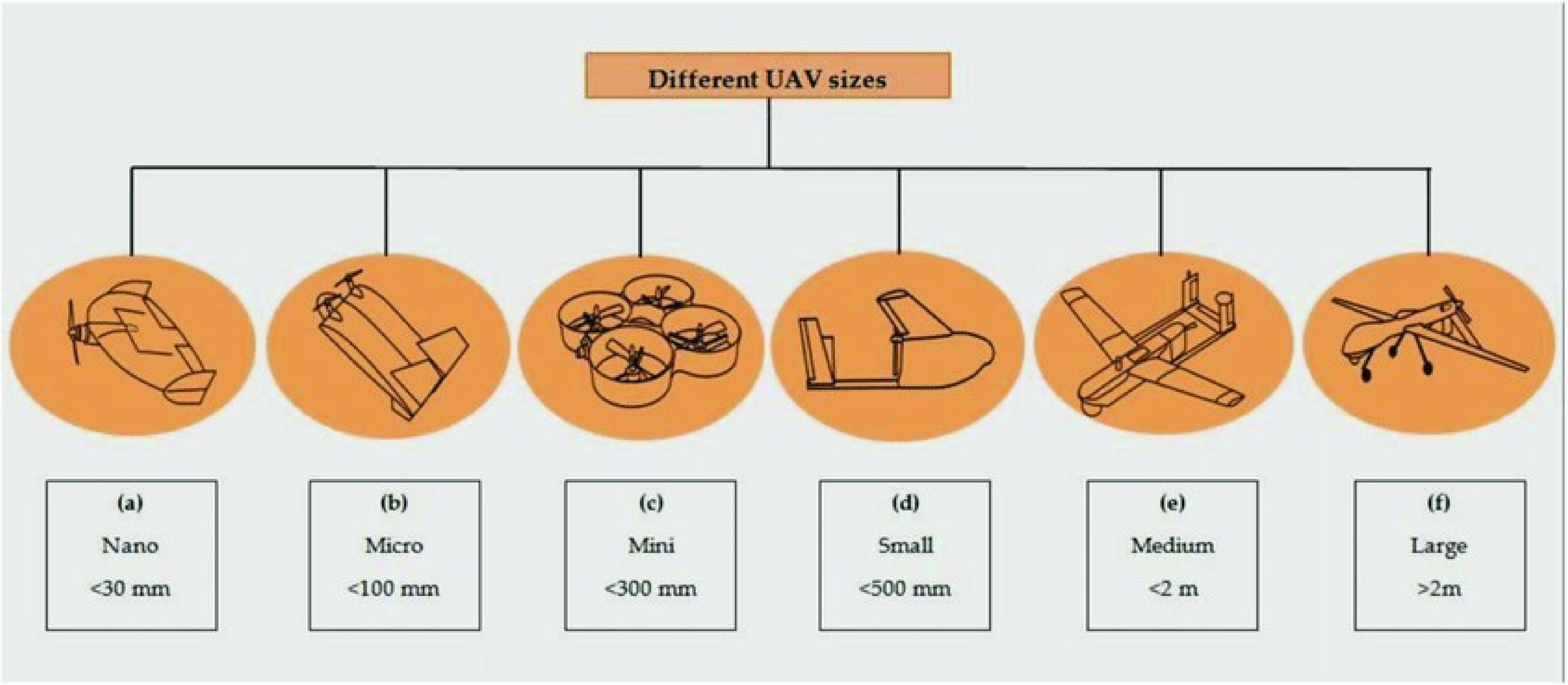
UAV TYPES – SIZE



Rahman i in. (2021), „A Comparative Study on Application of Unmanned Aerial Vehicle Systems in Agriculture”

UAV TYPES – RANGE/ALTITUDE

Category	NASA UAS Class	Weight (in kg)	Normal Operating Altitude (in m)	Mission Radius, Range (in Km)	Typical Endurance (in hrs)	Payload (in kg)	Available UAV Models in Market
Micro	sUAS Class I	<2	<140	5	<1	<1	DJI Spark, DJI Mavic, Parrot Bebop2
Mini		2–25	<1000	25	2–8	<10	DJI Matrice600, DJI Inspire2, Airborne Vanguard
Small		25–150	<1700	50	4–12	<50	AAI Shadow 200, Scorpion 3 Hoverbike
Medium	Class II	150–600	<3300	200–500	8–20	<200	Griff 300, Ehang 216
Large/Tactical	Class III	>600	>3300	>1000	>20	>200	Boeing X-45A UCAV

Lykou, Moustakas, i Gritzalis (2020), „Defending Airports from UAS".

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UAV TYPES – APPLICATION AREA

1 **Military**

Use advanced, encrypted communication channels with the highest level of security, such as AES and military protocols.

2 **Commercial**

Varying levels of encryption depending on the application. High security for critical infrastructure inspections, medium for marketing and photography.

3 **Recreational (Hobby) / Toy**

No or very low encryption, simple radio connections (2.4 GHz or 5.8 GHz). Examples: Syma X5C, Holy Stone HS210

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UAV – SAMPLE APPLICATIONS (I)

- photography and filmmaking,
- agriculture,
- rescue and safety;

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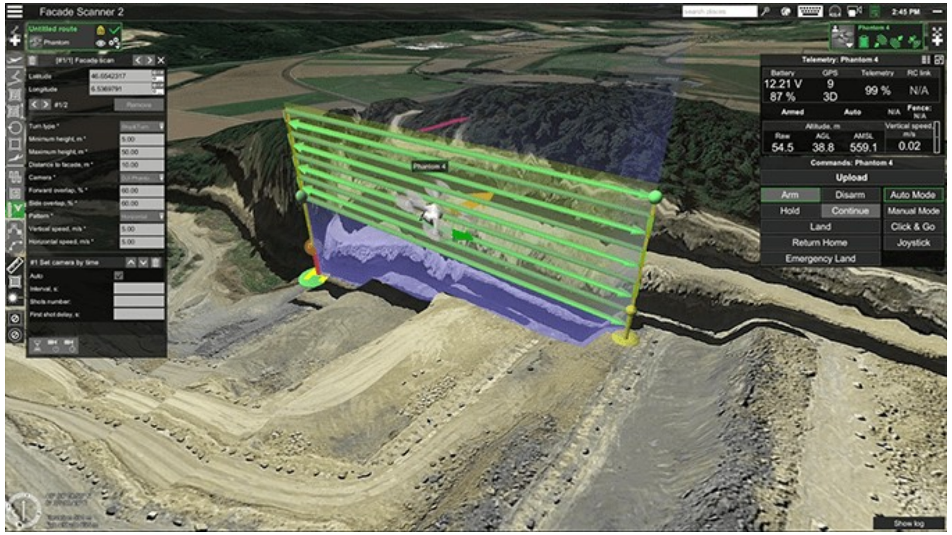
UAV – SAMPLE APPLICATIONS (II)

- inspections and monitoring,
- logistics and deliveries,
- military;



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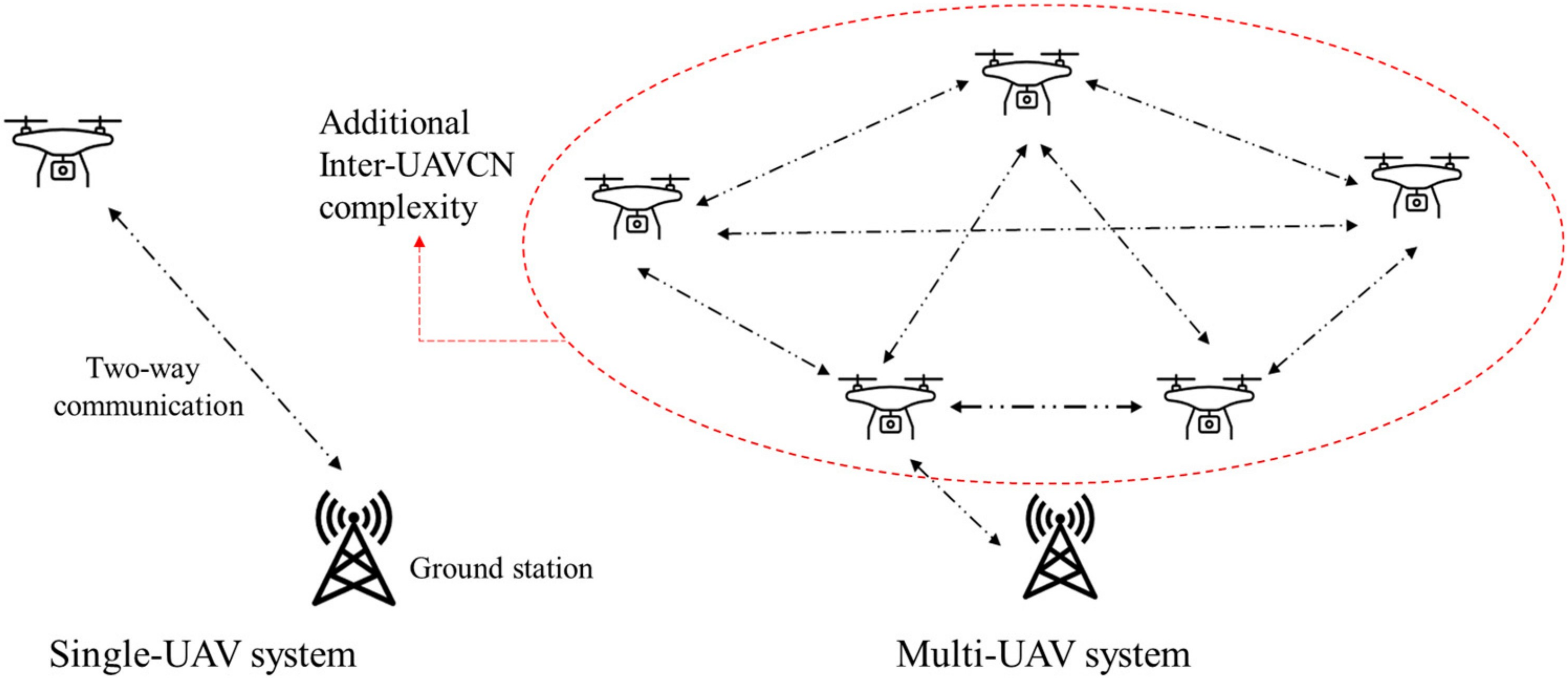
UAV REGULATIONS

European Union	Australia	Poland	United Kingdom
- The EU does not regulate drone use for drones weighing less than 150 kg. - Proposed regulations aim to integrate all drones into the EU aviation safety framework, focusing on compliance with manned aircraft requirements. - Personal data processing and privacy are strictly regulated.	- New regulations allow commercial drone operations for drones under 2 kg without a license, under standard conditions. - Medium-sized and larger drones require licenses and certifications. - Operators must meet specific qualifications and have the necessary facilities for safe operations.	- Commercial drone use requires a certificate of competence. - Drones weighing over 25 kg must be certified and registered. - Flights near airports and special zones are restricted. - Compliance with operational restrictions is mandatory.	- Drone operations in the UK are regulated by air navigation laws. - Stricter rules apply to drones equipped with cameras. - The Civil Aviation Authority enforces drone regulations. - Additional regulations for drone use are currently being explored.

MULTI-UAV VS SINGLE-UAV (I)



Afrin i in. (2024), „Advancements in UAV-Enabled Intelligent Transportation Systems".

MULTI-UAV VS SINGLE-UAV (II)

Feature	Multi-UAV	Single-UAV
Scalability	High	Limited
Antenna	Directional	Omni-directional
mission speed	Fast	Slow
Required bandwidth	Medium	High
Control complexity	High	Low
Failure effect	System can reconfigure	Mission fails
Topology	Direct, and simple connection	Complex topology
Survivability	High	Poor
Heterogeneous configuration	Applicable	Inapplicable
Coverage area	Large	Small

Al-Absi i in. (2021), „Moving Ad Hoc Networks—A Comparative Study".

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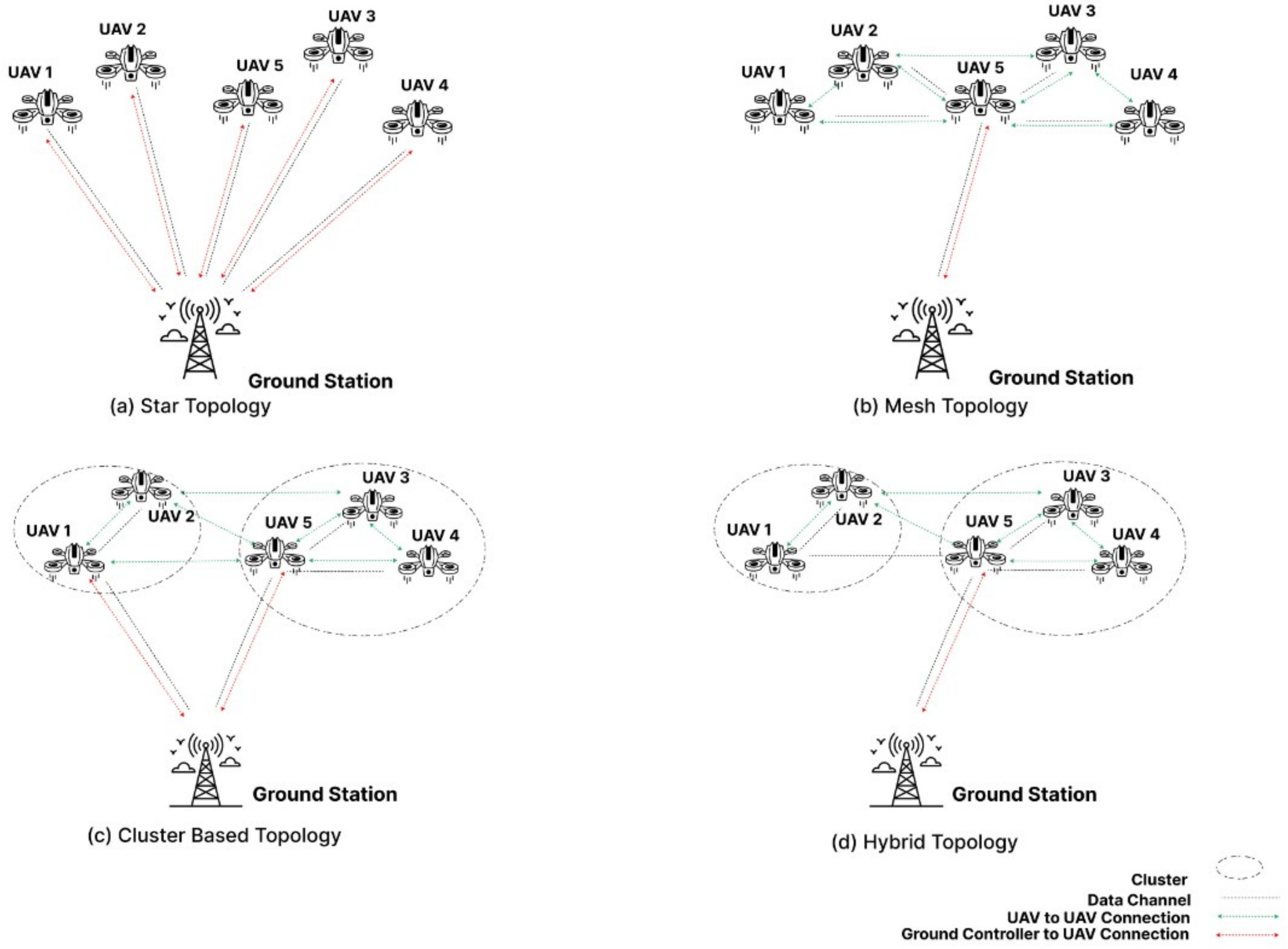
NETWORK TOPOLOGIES (I)



Mansoor i in. (2023), „A Fresh Look at Routing Protocols in Unmanned Aerial Vehicular Networks".

NETWORK TOPOLOGIES (II)

- star topology:
  - Ground Station (GS) directly connected with every UAV (node),
- mesh topology:
  - GS connected to single node (cluster head), that passes data to own nodes,
- cluster based topology:
  - GS connected to multiple cluster heads, that passes data to own nodes,
- hybrid topology
  - GS connected to multiple cluster heads, that passes data to own nodes,
  - cluster heads can also pass data to other cluster heads;

Mansoor i in. (2023), „A Fresh Look at Routing Protocols in Unmanned Aerial Vehicular Networks”.

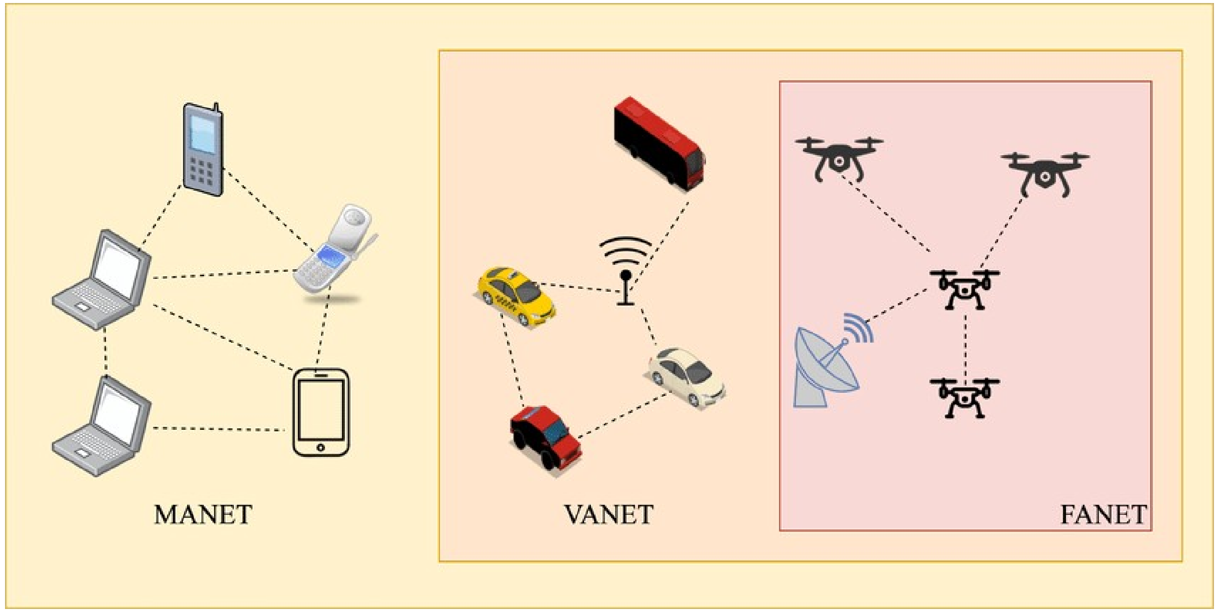
NETWORK TOPOLOGIES (III)

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
Scalable	Not scalable

Gupta, Jain, i Vaszkun (2016), „Survey of Important Issues in UAV Communication Networks”.

FLYING AD-HOC NETWORK

- fast mobility (30 km/h – 460 km/h),
- some movement patterns,
- low nodes density,
- Line of Sight (LoS) propagation model in many cases,
- high computational power,
- fluent topology in many cases,
- power often based on fuel / battery / solar cells,
- GPS usage;



Al-Emadi i Al-Mohannadi (2020), „Towards Enhancement of Network Communication Architectures and Routing Protocols for FANETs".

H. Sawalmeh i Shamsiah Othman (2018), „An Overview of Collision Avoidance Approaches and Network Architecture of Unmanned Aerial Vehicles (UAVs)".
Aranzazu Suescun i Cardei (2016), „Unmanned Aerial Vehicles Networking Protocols".

FANET ROUTING PROTOCOLS (I)

- topology-based routing – usage of information of existing nodes:
  - static:
    - predetermined routes, uploaded to UAV before mission,
  - proactive:
    - up-to-date routing table on every UAV,
    - requires constant update of network information,
  - reactive:
    - on-demand, constructing route when communication needed,
  - reactive/proactive hybrid,

Almansor i in. (2024), „Routing Protocols Strategies for Flying Ad-Hoc Network (FANET)"

FANET ROUTING PROTOCOLS (II)

- position-based routing:
  - usage of information of location of node,
- hierarchical-based routing:
  - cluster formations, cluster heads transmitting data,
- swarm-based routing:
  - bio-inspired, eg. Ant Colony Optimization-based Polymorphism Aware Routing,
- delay-tolerant networking routing (DTN):
  - packet loss prevention in fragmented networks,
- routing based on ML, eg. reinforcement learning algorithms;

Almansor i in. (2024), „Routing Protocols Strategies for Flying Ad-Hoc Network (FANET)”

NETWORK HOMOGENEITY (I)

- homogeneous network (eg. same flight pattern and speed):
  - sample architecture:
    - Multigroup UAV Network,
- heterogeneous network (eg. different flight pattern or speed):
  - sample architecture:
    - Multilayer UAV Network;

H. Sawalmeh i Shamsiah Othman (2018), „An Overview of Collision Avoidance Approaches and Network Architecture of Unmanned Aerial Vehicles (UAVs)”.
Aranzazu Suescun i Cardei (2016), „Unmanned Aerial Vehicles Networking Protocols”.

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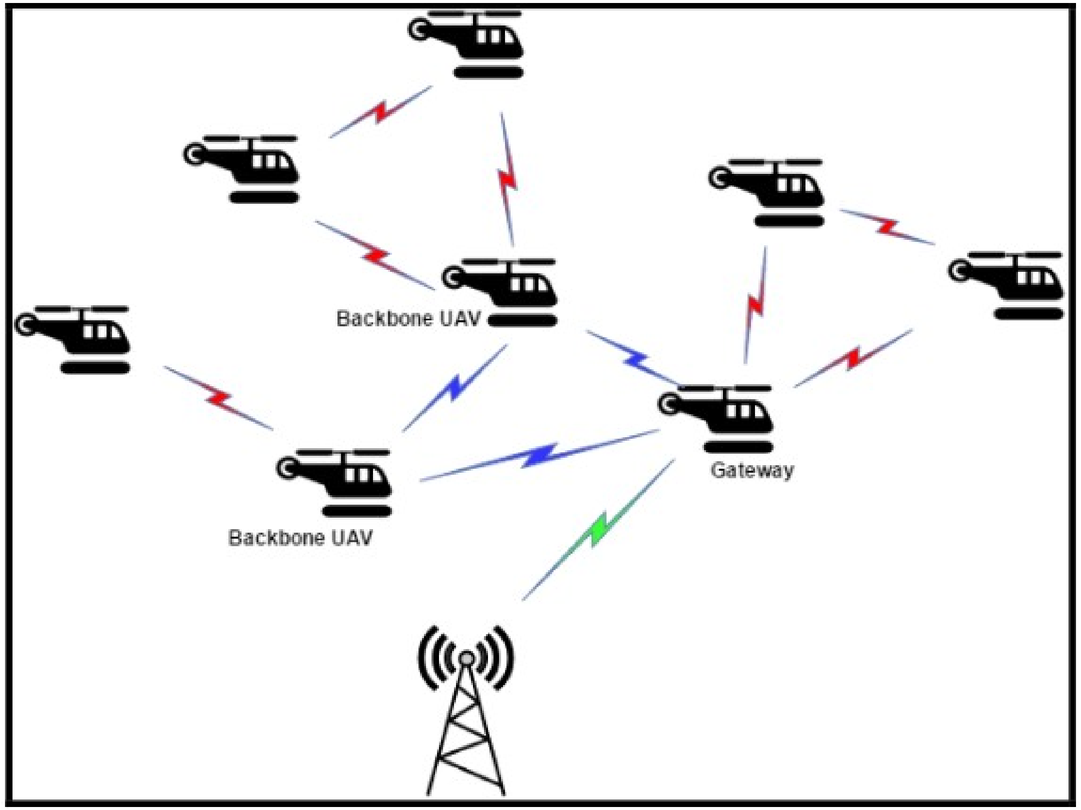
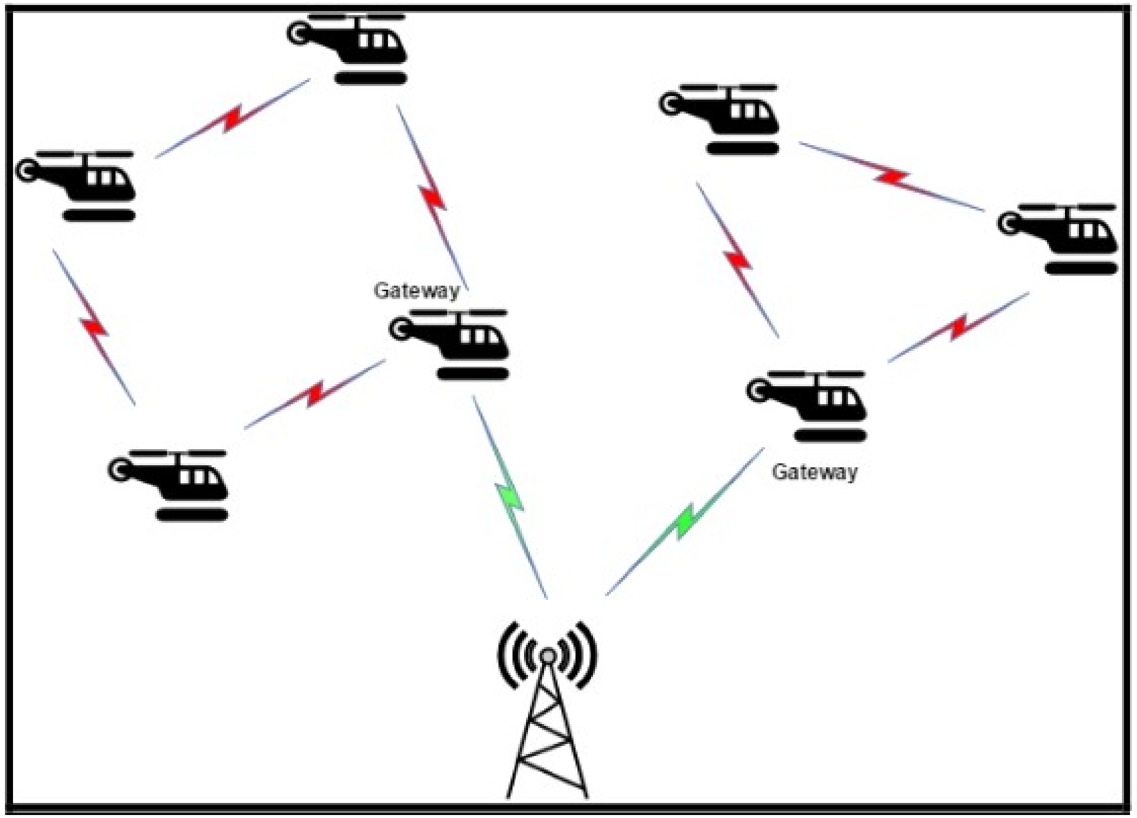
NETWORK HOMOGENEITY (II)

- Multilayer UAV Network

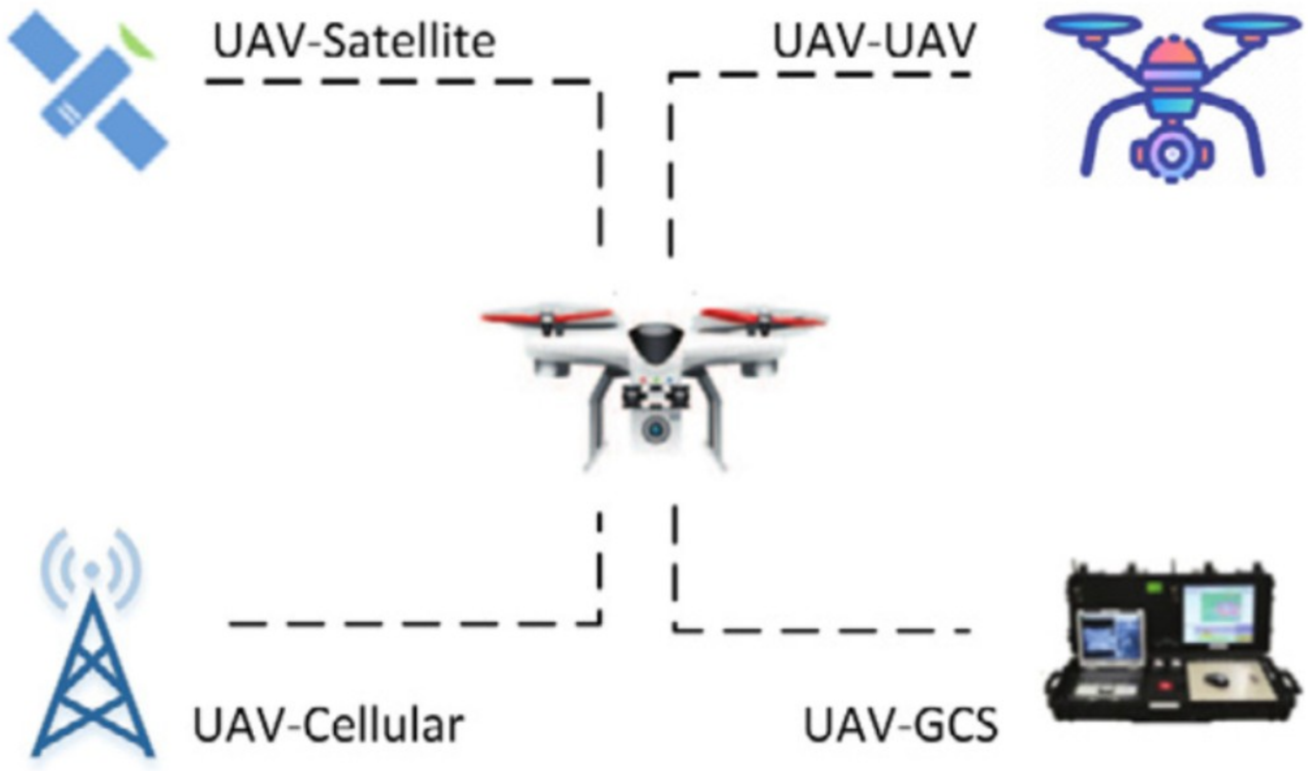


- Multigroup UAV Network



Aranzazu Suescun i Cardei (2016), „Unmanned Aerial Vehicles Networking Protocols".

COMMUNICATION METHODS (I)



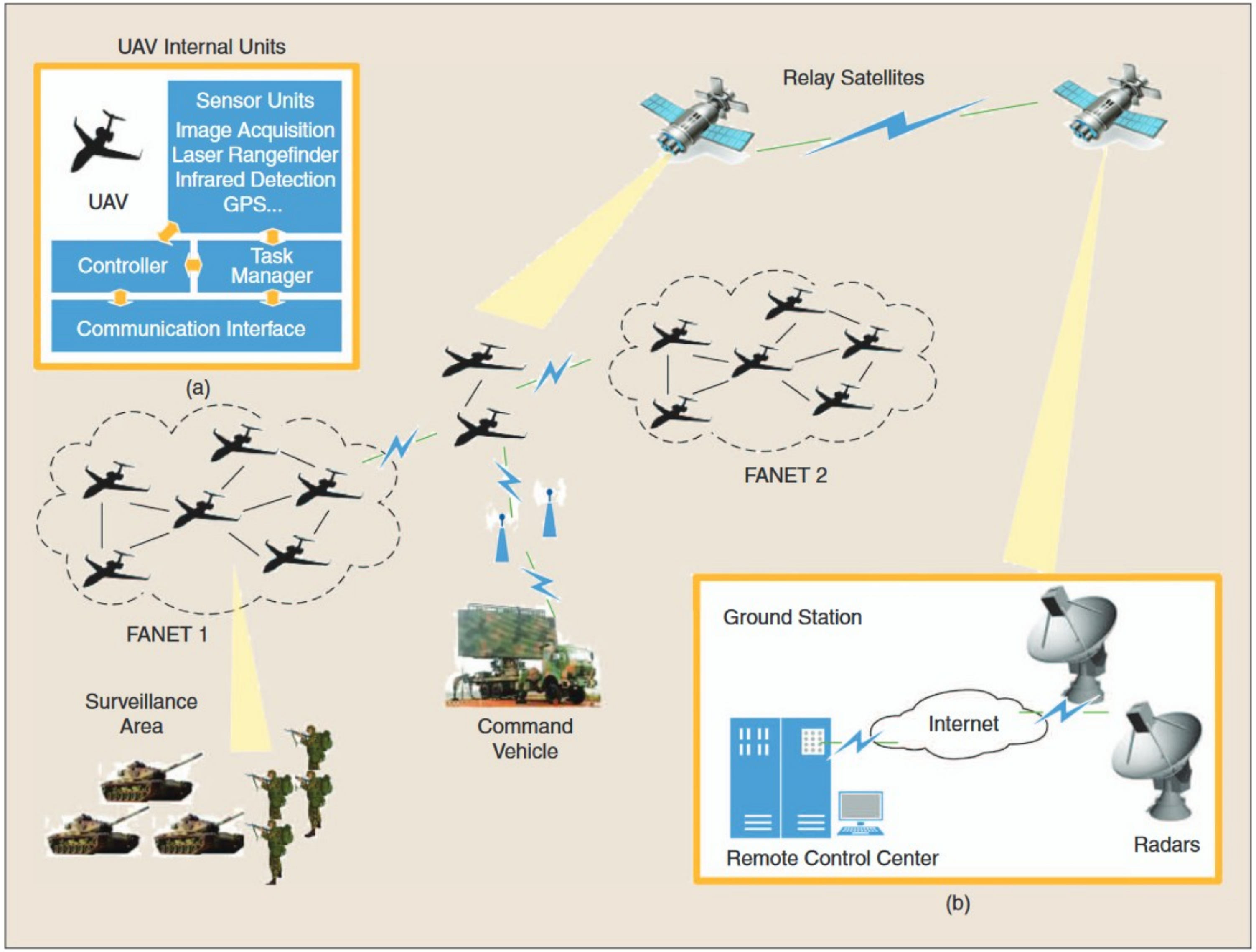
Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity”

COMMUNICATION METHODS (II)

- Wi-Fi networks:
  - short-range communication between GS and UAV(s),
- cellular networks:
  - long-range communication between GS and UAV(s),
- satellite networks:
  - global communication coverage for UAV(s);

Madhuvanthi T., Revathi A. (2024), „A Survey on UAV Network for Secure Communication and Attack Detection"

UNMANNED AERIAL SYSTEM



Wang i in. (2017), „Taking Drones to the Next Level”.

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UAV INTERNAL STRUCTURE

- flight controller:
  - covers internal protocols,
  - often built using popular MCUs,
  - analogue and/or digital protocols,
  - physical layer often built upon copper, sometimes optical or wireless
- sensors, eg. GPS, video, range detection,
- engine,
- fuselage;

Autonomian, *UAV Data Transmission and Communication Protocols*
Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity"

UAS – SECURITY CHALLENGES

- some similarities to industrial systems (traditional approach),
- additional challenges:
  - high speed,
  - complex environments,
  - dynamic network topology / intermittent connections,
  - resource-constrained flight information system,
  - many components → many attack surfaces;

Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity"

COMMUNICATION SECURITY

Sample attack surfaces

- client terminals ↔ Ground Station (GS),
- GS ↔ backbone UAV / gateway,
- backbone UAV / gateway ↔ other UAVs in FANET,
- legitimate UAVs in FANET,
- FANET ↔ unknown UAV that wants to join,
- computational services ↔ client terminal / GS / UAVs

Tsao, Girdler, i Vassilakis (2022), „A Survey of Cyber Security Threats and Solutions for UAV Communications and Flying Ad-Hoc Networks".

COMMUNICATION SECURITY

Selected vulnerabilities and threats (I)

- communication links between different entities in UAS targeted,
- physical layer vulnerabilities/threats:
  - eavesdropping:
    - eg. capturing packets to listen the communication,
  - tampering:
    - eg. introducing false information or deleting proper one,
  - interfering:
    - eg. disrupting radio signal,

Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity"

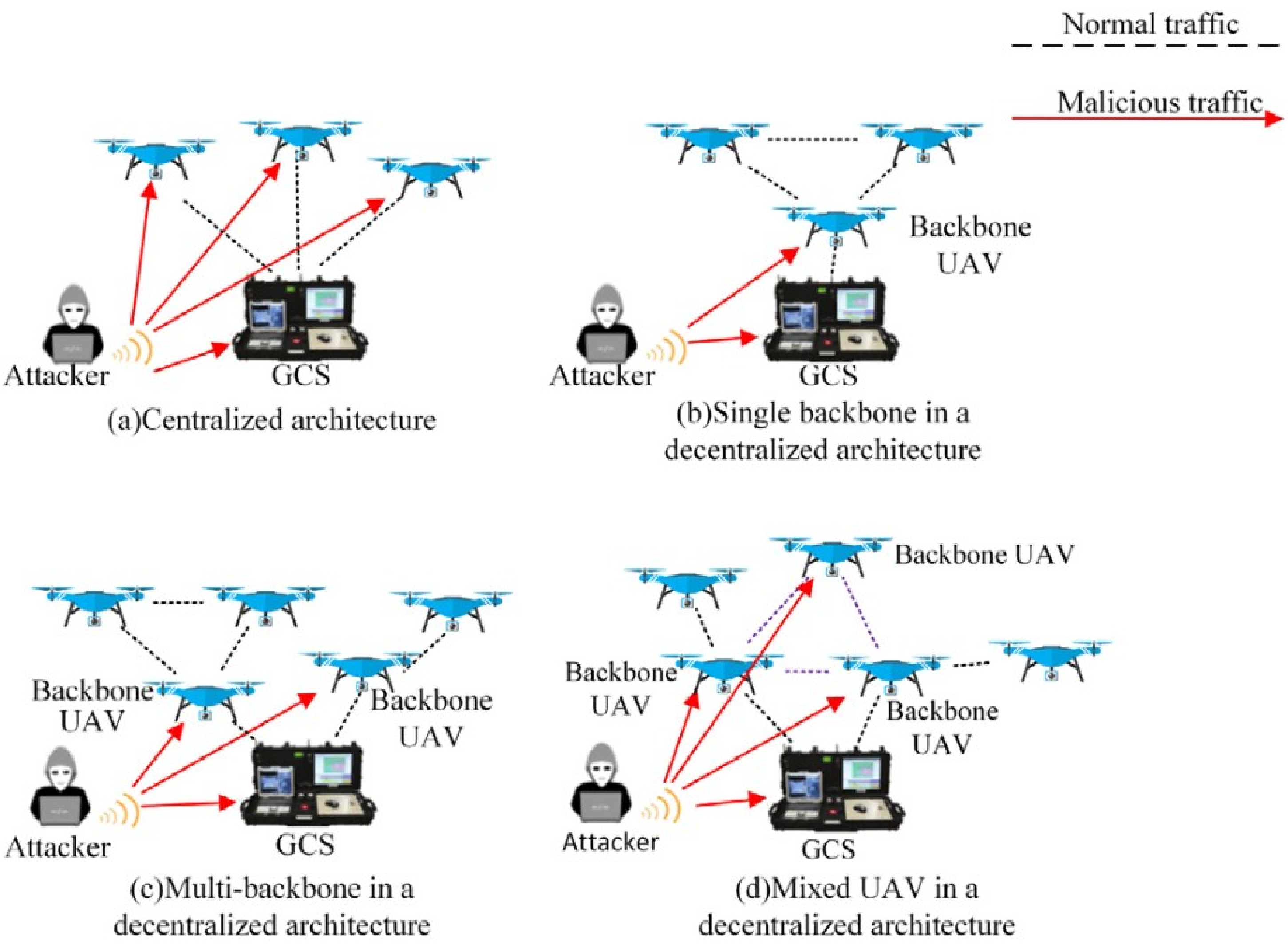
COMMUNICATION SECURITY

Selected vulnerabilities and threats (II)

- network layer vulnerabilities/threats:
  - topology-based attacks:
    - eg. targeting with malicious traffic single-point-of-failure (if exists),
  - resource consumption:
    - eg. trying to deplete computing resources or energy limits,
  - traffic analysis:
    - eg. Man-in-the-Middle, blackhole attack, routing table overflow,

Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity"

COMMUNICATION SECURITY



Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity”

COMMUNICATION SECURITY

Selected vulnerabilities and threats (III)

- transport layer vulnerabilities/threats:
  - often lightweight transmission protocols due to resource constraints:
    - possible weak/lack of encryption,
    - possible weak/lack of authentication,
    - missing unified security standards,
    - possible firmware/software vulnerabilities;

Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity"

COMMUNICATION SECURITY

Selected countermeasures

- encryption algorithms,
- authentication verification,
- wireless communication spectrum management,
- artificial noise generation for unauthenticated users to avoid eavesdropping,
- taking care of communication protocols security,
- IDS/IPS based on rules, signatures, bio-inspirations, machine learning, blockchain-inspirations, SDN

Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity”

UAV SENSORS SECURITY

Selected vulnerabilities and threats

- data gathering for flight control and mission payload targeted,
- utilizing sensor channels (eg. acoustic, optical, infrared) for deception attacks or interference attacks,
- injecting false data into sensors (eg. GPS, range detection, inertial),
- jamming transmission, eg. GPS disruption;

Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity”

UAV SENSORS SECURITY

Selected countermeasures

- sensors physical protection,
- sensors software protection:
  - authentication,
  - encryption,
- detection protection:
  - intrusion detection/prevention,
  - multi-sensor assisted detection;

Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity”

UAV PAYLOAD SECURITY

Sample vulnerabilities and threats

- UAV payload targeted, eg. flight control system, engine, fuselage,
- malware affecting software, eg. backdoors, trojans,
- malware affecting hardware, eg. tampering with circuits, altering logic gates,
- physical collisions,
- hardware failures,
- software problems,

Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity”

UAV PAYLOAD SECURITY

Selected countermeasures

- communication encryption and authentication to avoid malware injections,
- intrusion detection systems,
- circuit analysis to avoid/detect hardware tampering,
- UAV’s battery secure circuits and physical protection,
- supply chain management;

Bai, Hu, i Wang (2024), „A Survey on Unmanned Aerial Systems Cybersecurity”

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POLITECHNIKA POZNAŃSKA

Thank you very much. Any questions?