Routing Advances in Unmanned Aerial Vehicle Networks

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- **Expertise:** telecommunications and computer networks architectures, technologies and services: network architectures and services, management/control/data plane, protocols, 5G,6G, SDN, NFV, virtualization, QoS assurance, multimedia services over IP networks

- **Our UPB team:**
  - **Recent research interest :** Software Defined Networking (SDN), Network Function Virtualization (NFV), MEC/edge computing, 5G networking and slicing, vehicular communications, AI in 5G. 6G -management and control
  - **Partners in many research European** and bilateral projects in the above domains

- **Acknowledgement**

- This **overview text** and analysis is compiled and structured, based on several public documents, conferences material, studies, research papers, standards, projects, surveys, tutorials, etc. (see specific references in the text and Reference list).
  - The selection and structuring of the material belong to the author.
  - Given the extension of the topics, this **presentation is limited to a high- level view only. The list of topics discussed is also limited.**

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- **Motivation of this talk**
  - **UAV(drones)** - popular for many applications and services (civilian, military)
  - UAVs are **wirelessly interconnected** in ad hoc manner, composing UAV networks (**UAVNET**)

  - UAVNETs - **features and characteristics different from traditional mobile ad hoc networks (MANET) and vehicular ad hoc networks (VANET)**
    - **dynamic behavior, rapid mobility and topology changes**
    - **large variety of applications and operational contexts**
    - cooperation is needed between**: UAV-ground stations (GS), UAV-UAV, UAV-satellites, etc.;** work in 3D environment, including space communications
    - In some cases - need for **delay tolerant network (DTN) –** dedicated protocols and mechanisms to accommodate high delays and intermittent connectivity

  - **Need of new specific methods and technologies** for Management & Control (M&C) C different layers
    - Phy level, **routing, path planning, tracking**, traffic engineering, cooperation, security, etc.
    - **UAV Routing algorithms and protocols** – important area of UAV problems
  - **Mobile technologies 5G, 6G** can offer a strong support for UAV-based communications and services

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1. Introduction

1.1 Unmanned Aerial Vehicles (UAV) (drones)

- **UAVs- popular solutions** for many applications (civilian, military domains)
  - objectives
    - surveillance, delivery, transportation in different fields, agriculture, forestry, environmental protection
    - **critical operations -** rescue/emergency, military domains, security

- **UAVs are wirelessly interconnected** in ad hoc manner → **UAVNET**

- The **communication technologies in** UAVNETs depend on applications
  - **Examples:**
    - **Outdoor** - a simple line of sight 1-to-1 link with continuous signal transmission E.g., Surveillance–UAVs can communicate through satellite communication links
    - **Satellite communication** - preferable solution - for security, defense, or more extensive outreach operations
    - **Civil and personal applications** - cellular communication technologies are preferred
    - **Indoor communication** - e.g. in mesh network and Wireless Sensor Network (WSN) - Bluetooth or point-to-point (P2P) protocols
    - **Communication to a multi-layered network** – complex process in UAV context

1. Introduction

1.1 Unmanned Aerial Vehicles (UAV)

- **UAV Classfication-** criteria: communication capability, radius range of UAV data link
  - **Long-endurance** UAVs- (reconnaissance, interception or attack)
  - **Mid-range** UAVs- action radius of ~ 650 km (mid-range reconnaissance and combat effect assessment)
  - **Short-range** small UAVs - action radius < 350 km, flight altitude - less than 3 km, flight span ~ 8-12 hours
  - **Close-range** UAVs - limited cruising duration 1 -6 hours, depending on the mission, coverage of at least 30 km
  - **Low cost, close-range** UAVs -flight-span ~ about 5 km
  - **Commercial and consumer UAVs** - very limited range (controlled from a console, App on a smart phone, tablet)

Source: C.Yan, L.Fu, J.Zhang, , and J.Wang , A Comprehensive Survey on UAV Communication Channel Modeling, IEEE Access, 2019, https://ieeexplore.ieee.org/document/8787874

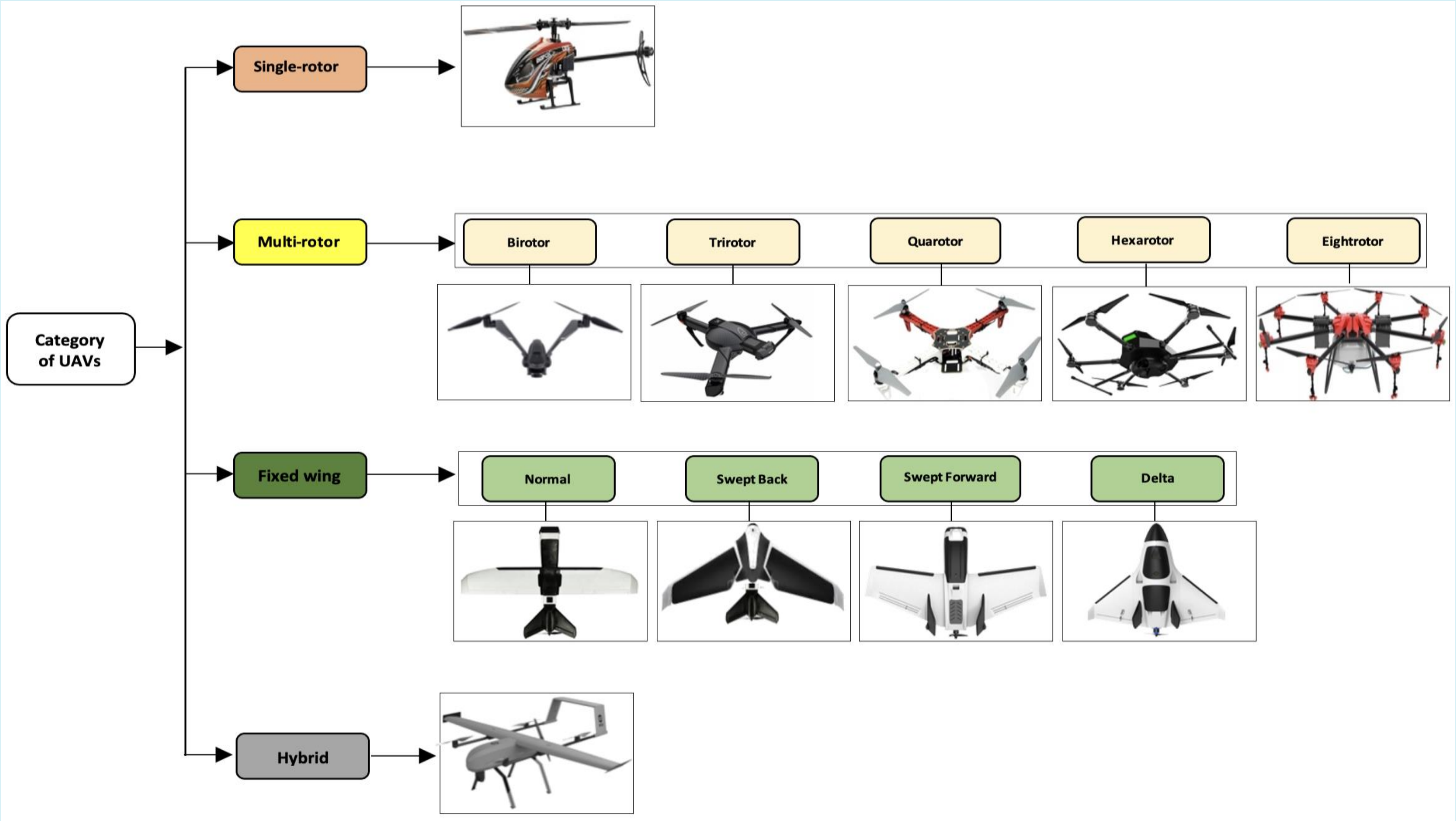
- **Other UAV taxonomies also exist**- they can be classified like any other aircraft, according to design configuration such as ***weight* or *engine type*, *maximum flight altitude*, *degree of operational autonomy, operational role,* etc**.

- **UAS = UA System** = the entire system that supports and controls the UAVs

1. Introduction

1.1 Unmanned Aerial Vehicles (UAV)

- Different types of UAVs



Source: W.Y.H. Adoni, S.Lorenz, J.S.Fareedh, R.Gloaguen and M.Bussmann, Investigation of Autonomous Multi-UAV Systems for Target Detection in Distributed Environment: Current Developments and Open Challenges, 2023, https://doi.org/10.3390/drones7040263

1. Introduction

1.2 UAV Applications examples

- **Individual, Business and Governments**
  - Express shipping and delivery, Unmanned cargo transport
  - Aerial photography for journalism and film
  - Disaster management: gathering information or supplying essentials
  - Storm tracking and forecasting hurricanes and tornadoes
  - Thermal sensor drones for search and rescue operations
  - Geographic mapping of inaccessible terrain and locations
  - Building safety inspections, Precision crop monitoring
  - Law enforcement and border control surveillance
  - **In progress: development of many other use cases**

YoY = Year-over-Year

Source: https://www.aonic.com/my/blogs-drone-technology/top-10-applications-of-drone-technology/

1. Introduction

1.2 UAV Applications examples

- **Delivery** Drones Technology
  - known as “last mile” delivery drones; deliveries from nearby retailers or warehouses
- **Emergency Public Rescue**
  - E.g., Disaster areas, Autonomous Underwater Vehicle (AUV)
- **Military domain**: thermal imaging, laser range finders, airstrike, surveillance, etc.
- **Agriculture:** field surveys, sowing across fields, tracking livestock, and predicting crop yields easier while saving workers’ important time
- UAV for **Outer Space**
- UAV for **Wildlife and Historical Conservation**
- **Medicine**
  - to transport/deliver medical supplies and goods in remote areas
  - to transport transplant organs to surgery locations
- **Drone for 3D Modeling creation**
  - LiDAR drones can be equipped with LiDAR sensors, which survey landscapes and collect detailed data that can be used to create 3D models
    - Light Detection and Ranging (LiDAR - a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth)
- Drone for **Photography**

Source: https://www.aonic.com/my/blogs-drone-technology/top-10-applications-of-drone-technology/

1. Introduction

1.3 UAV Networks

- **UAV networks** – characteristics different w.r.t. MANETs and VANETs
  - **dynamic behavior -** rapid mobility and topology changes
  - **new challenges** for communication at: PHY layer, management and control, **routing and path planning,** traffic management, cooperation, security

- **Inter-UAV wireless communication** is necessary in **UAV communication networks (UAVCN) ,** a.k.a. **flying ad hoc network (FANET)**
  - **Notation**
    - **UAV network = FANET= UAVCN drone ad hoc network**

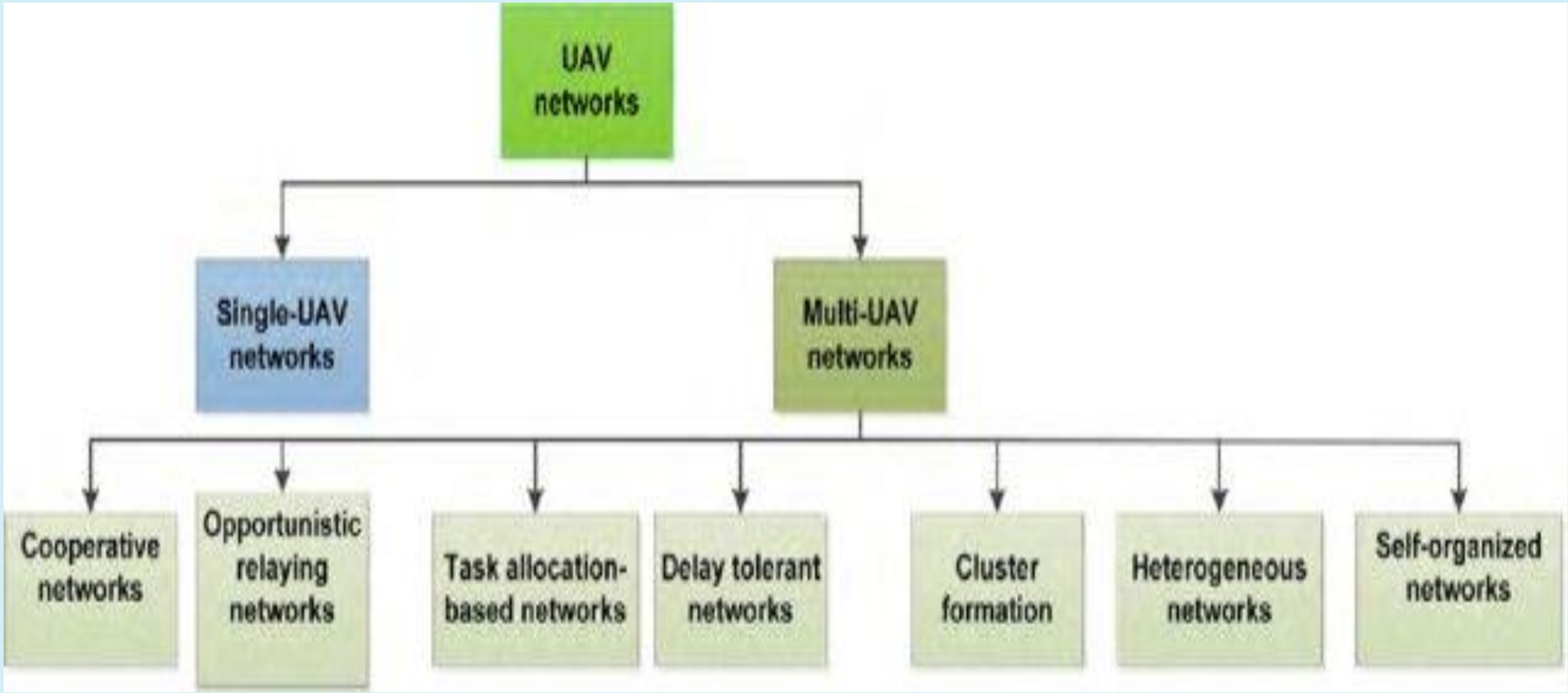
- Two **basic types** of UAVCN networks
  - **single-UAV network** - the UAV device is linked to a **ground base station (GS),** or to a satellite; each UAV acts as an *isolated node*
  - **multi-UAV network** – many UAV devices are linked
    - to each other (**U2U links**)
    - to the **ground base station (U2G links), or satellite**
    - the topologies can be configured dynamically

  - **Multi-UAV systems** are more efficient and cost-effective in collaborative missions

1. Introduction

1.3 UAV Networks

- **Taxonomy of UAV networks**



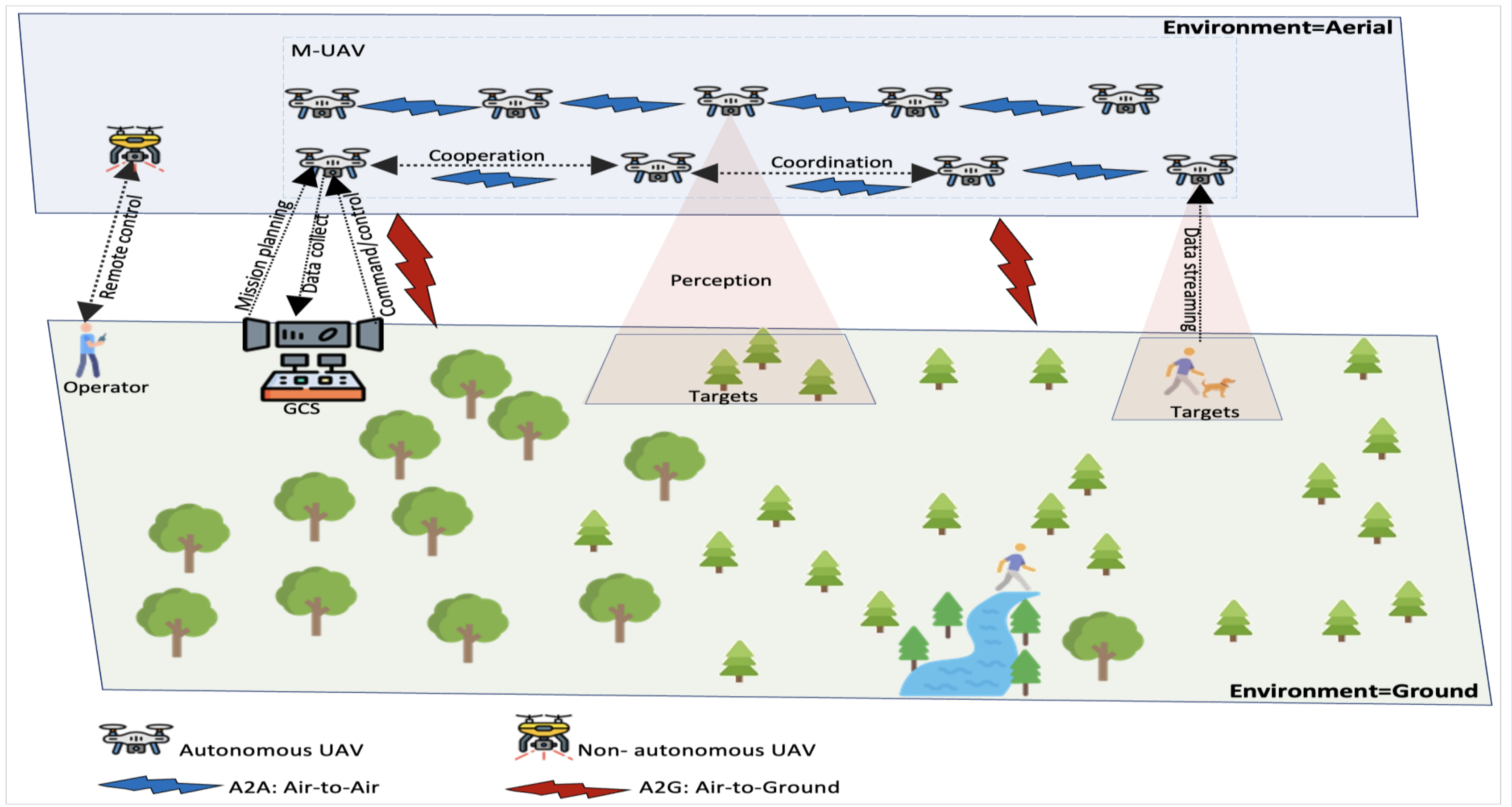
Source: M.Yeasir Arafat and S.Moh, Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey, DOI 10.1109/ACCESS.2019.2930813, IEEE Access, 2019

1. Introduction

1.3 UAV Networks

GCS- Ground Control Station

- **Overview of a multi-UAV ecosystem**



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1. Introduction

1.3 UAV Networks

- **Different views on UAV networks architectures**

- **Cooperative Multi-UAVs**
  - **Cooperative UAVs- based task achievement**
  - **(+)- advantages (-) -issues**

  - **Opportunistic relaying networks**
    - (+) Execute tasks based on **coordination**, support for dynamic network, **tolerant to link failures** (opportunistic transmissions), good utilization of network resources
    - (-) Use various estimations and approximations, **UAVs collision- problem**, **complex computations**, packet duplication, high energy consumption

  - **Delay-tolerant UAVs networks**
    - (+) Support **UAVs with limited power resources**, **store and forward** method can avoid the routing complexity
    - (-) **Low (intermittent) connectivity**, no E2E connectivity**, high latency**, issues with buffer and bandwidth capacity, security

Source: A.I.Hentati, L.C. Fourati, Comprehensive survey of UAVs communication networks, Computer Standards & Interfaces 72 (2020) 103451, www.elsevier.com/locate/csi

1. Introduction

1.3 UAV Networks

- **Different views on UAV networks architectures** (cont'd)
- **Multi-Layers UAV Networks**
  - **UAV swarms**
    - (+) Many UAVs in the large mission areas, few communications with GSs
      - They can cooperate to solve complex tasks
    - (-) UAV collisions, complex computations for coordination
  - **Ground WSN**
    - (+) Multiple/distributed data sources, available UAVs sensors, fast data collection
    - (-) Limited opportunities to communicate with sensors, limited trs. range
  - **Internet of Things (IoT)**
    - (+) Layered network architecture, fast aerial packets delivery, various applications and services, efficient traffic management
    - (-) Low UAVs energy, UAVs range limitations, UAVs landing restrictions, congestion in urban airspace
  - **Cooperation with Cloud Computing**
    - (+) UAVs offload heavy computations -> cloud data centers, remote computation and storage services
    - (-) Latency, UAVs range limitations, security issues

Source: A.I.Hentati, L.C. Fourati, Comprehensive survey of UAVs communication networks, Computer Standards & Interfaces 72 (2020) 103451, www.elsevier.com/locate/csi

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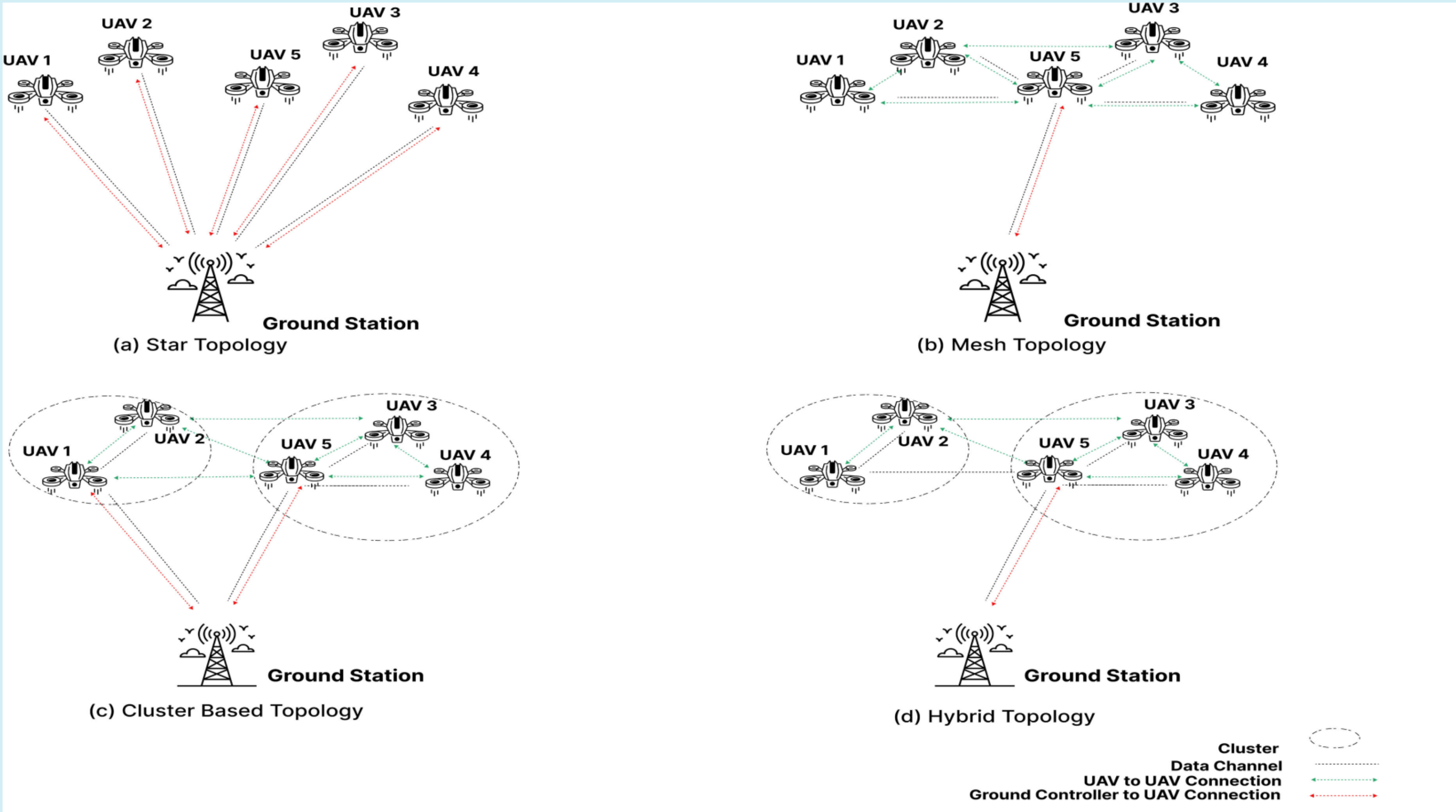
1.3 UAV Networks

- **Multi-UAV topologies- examples**
  - **(a) Star topology:** each UAV (node) is directly connected with GS node
  - **(b) Mesh topology**: the GS is only connected to a single node (**cluster head** of the UAV group- playing a role of Gateway)
    - The cluster head passes the data packets from the GS to the other member nodes and vice-versa
  - **(c) Cluster-based network topology**
    - The UAVs are grouped in clusters; each cluster has a head
    - GS is connected to heads UAVs of clusters
    - The heads collect data packets from the member UAVs and forward them to the GS and vice versa
  - **(d) Hybrid mesh network**- one cluster head UAV is connected to the GS
    - The head can pass the information to the UAVs of its group but also pass information to other nearby cluster heads
    - The head can pass information from the GS to other connected nodes and vice-versa
    - The GS can be connected also to single UAVs or group cluster heads
    - The cluster heads can share information within their groups or the head UAVs of another group
  - **Inter-UAV communication topologies: star, ring, mesh**

1. Introduction

1.3 UAV Networks

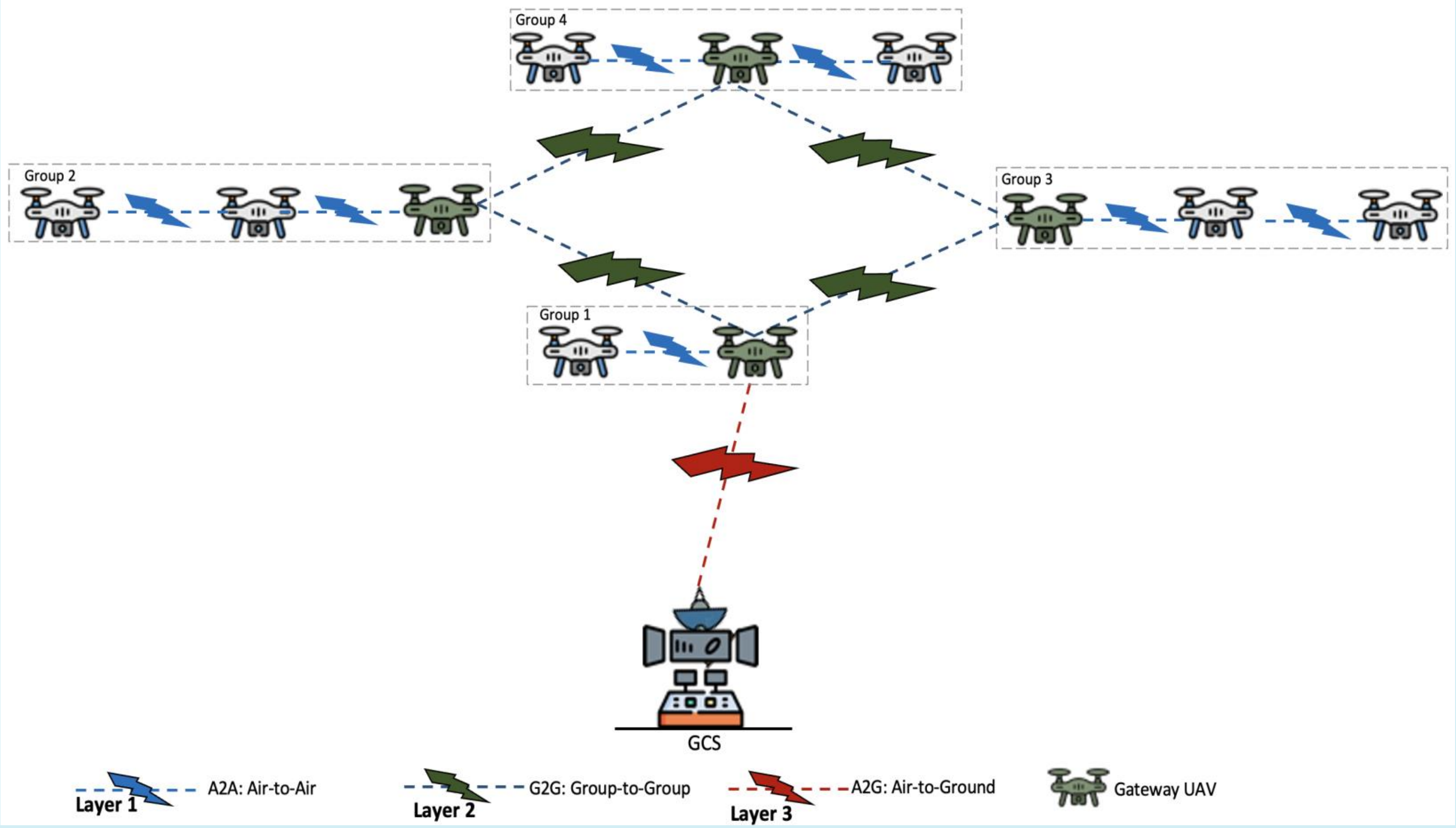
- **Multi-UAV topologies: (a) Star b) Mesh (c) Cluster-based (d) Hybrid mesh**



Source: N. MANSOOR et al., A Fresh Look at Routing Protocols in Unmanned Aerial Vehicular Networks: A Survey, IEEE Access June 2023

1. Introduction

- **1.3 UAV Networks**
- **Multi-level example**



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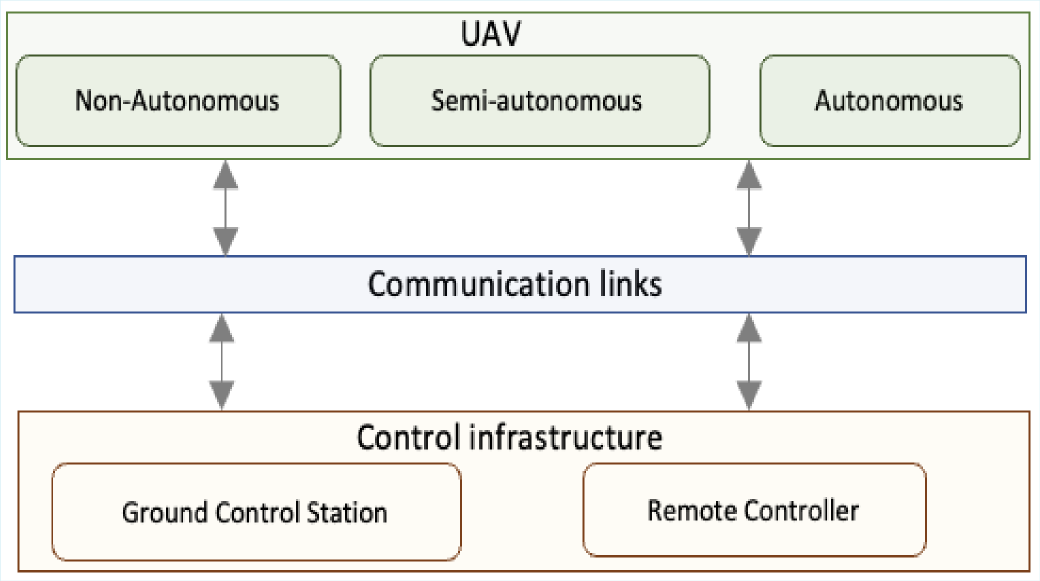
1.4 UAV System- simplified functional architecture

- **UAS Functional components**
- **Uncrewed Aerial System (UAS)** a.k.a. **Remotely Piloted Aircraft System (RPAS)**
  - The interaction with the UAV is realized through a ground control station, a remote controller, a data transmission system, and dedicated HW/SW support



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2. Routing and Path Planning Problems

2.1 UAV General Routing Requirements

- **Existing routing algorithms and protocols used in MANETs and VANETs cannot fully solve the UAV networks needs**
  - UAV - large sets of applications and routing criteria, varying levels of dynamism, 3D, geographical different contexts, intermittent links, fluid topology, etc.

- **General requirements of UAVs routing protocols**
  - must select the most effective communication paths for reliable and stable data transmission
    - Various factors/requirements to consider
      - various criteria/metrics of routes finding
      - E2E delay, throughput, managing dynamic topology, network density, intermittent links, power constraints and changing link quality
      - Mobility; the lifespan of UAV nodes is limited -> seamless handovers are important
      - energy efficiency needs
      - security guarantees, dependable, and reliable data transmission
      - special QoS requirements in some use cases

    - **Architecture**: **centralized, distributed or hybrid**

2. Routing and Path Planning Problems

2.2 Basic routing principles - still valid for UAV case

- **Legacy routing principles: Hop-by-hop routing** or **Source routing**

General taxonomy of routing protocols

- **Static (**fixed) **routing protocols**
  - a routing table is calculated and uploaded to the UAVs before flight
    - (-) not possible to update or modify during UAV operation
    - (-) no dynamicity, not fault-tolerant

- **Proactive protocols (PRP)- classical/basic principle**
  - the routing/forwarding tables store all the routing information
  - tables are updated and shared periodically among the nodes (inter- node messages)
    - (+) always contains the latest information
    - (-) control traffic overhead; possible slow response to network changes (delays)
    - higher speed solution: event-triggered message exchanges between routers

- **Reactive (on-demand) routing protocols (RRP)**
  - a route is computed at the source node request and stored for a limited time
    - (+) overcome the overhead problem of PRP
    - (-) possible higher latency in finding the route (the route computation starts when a request is coming from a source node)

2. Routing and Path Planning Problems

2.2 Basic routing principles

- **Taxonomy of UAV routing protocols**

- **Hybrid routing protocols (HRP)**
  - combine PRP-RRP; good for large-scale networks that may have several sub-network areas; intra-zone routing can use PRP, and inter-zone use RRP

- **Specific to UAV**
  - **Position based routing protocols** (using geographical information)
  - **Hierarchical protocols** (for large networks)

- **High level view comparison** (summary)

Routing approach	Static/ Dynamic	Network size	Real time Overhead	Latency	Mobility	Computation Complexity
Static	Static	Small	No	Low	Fast	Low
Proactive	Dynamic	Small	Yes	Low	Slow	Medium
Reactive		Larger		High	Average	Average
Hybrid		Any		High	Average	Average
Position-based		Large		Low	Average	High
Hierarchical		Large		High	Average	High

2. Routing and Path Planning Problems

2.3 UAV routing styles

- **Delivery schemes**
  - **unicast** (source node to destination node)
  - **multicast** (source node - to a registered members of group)
  - **broadcast** (source to all)
  - **geocast** (source **–** only to nodes located in a specific geographical area)

- **Single path method**
  - used to transmit data between two specific nodes
  - the path is calculated using simple routing/forwarding tables
  - the routing table is predefined; no alternative paths exist in the case of faults in the network

- **Multipath routing methods**
  - several paths between the source and destination nodes are possible
  - (+) the network is better defended against jamming attack (e.g., disruption of wireless communications by decreasing the SNR at receiver because of interfering wireless signals) or path failures
  - (+) efficient and reliable data transmission is possible
  - (-) maintaining the routing table can be costly (e.g., in case of many routing paths)
    - possibility of route loops if errors occur

2. Routing and Path Planning Problems

2.4 Path planning problem in UAV

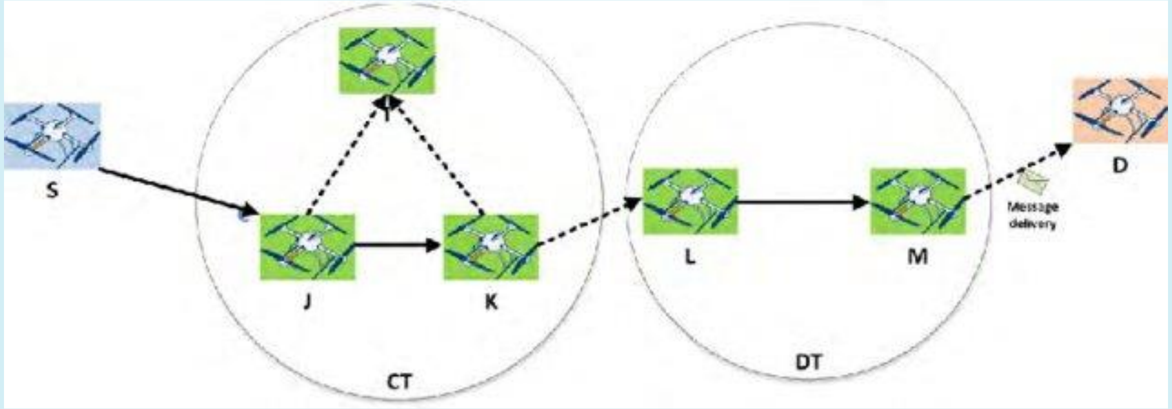
- **Objectives**:
  - to find an optimal (e.g., shortest path) but also to provide the collision-free environment to the UAVs
  - short route computation time
- **Coverage Path Planning (CPP)** is a critical issue for many UAV applications
  - Depending whether the environment is known or not, CPP algorithms can be divided into two categories:
    - **Offline CPP**
      - Assumption: all environmental information is known in advance
      - CPP algorithms only depend on static environmental information
    - **Online CPP**
      - CPP algorithms do not know in advance the complete information of the environment to be covered; they plan local paths based on real-time sensor information
  - According to the employed cellular decomposition technology, CPP algorithms can be divided into three main types:
    - **no decomposition, exact cellular decomposition** and **approximate cellular decomposition**

Source: Cabreira TM, Brisolara LB, Ferreira PR (2019) Survey on coverage path planning with unmanned aerial vehicles. Drones 3(1):4. https:// doi. org/10. 3390/ drone s3010 004

2. Routing and Path Planning Problems

2.5 UAV routing-related methods - examples

- **UAV position tracking**
  - UAVs use the GPS signal (RF signal transmitted by satellites) containing location and time information
    - or, other positioning systems, such as GLONASS, Galileo or BeiDou, for greater accuracy and better coverage in different regions of the world
- **Cooperative routing**
  - higher communication reliability; the **nodes helps each other** with information by exploiting broadcasting schemes
  - the neighboring nodes are considered as relay nodes
  - link types : cooperative trs. (CT) and direct transmission (DT)



Source: M.Yeasir Arafat and S.Moh, Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey, DOI 10.1109/ACCESS.2019.2930813, IEEE Access

2. Routing and Path Planning Problems

2.5 UAV routing-related methods -examples

- Path discovery
  - **assumptions**
    - bi-directional paths
    - the geographical position of the target destination node is known by the source node
    - on-demand style of route finding
    - a **backward learning** method can be used
  - to reach the destination, a **route request (RREQ) message is sent**
    - (RREQ-similar method is used in also MANET AODV –Ad Hoc On Demand Distance Vector Routing Protocol)
      - using broadcast mode, i.e., on all-possible paths from source node to destination node
    - the packets going to the destination collect information about the path
    - if an intermediate node already knows the path requested, then it answers to the source node
  - the destination node receives several replicas of interrogation packets
    - it can select the best path on some conditions
    - the selected path is used for data transmission
  - a response (RREP) is returned to the source, indicating the best path
  - this path is stored for some life-time and can be used in the future by the source

2. Routing and Path Planning Problems

2.5 UAV routing-related methods-examples

- **Store-carry-and-forward (SCF) routing technique**
- It can be used in several cases: intermittent connectivity; high mobility; long delays; when a direct E2E connection is not available

- **Main idea**: information is sent to an intermediate station where it is stored and sent at a later time instant to the final destination, or to another intermediate station
  - the intermediate station/ node verifies the message integrity before forwarding it
  - in SCF the messages are forwarded among encountered mobile relay nodes (called SCF routers)

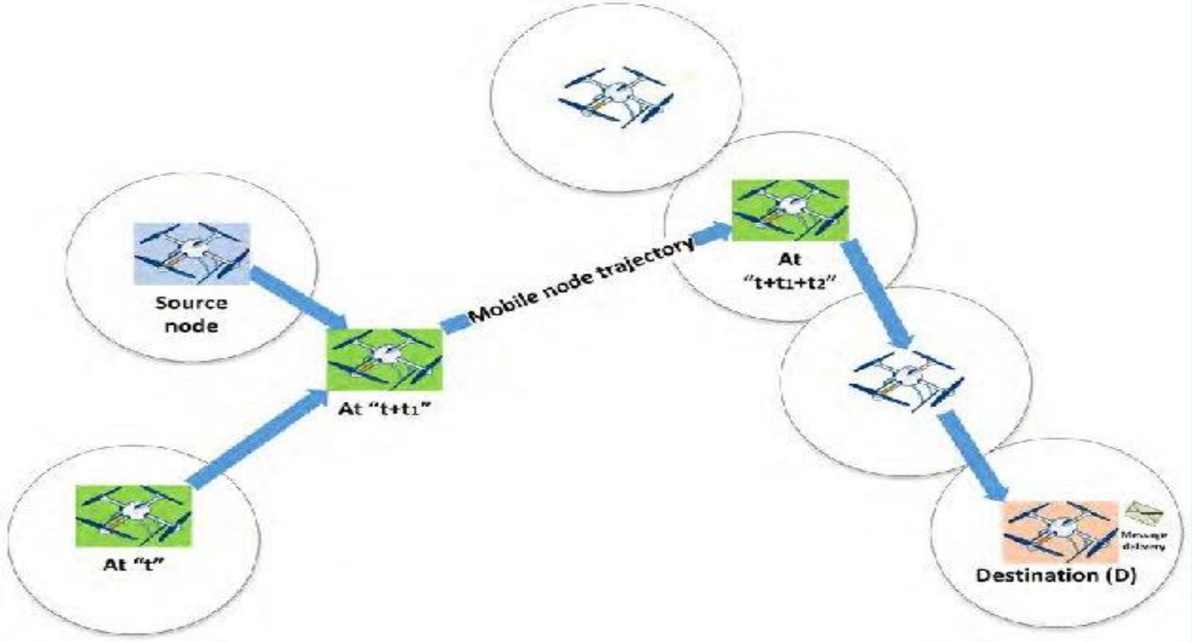
- SCF it is used when some network fault causes a disconnect from its next relay node
  - but forwarding data is still necessary
  - and it is also not possible to transmit data to next hop, as the node is out of transmission range
  - in this case the current packet holder node carries the data until it meets another node or the destination node
  - a decision is made at each relay node (SCF router) to store, replicate, or delete a message

2. Routing and Path Planning Problems

2.5 UAV routing-related methods- examples

- **Store-carry-and-forward (SCF) routing technique** (cont'd)
  - SCF is efficiently used in FANETs, if the UAV nodes are sparsely distributed
  - SCF can be exploited in **delay-tolerant networks (DTN)** with ferrying UAVs
    - ensures high throughput in delay-tolerant routing in UAV networks.
  - **Disadvantage:** high delay may happen

Figure: when the network suffers from intermittent connectivity, the forwarding node carries data packets until it meets with another node or reaches to the destination



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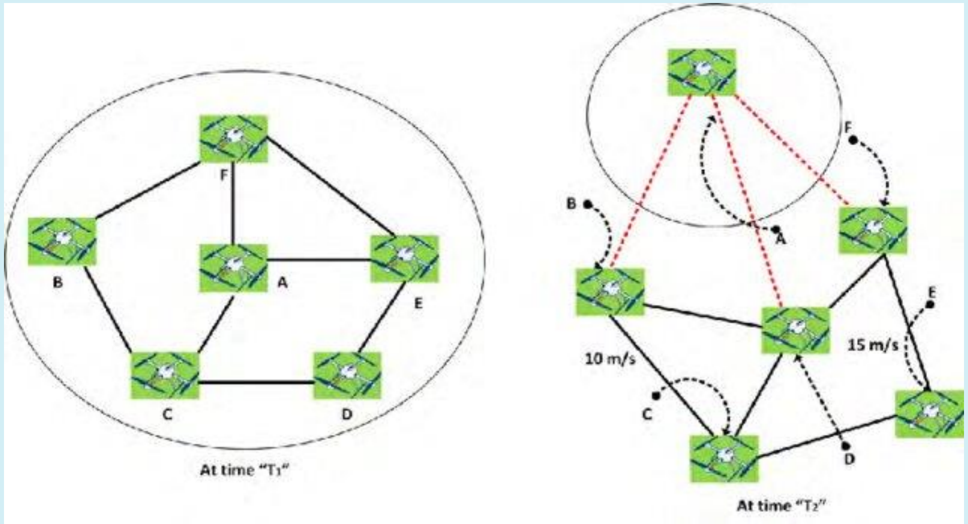
2. Routing and Path Planning Problems

2.5 UAV routing-related methods -examples

- **Prediction methods**
  - common methods - based on the direction, geo location, and speed of the UAVs used by the source node to transmit data to the next node
    - the parameters usually provide enough good approximations about the next relay node in communication network
  - Figure- shows how predicting geo location is used to find the next relay node (UAVs positions evolution in time - is shown)
  - SCF method could be used to avoid packet loss in the network; path discovery can find active paths between nodes

Prediction technique-example



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2. Routing and Path Planning Problems

2.5 UAV routing-related methods - examples

- **Greedy forwarding (GF)**
  - It is used when UAVs are densely deployed in a network
  - GF is a **distance-based (location-based) greedy routing algorithm** for UAV networks solely based on UAVs' local observations of their surrounding subnetwork

  - **Objective:** to **minimize the number of hops** in the transmission path
  - Approach: to choose a relay node that is *geographically* nearest to the destination node
  - GF is a progress-based forwarding strategy
  - A node forwards the packet to the neighbour node having the lowest distance to the destination node
    - If there is no neighbour node closer to the destination node, the algorithm fails and the node keeping the packet is called local minimum

  - **Drawbacks**
    - local optimum problem (it may not find the best relay node to reach its destination)
    - high overhead

2. Routing and Path Planning Problems

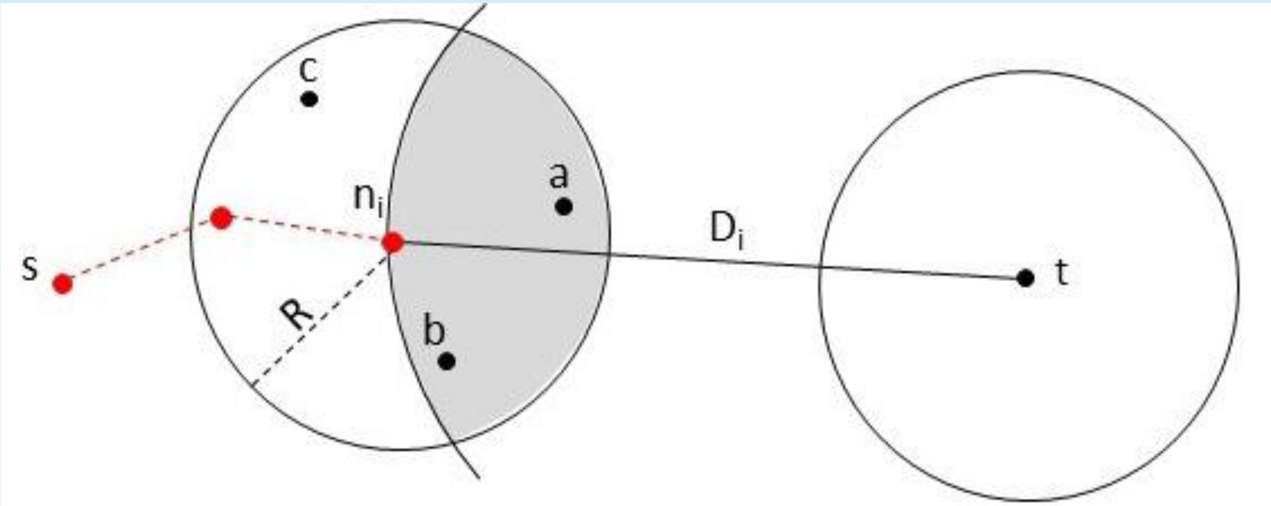
2.5 UAV routing-related methods -examples

- **Greedy forwarding (GF)** (cont'd)
- **GF example**
  - The source node **s** wants to send a packet to a destination node **t** which is located at distance **D**
  - At each step **i**, the current node $\mathbf{n_i}$ passes the packet to a neighbour node $\mathbf{n_j}$ which is closest to the destination
  - The packet is passed only if the next node makes a progress, (i.e. if the next node is closer to the destination than the current node: $d_{i+1;t} < d_{i;t}$)
  - If such a neighbour does not exist, the current session fails, and the packet journey is re-initiated
  - This algorithm continues until the packet is eventually delivered to the destination
  - This constraint is required to ensure a loop-free path towards the destination
    - In this way, at each step, a progress is guaranteed, provided that there is at least one neighbour in the progress area

2. Routing and Path Planning Problems

2.5 UAV routing-related methods -examples

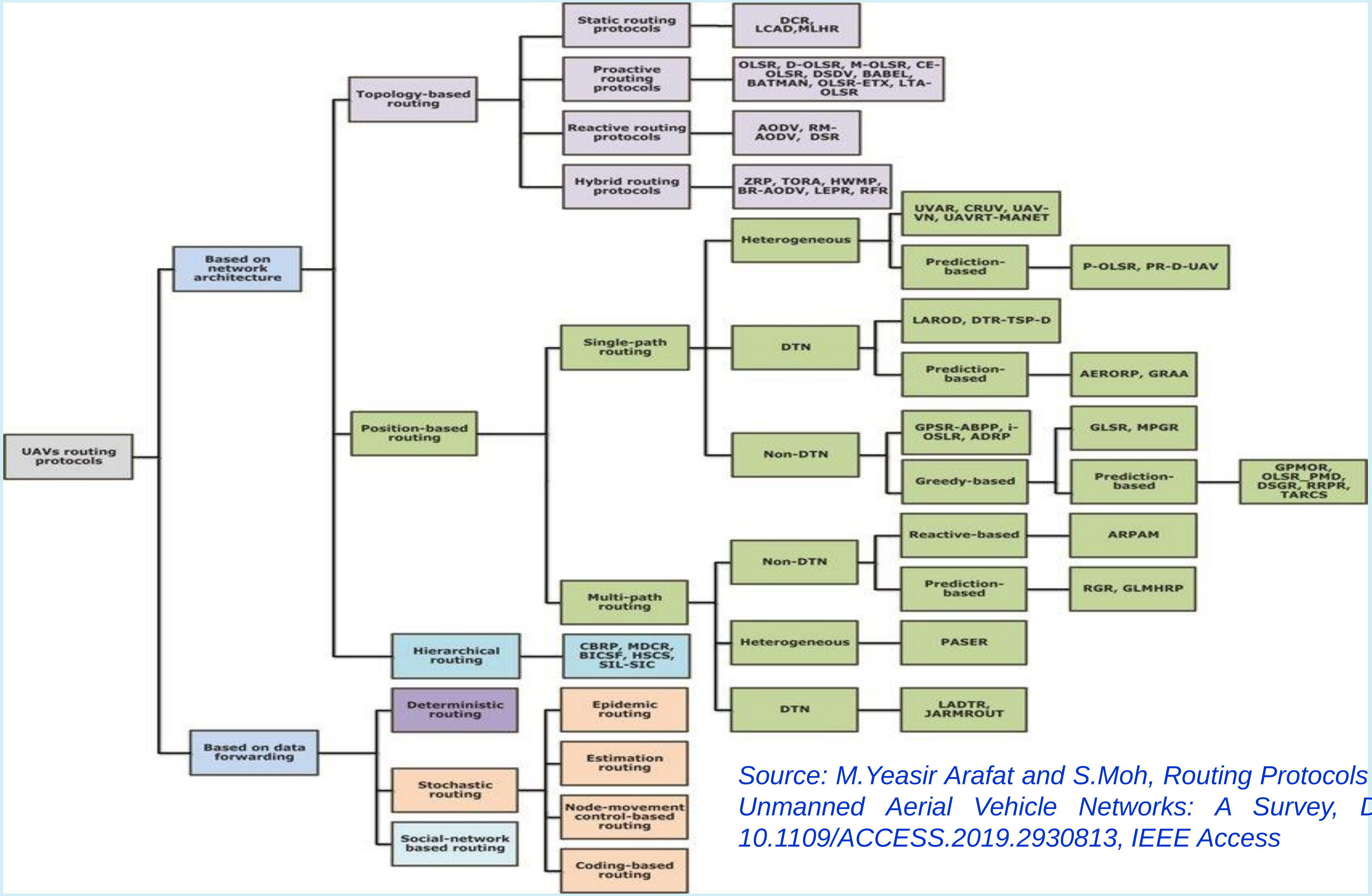
- **Greedy forwarding (GF)** (cont'd)
- **GF example** (cont'd)
  - The Figure represents one intermediate iteration of this algorithm
  - The shaded area represents the valid locations for the next node
    - here, the progress area is the intersection of two circles centred at $\mathbf{n_i}$ and **t** with radii **R** and $\mathbf{D_i}$,; $\mathbf{D_i}$ is the remaining distance to the destination, once the packet reaches node $\mathbf{n_i}$.
  - The algorithm chooses the best node towards the destination (here $\mathbf{n_{i+1} = a}$).



Source: Mehrdad Khaledi, Arnau Rovira-Sugranes, Fatemeh Afghah, and Abolfazl Razi, On Greedy Routing in Dynamic UAV Networks, arXiv:1806.04587v1 [cs.NI] 4 Jun 2018

2. Routing and Path Planning Problems

2.6 UAV routing protocols taxonomy – criterion: **based on network arch. or on data fwd**



Source: M.Yeasir Arafat and S.Moh, Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey, DOI 10.1109/ACCESS.2019.2930813, IEEE Access

2. Routing and Path Planning Problems

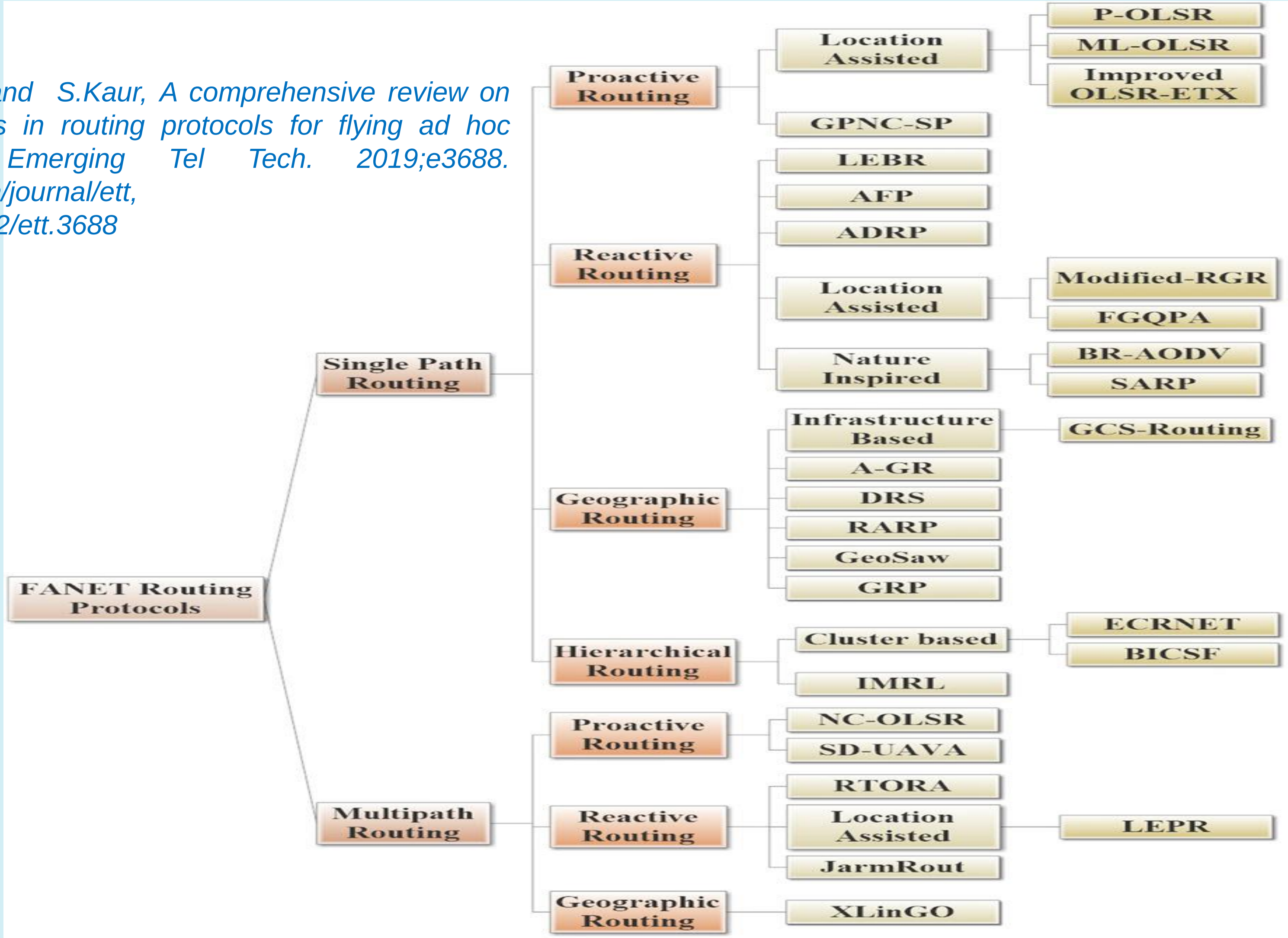
2.6 UAV routing protocols taxonomy – notations

- ADRP Adaptive Density-based Routing Protocol
- AODV Ad-hoc On-Demand Distance Vector
- BATMAN Better Approach to Mobile Ad hoc Network
- BICSF Bio Inspired Clustering Scheme for FANET
- CBRP Cluster-based Routing Protocol
- DCR Data Centric Routing
- DSGR Distance-based Greedy Routing
- DTP-TSP-D Deadline Triggered Pigeon with Travelling Salesman Problem
- DSR Dynamic Source Routing
- DOLSR Directional Optimized Link State Routing
- DEQPSO Differential Evolution and Quantum-Behaved Particle Swarm Optimization
- DSDV Destination Sequence Distance Vector
- DTN Delay Tolerant Network
- GLSR Geographic Load Share Routing
- GPMOR Geographic Position Mobility-Oriented Routing Protocol
- GLMHRP Geolocation-based Multi-hop Routing Protocol
- GPSR Greedy Perimeter Stateless Routing
- GPSR-ABPP GPSR-Adaptive Beacon and Position Prediction
- HSCS Hybrid Self-organized Clustering Scheme
- HWMRP Hybrid Wireless Mesh Routing Protocol
- HWMP HRC Hybrid Routing based on Clustering
- JARMROUT Jamming -Resilient Multipath Routing
- LADTR Location Aided Delay Tolerant Routing
- LCAD Load-Carry-and-Deliver
- LEPR Link Estimation Preemptive Routing
- MDCR Modularity-based Dynamic Clustering Relay
- MPCA Mobility Prediction Clustering Algorithm
- ML-OLSR Mobility and Load aware OLSR
- MLHR Multi Level Hierarchical Routing
- OLRS Optimized Link State Routing
- OLSR-PMD OLSR with Mobility and Delay Prediction
- POLSR Predictive-OLSR
- PASER Position Aware Secure and Efficient Mesh Routing
- RGR Reactive-Greedy-Reactive
- RM AODV Radiometric AODV
- RRPR Robust and Reliable Predictive Routing
- RTORA Rapid-reestablish Temporally Ordered Routing Algorithm
- RSGFF Recovery Strategy Greedy Forwarding Failure
- SIL-SIC Swarm Intelligence-based Localization and Clustering
- TARCS Topology-Aware Routing Choosing Scheme
- TORA Temporally Ordered Routing Algorithm
- TBRPF Topology Broadcast based on Reverse-Path Forwarding
- UVAR UAV-Assisted Routing
- ZRP Zone Routing Protocol

2. Routing and Path Planning Problems

2.6 UAV routing protocols taxonomy1 – criterion: **routing method used**

Source:A. Malhotra and S.Kaur, A comprehensive review on recent advancements in routing protocols for flying ad hoc networks, Trans Emerging Tel Tech. 2019;e3688. wileyonlinelibrary.com/journal/ett, https://doi.org/10.1002/ett.3688



2. Routing and Path Planning Problems

2.6 UAV routing protocols taxonomy1-– notations

- ADRP Adaptive Density-based Routing Protocol
- AFP Adaptive Forwarding Protocol
- A-GR: Geographical Routing Protocol
- AODV Ad-hoc On-Demand Distance Vector
- BICSF bioinspired clustering scheme for FANETs
- DRS Directional Routing Scheme
- DSGR Distance-based Greedy Routing
- DSR Dynamic Source Routing
- DSDV Destination Sequence Distance Vector
- DTN Delay Tolerant Network
- ECRNET Energy aware Cluster-based Routing in flying ad-hoc Networks
- ETX Expected Transmission Count
- FSR Fisheye State Routing
- GPSR Greedy Perimeter Stateless Routing
- GPNC-SP Shortest Path Routing based on Grid Position.
- LEPR Link Estimation Preemptive Routing
- OLRS Optimized Link State Routing
- OLSR-PMD OLSR with Mobility and Delay Prediction
- POLSR Predictive-OLSR
- RGR Reactive-Greedy-Reactive
- RTORA Rapid-reestablish Temporally Ordered Routing Algorithm
- SARP Stable Ant-based Routing Protocol

2. Routing and Path Planning Problems

2.6 UAV routing protocols taxonomy – summary discussion

- **Network architecture-based protocols**
  - **Topology-based protocols**
    - **Tree-based**
      - Source-rooted tree routing
        multicast routing (the source node is the root of multicast tree and maintains the tree construction and distribution)
      - core-rooted based routing
        - cores are nodes with special functions, like multicast data distribution and membership management
    - **Mesh-based**
      - packets are distributed among all interconnected nodes in the mesh
      - mesh building
        route discovery – by broadcasting method
        mesh building - core point is used
      - in high mobility network performance is better than for tree-based routing
      - provides alternate paths from the source to destination
      - to maintain and manage the routing topology- control packets are needed, which makes routing overhead and power inefficiency
    - **Hybrid -** combines the tree and mesh-based routing
      - advantages: multiple routing paths

2. Routing and Path Planning Problems

2.6 UAV routing protocols taxonomy - discussion

- **Network architecture-based protocols** (cont'd)
  - **Position-based protocols**
    - based on the **knowledge of geographical positions,** where **GPS can define nodes**
    - protocols are appropriate for highly dynamic UAV networks
    - **Categories:** single-path and multi-path; both types of protocols can be further categorized into
      - heterogeneous networks
      - delay-tolerant networks (DTNs)
      - non-delay tolerant networks (Non-DTNs).
  - **Hierarchical routing protocols**
    - In a hierarchical network, several numbers of clusters can perform in various operations
    - The hierarchical architecture is used to increase the network operation area and size
    - UAV networks may be divided into several clusters, and only the cluster head (CH) links with another cluster group head, and as well as to the ground node

3. Routing and Path Planning Problems

3.6 UAV routing protocols taxonomy - discussion

- **Data forwarding-based**
  - **Deterministic routing protocols**
    - This protocol is useful when
      - **the UAVs flight is in controlled formations**
      - future availability and location of the nodes are known
      - further movement of a node is already known by neighbouring nodes
    - Assumption: all nodes have the information on other nodes in terms of mobility, availability, and motion
      - then a tree approach could be designed for select paths
    - In the tree, the source node is considered as the root node and other nodes as child nodes
    - Paths are selected through tree, based on the earliest time to reach the destination node

2. Routing and Path Planning Problems

2.6 UAV routing protocols taxonomy - discussion

- **Data forwarding-based protocols** (cont'd)
  - **Stochastic routing protocols**
    - Suitable for networks where network behaviour is unknown and random; time-varying network topology
    - In this condition, packet delivery decision becomes important
    - Objective: to minimize the E2E delay by maximizing the probability of delivery at the destination
    - Solution example –data forwarding to the next visible node in communication range
    - Here, historical data, mobility patterns, etc., are all considered for routing
    - **Categories:** *epidemic routing-based approach; estimation-based routing; node movement and control-based routing; coding-based routing*

- **Social networks (SN) - based routing protocols**
    - When the mobility of the nodes is not random, but rather fixed, then the use of large numbers of networking protocols is not realistic
    - When a nodes visits a place, it can store data of the visiting place in a database for further use. Using this database, the node can select paths very quickly in its subsequent attempts
    - This protocol is useful when UAV nodes store node information, like location
    - SN-based routing requires higher buffer size and higher bandwidth

CONTENTS

3. UAV in Cellular and Satellite Networks

3.1 UAVs in cellular networks

- The **Third Generation Partnership Project (3GPP)** started a study (2017) for serving the UAVs as a new type of **user equipment (UE),** referred to as **aerial UE**

- **Aerial User Equipment (UAV-UE)** or **Aerial Base Stations (UAV-BS)**
- **A. UAVs as aerial User Equipment**
  - The ground pilot can remotely control the UAV-UEs with unlimited operation range
  - UAV-UE - connectivity between UAVs and the ground user equipment and the air traffic controllers
  - Good reliability, data throughput, security, cost-effective
  - **Open issues –** flight altitude, mobility and handover, routing, interference, cyber-physical attacks and security, energy efficiency, etc.
    - **need of**
      - **novel mathematical and algorithmic solutions**
      - **cell interference coordination** techniques
  - AI/NN solutions proposed for **security** and **resource allocation optimization**

Sources: Fotouhi, et al., Survey on UAV Cellular Communications: Practical Aspects, Standardization Advancements, Regulation, and Security Challenges, JOURNAL OF COMMUNICATIONS SURVEYS AND TUTORIALS, arXiv:1809.01752v2 [cs.NI] 2019
3GPP Technical Report 36.777. TSG RAN ; Study on enhanced LTE support for aerial vehicles (Release 15). Dec. 2017.

3. UAV in Cellular and Satellite Networks

3.1 UAVs in cellular networks

- **B. UAVs as aerial base stations (UAV-BS)**
  - They can be supported by the existing terrestrial cellular networks
  - **UAV- BS can adjust their altitude**, enhance establishing LOS links with the ground users, and avoid obstacles
  - **UAV- can complement the existing cellular systems :** flexibility, mobility, and adaptive altitude, improved network
  - **Open issues:**
    - **Optimization of placement and mobility, power consumption**
      - **security** solved at several architectural layers – even PHY

        e.g., maximize the secrecy rate by jointly optimizing the transmit beamforming and the UAV power consumption
    - **network throughput and coverage improvement** for deploying UAV-BSs
      - Solution example: UAV-artificial bee colony mechanism for UAV-BSs deployment, determining the optimal flight location of each UAV-BS in order to maximize the network throughput
    - **UAV-BS trajectories -** Solution example: **Deep Reinforcement Learning (DRL)** based on the flow level model for learning the optimal traffic-aware UAV-BS trajectories

3. UAV in Cellular and Satellite Networks

3.2 UAV in Satellite Networks

- **Satellites can**
  - **relay data** between UAVs and the GSs (where WiFi or cellular network coverages are unavailable)
  - be exploited for **UAVs localization and navigation**
- **Limitations/challenges** of using satellites for UAV communications
  - Propagation loss and delay
  - UAVs - power and weight constraints and the small size- they cannot carry the heavy energy-consuming communication equipment
  - Satellite communication - high operational cost which limits their wide usage for UAV communications

- **Examples of solutions** proposed

  - **Use of both the UAVs and satellites** to ease the integration of a huge number of IoT objects in the 5G framework
    - **Satellites** are used as **relay nodes**, UAVs as 5G-user equipment, and 5G-gNBs are on the ground
    - This solution overcomes some problems of the terrestrial infrastructure like the densification of the IoT devices and the restricted covered areas

CONTENTS

1. Introduction
2. UAV Routing and Path Planning Problems
3. UAV in Cellular and Satellite Networks
4. ➡ UAV in 5G, 6G Networks
5. AI in UAV Routing
6. Conclusions

4. UAV in 5G, 6G Networks

4.1 Categories of 5G main scenarios

- **Massive machine type communication (mMTC)**
- **Ultra reliability low latency communication (URLLC)**
- **Enhanced mobile broadband (eMBB)**
- **Specific requirements for 5G categories:**
  - **functional** (e.g. priority, charging, policies, security, and mobility)
  - **performance** (e.g. data rates, latency, mobility, availability, reliability, no. of users)
  - **Solution: dedicated parallel virtual networks (slices) on the same physical infrastructure** can be constructed

Characteristics	mMTC	URLLC	eMBB
Availability	Regular	Very High	Regular (baseline)
E2E latency	Not highly sensitive	Extremely sensitive	Not highly sensitive
Throughput type	Low	Low/med/high	Medium
Frequency of Xfers	Low	High	High
Density	High	Medium	High
Network coverage	Full	Localized	Full

4. UAV in 5G, 6G Networks

4.2 UAV Roles in 5G networks

- **Assisting UAVs or user UAVs (UAV UEs)**
- **UAV-assisted networks**
  - **UAVs can**
    - cooperate with technologies like mmWave and MIMO, assistance and prevention of service interruptions/network failures, enhancing capacity, coverage, performance
    - assist the network beyond fixed coverage range (flying BSs)
  - **Examples of UAV possible roles**
    - **UAV-BS, or Aerial Base Station (ABS), a.k.a Flying Base Station (FBS)**
      - deployed where no BSs, or assist existing terrestrial BSs
      - UAV-BS have a subset of regular BS properties
    - UAV wireless relays
    - UAVs as flying backhaul relays for terrestrial networks
    - UAV flying edge nodes / MEC-enabled UAV
    - To enable QoS , Throughput maximization
    - Scalability, capacity, and flash crowds
    - Coverage extension of in rural areas
    - Enabling D2D, M2M and vehicular communication

Source: T.Bouzid, Member, N. Chaib, M.L.Bensaad and O.S.Oubbati, 5G Network Slicing With UAVs: Taxonomy, Survey, And Future Directions, TRANSACTIONS ON EMERGING TELECOMMUNICATIONS TECHNOLOGIES, 2022
https://doi.org/10.1002/ett.4721

4. UAV in 5G, 6G Networks

4.2 UAV Roles in 5G networks

UAVs as users (UAV- UE)

- **UAVs can exploit the 5G infrastructure**, both in **non-sliced** and **sliced** networks
  - URLLC is currently the slice suited for UAV (low latency critical for UAVs)

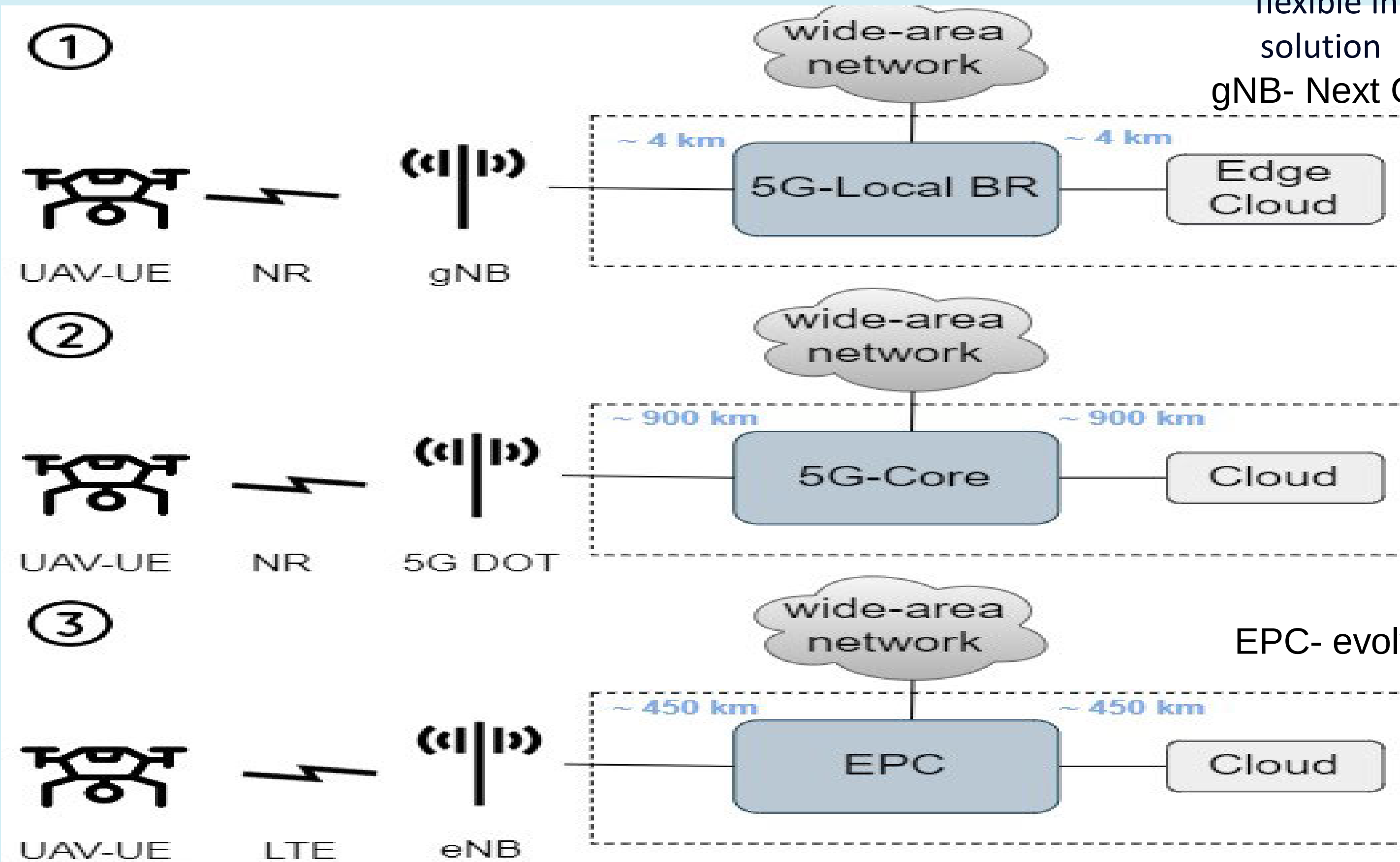
- **Sensing and collecting information**
  - UAVs may use networks to perform **specific tasks**, e.g., sensing data
  - **UAVs are enablers for sensing and data collection**
    - embedded software, sensors, cameras and antennas.
    - mobility, fast deployment, and affordability

  - **UAVs can replace some IoTs,** due to recharge-ability and low maintenance requirements
  - **Use cases** : smart cities and agricultural fields …to extreme conditions fields
    - sense and collect information about pollution, industrial accidents, plant and water conditions, etc.

4. UAV in 5G, 6G Networks

4.3 Examples of network topologies for UAV-UE in 4G/5G

NR- New Radio
DOT-5G Ericsson Radio DOT flexible indoor connectivity solution
gNB- Next Generation Node B



EPC- evolved Packet Core

Source: G. Damigos, T.Lindgren, and G. Nikolakopoulos, Toward 5G Edge Computing for Enabling Autonomous Aerial Vehicles, IEEE Access, 2023, DOI 10.1109/ACCESS.2023.3235067

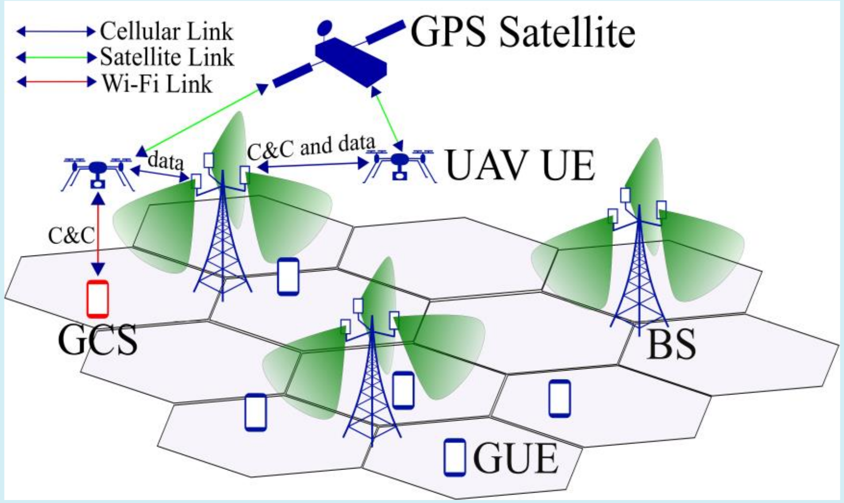
4. UAV 5G, 6G Networks

4.4 Combined scenarios / topologies: cellular, WiFi, satellites

Navigation information, e.g., position, timing and velocity can be acquired from GPS satellites through satellite connections

- GCS- Ground Control Station; C&C – Communication and Control

- **UAV as Cellular UEs (UAV-UE)**
- Types of Radio Links
  - Cellular: Ground BSs -- UAVs
  - Satellite: UAVs -- GPS satellites:
  - Wi-Fi Drones -- GCSs



UAV-UEs can be directly controlled either

- by ground BSs (data and C&C messages travel via cellular connections)
- by GCSs through non-cellular connections, e.g. Wi-Fi (data and C&C messages use two separate radio links)

Some UAVs can be remotely controlled by GCSs via satellite connections

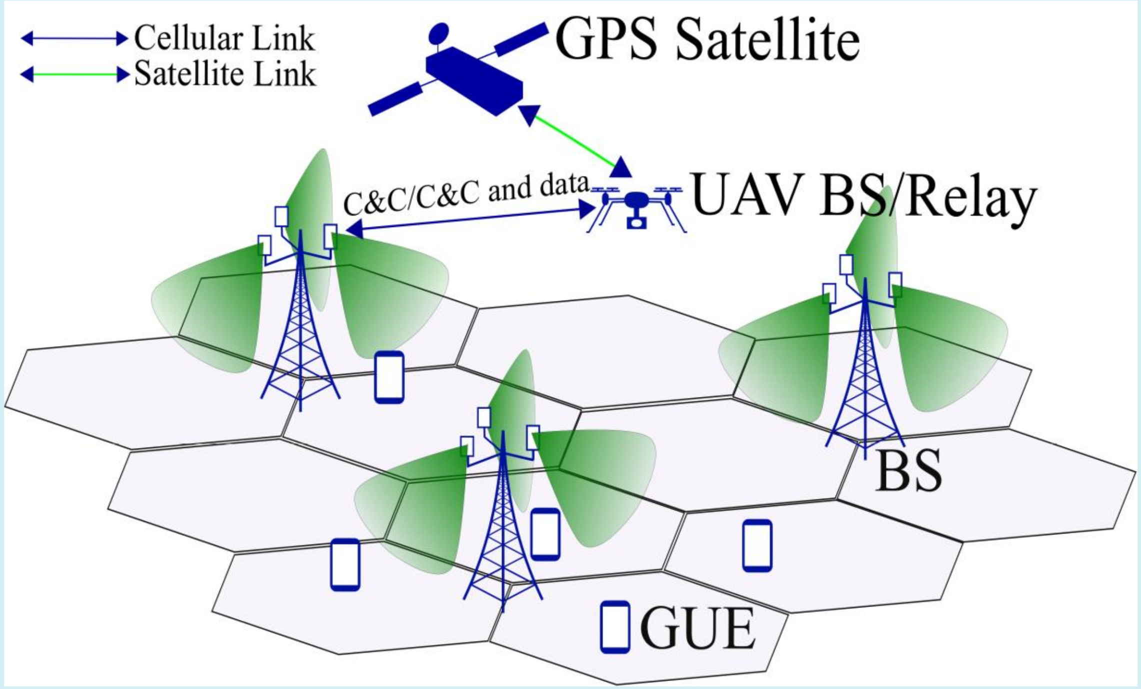
Source: A.Fotouhi, H.Qiang, , M.Ding, M.Hassan, L.G.Giordano, A.Garcia-Rodriguez, J.Yuan Survey on UAV Cellular Communications: Practical Aspects, Standardization Advancements, Regulation, and Security Challenges, JOURNAL OF COMMUNICATIONS SURVEYS AND TUTORIALS, arXiv:1809.01752v2 [cs.NI] 31 Mar 2019

4. UAV in 5G, 6G Networks

4.4 Combined scenarios/ topologies: cellular, WiFi, satellites

- **Flying BSs/Relays**
  - **(controlled by Ground BSs)**
- Types of Radio Links
  - Cellular: Ground BSs -- UAV
  - Satellite: UAV--GPS satellites

- Control and data messages are transported through cellular channels between Ground BSs and UAVs

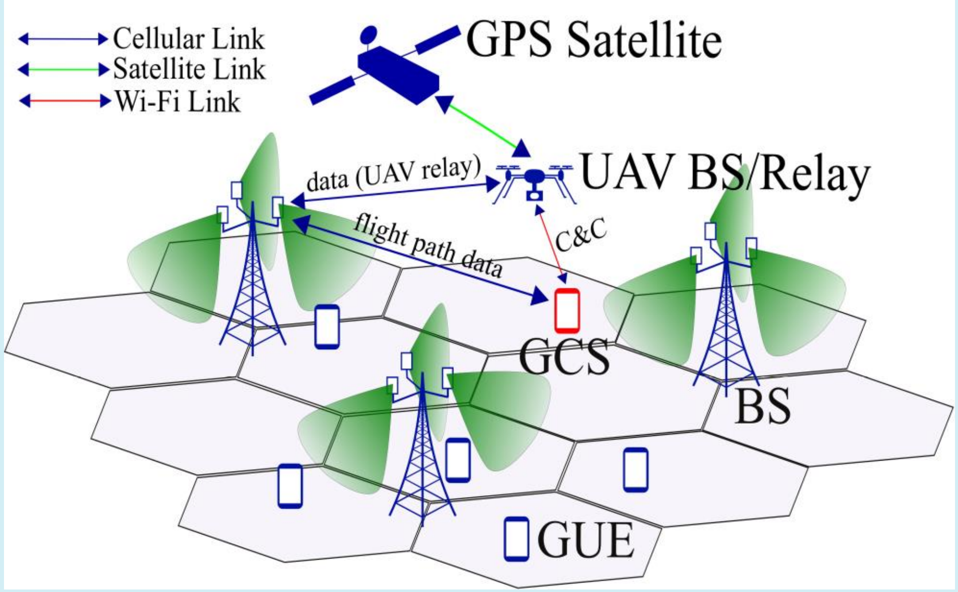


Source: A.Fotouhi, H.Qiang, , M.Ding, M.Hassan, L.G.Giordano, A.Garcia-Rodriguez, J.Yuan Survey on UAV Cellular Communications: Practical Aspects, Standardization Advancements, Regulation, and Security Challenges, JOURNAL OF COMMUNICATIONS SURVEYS AND TUTORIALS, arXiv:1809.01752v2 [cs.NI] 31 Mar 2019

4. UAV in 5G, 6G Networks

4.4 Combined scenarios/ topologies: cellular, WiFi, satellites

- **Flying BSs/Relays**
  - **(controlled by Third Party GCSs)**
- Types of Radio Links
  - Cellular: Ground BSs --UAVs
  - Cellular: Ground BSs ---third party GCSs
  - Satellite: UAV--GPS satellites:
  - Wi-Fi: Third party GCSs --UAVs

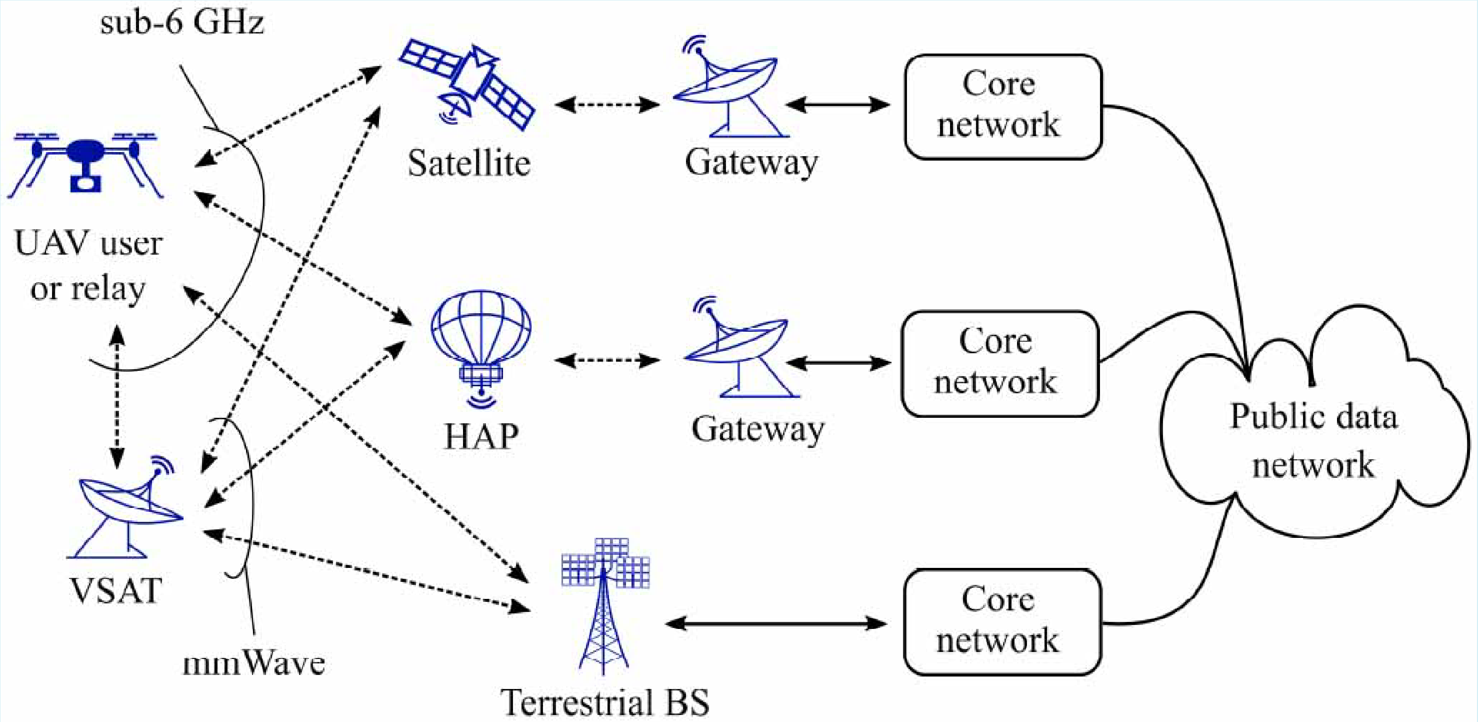


- **Security issues**
- Data and control signals are transmitted through the radio links
- Security of these wireless communication channels is important
- Wi-Fi channels are more insecure (high risk) w.r.t. cellular networks and GPS channels
  - GPS signals are broadcasted and the signal format is specified to the public (medium risk)
  - Cellular connections – (lowest risk)
    - it is more difficult to attack cellular connections where encryption keys and scrambling code are E2E exchanged

4. UAV in 5G, 6G Networks

4.4 Combined scenarios/ topologies: cellular, WiFi, satellites

- Example of an architecture for an integrated ground-air-space network supporting a UAV
  - HAP – High Altitude Platform
  - VSAT- very-small-aperture terminal (two-way satellite ground station with a dish antenna that is smaller than 3.8 meters).

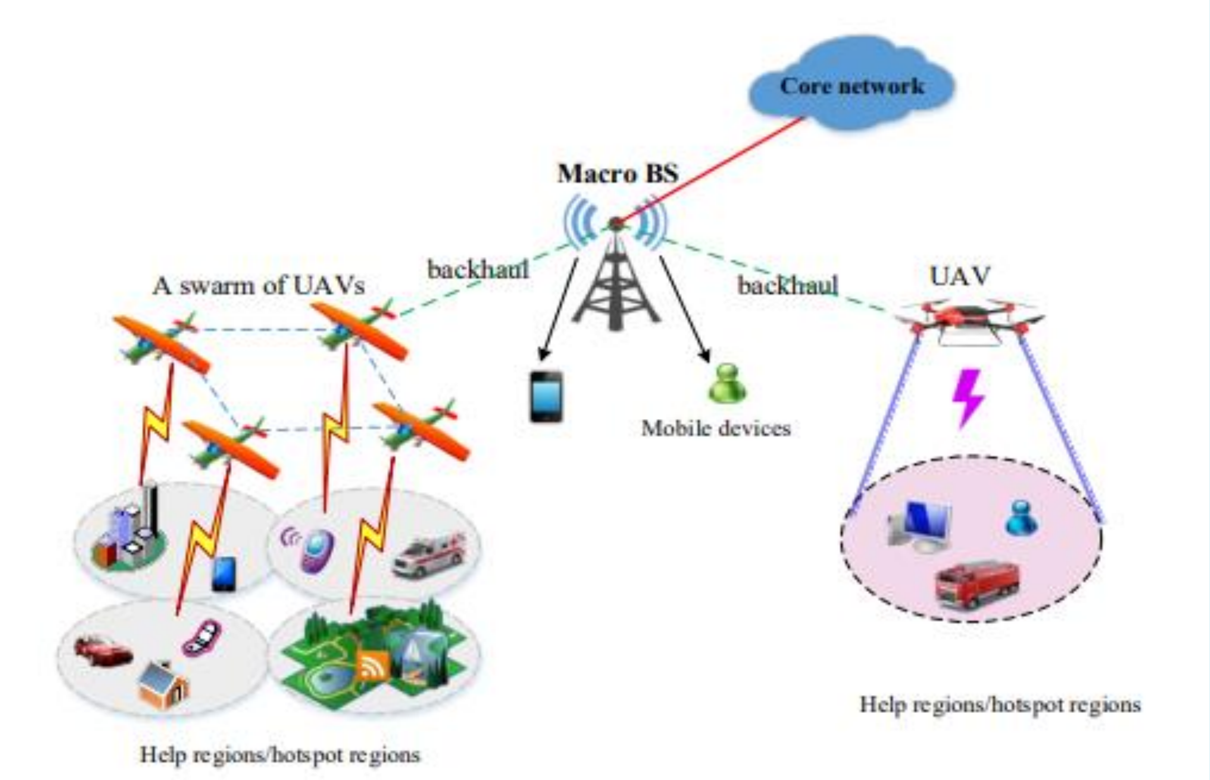


Source: G.Geraci et al., What Will the Future of UAV Cellular Communications Be? A Flight From 5G to 6G, IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 24, NO. 3, THIRD QUARTER 2022

4. UAV in 5G, 6G Networks

4.5 Example of scenario

- UAV can complete cellular systems by helping in hotspot regions
  - **Example:** UAVs serve as hovering BSs
  - UAV has transceivers allowing them to communicate with ground users and also with other UAVs

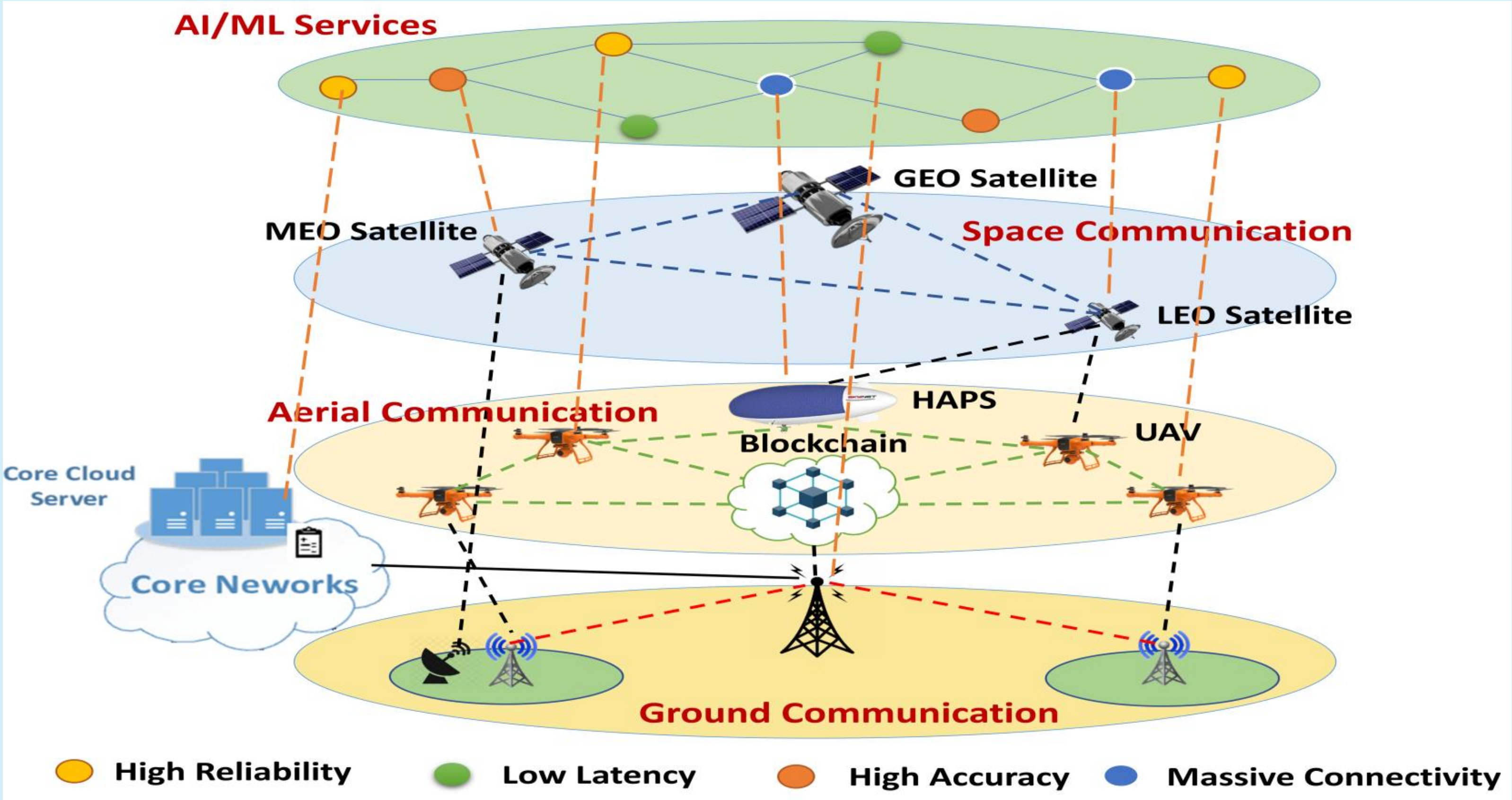


Source: B.Li, Z.Fei,and Y.Zhang, UAV Communications for 5G and Beyond: Recent Advances and Future Trends IEEE INTERNET OF THINGS JOURNAL, 2019, arXiv:1901.06637v1 [cs.NI] 20 Jan 2019

4. UAV in 5G, 6G Networks

4.6 Example of architecture for 6G-enabled UAV network

- Interactions among different technologies are shown



Source: M.A.Khan , N.Kumar,, Syed Agha Hassnain Mohsan, Wali Ullah Khan, M.M. Nasralla, M.H. Alsharif, J.Zywiołek, and I.Ullah, Swarm of UAVs for Network Management in 6G:A Technical Review , https://doi.org/10.48550/arXiv.2210.03234

CONTENTS

5. AI in UAV Routing

5.1 Artificial intelligence in UAV networks

- AI can help for **better reliability, connectivity, and security** by offering data-driven solutions for management of interference , mobility HO , security, etc.
- **Major idea:** to **integrate AI algorithms into networking and control protocols** to assist UAVs in perceiving the networks and environments overall conditions based on limited observations.
- **Benefits of using AI in UAVs - examples**
  - AI based decision-making with real-time data (continuous feedback in inaccessible areas to keep functions alive)
  - Training nodes -> more accurate results than taking actions blindly
  - Improved resource management for energy optimization and trajectory design to avoid obstacles.
- **Challenge: computational cost**
  - For each scenario one should analyze the benefits/drawbacks of using AI methods
- **New networking AI-based algorithms** (partially commercialized) are developed on top of the communication protocols
  - **Examples**
    - **Spectrum sharing / leasing** for drones (to extend the connectivity when wireless coverage is accessible; integrating WiFi and Cellular access)
    - **Beamforming** to extend the communication range and reduce the interference
    - **AI enabled routing, compression, and task coordination** protocols

5. AI in UAV Routing

5.2 AI-enabled routing protocols - Examples (selected list)

- **ML algorithms can help for optimal route path selection** (a more accurate topology perception, channel status, user behavior, traffic mobility, considering dynamicity, etc.)

- ***1. Topology predictive routing protocols***
  - ML algorithms can predict the node's motion trajectories (as an approx. of the network topology, provided that the comm. range of nodes is known) and include this info into the path selection
  - **Learning-based Adaptive Position MAC protocol**
    - Hybrid comm. protocol integrating a novel Position-Prediction-based directional MAC protocol (PPMAC) and a Self-learning Routing Protocol based on Reinforcement Learning (RLSRP).
  - **Predictive Dijkstra protocol**
    - It assumes that the intermediate nodes' locations when the packet is supposed to meet them - are predicted using ML methods
    - The predictive info is used for the path selection criterion
    - Higher performance w.r.t. standard Dijkstra algorithm
    - **Issues**: its reliance to accurate trajectory prediction methods; need for global location information exchange.

Adapted from source: A.Rovira-Sugranes, A.Razi, F.Afghah, J.Chakareski , A review of AI-enabled routing protocols for UAV networks: Trends, challenges, and future outlook, Ad Hoc Networks 130 (2022) 102790, www.elsevier.com/locate/adhoc

5. AI in UAV Routing

5.2 AI-enabled routing protocols - Examples (selected list)

- *1. Topology predictive routing protocols (cont'd)*

  - **Predictive greedy routing**:
    - Distance-based greedy routing algorithm; it relies solely on the UAVs' local observations of their surrounding subnets
    - Each node estimates its neighbors locations of (e.g., using model-based object motion trajectory prediction) and selects the next node that makes maximum progress toward the destination node
    - Adapted to highly dynamic network topology
    - Low complexity and low overhead with no need for an initial route setup.
    - Improvement, w.r.t. centralized shortest path routing algorithms

  - **Predictive Optimized Link State Routing (P-OLSR)**
    - It exploits GPS info. and calculates an Expected Transmission (ETX) count metric to estimate the link quality when finding the optimal path
    - It outperforms other algorithms such as OLSR and BABEL under dynamic network topology

5. AI in UAV Routing

5.2 AI-enabled routing protocols - Examples (selected list)

- ***1. Topology predictive routing protocols*** *(cont'd)*

  - **Geographic Position Mobility Oriented Routing (GPMOR)**
    - Geo-based protocol using the Gauss–Markov mobility model to predict the movement of UAVs. It
    - It selects the next hop according to the mobility relationship in addition to the Euclidean distance to make more accurate decisions
    - provides effective and accurate data forwarding solutions
    - decreases the impact of intermittent connectivity and achieves a better latency and packet delay rate than other position-based routing protocols

  - **Robust and Reliable Predictive (RARP)**
    - It combines omni and directional trs. with dynamic angle adjustment
    - It has a hybrid use of unicasting and geocasting routing protocols using the location and trajectory information
    - The intermediate node locations are predicted using 3-D estimation; then, directional trs. is used toward the predicted location, enabling a longer transmission range and tracking topology changes

5. AI in UAV Routing

5.2 AI-enabled routing protocols -Examples (selected list)

- ***1. Topology predictive routing protocols*** *(cont'd)*
  - **Q-learning-based Geographic ad-hoc routing protocol (QGeo)**
    - ML-based geo-routing scheme to reduce network overhead in high-mobility scenarios.
    - The nodes make geographic routing decisions distributively, utilizing a RL method without knowing the entire network topology
    - It consists of location estimation, a neighbor table, and a Q-learning module
    - The location estimation module updates the current location information reported by the GPS or other localization methods.
    - QGeo provides a higher packet delivery rate and a lower network overhead w.r.t. other geo-position-based protocols

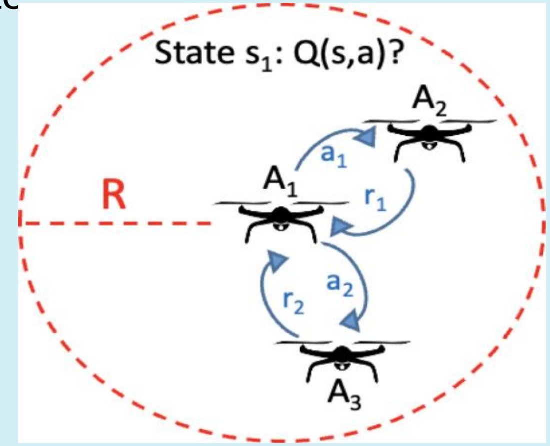
- ***2. Self-adaptive learning-based routing protocols***
  - **Reinforcement Learning (RL)** is frequently used to make routing decisions
    - It applies continuous and online learning of the environment and their decision consequences on desired performance metrics such as delay, throughput, energy efficiency, and fairness
    - (+) abstract formulation which brings independence from topology prediction and channel estimation (this comes from the concept of learning from experience).

5. AI in UAV Routing

5.2 AI-enabled routing protocols -Examples (selected list)

- ***2. Self-adaptive learning-based routing protocols*** *(cont'd)*
  - **Basic RL-based scenario**
    - In state *s*1, node or agent *A*1 has two candidate neighbors *A*2 and *A*3 to send its packet. It must select between action *a*1 or *a*2 based on the reward expected for each action *a* at state *s*, defined as *Q*(*s, a*).
    - Once *A*1 selects the appropriate action, it obtains an immediate reward from the environment, *r*1 or *r*2, respectively
    - Next, the same process is started in a new state *s*2; the decisions will be made based on the new environmental conditions and the learned policy in terms of actions rewards relations.
    - The end goal: to find an optimal policy in which the cumulative reward over time is maximized by assigning optimal actions to each state

Adapted from source: A.Rovira-Sugranes, A.Razi, F.Afghah, J.Chakareski , A review of AI-enabled routing protocols for UAV networks: Trends, challenges, and future outlook, Ad Hoc Networks 130 (2022) 102790, www.elsevier.com/locate/adhoc



5. AI in UAV Routing

5.2 AI-enabled routing protocols -Examples (selected list)

- ***2. Self-adaptive learning-based routing protocols*** *(cont'd)*
  - **Q-Routing ideas:**
    - ***Exploration* phase** - evaluating the impact of routing strategies on performance metric by investigating different paths
    - *Exploitation* phase : to use the discovered best paths
    - Issues:
      - Exploration imposes a system overhead; however, it is critical for finding newly optimal paths (e.g in dynamic context of the topology)
      - Need to adaptively solve the trade-off exploration/ exploitation times to cope with topology dynamicity
  - **Q-Routing –Examples**
  - **Initial Q-Routing Protocol** (learning from experience)
    - Each node
      - stores the expected time to the destination through any of its neighbors as Q-values in a Q-table
      - selects the next node that minimizes the expected travel time to the destination.
      - after a packet is received by a node, it sends back the real travel time to the previous node to updates its Q-values for the next round

5. AI in UAV Routing

5.2 AI-enabled routing protocols -Examples (selected list)

- ***2. Self-adaptive learning-based routing protocols*** *(cont'd)*
  - **Q-Routing –Examples**
  - **Predictive Q-Routing (PQ-Routing)**
    - Extension of the conventional Q-Routing; Fine-tuning the routing policies to get an exploration–exploitation trade-off and
    - Learning and storing new optimal policies under decreasing load conditions and reusing the learned best experiences by predicting the traffic trend
    - Re-investigate the paths that remain unused for a while due to the congestion-related delays.
    - PQ-Routing outperformes the Q-Routing w.r.t. learning speed and adaptability.
    - Issues: It requires large memory for the recovery rate estimation
      - Not accurate in estimating the recovery rate under fast varying topology changes
  - **Full-echo Q-Routing**
    - It accelerates the learning speed of conventional Q-Routing
    - In conventional Q-Routing, each node only updates the Q-values for its selection (the best neighbor)
    - *Full-echo* routing: - a node gets each neighbor's estimate of the total time to the destination, which helps update the Q-values accordingly for each of the neighbors

5. AI in UAV Routing

5.2 AI-enabled routing protocols -Examples (selected list)

- ***2. Self-adaptive learning-based routing protocols*** *(cont'd)*
  - **Q-Routing –Examples**

  - **Dual Reinforcement Q-Routing (DRQ-Routing)**
  - It uses forward and backward explorations by the sender and receiver of each comm. hop, by appending information to the packets they receive from their neighbors.
  - It learns the optimal policy faster than the standard Q-Routing
  - Q-learning approach performs better than the traditional non-adaptive approach under scenarios with increasing traffic that causes node and link failures.
  - **Issues:**
    - Q-Routing does not always guarantee finding the shortest path
    - It does not explore multiple forwarding options in parallel

- Note: an extended list of routing protocols examples can be found, e.g., in :

A.Rovira-Sugranes, A.Razi, F.Afghah, J.Chakareski , A review of AI-enabled routing protocols for UAV networks: Trends, challenges, and future outlook, Ad Hoc Networks 130 (2022) 102790, www.elsevier.com/locate/adhoc

CONTENTS

6. Conclusions

- **UAV technologies – strong development, high interest for many applications and services**
- Seamless UAV integration in conventional networks is a complex task; there are significant challenges for networking, compared to traditional mobile networks
-
- **Routing problem**: **complex**- many factors may have impact on routing solutions
  - Physical layer issues, dynamic topologies, 3D mobility and large range of speeds, delay tolerant networks problems, multi-UAV networks, multi-dimensional metrics for routing, need to support collaborative tasks (swarms), coverage areas, areas, integration problems in 5G, 6G, energy consumption control, different objectives for UAV activities in different classes of services, security, etc.
  - Many routing algorithms and protocols have been proposed

6. Conclusions

- **Open research areas – examples**
  - Airspace regulations aware network model
  - Collision awareness, Link disconnection, DTN issues
  - Dynamic route selection
  - Hybrid multi-criteria metrics for routing
  - Energy efficient routing
  - Prediction capable algorithms and protocols
  - Data-centric routing
  - Cognitive radio technology in UAVs
  - Real-time response of the algorithms
  - Secure routing and intrusion detection
  - Cooperation with traditional and novel network technologies 5G, 6G
  - AI/ML-based novel routing algorithms and protocols

- Thank you !
- Questions?

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Routing Advances in Unmanned Aerial Vehicle Networks

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Routing Advances in Unmanned Aerial Vehicle Networks

- **List of general Acronyms**

5G CN	Core Network
5G-AN	5G Access Network
5GS	5G System
AF	Application Function
AI	Artificial Intelligence
AMF	Access and Mobility Management Function
AS	Access Stratum
BBU	Baseband Unit
BSF	Binding Support Function
CC	Cloud Computing
CP	Control Plane
CRAN	Cloud based Radio Access Network
D2D	Device to Device communication
DL	Downlink
DN	Data Network
DNN	Data Network Name
DoS	Denial of Services
DP	Data Plane (User Plane UP)
FANET	Flying Ad hoc Network
FC	Fog Computing
GMLC	Gateway Mobile Location Centre
GPS	Global Positioning System
HR	Home Routed (roaming)
IaaS	Infrastructure as a Service
INaaS	Information as a Service

IoT	Internet of Things
IT&C	Information Technology and Communications
ITS	Intelligent Transportation Systems
LADN	Local Area Data Network
LLC	Logical Link Control
MANET	Mobile Ad hoc Network
MCC	Mobile Cloud Computing
MEC	Multi-access (Mobile) Edge Computing
NaaS	Network as a Service
NF	Network Function
NFV	Network Function Virtualisation
NR	New Radio
NS	Network Service
NSL	Network Slice
NSLI	Network Slice Instance
ONF	Open Networking Foundation
PaaS	Platform as a Service
PCF	Policy Control Function
PKI	Public Key Infrastructure
QFI	QoS Flow Identifier
QoE	Quality of Experience
RAN	Radio Access Network
RRH	Remote Radio Head
RPAS	Remotely Piloted Aircraft System
RSU	Road Side Unit

Routing Advances in Unmanned Aerial Vehicle Networks

- **List of general Acronyms**

SaaS	Software as a Service
SBI	Service Based Interface
SDN	Software Defined Networking
SM	Service Management
SMF	Session Management Function
S-MIB	Security Management Information Base
SMSF	Short Message Service Function
SSE	Smart Safety and Efficiency
TNL	Transport Network Layer
UAV	Unmanned Aerial Vehicle
UAVNET	Unmanned Aerial Vehicle Network
UAV-BS	UAV- Base Station
UAV-RS	UAV Relay Station
UL	Uplink
UPF	User Plane Function
V2X	Vehicle-to-everything
VANET	Vehicular Ad hoc Network
VID	VLAN Identifier
VLAN	Virtual Local Area Network
VM	Virtual Machine
WAT	Wireless Access Technologies
WSN	Wireless Sensor Network

- **Backup slides**

1. Introduction

1.5 UAV Swarms

- **A number of drones, usually limited-capability used to collectively perform a mission with no or minimal operator intervention**
- **Advantages**
  - shortening the task completion time, extending the coverage area, and reducing the operation cost
    - increase the predictability of the mission (e.g., in military domain)
  - swarm systems can be equipped with anti-jamming systems to more efficiently block cyber attack
  - if incorporating authentication protocols then it can authenticate multiple devices at rapidly with high scalability
  - enable search and rescue missions over big areas
  - useful in agriculture for large areas

- **Swarm architectures**
  - **Infrastructure-based architecture**
    - A central node -Ground Control Station (GCS)
      - collects and processes real-time information from all swarm members;
      - returns control commands (e.g., navigation, sensor actuation, sampling rate, camera control, etc.)

1. Introduction

1.5 UAV Swarms

- **Infrastructure based architecture (cont'd)**
  - (+)
    - feasibility of mission for low-capability UAVs by offloading the computation load to a more capable GCS,
    - global optimality of decisions
    - no need for complex networking protocols for inter-UAV communications
  - (-)
    - central control system-issues: GSC malfunction, hijack, or cyber threats;
    - limited mission area to the accessible range of the GCS.
- **Ad-hoc structure-free architecture**
  - direct communication between UAVs with no need for APs or routers, and can utilize distributed decision making
  - one UAV communicates with a GCS
  - (+)
    - eliminates the sensitivity of the mission to the GCS function
    - relaxes the constraints on the mission area
  - (-)
    - need for more capable UAVs for local decision making; a routing protocol to accommodate dynamic network topology

1. Introduction

1.5 UAV Swarms

- **Hybrid swarm architecture**
  - uses a cellular network to connect UAVs while using distributed decision-making without the need for a central controller
  - it combines the advantages of the previous ones by enabling long-range missions with reliable networking among UAVs while not relying on a GCS
  - it can benefit from LTE, 5G, 6G capabilities

(a) Infrastructure-based (b) Ad-hoc structure-free (c) Hybrid architecture.

Adapted from source: A. Rovira-Sugranes, A.Razi, F.Afghah, J.Chakareski , A review of AI-enabled routing protocols for UAV networks: Trends, challenges, and future outlook, AD-hoc networks, Elsevier, https://doi.org/10.1016/j.adhoc.2022.102790

2. Routing and Path Planning Problems

2.2 Taxonomy of routing protocols based on dynamicity

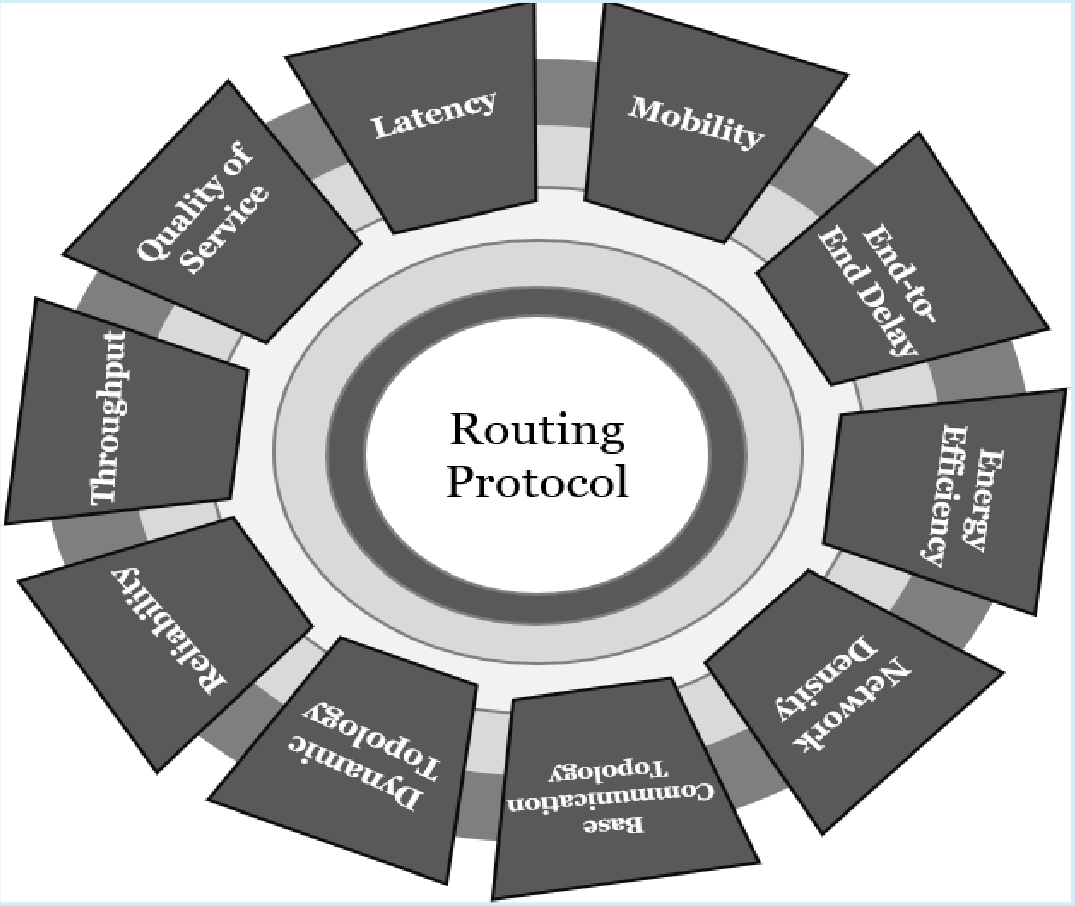
- **Proactive routing protocols (PRP)- classical/basic principle in Internet routing**
  - the routing/forwarding tables store all the routing information
  - tables are updated and shared periodically among the nodes (inter- node messages)
  - (+) always contains the latest information
  - (-) control traffic overhead; possible slow response to network changes (delays)
    - upgrade solution: event-triggered message exchanges between routers, to make the updating faster

- **Reactive (on-demand) routing protocols (RRP)**
  - design objective: to overcome the overhead problem of PRP
  - a route is computed at the source node request
  - the route between a pair of nodes is stored when they are inter communicating
  - problem: high latency may appear in finding the route (the route computation starts when a request is coming from a source node)
  - **categories: hop-by-hop routing and source routing**

- **Hybrid routing protocols (HRP)**
  - combine PRP-RRP
  - appropriate for large-scale networks that may have several sub-network areas, where intra-zone routing uses PRP and inter-zone uses RRP

2. Routing and Path Planning Problems

2.3 Performance metrics of UAV routing protocols



Source: N. MANSOOR et al., A Fresh Look at Routing Protocols in Unmanned Aerial Vehicular Networks: A Survey, IEEE Access June 2023

4. UAV in 5G, 6G Networks

4.2 UAV possible roles in 5G sliced networks (additional slides)

- **1.UAV-BS**
  - has a partial set of terrestrial BS capabilities, plus specific features
  - can adapt to dynamic contexts and scale according to the network demands
  - can be useful when no terrestrial BSs are available (eMBB and URLLC use cases)
- **2. UAV relay -**primarily utilized to extend mMTC or URLLC slices
  - relays commands and data between a control center and a device
  - can assist by gaining a high altitude to access both the devices and control stations
  - LoS capability of the UAV makes this usage convenient for URLLC slices
- **3. UAV data collectors**
  - the UAVs' high mobility allows them to fly near IoT devices and into their radio range
  - data collection is different from UAV relays scenarios since it collects all data before either transmitting them or flying to the data center to deliver the data
- **4.UAVs -MEC capable**
  - MEC is beneficial to IoT devices, (the IoTs have low capabilities)
  - UAVs can perform computation or other tasks and thus save energy for the IoT devices
  - MEC UAVs can also enable on-demand MEC deployment for optimal efficiency.
- **5. UAVs as users**
  - UAVs can play UE role and exploit a slice (e.g. , URLLC, eMBB slices).

4. UAV in 5G, 6G Networks

4.2 UAV possible roles in 5G sliced networks

- **UAV-assisted network slicing**
  - It **is** a specific scenario of general UAV-assisted networks
  - In UAV-assisted networks case the solutions mostly affect a small group of devices or a portion of the network.
    - E.g.: for providing connectivity or collecting data the administrators or developers are responsible for performance and quality
  - **UAV-assisted network slicing requirements are stronger than in assisting traditional networks**
    - **Reasons**
      - UAV-assisted traditional networks are more flexible in terms of expectations and thus more types tasks can be performed by UAVs
      - **while Each slice must have guaranteed properties** (e.g., for latency, throughput, and energy requirements in mMTC)

Challenge for UAV in slices: guaranteeing the advertised parameters of each slice is difficult for UAVs due to their specific acting and nature

An UAV may lose power or change the planned trajectory due to special conditions

Source: T.Bouzid, Member, N. Chaib, M.L.Bensaad and O.S.Oubbati, 5G Network Slicing With UAVs: Taxonomy, Survey, And Future Directions, Transactions on Emerging Telecommunications Technologies, 2022 https://doi.org/10.1002/ett.4721

4. UAV Routing in 5G, 6G Networks

4.8 UAV possible roles in 5G sliced networks

- **Use cases of UAVs**
  - **UAV-BS –**eMBB, mMTTC, URLLC, Hybrid slices
  - **UAV relays -** eMBB, URLLC, Hybrid slices
  - **UAV as users-** URLLC
  - **UAV equipped with MEC** – mMTC, URLLC
  - **UAV data collector** - mMTC

Source: T.Bouzid, Member, N. Chaib, M.L.Bensaad and O.S.Oubbati, 5G Network Slicing With UAVs: Taxonomy, Survey, And Future Directions, Transactions on Emerging Telecommunications Technologies, 2022 https://doi.org/10.1002/ett.4721

4. UAV in 5G, 6G Networks

4.7 Examples of use cases, solutions and challenges

- **UAV as BS or relays in eMBB slices**
  - use multiple UAVs to serve multiple quasi-static ground UEs
  - The majority of users: devices using a lot of data (for video streaming, content-oriented apps, web navigation, etc.
  - UAVs are usually BSs or relays
  - Scenarios are in development where UAVs offer eMBB slices to mobile devices in different areas or to assist congested BSs.
  - **Challenges**
    - dynamically admitting the UEs' slice access requests and providing them with adequate eMBB slice services (based on a a virtual *UAV slicing coordinator*)
    - configuring UAV slices by planning UAV trajectories and improving the UAVs' transmit power
    - network slicing and sharing of RAN resources to provide UEs with energy-efficient eMBB services, under UAV energy consumption and trajectory constraints
    - energy-aware network with *Non-Orthogonal Multiple Access (NOMA)* transmission and subchannel allocation in a multi-UAV-aided network

Source: T.Bouzid, Member, N. Chaib, M.L.Bensaad and O.S.Oubbati, 5G Network Slicing With UAVs: Taxonomy, Survey, And Future Directions, Transactions on Emerging Telecommunications Technologies, 2022 https://doi.org/10.1002/ett.4721

4. UAV in 5G, 6G Networks

4.7 Examples of use cases, solutions and challenges

- **UAVs in mMTC slices**
  - Machine Type Communication Devices (MTCDs) – typically IoT devices and sensors
    - are typically scattered in distant areas and have a low transmission range
    - can be served with the mMTC slice by UAVs
  - **UAVs can assist (MTCDs) : to collect their data, to provide them with network access or enabling MEC capabilities**
  - **Challenge :**
    - in mMTC energy has priority over data rate and latency for its low-energy users
    - need to reduce the energy consumption and increase efficiency
  - **Examples**
    - **UAV data collector**
      - UAV-aided network for ground mMTC devices focused on maximizing battery life maximization and energy efficiency improvement (e.g., by by optimizing the UAV's trajectory with greedy design)
      - Sensors are deployed on an agricultural field
        - -The UAV acts as a mobile GW and stops at predetermined spots to estimate the number of active sensors before collecting their actual data
        - -UAV delivers the collected information to the control station using a satellite link