Unmanned Aerial Vehicles Communication in 5G, 6G Networks

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- **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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Unmanned Aerial Vehicles Communication in 5G, 6G Networks

- **Motivation of this talk**
  - **UAV(drones)** - increased popularity for diverse applications and services (civilian, military)
  - UAVs are **wirelessly interconnected** in ad hoc manner, resulting in a 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 connections
  - **Need of new specific methods and technologies** for management and control at different layers: physical layer problems, routing, path planning, tracking, traffic engineering, cooperation, security, etc.
  - **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 diverse 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 mechanisms in** UAVNETs depends on applications
  - **Examples:**
    - **Outdoor** - a simple line of sight 1-to-1 link with continuous signal transmission. Surveillance – UAVs can communicate through satellite communication links
    - **Satellite communication** - preferable choice for communication- 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**: communication capability, the 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 is 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

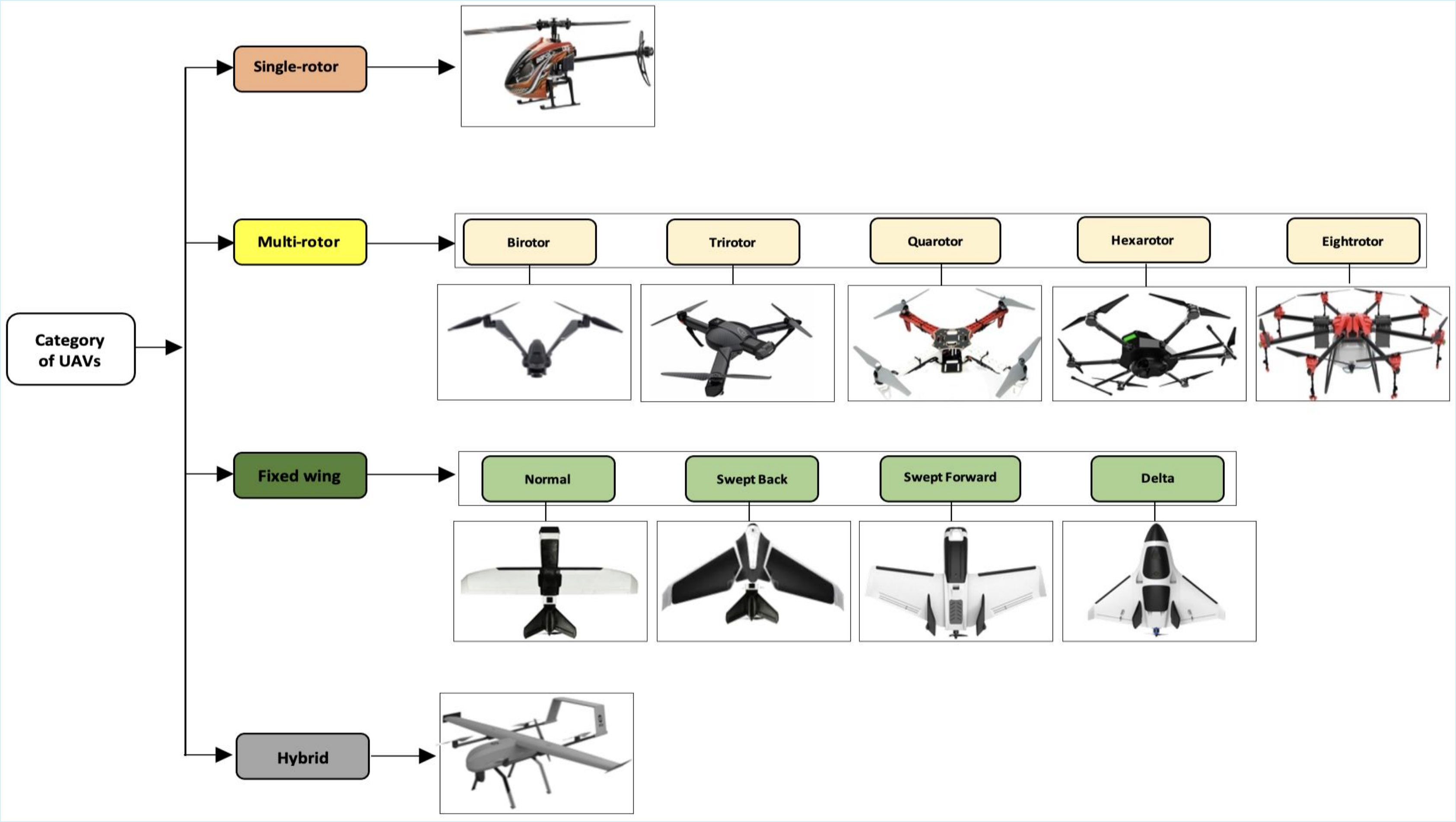
- **Other UAV taxonomies also exist**- they can be classified like any other aircraft, according to design configuration such as weight or engine type, maximum flight altitude, degree of operational autonomy, operational role, etc.

- **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

- **Military domain**: thermal imaging, laser range finders, airstrike, surveillance, etc.

- **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)

- **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**
- UAV in **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
- 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 in UAV networks
  - **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**

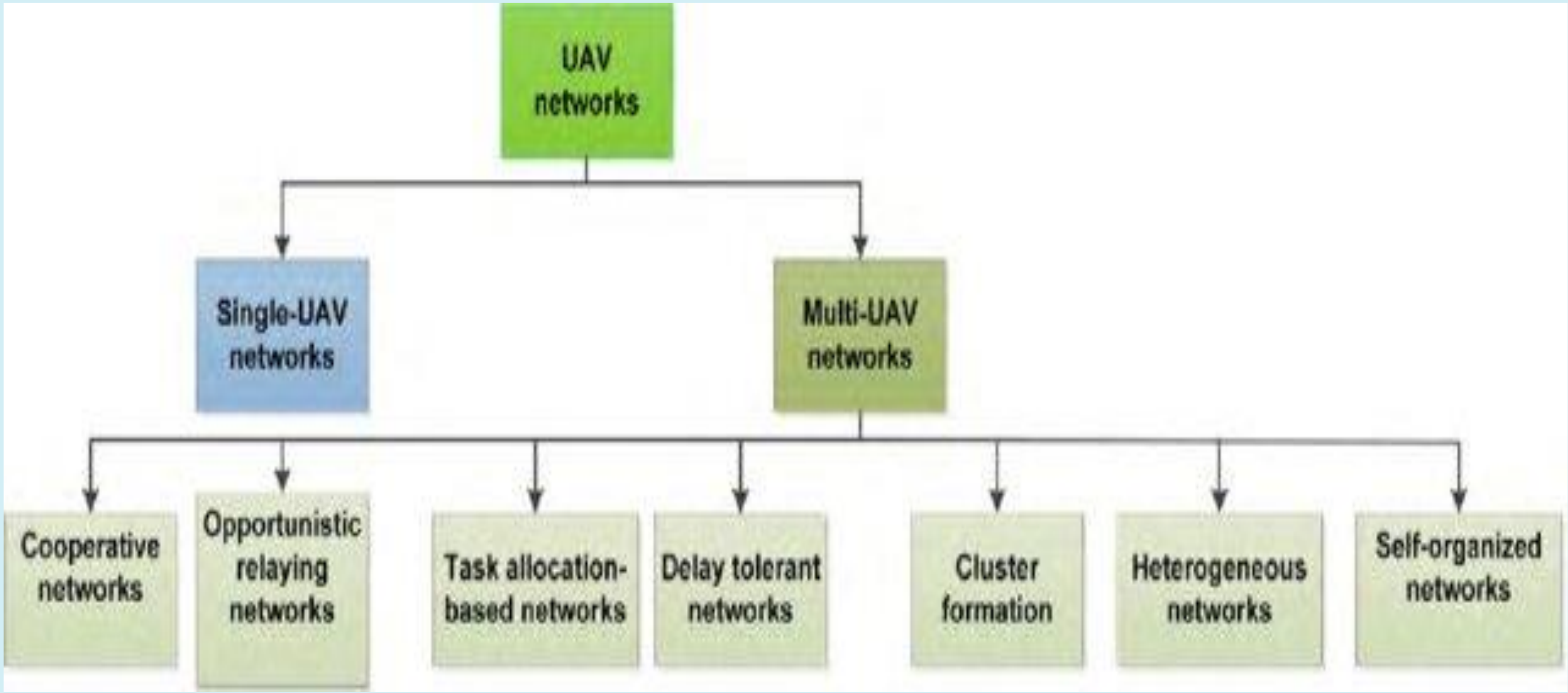
- Two **basic types** of UAVCN networks
  - **single-UAV network** - the UAV device is linked to a **ground base station (GS),** or to a satellite; each UAV acts as an isolated node
  - **multi-UAV network** – many UAV devices are linked
    - to each other (**U2U links**)
    - to the **ground base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

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

1. Introduction

1.3 UAV Networks

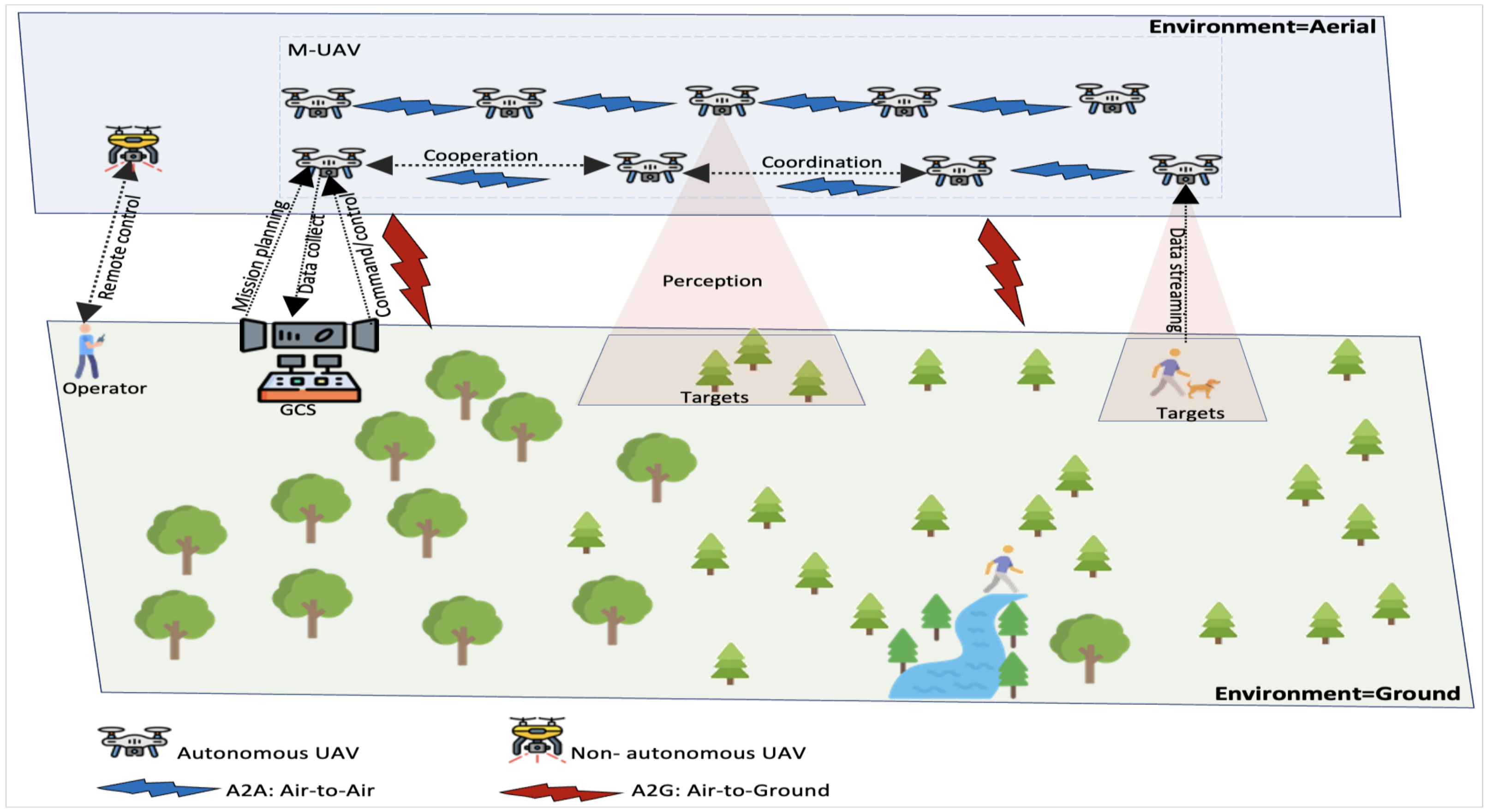
- **Taxonomy of UAV networks**



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

1.3 UAV Networks

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



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

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1.3 UAV Networks

- **Different views on UAV networks architectures**

- **Cooperative Multi-UAVs**
  - **Cooperative UAVs- based task achievement**

  - **Opportunistic relaying networks**
    - **(+)- advantages (-) -issues**
    - (+) Execute tasks based on coordination, support for dynamic network, tolerant to link failures (opportunistic transmissions), good network resources utilization
    - (-) 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
    - (-) UAV collisions, complex computations for coordination
  - **Ground WSN**
    - (+) Multiple and distributed data sources, available UAVs sensors, fast data collection
    - (-) Limited opportunities to communicate with sensors, limited transmission 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

1. Introduction

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**

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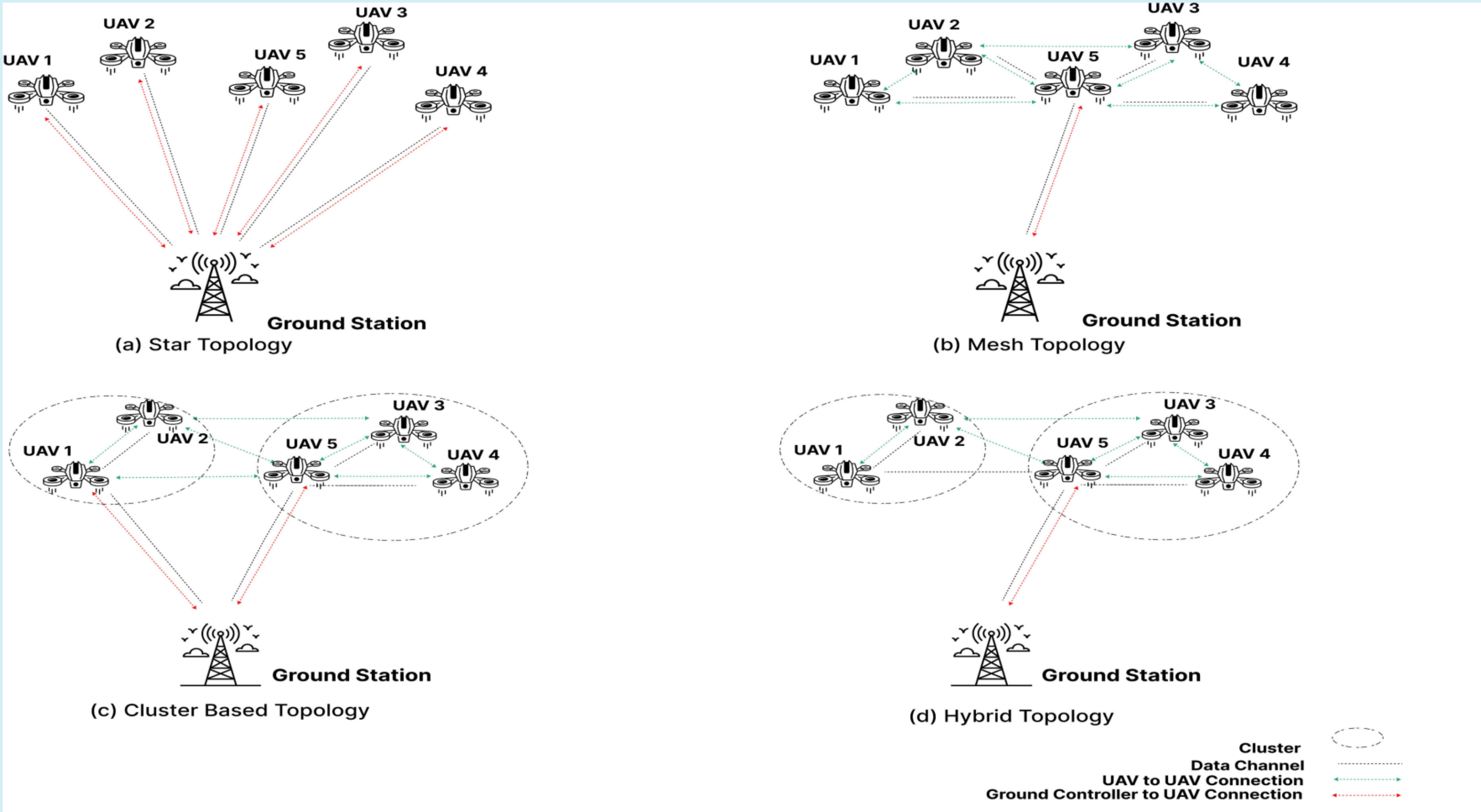
1.3 UAV Networks

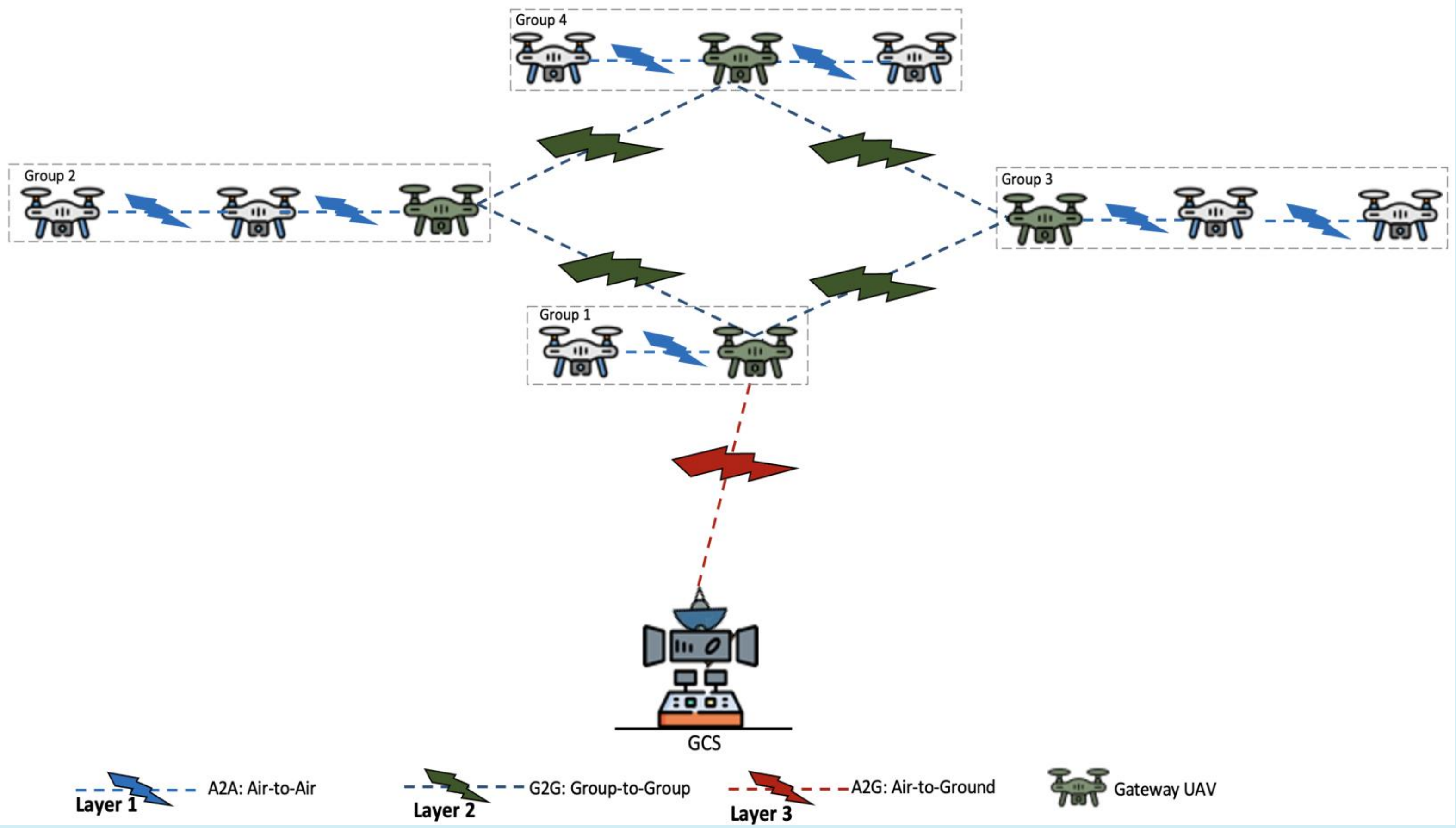
- **Multi-UAV topologies: (a) Star b) Mesh (c) Cluster-based (d) Hybrid mesh**



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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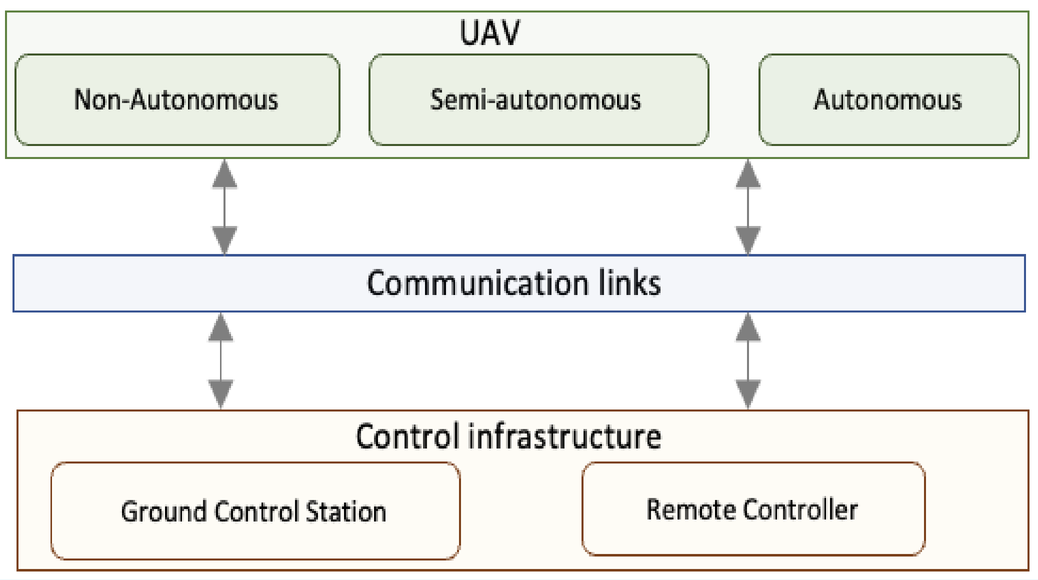
1.4 UAV System- simplified architecture

- **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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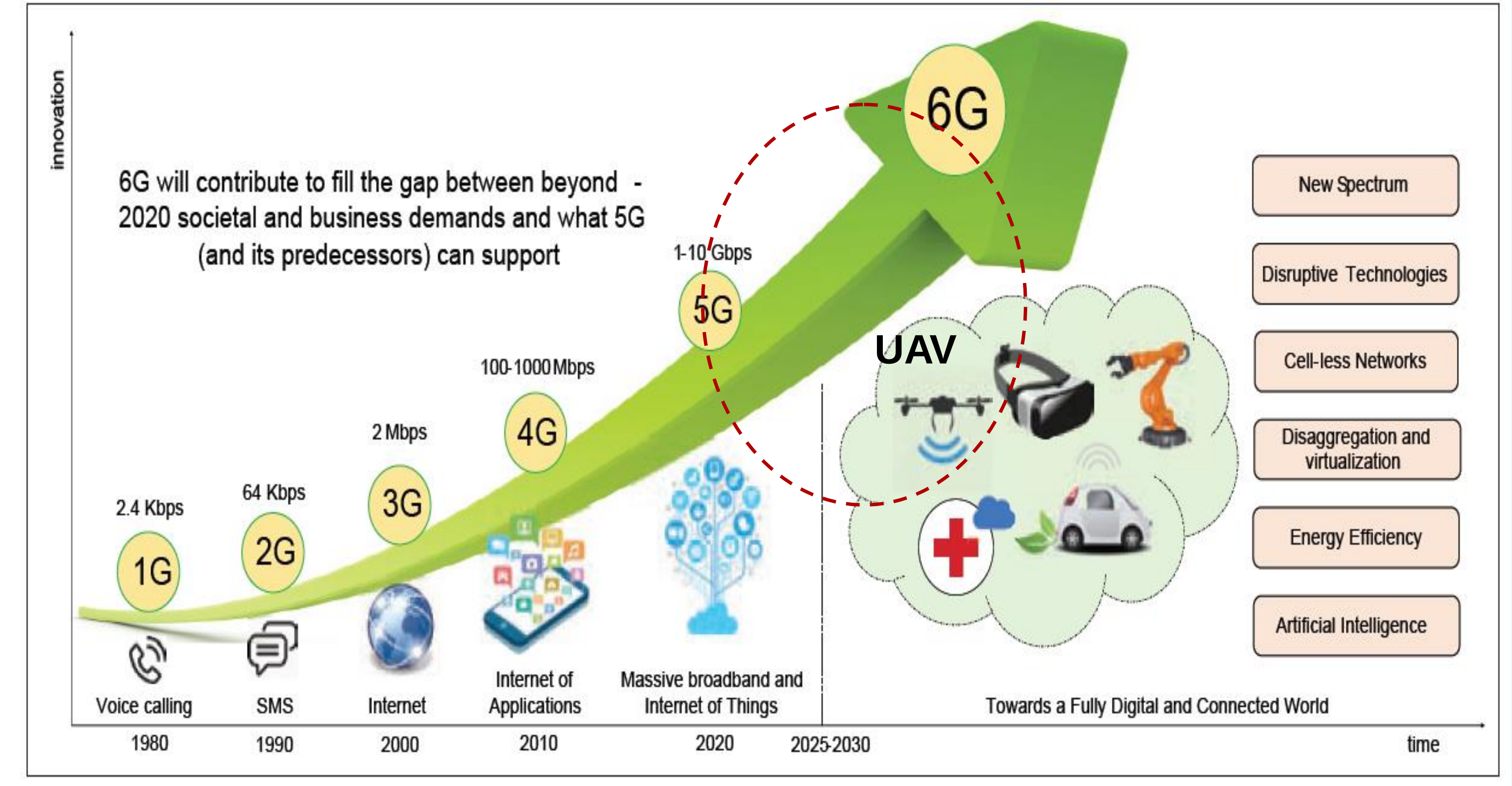
1.5 Mobile communications evolution

- **Historical and estimated 1G ..6G evolution**



Source: M. Giordani, et al., "Toward 6G Networks:Use Cases and Technologies", IEEE Communications Magazine , March 2020

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2. Specific Aspects of UAV in Cellular and Satellite Networks

2.1 Trends

- **Many benefits –to use UAV technologies in cellular networks**
- The **standardization bodies** are exploring possibilities for serving commercial UAVs with cellular networks
- **Industries** - trials with prototypes of **flying base stations** or **flying user equipment**
- **Academia** is researching for mathematical and algorithmic solutions to address new problems arising from flying nodes 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**
  - **Problem:** the enhanced **line-of-sight (LOS)** between **aerial UE** and **ground base stations (BSs)** would significantly increase interference in the system
    - new strategies and methods are proposed to accommodate both aerial and ground UEs in the same system
  - It is explored to realize **UAV-mounted flying relays** and **BSs** that can dynamically reposition themselves to boost coverage, spectral efficiency, and user quality of experience (QoE)

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.

2. Specific Aspects of UAV in Cellular and Satellite Networks

2.2 UAVs in cellular networks

- **Aerial User Equipment (UAV-UE)** or **Aerial Base Stations (UAV-BS)**
- **UAVs as aerial User Equipment**
  - **Applications** : real-time video streaming, area surveillance, item delivery, etc.
  - The ground pilot can emotely control and command the UAV-UEs with unlimited operation range
  - UAV-UE - efficient solution to keep connectivity between UAVs and the ground user equipment and the air traffic controllers
  - Good reliability, data throughput, security
  - Cost-effective (reuse the millions of cellular base stations existent infrastructures

  - **Open issues –** are related to: flight altitude, mobility and handover, interference management, cyber-physical attacks, energy efficiency, authentication, etc.
    - **need of novel mathematical and algorithmic solutions**
    - **cell interference coordination** technique and an air-ground performance trade-off
      - centralized inter-cell interference coordination technique to obtain locally an optimal solution
      - decentralized scheme by dividing the cellular base stations into clusters to exchange data only between the cluster-head and the UAV
  - AI/NN solutions proposed for **security** and **resource allocation optimization**

2. Specific Aspects of UAV in Cellular and Satellite Networks

2.2 UAVs in cellular networks

- **UAVs as aerial base stations (UAV-BS)**
  - Cost-effective and reliable wireless communication for cellular networks
  - 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 coverage (to reach rural areas and further capacity to hotspot areas)
  - **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

2. Specific Aspects of UAV in Cellular and Satellite Networks

2.3 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

2. Specific Aspects of UAV in Cellular and Satellite Networks

2.3 UAV in Satellite Networks

- **Examples of solutions** proposed (cont'd)

  - **Multi-antenna multi-user system -** UAV and satellite cooperative network providing seamless connectivity to users
    - UAV is used as an aerial relay to transmit signals between satellite and several ground users based on amplify-and-forward protocol
    - The outage probability and SNR evaluation have been exploited to determine the coding gain and the diversity order

  - **Resource allocation study for an integrated UAV-satellite network**
    - UAV-BS provides downlink connectivity to ground users if they are not satisfied by terrestrial BS
    - Jointly considered resource management and the user association for the system
    - The terrestrial backhaul links share resources with the satellite backhaul links and the terrestrial radio links

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

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3. Routing and Path Planning Problems

3.1 UAV General Routing Requirements

- **Existing routing algorithms and protocol used in MANETs and VANETs cannot fully solve the needs of UAV networks**
  - 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 while ensuring reliable and stable data transmission
  - should consider
    - various factors on which the communication performance depend (E2E delay, throughput, dynamic topology, etc.)
    - various criteria of routes finding
  - must adapt to high mobility, dynamic topology, network density, intermittent links, power constraints and changing link quality
  - the lifespan of UAV nodes is limited -> seamless handovers are important
  - energy efficient protocols at different layers
  - must guarantee secure, dependable, and reliable data transmission
  - should be based on centralized, distributed or hybrid solutions

3. Routing and Path Planning Problems

3.2 Basic UAV routing principles (reminder)

- **Hop-by-hop routing** versus **Source routing**
  - **Hop-by-hop routing**
    - route to the destination is distributed in the nodes
    - a receives packet by a node is forwarded to the nearest next hop towards the destination node (based on existing forwarding tables)
  - **Source-based routing**
    - the source includes the routing information in outgoing packets
    - intermediate nodes need not to maintain updated routing information to forward the packet
    - major limitation : overhead
      - routing table is long for a large network; every packet should contain the entire route information in the header file (bandwidth waste)

3. 3 Taxonomy of routing protocols based on their dynamicity

- **Static routing protocols**
  - they have fixed routing
  - 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-tolerancy

3. Routing and Path Planning Problems

3.3 Taxonomy of routing protocols based on dynamicity

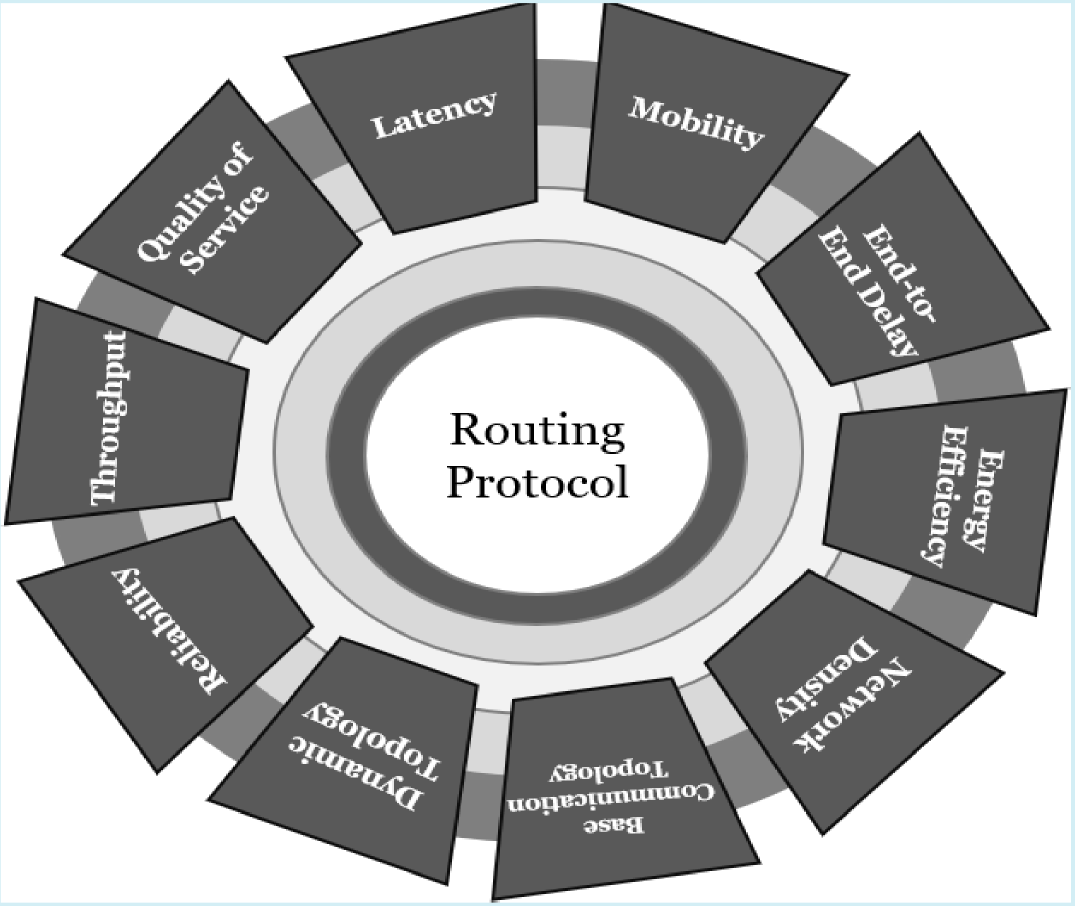
- **Proactive routing protocols (PRP)- classical/basic principle in Internet routing**
  - the routing/forwarding tables store all the routing information
  - tables are updated and shared periodically among the nodes (inter- node messages)
  - (+) always contains the latest information
  - (-) control 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

3. Routing and Path Planning Problems

3.4 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

3. Routing and Path Planning Problems

3.5 UAV routing-related methods

- **Delivery schemes**
  - unicast, multicast, broadcast
  - a **geocast-based protocol** uses a multicast routing to deliver a message to all nodes situated in a specific geographical area
- **Single path method**
  - used to transmit data between two 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

3. Routing and Path Planning Problems

3.5 UAV routing-related methods

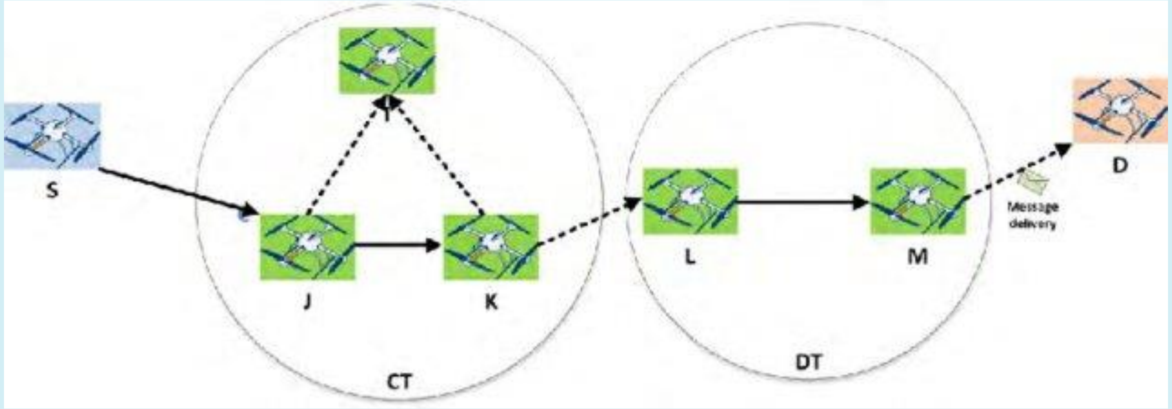
- **Path planning problem in UAV**
  - The aim of path planning techniques is not only to find an optimal and shortest path but also to provide the collision-free environment to the UAVs
    - Also, to compute a safe path to the destination, in the shortest possible time
  - **Coverage Path Planning (CPP)** is a critical issue for many UAV applications
  - Depending wheather the environment is known or not, CPP algorithms can be divided into two categories:
    - **Online CPP**
      - CPP algorithms don’t need to know in advance the complete information of the environment to be covered, and they plan local paths based on real-time sensor information
    - **Offline CPP**
      - CPP algorithms only depend on static environmental information, assuming that all environmental information is known in advance
  - 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

3. Routing and Path Planning Problems

3.5 UAV routing-related methods

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



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3. Routing and Path Planning Problems

3.5 UAV routing-related methods

- **Path discovery**
  - **assumptions**
    - bi-directional paths
    - the geographical position of the target destination node is known by the source node
    - 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. 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
  - then, the selected path is used for data transmission
  - a response (RREP) is returned to the source, indicating the best path
  - this path can be used in the future by the source; it is also stored for some time

3. Routing and Path Planning Problems

3.5 UAV routing-related methods

- **Quorum-based routing**
  - method used to develop a **location service**
  - the location service and forwarding scheme are essential for position-based routing
  - the location service is needed to learn the current position of a specific node, in which four kinds of approaches can be used: some-for-some, some-for all, all-for-some, and all-for-all
  - the forwarding scheme can be classified as **restricted directional flooding, greedy forwarding, and hierarchical approaches**

- **Store-carry-and-forward (SCF) routing technique**
- In general, in the **Store and forward** method, 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
  - this technique can be used in several cases: intermittent connectivity; high mobility; long delays; when a direct E2E connection is not available
  - in SCF the messages are forwarded among encountered mobile relay nodes (called SCF routers)

3. Routing and Path Planning Problems

3.5 UAV routing-related methods

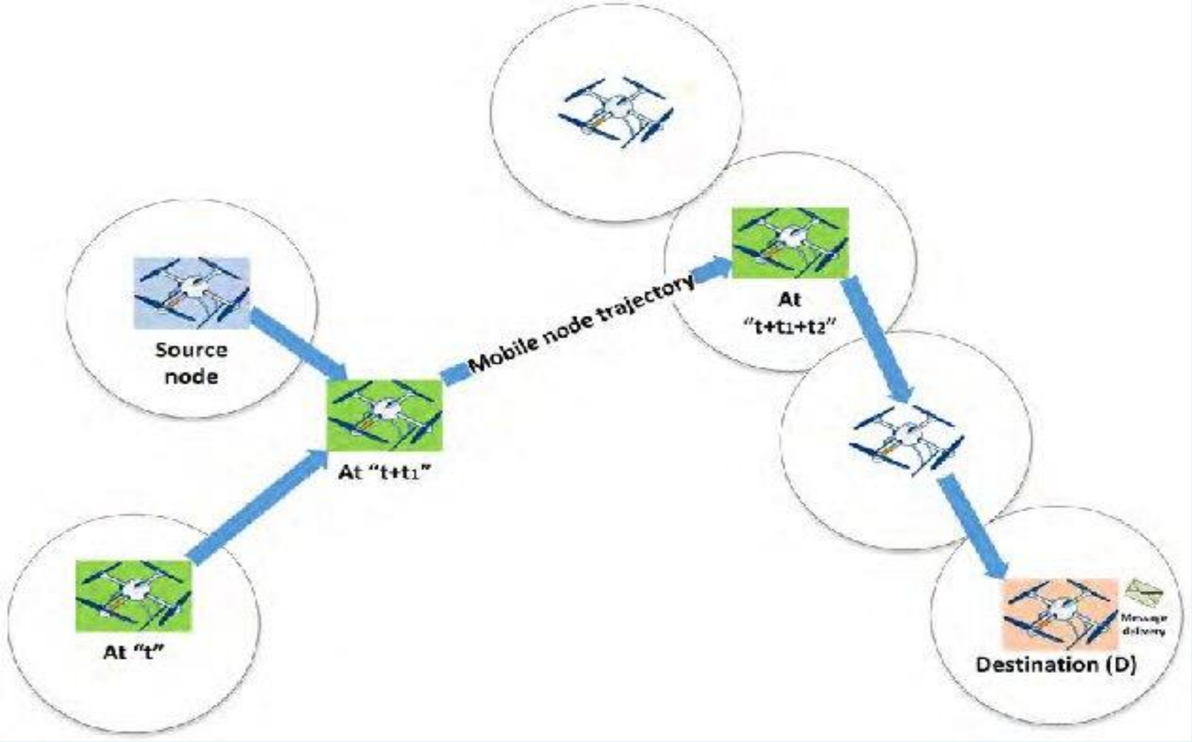
- **Store-carry-and-forward (SCF) routing technique** (cont'd)
  - SCF it is used when some fault in the network causes a disconnect from its next relay node
    - but forwarding data is still necessary
    - and it is also not possible to transmit data to next hop, as the node is out of transmission 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
  - SCF is efficiently used in FANETs, in case the UAV nodes are sparsely distributed
  - This technique
    - 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

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

3. Routing and Path Planning Problems

3.5 UAV routing-related methods

- **Store-carry-and-forward (SCF) routing technique** (cont'd)
  - 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



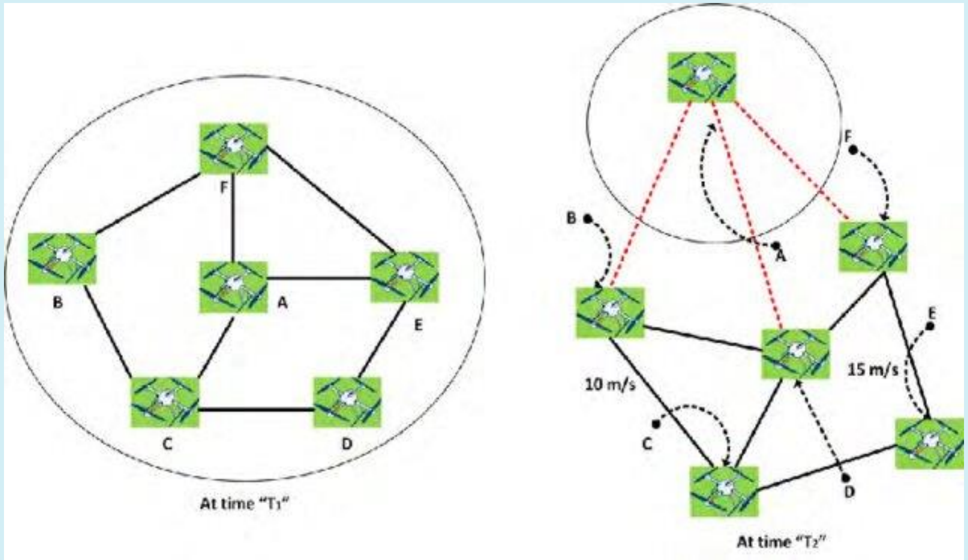
Source: M.Yeasir Arafat and S.Moh, Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey, DOI 10.1109/ACCESS.2019.2930813, IEEE Access

3. Routing and Path Planning Problems

3.5 UAV routing-related methods

- **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



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

3. Routing and Path Planning Problems

3.5 UAV routing-related methods

- **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

3. Routing and Path Planning Problems

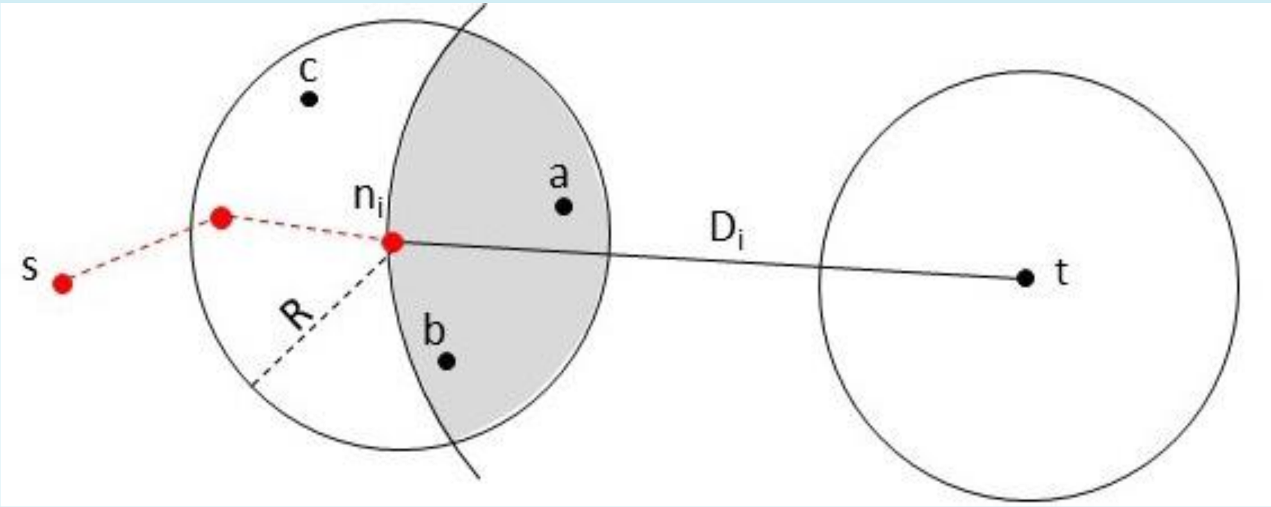
3.5 UAV routing-related methods

- **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 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

3. Routing and Path Planning Problems

3.5 UAV routing-related methods

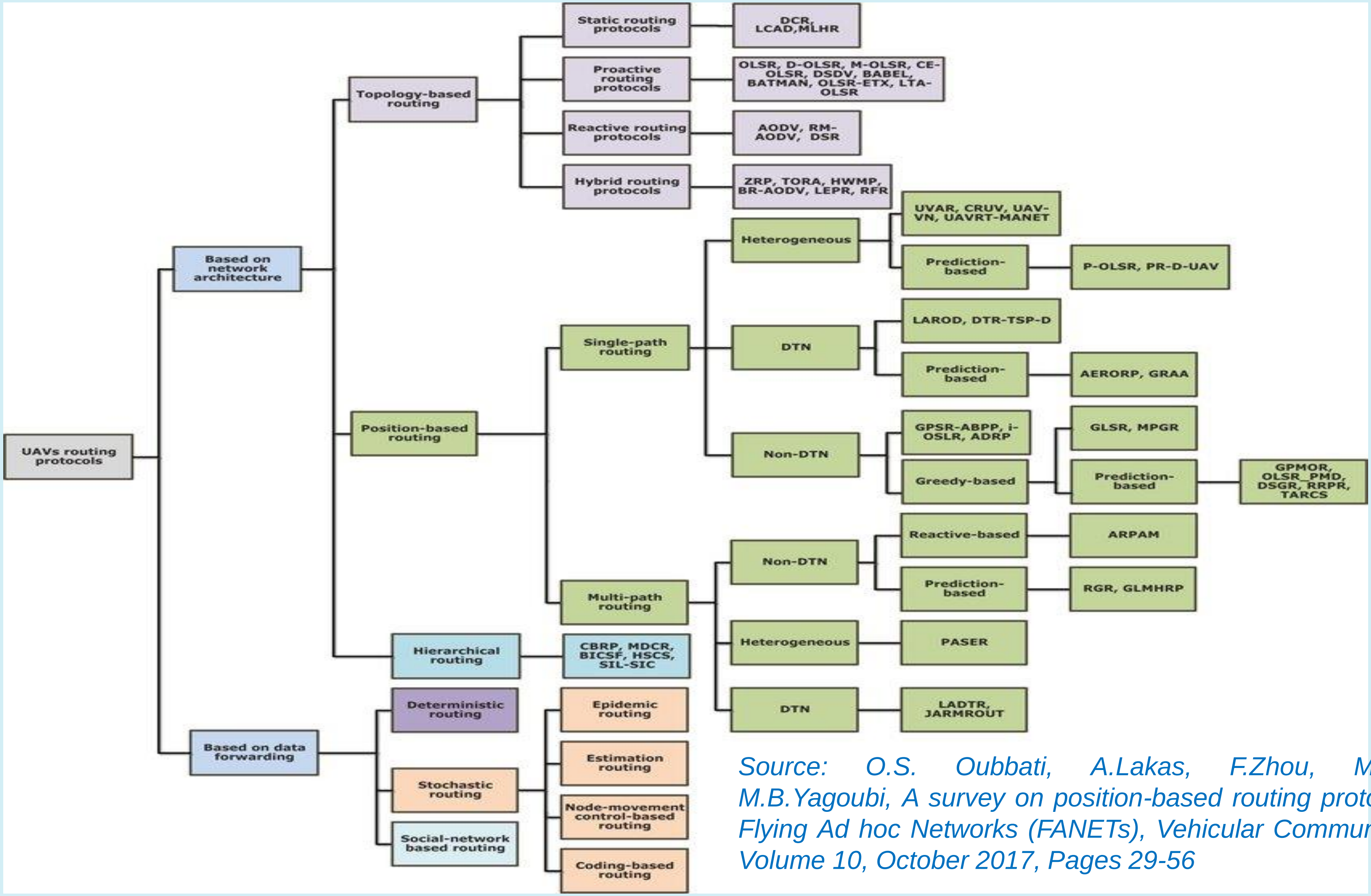
- **Greedy forwarding (GF)** (cont'd)
- **GF example** (cont'd)
  - The Figure represents one intermediate iteration of this algorithm
  - The shaded area represents the valid locations for the next node
    - here, the progress area is the intersection of two circles centred at $\mathbf{n_i}$ and **t** 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

3. Routing and Path Planning Problems

3.6 UAV routing protocols taxonomy - example



Source: O.S. Oubbati, A.Lakas, F.Zhou, M.Güneş, M.B.Yagoubi, A survey on position-based routing protocols for Flying Ad hoc Networks (FANETs), Vehicular Communications Volume 10, October 2017, Pages 29-56

3. Routing and Path Planning Problems

3.6 UAV routing protocols taxonomy - example

- **Partial description of the Taxonomy tree**
- **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

3. Routing and Path Planning Problems

3.6 UAV routing protocols taxonomy - example

- **Partial description of the Taxonomy tree** (cont'd)
- **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 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 the ground node

3. Routing and Path Planning Problems

3.6 UAV routing protocols taxonomy - example

- **Partial description of the Taxonomy tree** (cont'd)

- **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

3. Routing and Path Planning Problems

3.6 UAV routing protocols taxonomy - example

- **Partial description of the Taxonomy tree** (cont'd)
- **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

4. UAV in 5G Networks

4.1 5G Key concepts (summary)

- **Three main 5G features**
  - ***Ubiquitous connectivity for large sets of users*** *:* devices connected ubiquitously; uninterrupted user experience
  - ***Very low latency*** (~ few ms): for life-critical systems, real-time applications, services with zero delay tolerance
  - ***High-speed Gigabit connection***

- **5G: evolution of mobile *broadband networks + new unique network and service capabilities*:**
  - It will ensure *user experience continuity* in various situations
    - high mobility (e.g. in trains)
    - very dense or sparsely populated areas
    - regions covered by heterogeneous technologies (including the traditional ones)

- **5G- should offer universal support for a large set of applications and services**
  - Industry, health, governance, education, environment, commerce, etc.
  - 5G - key enabler for the Internet of Things, M2M

4. UAV in 5G Networks

4.2 5G Key characteristics

- Heterogeneous set of integrated air interfaces
- Cellular and satellite solutions
- Simultaneous use of different **Radio Access Technologies (RAT)**
  - **Seamless handover** between heterogeneous RATs
- Ultra-dense networks with numerous small cells
  - Need new interference mitigation, backhauling and installation techniques

- **Driven by SW**
  - unified OS in a number of PoPs, especially at the network edge

- To achieve the required performance, scalability and agility it will rely on
  - Software Defined Networking (SDN)
  - Network Functions Virtualization (NFV)
  - Cloud/Mobile Edge Computing (MEC) /Fog Computing (FC)
  - Artificial Intelligence/ Machine Learning

- **Ease and optimize network management** operations, through
  - **cognitive features and AI-embedded capabilities**
  - advanced **automation** of operation through proper algorithms
  - Data Analytics and Big Data techniques -> monitor the users' QoE

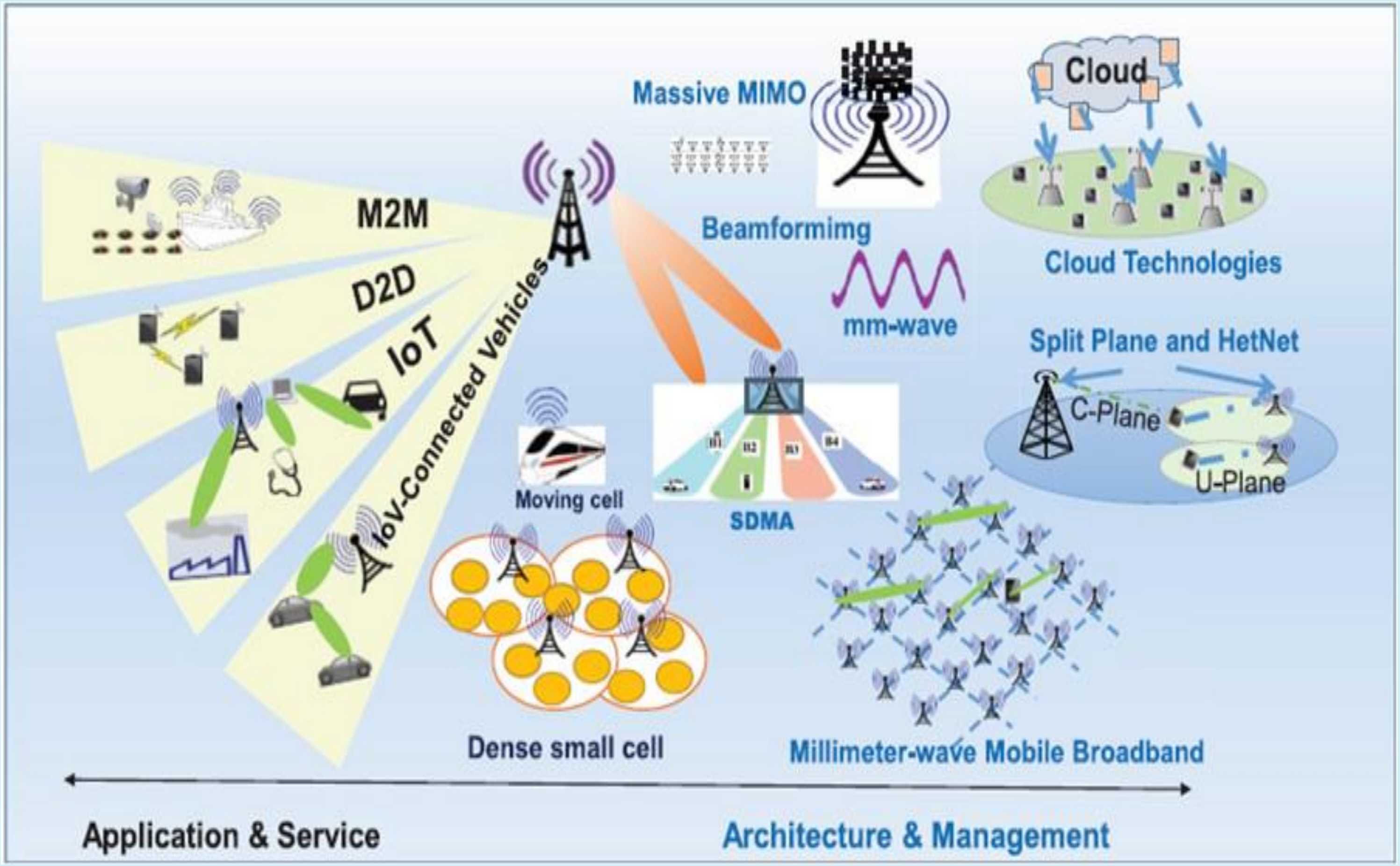
4. UAV in 5G Networks

4.3 5G disruptive capabilities

- **General requirements**
  - **x 10 improvement in performance (versus 4G)** : capacity, latency, mobility, accuracy of terminal location, reliability and availability
  - **simultaneous connection of many devices +** improvement of the terminal battery capacity life
  - **lower energy consumption** w.r.t. today 4G networks; energy harvesting
  - **better spectral efficiency than** in 3G, 4G
  - **citizens may manage their personal data**, tune their exposure over the Internet and protect their privacy
  - **reduce service creation time** and facilitate integration of various players delivering parts of a service
  - built on **more efficient hardware**
  - **flexible and interworking in heterogeneous** environments

4. UAV in 5G Networks

4.4 5G generic architecture



M2M- Machine to Machine
D2D- Device to Device
IoT - Internet of Things
IoV- Internet of Vehicles
MIMO- Multiple Inputs Multiple Outputs

Arhitectural functional planes
C-Plane Control Plane
U-Plane- User Plane

Source: Agiwal, M.; Roy, A.; Saxena, N. Next generation 5G wireless networks: A comprehensive survey. IEEE Commun. Surv. Tutorials 2016.

4. UAV in 5G Networks

4.5 Categories of 5G main scenarios

- Massive machine type communication (mMTC)
- Ultra reliability low latency communication (URLLC)
- Enhanced mobile broadband (eMBB)

- **Enhanced Mobile Broadband (eMBB)**
  - **Objectives:** High data rate, large data applications, high capacity
  - **Features:** Transfer high volume of data, millions of users, support for social media, 500 km/h mobility, peak data rate: 20 Gbps for downlink & 10 Gbps for uplink
  - **Main applications**: Fixed wireless, Ultra high definition (UHD) video, Video call, Mobile cloud computing, Virtual reality (VR) /Augmented reality (AR)
- **Ultra-Reliable, Low Latency Communications (uRLLC)**
  - **Objectives:** Fast and highly reliable, perfect coverage and uptime, strong security
  - **Features:** Ultra-high reliability (99.9999 %),Ultra-responsive, Data rate: 50 kbps .. 10 Mbps, Low latency: < 1 ms air interface and 5 ms E2E latency
  - **Main Applications:** Vehicular networks, Industrial automation, Public safety, Health systems
- **Massive Machine Type Communications (mMTC)**
  - **Objectives**: Massive connection density, energy efficiency, reduced cost per device
  - **Features:** Cover 30 billion 'things' connected, Low cost and low energy consumption, Density of up to 10^6 devices/km^2, 1 to 100 kbps/device, 10 years battery life
  - **Main Applications:** IoT, Wearables, Health care monitoring, Smart home/city, Smart sensors

4. UAV in 5G Networks

4.5 Categories of 5G main scenarios

- **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

Source: End to End Network Slicing – White paper 3 Outlook 21, Wireless World , Nov 2017

4. UAV in 5G Networks

4.6 UAV Roles in 5G networks

- **Assisting UAVs or user UAVs (UAV UEs)**
  - **UAV-BS** - aerial BSs (**or relays**) to enhance coverage, capacity, and energy efficiency or as relays, data collectors, and edge nodes
  - **UAV UEs** typically exploit the network to achieve their tasks

4.6.1 UAV-assisted networks

- **UAVs can**
  - cooperate with technologies like mmWave and MIMO to aid in optimizing QoS /QoE, provide assistance and prevent service interruptions /network failures, caused by infrastructure damage or flash crowds
  - assist the network in enhancing or guaranteeing certain capacity, coverage, and performance levels
  - 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)**
    - The UAV must have a subset of regular BS properties
    - **UAV-BSs** can be easily deployed in areas with no BSs; they can also assist existing terrestrial BSs, e.g., in case of high traffic demand

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 Networks

4.6 UAV Roles in 5G

- **Examples of UAV possible roles**
  - **UAV wireless relays:** UAVs can
    - act as simple relays or gateways close to the target devices enabling direct LoS and relaying data from nearby BSs, controllers, or other network sources; can reach remote areas or rural areas
    - be used in hard terrains, typically with mission-controlled robots to relay control information
  - **UAVs as flying backhaul relays for terrestrial networks**
    - This allows BSs to reach the backbone of their network without cabling
    - (e.g., when the infrastructure is damaged in case of natural disasters)
      - UAVs can provide a fast on-demand backhaul connection if the existing backhaul link is saturated
      - *Low Earth Orbit (LEO)* satellites and HAP UAVs are particularly useful backhaul enablers
  - **UAV flying edge nodes / MEC-enabled UAV**
    - UAVs can provide some light, edge capabilities
    - Here, UAVs function as edge caching nodes, fog nodes or edge computing nodes (It allows for very low latencies)
    - Devices with limited power or computing capabilities can benefit from UAVs equipped with UAV-mounted MEC can be used for IoT

4. UAV in 5G Networks

4.6 UAV Roles in 5G

- **Use cases of UAV assistance in 5G networks**
  - **Enabling QoS:**
    - **UAVs can be exploited to provide on-demand QoS**
    - **Examples**:
      - UAV path planning and 3D deployment
      - a set of rechargeable UAVs alternate in a closed loop can provide continuous and uninterrupted communication for IoT devices
      - UAV - as on-demand QoS enabler providing computing capabilities (i.e., MEC) for multimedia streaming and Augmented Reality (AR)
      - UAVs can guarantee different QoS requirements with a bandwidth-limited backhaul for delay-tolerant and delay-sensitive users
      - UAVs can serve as relay stations with joint management of bandwidth allocation and transmission power to improve the multi-user video streaming experience
  - **Throughput maximization**
    - When BSs are overloaded
    - UAVs can assist in maximizing throughput, especially on cell edges
    - **Examples :**
      - hybrid wireless network where UAV-BSs fly cyclically around the ground BS cell edge and assist in maximizing throughput
      - maximizing throughput with mobile relay UAVs, and a multi-hop UAV relay system

4. UAV in 5G Networks

4.6 UAV Roles in 5G

- **Use cases of UAV assistance in networks** (cont'd)
  - **Scalability, capacity, and flash crowds:**
    - UAVs can be deployed quickly and with minimal cost
      - to extend the capacity of already existing BSs for short periods, when necessary
    - UAVs can enhance the capacity, by helping in event scenarios
    - Challenges
      - Optimal placement for UAVs as an on-demand enabler for connectivity in event areas while maintaining UAV capacity constraints and QoS demand.
      - Joint optimization of the placement and number of UAVs is studied
- **Coverage extension of in rural areas**:
  - Low-cost alternative to provide coverage to sub-urban and lowly populated areas
- **Enabling D2D and vehicular communication:**
    - When traditional network infrastructure is unavailable, UAVs can be relays between human portable/wearable IoT devices, assisting in M2M communications
    - UAVs can act as energy sources for multiple D2D pairs
  - **M2M communications can be aided by UAVs** operating as flying mobile terminals and be used as relay nodes in out-of-coverage and **Non Line of Sight (NLoS)** scenarios

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 Networks

4.6 UAV Roles in 5G

- **Use cases of UAV assistance in networks** (cont'd)
- **Emergency situations and public safety**
  - UAVs can assist in pre-disaster preparedness, disaster assessment, response, and recovery even in the absence of infrastructure
  - **Examples** of proposals in different studies
    - **joint optimizing the UAV's 3D** location, power, and bandwidth allocation in an emergency where all BSs are destroyed. Instead, the UAV can serve a group of users with different QoS requirements in disaster-stricken areas
    - when **no ground BSs are** perceived, the UAV can use LEO satellites as backhaul nodes
    - **intelligent UAV-based 5G emergency network model** - where the UAV is equipped with BS, MIMO antennas, as well as small-scale core network functions
    - **three-layer architecture** for delay-sensitive services integrating UAVs deployed at the edge to provide edge computing and communication during an emergency. (SDN layer, data processing and communication provided by the UAV, RAN)
    - **multi-hop relaying scheme** to extend coverage in the case of disasters. The hovering positions of UAVs are optimized in the case of surviving ground BSs and when there is no available BSs
    - UAV-BS D2D communications extend the coverage

4. UAV in 5G Networks

4.6 UAV Roles in 5G

4.6.2 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 Networks

4.5 UAV Roles in 5G

4.6.2 UAVs as users (UAV- UE)

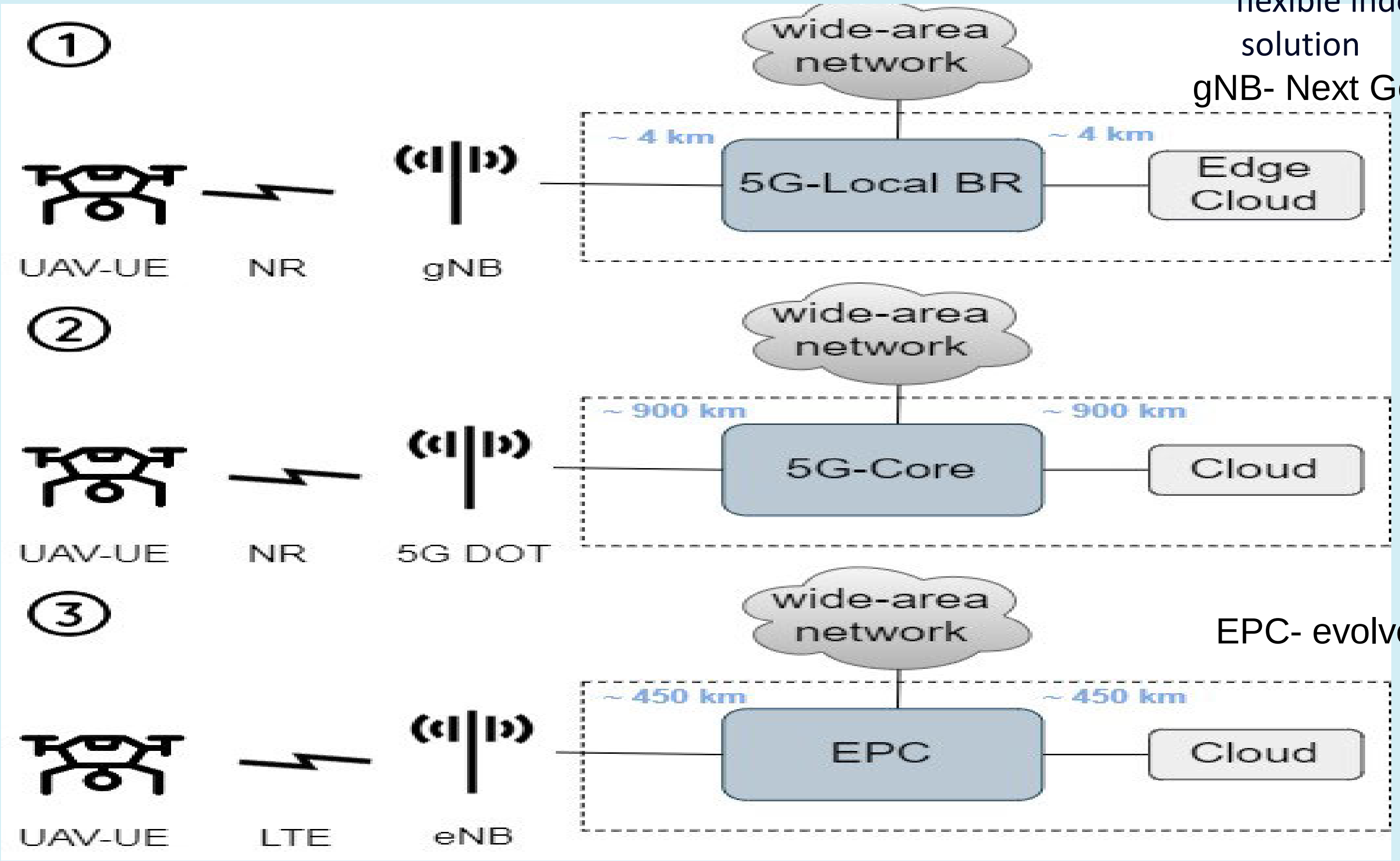
- **Surveillance, monitoring, and reconnaissance**
  - UAVs can send and receive data and commands for monitoring purposes
  - Typical UAVs usage - in military applications and missions
  - Civilian use cases – e.g., disasters to acquire information regarding terrain and infrastructure conditions
  - Deliver and update information about road traffic conditions
  - Photography and professional video capture
    - UAV should use the 5G network for remote control, live feed video, sending data, etc.

- **Package Delivery in commercial applications**
  - In urban areas, UAVs can avoid ground traffic and enable short time delivery duration
  - Cheaper solution in rural areas
  - Delivering goods in case of emergencies and disasters is convenient

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

4.7 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

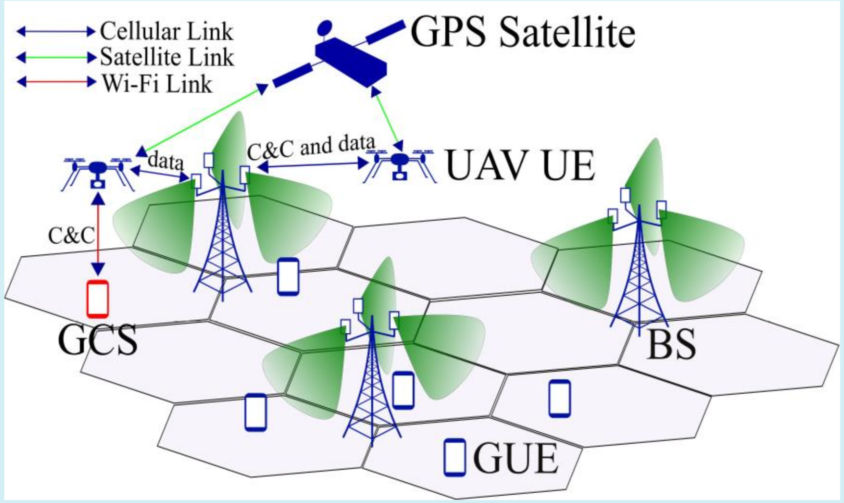
Source: G. Damigos, T.Lindgren, and G. Nikolakopoulos, Toward 5G Edge Computing for Enabling Autonomous Aerial Vehicles, IEEE Access, 2023, DOI 10.1109/ACCESS.2023.3235067

4. UAV in 5G Networks

4.8 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)

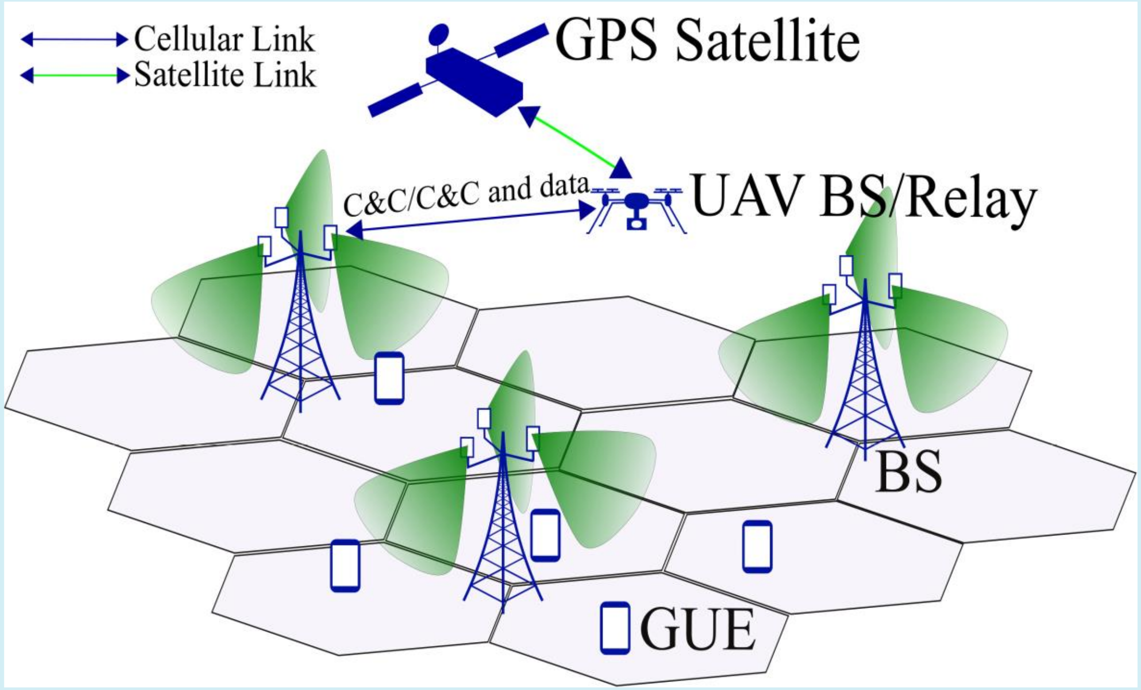
Some UAVs can be remotely controlled by GCSs via satellite connections

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

4.8 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

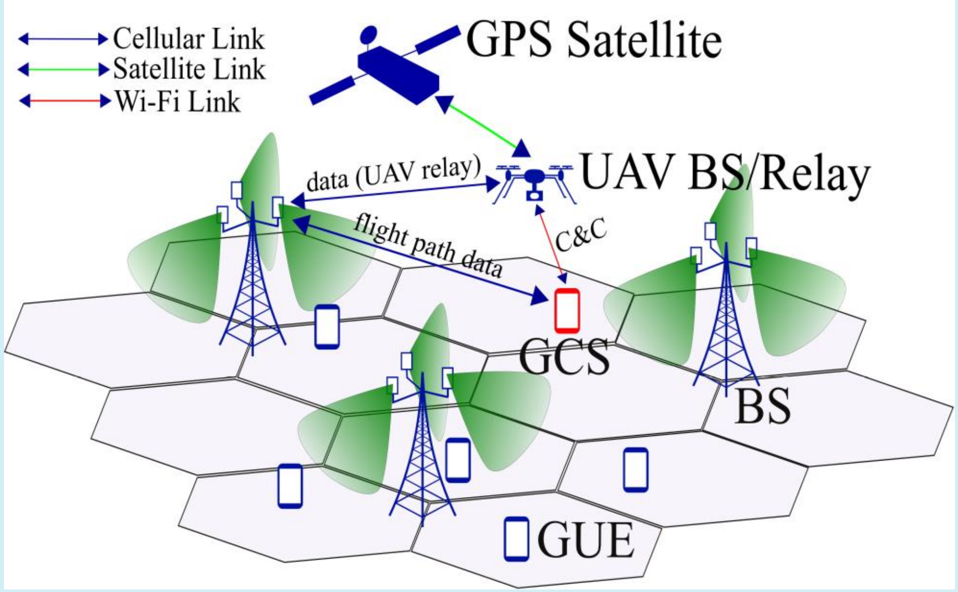


Source: A.Fotouhi, H.Qiang, , M.Ding, M.Hassan, L.G.Giordano, A.Garcia-Rodriguez, J.Yuan Survey on UAV Cellular Communications: Practical Aspects, Standardization Advancements, Regulation, and Security Challenges, JOURNAL OF COMMUNICATIONS SURVEYS AND TUTORIALS, arXiv:1809.01752v2 [cs.NI] 31 Mar 2019

4. UAV in 5G Networks

4.8 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

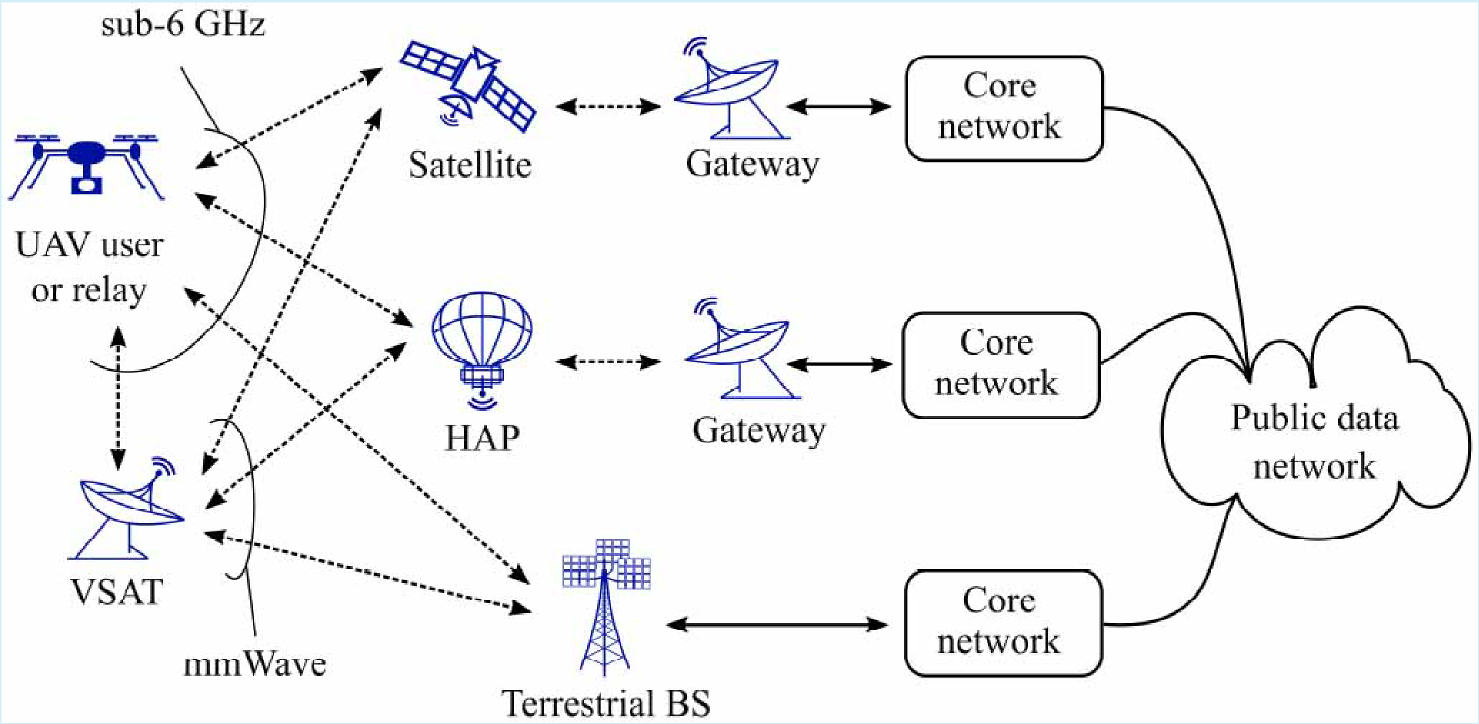


- **Security issues**
- Data and control signals are transmitted through the radio links
- Security of these wireless communication channels is important
- Wi-Fi channels are more insecure (high risk) w.r.t. cellular networks and GPS channels
  - GPS signals are broadcasted and the signal format is specified 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 Networks

4.8 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).

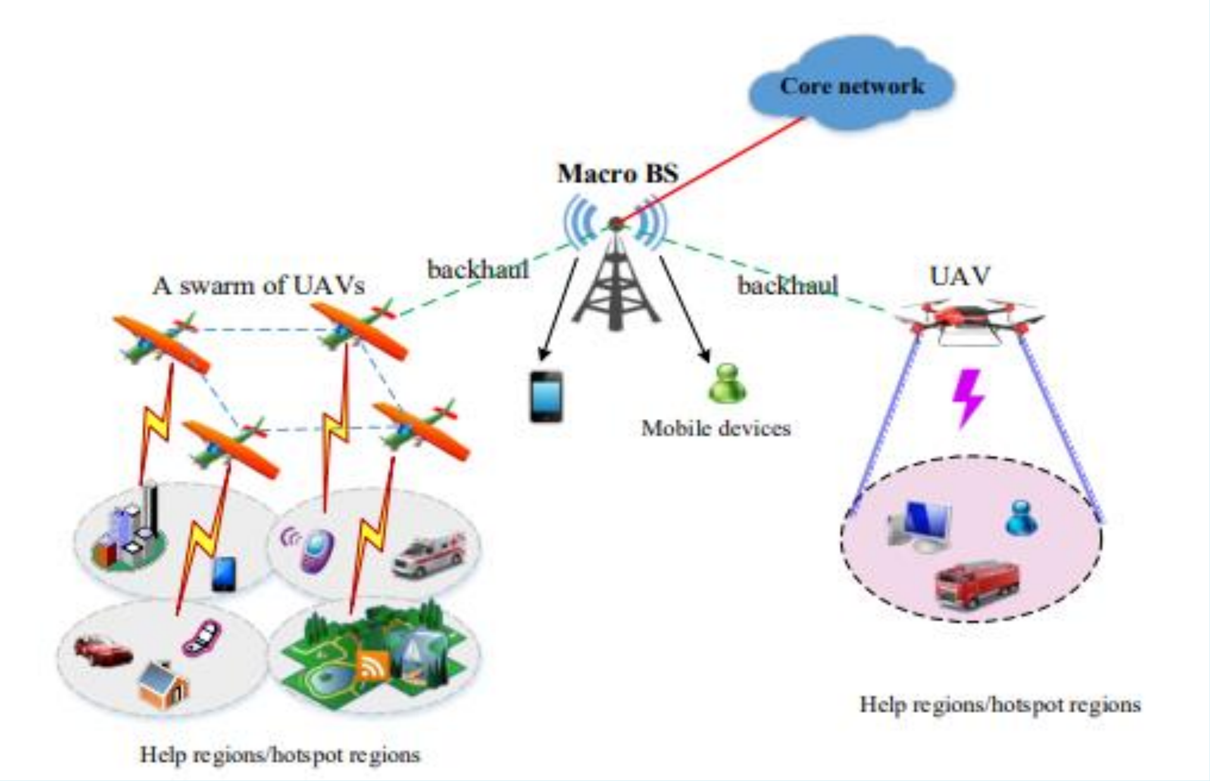


Source: G.Geraci et al., What Will the Future of UAV Cellular Communications Be? A Flight From 5G to 6G, IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 24, NO. 3, THIRD QUARTER 2022

4. UAV in 5G Networks

4.9 Example of scenarios

- 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

CONTENTS

5. UAV in Network Slicing

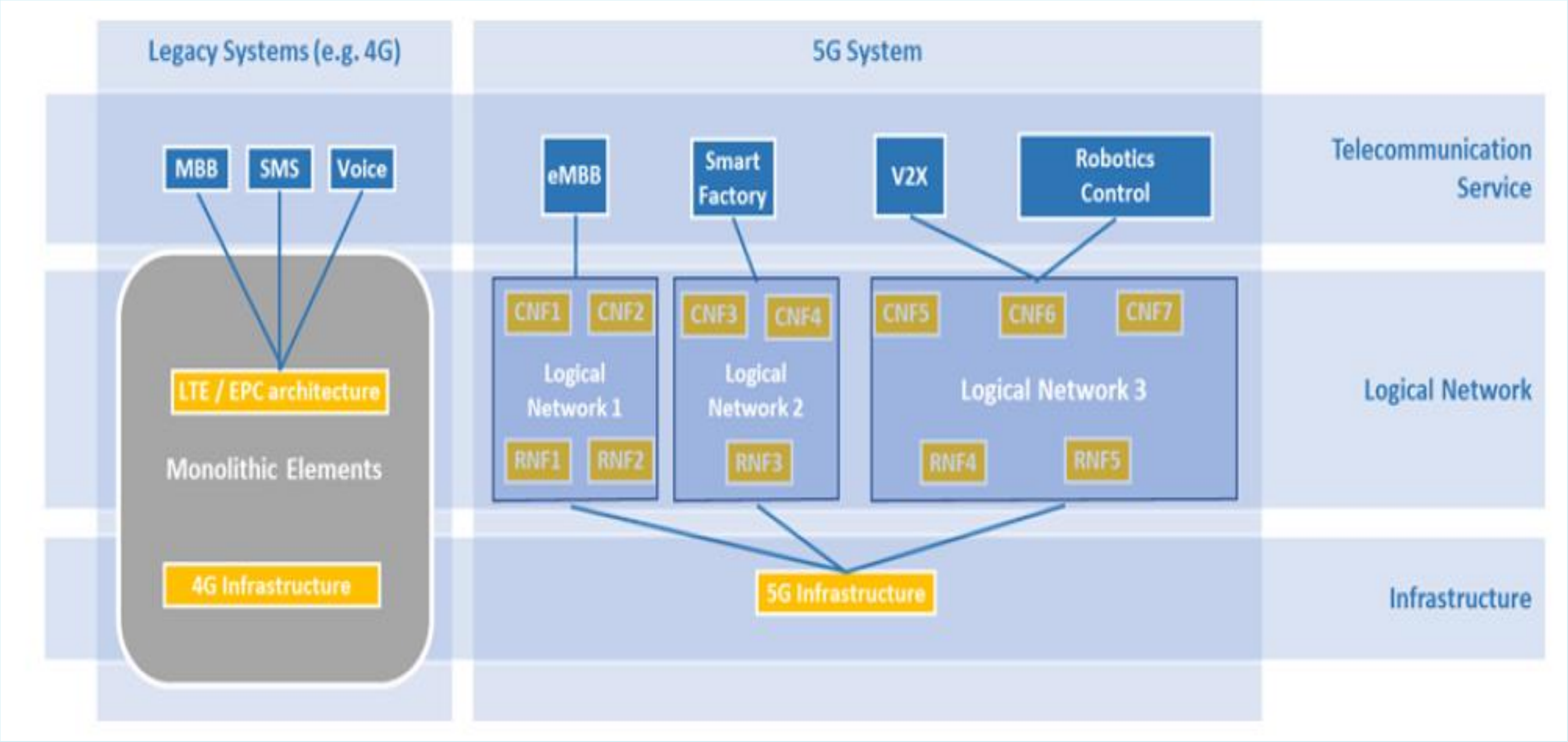
5.1 Network slicing concepts (summary)

- **General concepts**
  - **End to End (E2E) :** covers all network segments : radio, wire access, edge networks, transport and core (central) network
  - **concurrent deployment of multiple E2E logical, self-contained and independent shared** or **partitioned networks** on a **common infrastructure platform**
  - **Network Slices (NSL)**
    - created by **provisioning**, or **on demand**, each tailored for a given use case, mutually isolated with independent OM&C,
    - **composition** of adequately configured NFs, network apps., and the underlying cloud infrastructure (PHY/virtual/ emulated resources, etc.)
    - **resources are bundled together** to meet specific Use cases requirements (e.g., bandwidth, latency, processing, resiliency) coupled with a business purpose
    - **Slice life cycle:** Preparation, Instantiation, Configuration and activation, Run-time, Decommissioning -phases

- **Software Defined Networking (SDN) and Network Function Virtualisation (NFV)** – support technologies provide virtualisation, programmability, flexibility, and modularity to create **multiple network slices**

5. UAV in Network Slicing

5.2 4G versus 5G slicing concepts



MBB - Mobile Broadband;
LTE - Long Term Evolution (4G) ;
V2X - vehicle to X ; **CNF**- Core Network Functions;

SMS - Short Messages service;
EPC- Evolved Packet Core
RNF- RAN network Functions

5. UAV in Network Slicing

5.3 UAV possible roles in 5G sliced networks

- **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).

5. UAV in Network Slicing

5.3 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

5. UAV in Network Slicing

5.3 UAV 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

5. UAV in Network Slicing

5.4 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

5. UAV in Network Slicing

5.4 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

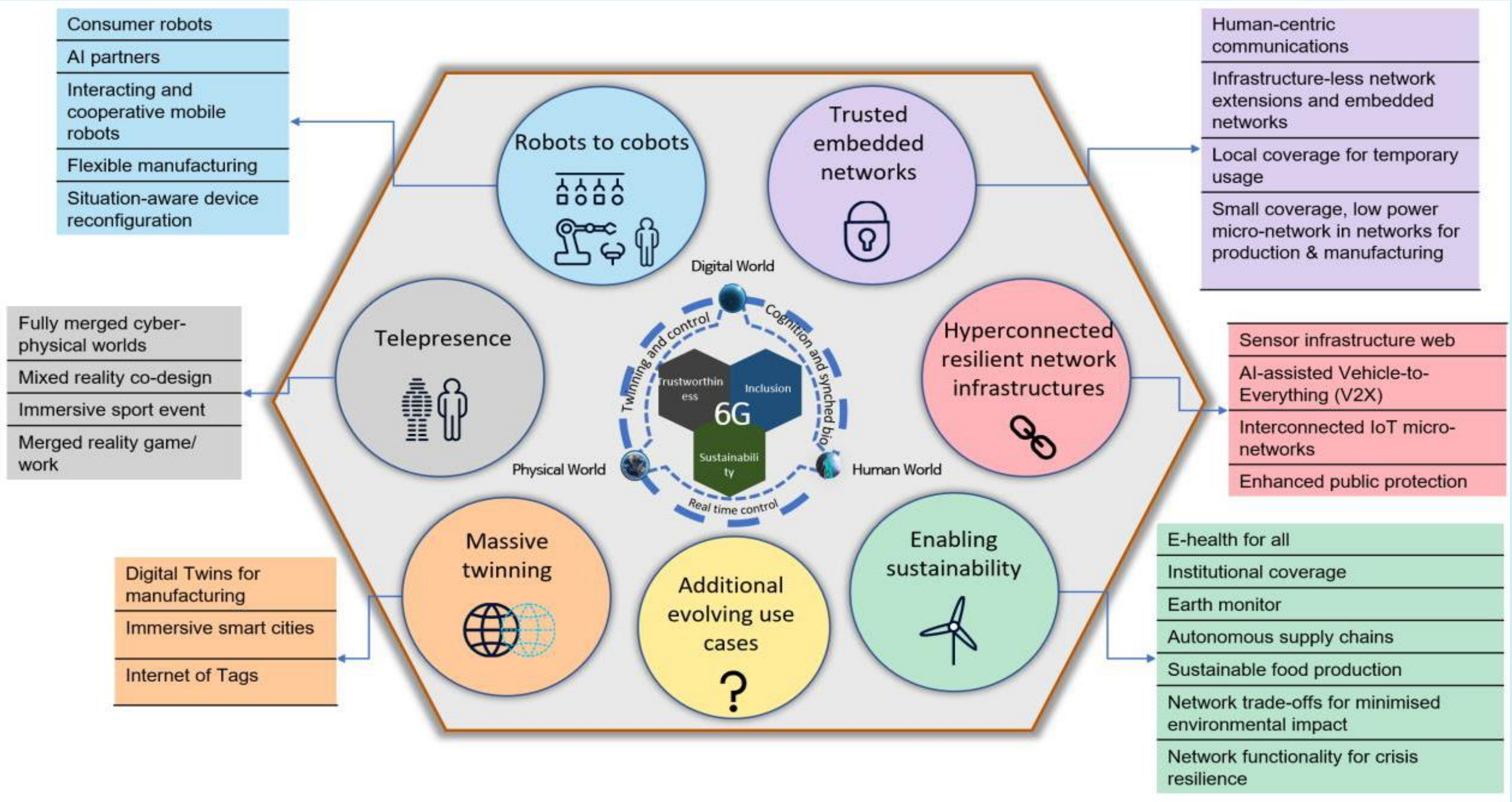
        -UAV delivers the collected information to the control station using a satellite link

CONTENTS

1. Introduction
2. Specific Aspects of UAV in Cellular and Satellite Networks
3. Routing and Path Planning Problems
4. UAV in 5G Networks
5. UAV in Network Slicing
6. ➡ **UAV in 6G Networks**
7. Conclusions

6. UAV in 6G Networks

6.1 6G Use cases and applications



Source: 5G PPP Architecture Working Group: The 6G Architecture Landscape, 2023
Source: Hexa-X Deliverable D1.3, "Targets and requirements for 6G – initial E2E architecture", Mar. 2022, https://hexa-x.eu/wp-content/uploads/2022/03/Hexa-X_D1.3.pdf.

6. UAV in 6G Networks

6.2 6G - advanced network architecture

General concepts

Overview of 6G system

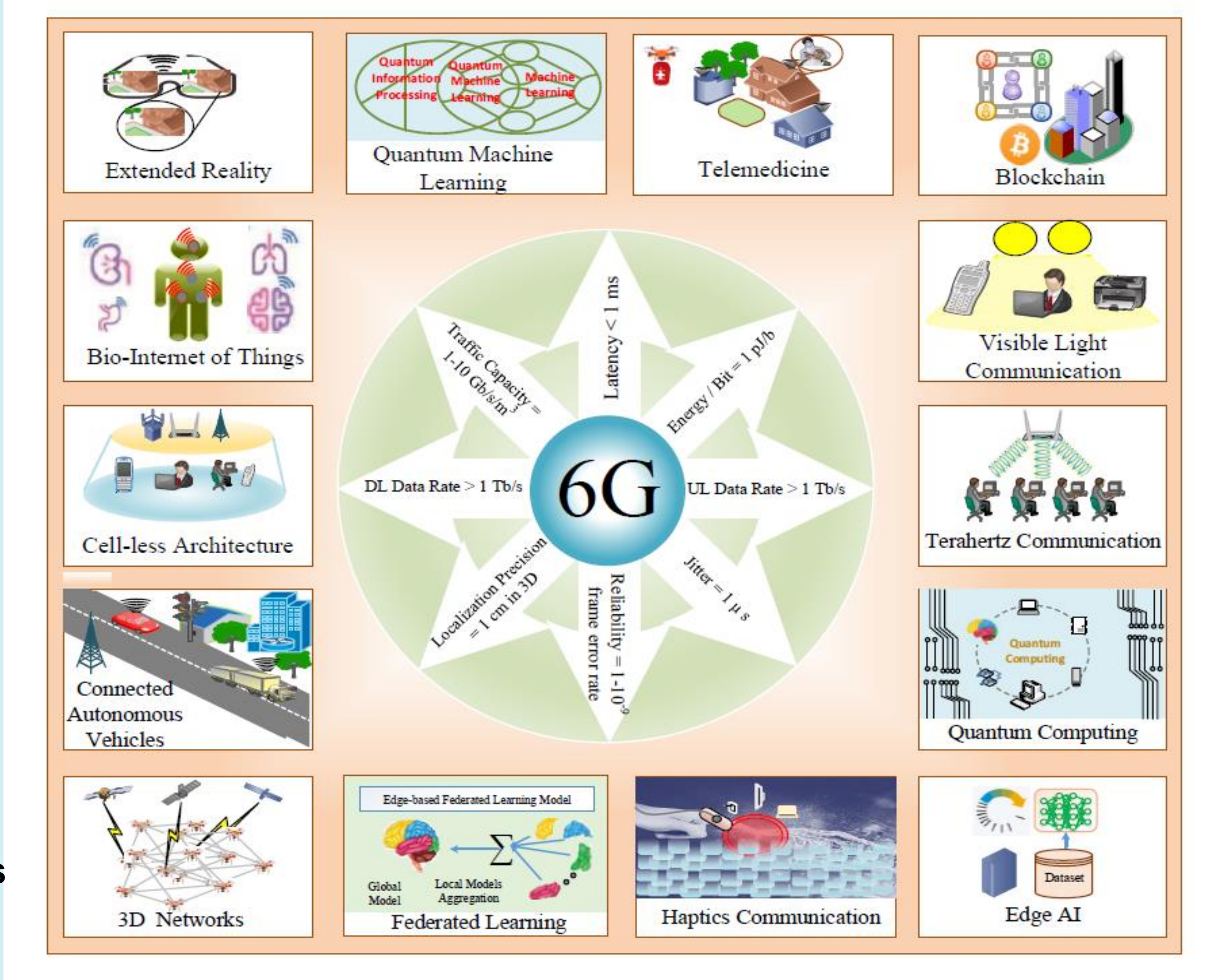
Advanced key requirements: capacity, UL/DL data rate, localization precision, reliability, latency, jitter, energy per bit

Several enabling technologies

Machine learning (quantum), federated learning
Computing (quantum)
3D networking
Edge Artificial Intelligence
Cell-less architecture
Blockchain
Haptic communication
Terahertz communication

Use cases – examples

Connected autonomous vehicles
Telemedicine
Extended reality
Internet of Things

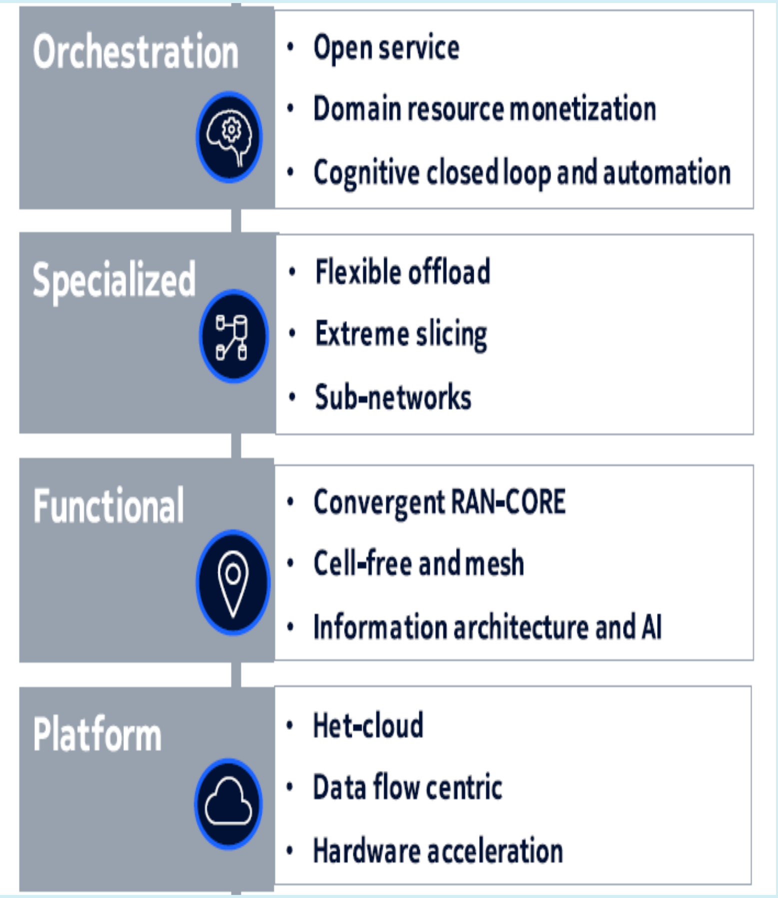


6. UAV in 6G Networks

6.2 6G - advanced network architecture

- **6G Architectural framework – building blocks example**
- **Four major interworking components, to provide an open and distributed reference framework**

- **Platform infrastructure:**
  - **"heterogeneous-cloud", open, scalable and agnostic run-time environment**
  - **data flow centricity, hardware acceleration**
- **Functions (functional architecture)**
  - **RAN- CORE convergence**
  - **cell free and mesh connectivity**
  - **information architecture and AI**
- **Specialized networks and architectural enablers for**
  - **flexible off-load, extreme slicing, sub-networks**
- **Orchestration component**
  - **assures open service enabling and ecosystem play**
  - **domain resource monetization**
  - **cognitive closed loop and automation**

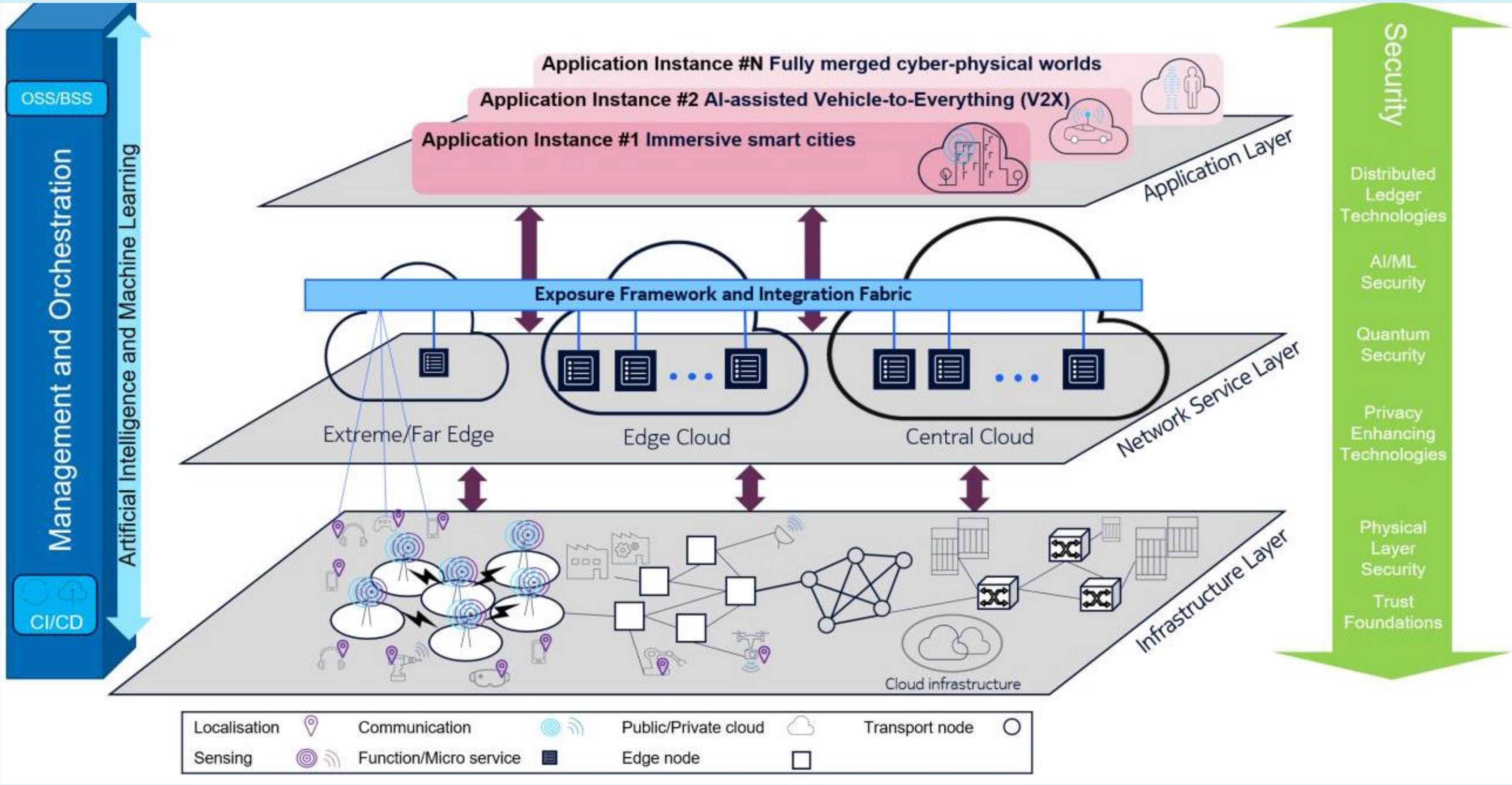


Source: V.Ziegler et al., "6G Architecture to Connect the Worlds", IEEE Access, Sept 2020, https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9200631

6. UAV in 6G Networks

6.3 6G – layered architecture

- **High-level view of the 6G layered architecture**



Source: 5G PPP Architecture Working Group: The 6G Architecture Landscape, 2023
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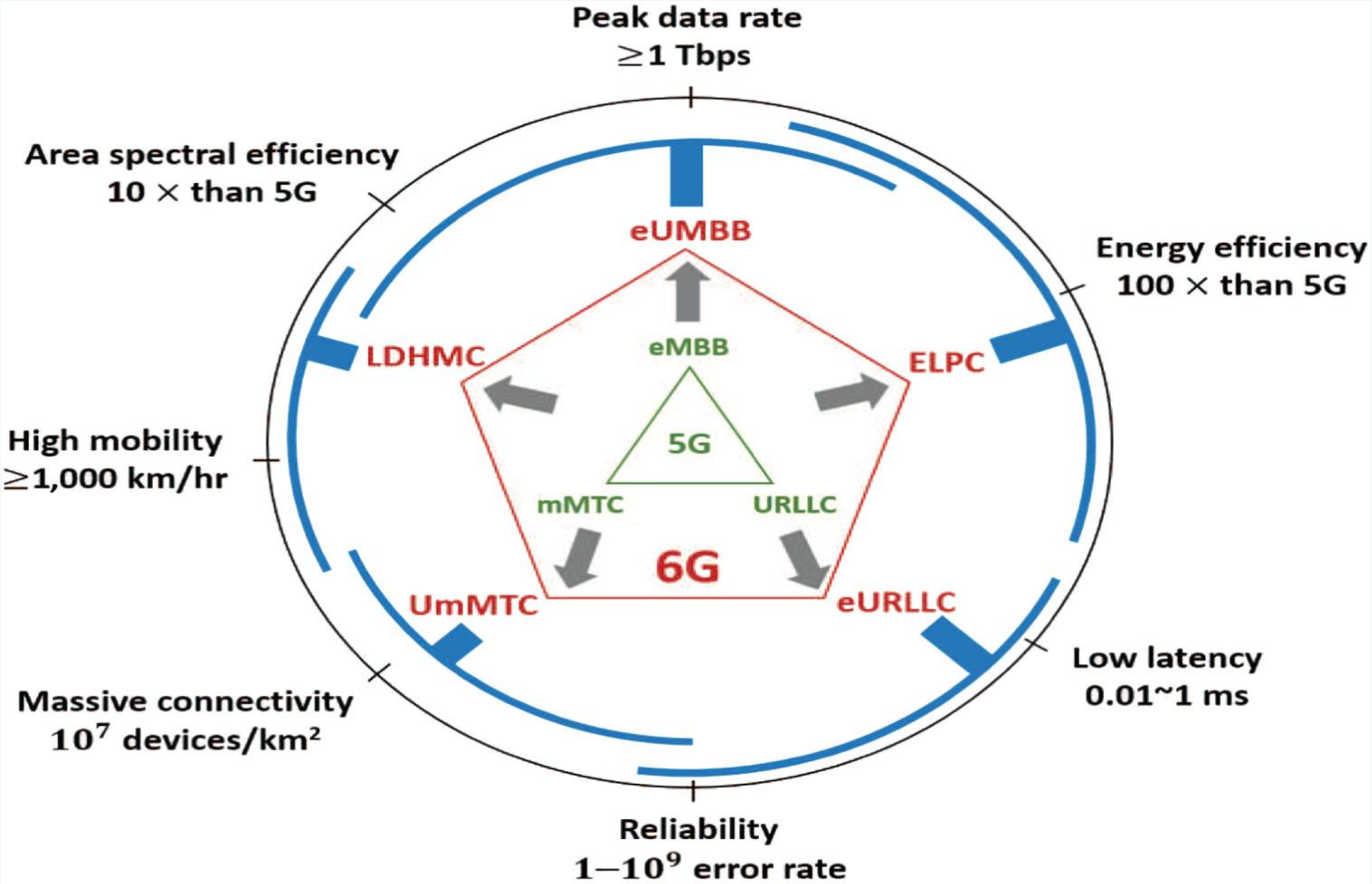
6. UAV in 6G Networks

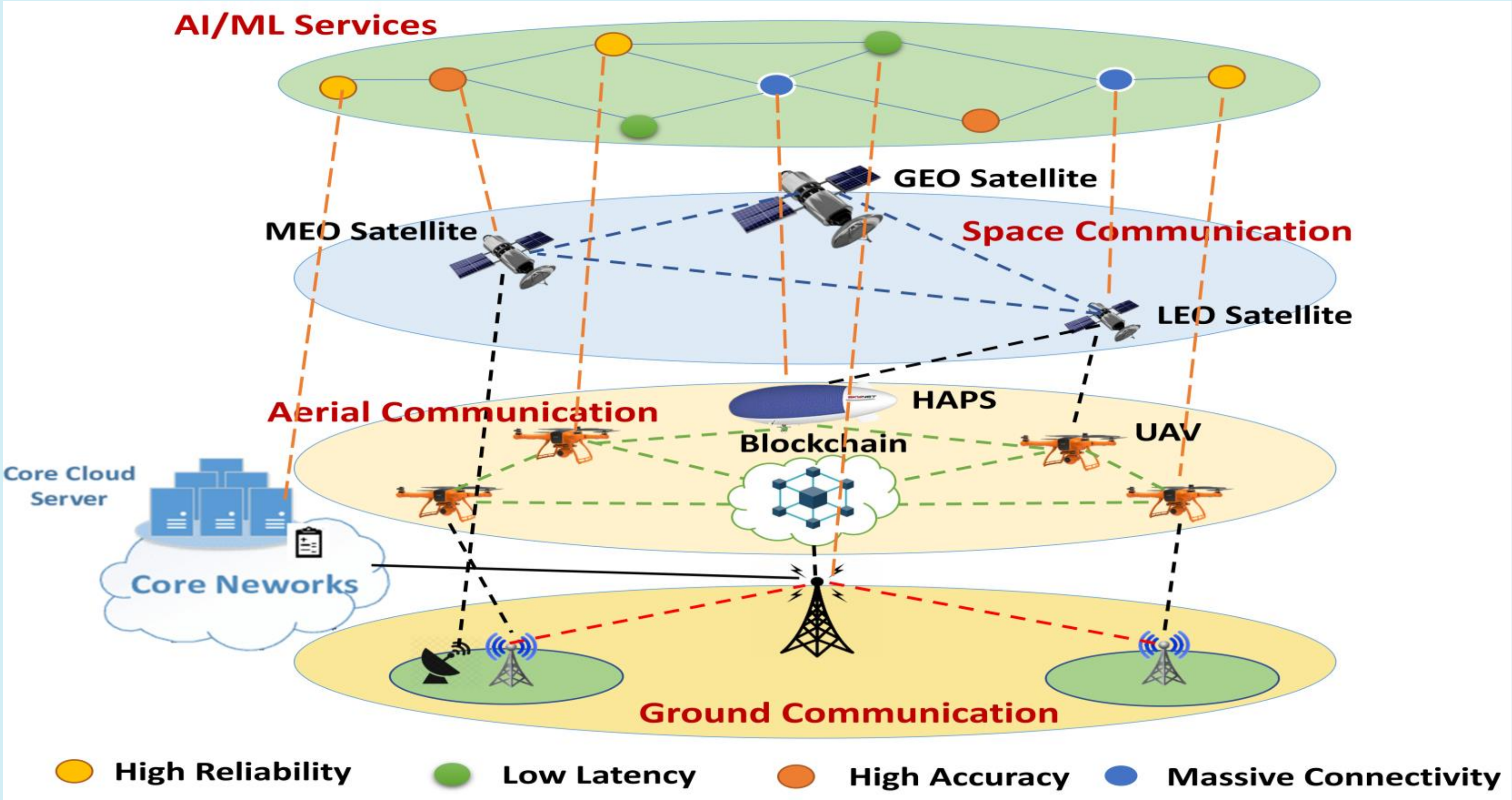
6.4 6G versus 5G in terms of connectivity capabilities



Source: Li-Hsiang Shen, Kai-Ten Feng, Lajos Hanzo, Five Facets of 6G: Research Challenges and Opportunities, ACM Comput. Surv. 55, 11, Article 235 2023, https://doi.org/10.1145/3571072

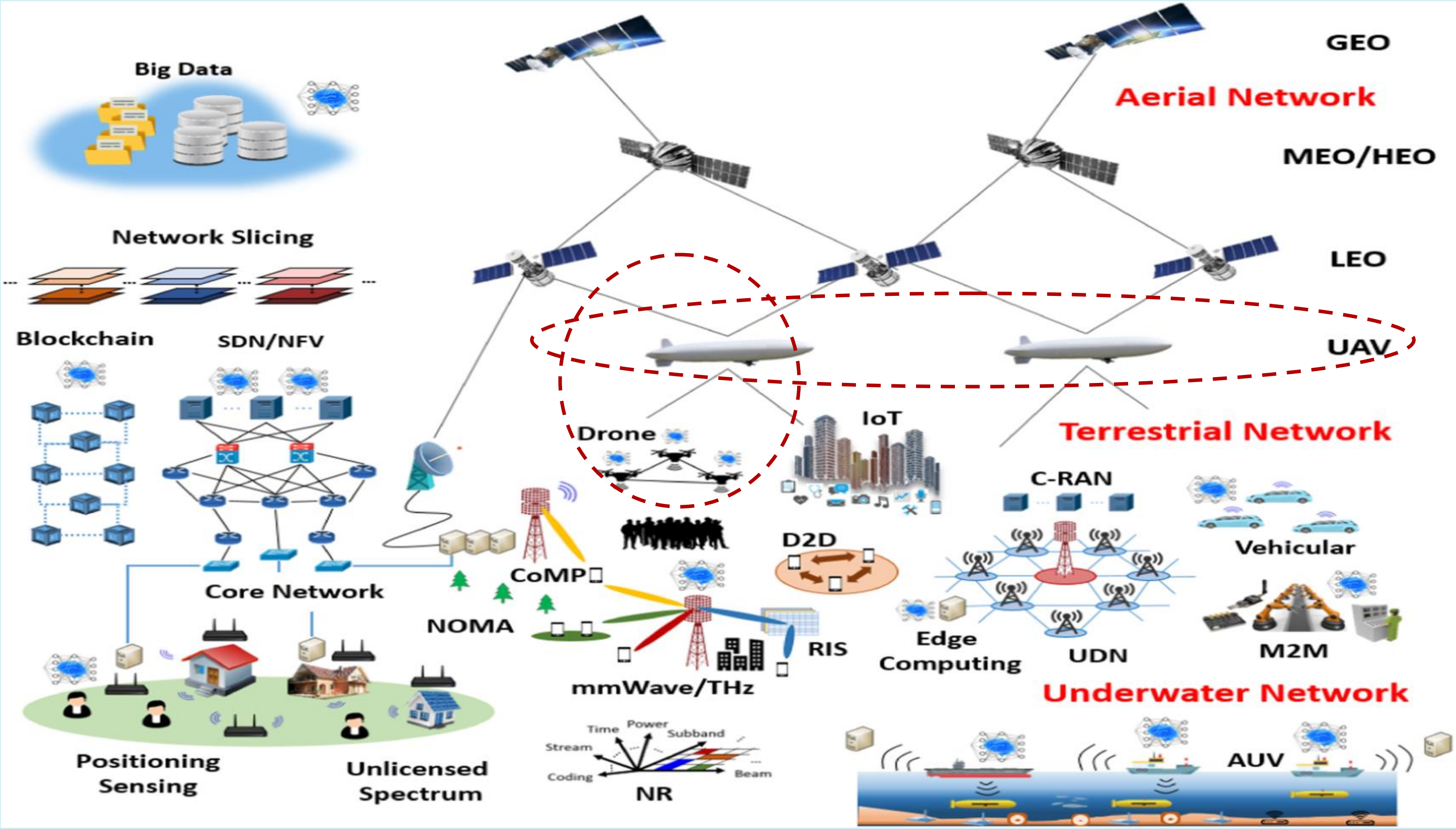
6.5 Example of an architecture for 6G-enabled UAV network

- 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

6.6 UAVs in the 6G landscape



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6. UAV in 6G Networks

6.6 UAVs in the 6G landscape (notations)

Acronyms

AI	Artificial Intelligence
AUV	Autonomous Underwater Vehicle
CoMP	Coordinated Multi-Point
C-RAN	Cloud/Centralized Radio Access Network
D2D	Device to Device
GEO	Geostationary Earth Orbit
HEO	High Earth Orbit
LEO	Low Earth Orbit
LoS	Line of Sight
M2M	Machine to Machine (Communication)
MEO	Medium Earth Orbit
NOMA	Non-Orthogonal Multiple Access
NFV	Network Function Virtualization
NR	New Radio
RIS	Reconfigurable Intelligent Surfaces
SDN	Software Defined Networking
UAV	Unmanned Aerial Vehicle
UDN	Ultra-Dense Networks

6. UAV in 6G Networks

6.7 UAVs integration into 6G networks

- The 6G mobile network will support a wide range of UAV applications
- UAVs will be integrated into space-aerial-terrestrial-sea segments (absent in 5G and B5G, such as
  - Ultra-high data density (uHDD)
  - Ultra-high speed low latency communications (uHSLLC)
  - Ubiquitous mobile ultra-broadband (uMUB)

- **Trends/goals in 6G which will support or use UAV capabilities to achieve UAV integration in 6G networks (examples)**

  - Hyperspectral and full spectral system (microwave, mm-wave, terahertz .. Laser)
  - UAV networks will provide full coverage (terrestrial, aerial, space, and maritime domains)
  - The 6G localization of UAVs will be precise, allowing for accurate RF operation, towards fine-grained analysis, modulation, and manipulation in the intensity-phase-frequency space

6. UAV in 6G Networks

6.7 UAVs integration into 6G networks

- **Trends/goals in 6G which will support or use UAV capabilities to achieve UAV integration in 6G networks- examples (cont'd)**

  - The 6G multi-functionality will enhance the 5G wireless communications capability, allowing.new advanced UAV-based apps and services (communication, control, sensing, computing, and imaging will converge).

  - 6G, photonics-defined radio (PDR), novel antenna arrays, photonic engine, and spectrum computation will contribute to increase UAV networks energy efficiency

  - AI subsystems will be ubiquitous; distributed intelligence will be present in all architectural layers from the app. layer to the physical one

Source: M.A.Khan,et al., Swarm of UAVs for Network Management in 6G:A Technical Review, IEEE Transactions on Network and Service Management,2023

CONTENTS

7.Conclusions

Trends and Research Challenges

- **UAV technologies – strong development, many applications and services**
- **Seamless UAV integration in conventional networks is a complex task**
- **Many open research issues and challenges can be identified. Partial list follows:**

- **General architectural and system aspects**
  - **Integration of UAVs** into heterogeneous networks:5G, 6G, WiFi, satellite – many architectural layers are involved
  - **Multiple UAVs operation** in coordinated groups (swarms), (reliability, enhanced coverage, scalability), for apps. like surveillance, delivery , emergency, etc. Developing efficient algorithms and protocols for seamless and reliable inter-UAV communication
  - **Control actions latency** should be reduced in 5G-UAV and 6G-UAV Enhancing GPS and UAV cooperation to improve system performance related to location finding
  - **Integration of UAVs into established air traffic management systems -** a paramount importance as the frequency of UAV operations continues to rise
  - **Architectural enhancement for cooperation of several technologies** with UAV systems: cloud/edge computing, SDN, NFV, AI/ML

7.Conclusions

Trends and Research Challenges

- **Security and privacy**
  - **Enhanced cryptographic techniques, trust-based protocols, and privacy-preserving mechanisms**, adapted to UAV communication networks
  - **Blockchain with distributed ledger technology-** for secure and transparent transactions, increasing trust and accountability in UAV networks (for sharing UAV-generated data among multiple stakeholders)
  - **Cyber-physical security issues are crucial for UAV networks**. In cellular systems, security becomes more important for providing coherence in networks
- **Advanced technologies**
  - **AI/ML algorithms and methods** designed for UAV context- adapted to UAV multi-dimensional network (more complex than current terrestrial networks); action areas examples-predictive path planning, resource allocation, and interference management.

7.Conclusions

Trends and Research Challenges

- **Physical layer challenges**
  - Enhanced spectrum sharing techniques to support spectrum management, aiming to enable UAVs to efficiently share spectrum resources
  - Wireless channels in connected UAVs is critical from reliability point of view. Unlike other commonly known fading channels, there are more parameters that characterize UAV communication channels
  - Challenges to the mobility management of cellular-connected UAVs in terms of reference signal received power (RSRP); this should be maintained when the distance is far between terrestrial BSs and UAV
- **Routing, path planning, localization issues**
  - Collision avoidance algorithms and protocols especially in multi-UAV environment
  - Interference aware path planning structure for solving the tradeoff problem between minimizing both the interference caused on the ground network along its route and maximizing the energy efficiency
- **Energy aspects**
  - UAVs have limited energy; all scenarios, algorithms, protocols, etc., related to UAVs must be designed by considering energy issues. Battery and charging optimization are complementary open research domains

- Thank you !
- Questions?

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Unmanned Aerial Vehicles Communication in 5G, 6G Networks

- **List of 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

Unmanned Aerial Vehicles Communication in 5G, 6G Networks

- **List of 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**

4. UAV in 5G Networks

4.3A 5G disruptive capabilities

- **Summary of 5G figures - strong goals - versus 4G:**
  - **1,000 X in mobile data volume** per geographical area reaching a target ≥ 10 Tb/s/km2
  - **1,000 X in number of connected devices** reaching a density ≥ 1M terminals/km2
  - **100 X in user data rate** reaching a peak terminal data rate ≥ 10Gb/s
  - **1/10 X in energy** consumption compared to 2010
  - **1/5 X in E2E latency reaching 5 ms** for e.g. tactile Internet and radio link latency reaching a target ≤ 1 ms, e.g. for Vehicle to Vehicle (V2V) communication
  - **1/5 X in network management** OPEX
  - **1/1,000 X in service** deployment time, reaching a complete deployment in ≤ 90 minutes

5. UAV in Network Slicing

5.1A Terminology summary in slicing

- **Service** - A SW piece performing one or more functions and providing one or more APIs to apps. or other services of the same or different layers Services can be combined with other services
  - **Service Instance** - An instance of an EU service or a business service that is realized within or by a network slice
- **Administrative domain (AD)** - A collection of systems and networks operated by a single organization or administrative authority
- **Infrastructure domain** – an admin. domain
  - providing virtualised infrastructure resources or a composition of resources
- **Tenant: one or more service users** sharing access to a set of physical, virtual resources or service resources (e.g. offered by NFV-MANO framework)
- **Multi-tenancy:** physical, virtual or service resources are allocated so that multiple tenants and their computations and data are isolated from each another
- **Tenant domain:** provides VNFs, and combinations of VNFs into Network Services, and is responsible for their management and orchestration, including their functional configuration and maintenance at application level

See:. L. Geng , et.al., IETF- "Network Slicing Architecture draft-geng-netslices-architecture-02", 2017
ETSI GS NFV 003 V1.3.1 (2018-01) Network Functions Virtualisation (NFV); Terminology for Main Concepts in NFV

5. UAV in Network Slicing

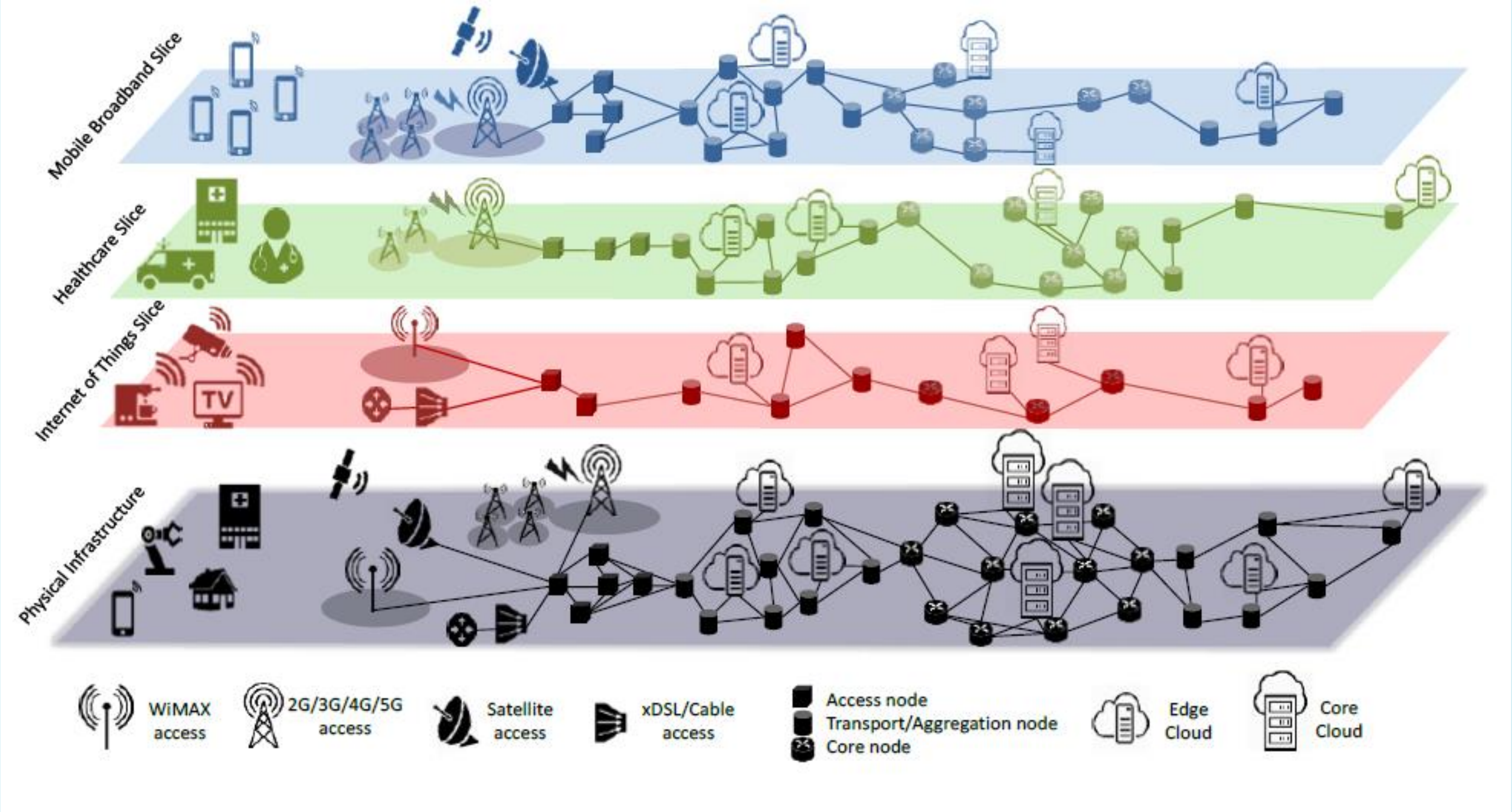
5.1A Terminology summary in slicing

- **Network Resources**
  - **Resource -** P/V (network, compute, storage) component available within a system (can be very simple or comprised of multiple other resources)
  - **Logical Resource** - An independently manageable partition of a Physical (P) resource, inheriting the same characteristics as the P resource
  - **Virtual Resource** - An abstraction of a P/L resource, maybe with different characteristics and extended capabilities w.r.t the original
  - **Network Function (NF)** - A processing function in a network, including but not limited to network nodes functionality
    - NFs implementation: as a network node on a dedicated HW, or as VNFs
  - **Virtual Network Function (VNF)** - A NF whose functional SW is decoupled from HW
    - It is implemented by **one or more virtual machines (VM)**
  - **Network Element (NE)** - a manageable logical entity uniting one or more network devices. This allows distributed devices to be managed in a unified way using one management system

See:. L. Geng , et.al., IETF- "Network Slicing Architecture draft-geng-netslices-architecture-02", 2017
ETSI GS NFV 003 V1.3.1 (2018-01) Network Functions Virtualisation (NFV); Terminology for Main Concepts in NFV

5. UAV in Network Slicing

5.2A 5G Network slicing generic example



Source: J. Ordonez-Lucena, P. Ameigeiras, D. Lopez, J.J. Ramos-Munoz, J. Lorca, J. Folgueira, Network "Slicing for 5G with SDN/NFV: Concepts, Architectures and Challenges" ,
IEEE Communications Magazine, 2017, Citation information: DOI 10.1109/MCOM.2017.1600935