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An Overview of Future UAVs with an Emphasis on Path Planning and Applications

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Outline

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- Greenwaterdrone (GWD): A smart agriculture application using UAVs

References

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Introduction

- Unmanned aerial vehicles (UAVs), also commonly known as drones, are aircraft piloted by remote control or embedded computer programs without any human onboard.
- UAVs were mainly used in military applications deployed in hostile territory for remote surveillance and armed attack, to reduce pilot losses.
- New applications include aerial inspection, photography, precision agriculture, traffic control, search and rescue, package delivery, and telecommunications.
- In June 2016, the U.S. Federal Aviation Administration (FAA) released the operational rules for routine civilian use of small unmanned aircraft systems (UASs) with aircraft weight less than 55 pounds (25 kg).
- In November 2017, FAA further launched a national program in Washington, namely “Drone Integration Pilot Program,” to explore the expanded use of drones, including beyond-visual-line-of-sight (BVLoS) flights, night-time operations, and flights above people.
- The scale of the UAV industry is potentially enormous with realistic predictions of $80 billion for the U.S. economy alone, which is expected to create tens of thousands of new jobs within the next decade.

Classification

- Fixed-wing and rotary-wing UAVs are the two main types of UAVs that have been widely used in practice.
- Typically,
  - fixed-wing UAVs have higher maximum flying speed and can carry greater payloads for traveling longer distances compared to rotary-wing UAVs, while
  - their disadvantages lie in that a runway or launcher is needed for takeoff/ landing as well as that hovering at a fixed position is impossible.
  - In contrast, rotary-wing UAVs are able to take off/land vertically and remain static at a hovering location.
- From a practical perspective, different applications usually require different types of UAVs due to different requirements in terms of payload, endurance, operating environment, cost, and so on.
- From a communication system design perspective, they mostly share similar characteristics and, thus, can be investigated in a unified manner.

Wireless communications for UAVs

- UAVs need to exchange safety–critical information with various parties, such as remote pilots, nearby aerial vehicles, and air traffic controllers, to ensure the safe, reliable, and efficient flight operation. This is commonly known as the **control and nonpayload communication (CNPC).**
- Depending on their missions, UAVs may need to timely transmit and/or receive mission-related data, such as aerial image, high-speed video, and data packets for relaying, to/from various ground entities, such as UAV operators, end users, or ground gateways. This is known as **payload communication**.

ITU categorization

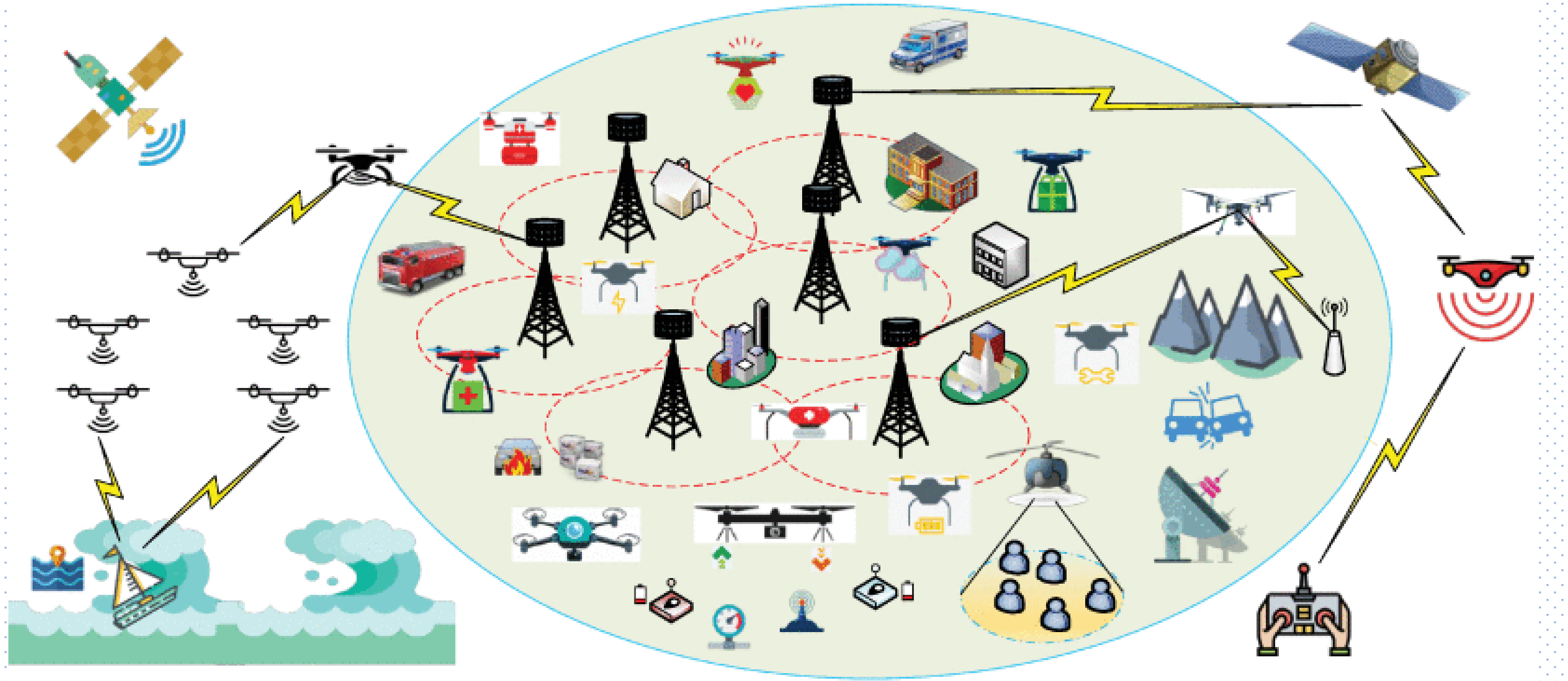
- The International Telecommunication Union (ITU) has classified the required CNPC to ensure safe UAV operations into three categories.

  Communication for UAV Command and Control: This includes the telemetry report (e.g., flight status) from the UAV to the ground pilot, the real-time telecommand signaling from the ground to UAVs for nonautonomous UAVs, and regular flight command update (such as waypoint update) for (semi) autonomous UAVs.

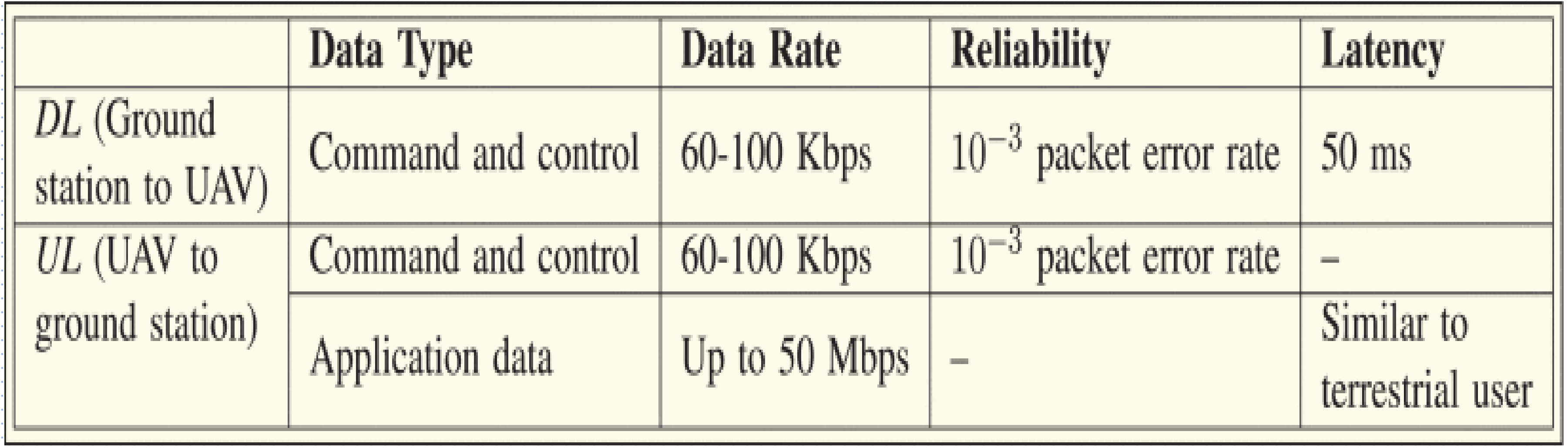
  Communication for Air Traffic Control (ATC) Relay: It is critical to ensure that UAVs do not cause any safety threat to traditional manned aircraft, especially for operations approaching areas with a high density of aircraft. To this end, a link between the air traffic controller and the ground control station via the UAV, called ATC relay, is required.

  Communication Supporting "Sense and Avoid": The ability to support "sense and avoid" ensures that the UAV maintains sufficient safety distance with nearby aerial vehicles, terrain, and obstacles.

Supporting UAV communications with an integrated network architecture.

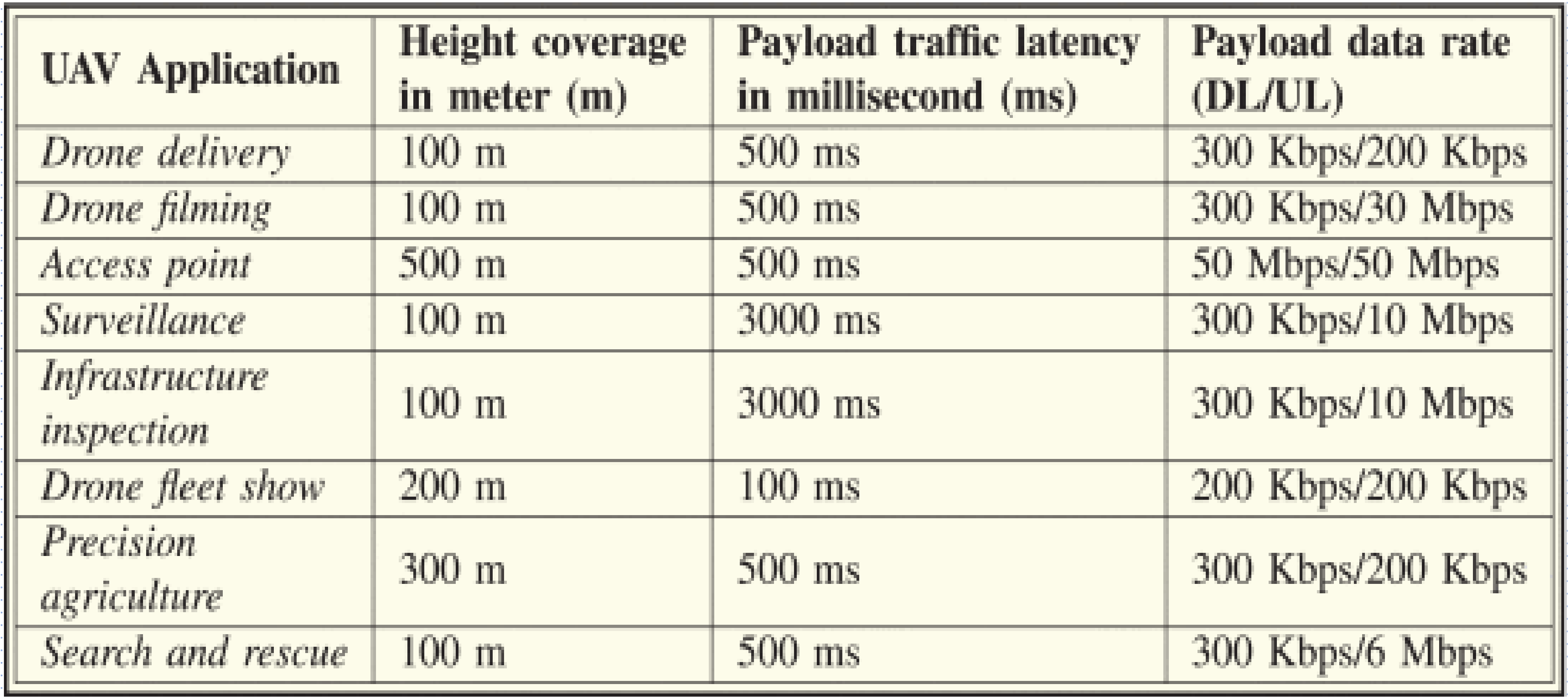


UAV Communication Requirements Specified by 3GPP



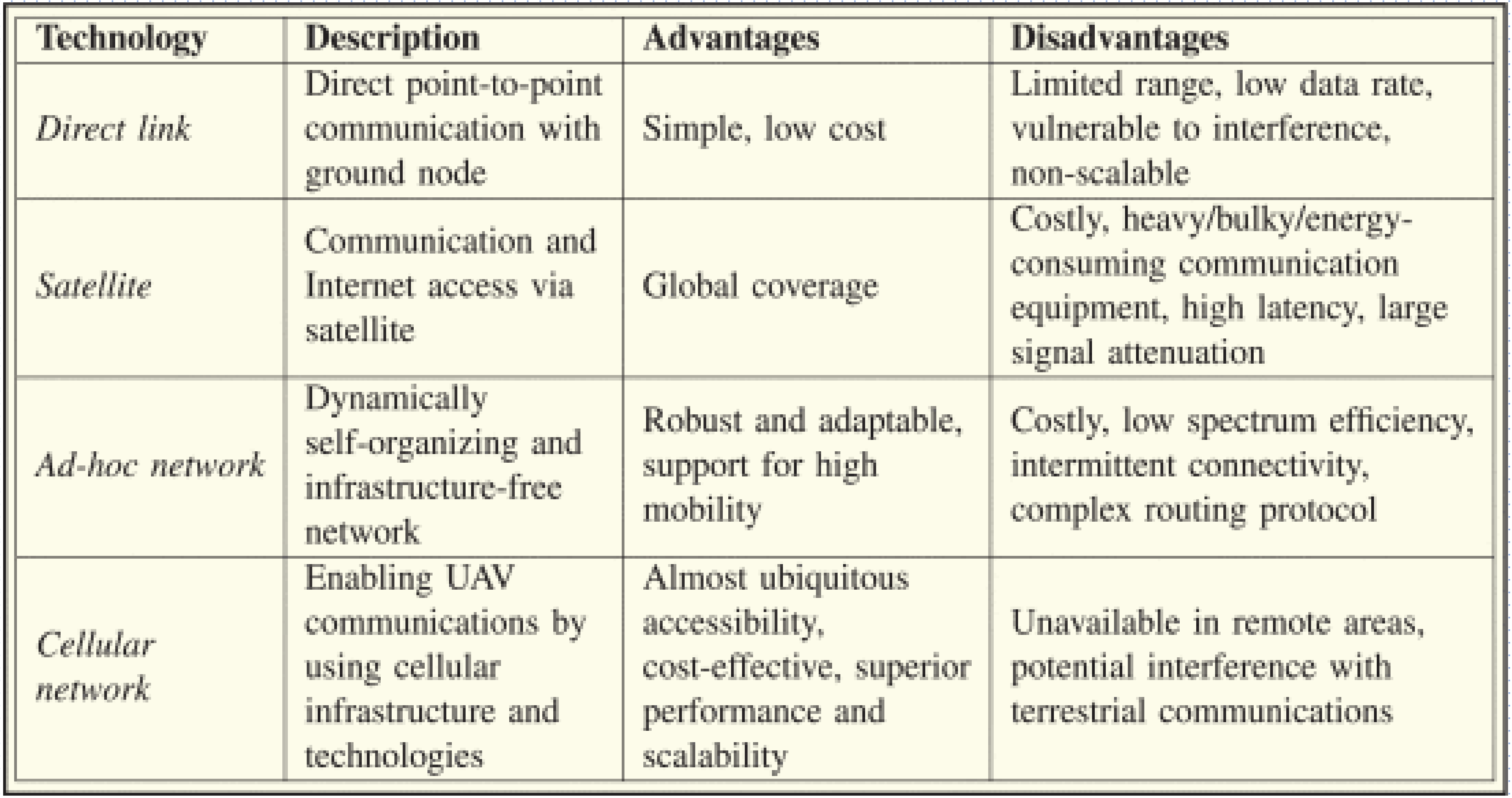
	Data Type	**Data Rate**	**Reliability**	**Latency**
DL (Ground station to UAV)	Command and control	60-100 Kbps	10^{-3} packet error rate	50 ms
UL (UAV to ground station)	Command and control	60-100 Kbps	10^{-3} packet error rate	–
	Application data	Up to 50 Mbps	–	Similar to terrestrial user

Communication Requirements for Typical UAV Applications



UAV Application	**Height coverage in meter (m)**	**Payload traffic latency in millisecond (ms)**	**Payload data rate (DL/UL)**
Drone delivery	100 m	500 ms	300 Kbps/200 Kbps
Drone filming	100 m	500 ms	300 Kbps/30 Mbps
Access point	500 m	500 ms	50 Mbps/50 Mbps
Surveillance	100 m	3000 ms	300 Kbps/10 Mbps
Infrastructure inspection	100 m	3000 ms	300 Kbps/10 Mbps
Drone fleet show	200 m	100 ms	200 Kbps/200 Kbps
Precision agriculture	300 m	500 ms	300 Kbps/200 Kbps
Search and rescue	100 m	500 ms	300 Kbps/6 Mbps

Comparison of Wireless Technologies for UAV Communication

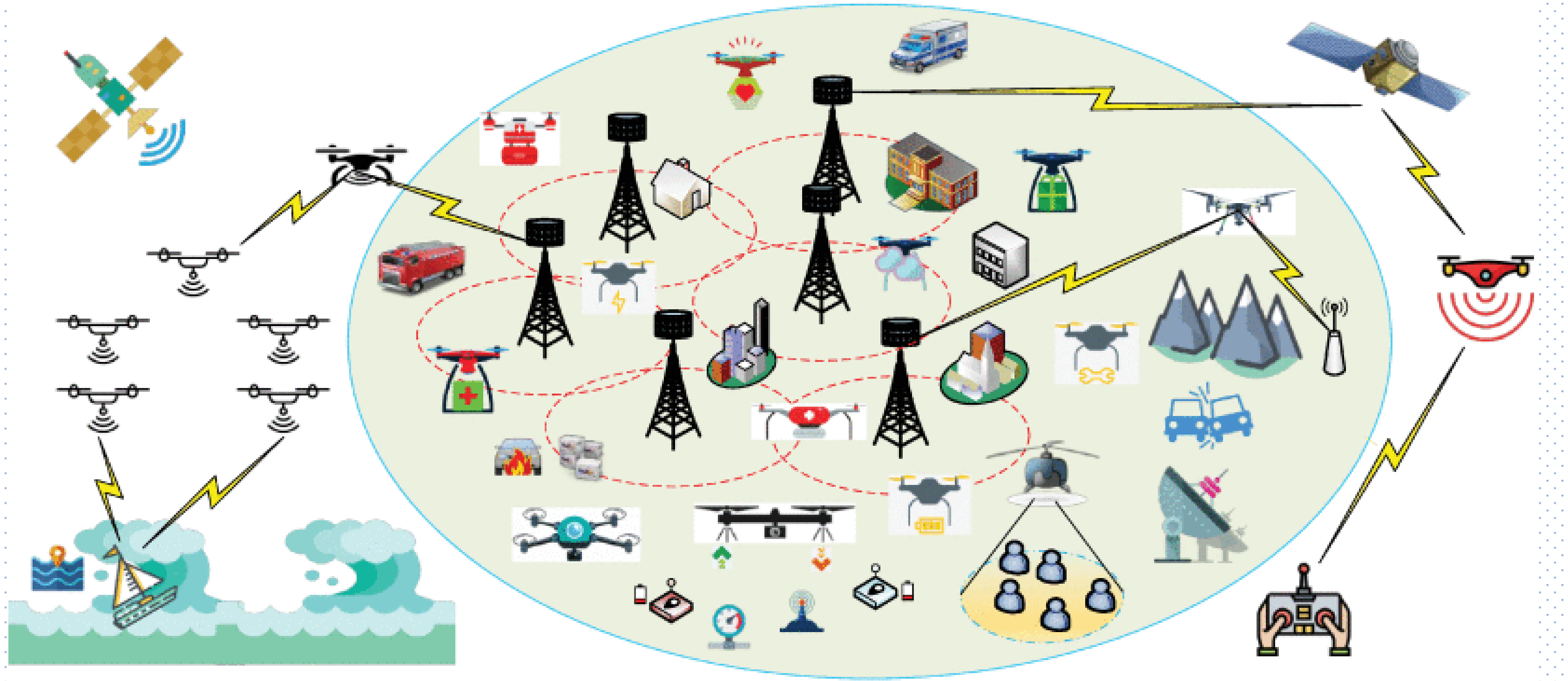


Technology	Description	Advantages	Disadvantages
Direct link	Direct point-to-point communication with ground node	Simple, low cost	Limited range, low data rate, vulnerable to interference, non-scalable
Satellite	Communication and Internet access via satellite	Global coverage	Costly, heavy/bulky/energy-consuming communication equipment, high latency, large signal attenuation
Ad-hoc network	Dynamically self-organizing and infrastructure-free network	Robust and adaptable, support for high mobility	Costly, low spectrum efficiency, intermittent connectivity, complex routing protocol
Cellular network	Enabling UAV communications by using cellular infrastructure and technologies	Almost ubiquitous accessibility, cost-effective, superior performance and scalability	Unavailable in remote areas, potential interference with terrestrial communications

Requirements

- Since the loss of a CNPC link may cause catastrophic consequences, the International Civil Aviation Organization (ICAO) has determined that CNPC links for UAVs must operate over the protected aviation spectrum.
- ITU studies have revealed that to support CNPC for the forecasted number of UAVs in the coming years, 34-MHz terrestrial spectrum and 56-MHz satellite spectrum are needed for supporting both LoS and beyond-LoS UAV operations [7].
    - To meet such requirement, the C -band spectrum at 5030–5091 MHz has been made available for UAV CNPC at the World Radiocommunication Conference (WRC)-12.
- More recently, the WRC-15 has decided that geostationary fixed-satellite service (FSS) networks may be used for UAS CNPC links.
- Compared to CNPC, UAV payload communication usually has much higher data rate requirements.
    - For instance, to support the transmission of full high-definition (FHD) video from the UAV to the ground user, the transmission rate is about several Mb/s, while for 4k video, it is higher than 30 Mb/s.
- The rate requirement for UAV serving as an aerial communication platform can be even higher, e.g., up to dozens of gigabits per second for data forwarding/backhauling applications.

Supporting UAV communications with an integrated network architecture.



Integrating UAVs Into Cellular Network

- On one hand, UAVs are considered as new aerial users that access the cellular network from the sky for communications, which we refer to as **cellular-connected UAVs**.
- On the other hand, UAVs are used as new aerial communication platforms, such as base stations (BSs) and relays, to assist in terrestrial wireless communications by providing data access from the sky, thus called **UAV-assisted wireless communications**.

Cellular-Connected UAVs

- By incorporating UAVs as new user equipment (UE) in the cellular network, the following benefits can be achieved.
- First, due to the almost worldwide accessibility of cellular networks, cellular-connected UAV makes it possible for the ground pilot to remotely command and control the UAV with virtually unlimited operation range.
- Besides, it also provides an effective solution to maintain wireless connectivity between UAVs and various other stakeholders, such as the end users and the air traffic controllers, regardless of their locations.
  - Thus, this opens up many new UAV applications in the future.
- Second, with the advanced cellular technologies and authentication mechanisms, cellular-connected UAV is expected to achieve significant performance improvement over the other technologies in terms of reliability, security, and data throughput.

Cellular-Connected UAVs

- Third, cellular-based localization service can provide UAVs a new and complementary means in addition to the conventional satellite-based global positioning system (GPS) for achieving more robust or enhanced UAV navigation performance.
- Last but not least, cellular-connected UAV is a cost-effective solution since it reuses the millions of cellular BSs worldwide without the need of building new infrastructure dedicated for UAS only.
- Thus, cellular-connected UAVs are expected to be a win–win technology for both UAV and cellular industries, with rich business opportunities to explore in the future.

UAV-Assisted Wireless Communications

- Due to the continuous cost reduction in UAV manufacturing and device miniaturization in communication equipment, it becomes more feasible to mount compact BSs or relays on UAVs to enable flying aerial platforms to assist in terrestrial wireless communications.
  - For instance, commercial LTE BSs with lightweight (e.g., less than 4 kg) are already available in the market, which are suitable to be mounted on UAVs with the moderate payload. Compared to conventional terrestrial communications with typically static BSs/relays deployed at fixed locations, UAV-assisted communications bring the following main advantages.
- First, UAV-mounted BSs/relays can be swiftly deployed on demand. This is especially appealing for application scenarios, such as temporary or unexpected events, emergency response, and search and rescue.
- Second, due to their high altitude above the ground, UAV-BSs/relays are more likely to have LoS connection with their ground users compared to their terrestrial counterparts, thus providing more reliable links for communication as well as multiuser scheduling and resource allocation.

UAV-Assisted Wireless Communications

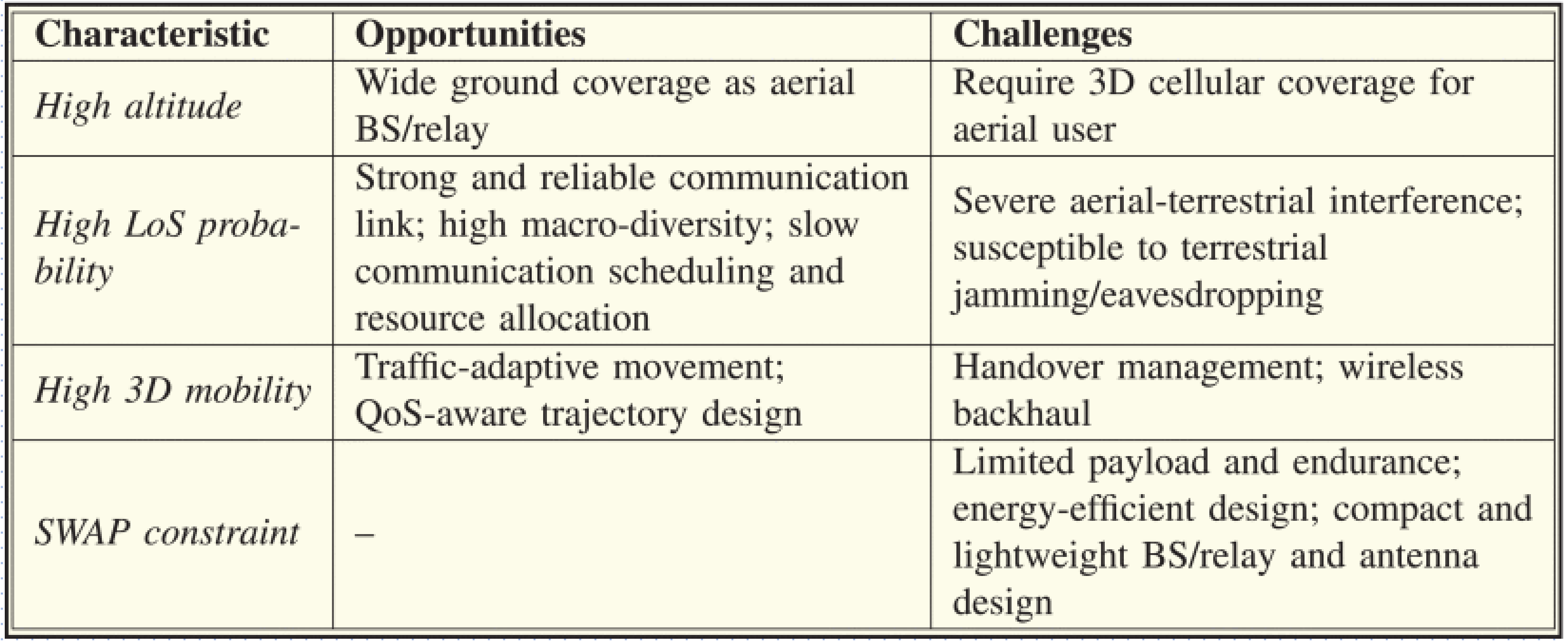
- Third, due to the controllable high-mobility of UAVs, UAV-BSs/relays possess an additional degree of freedom (DoF) for communication performance enhancement, by dynamically adjusting their locations in 3-D to cater for the terrestrial communication demands.

- The abovementioned benefits make UAV-assisted communication a promising new technology to support the ever-increasing and highly dynamic wireless data traffic in the future 5G-and-beyond cellular systems.
- There are abundant new applications in anticipation, such as for cellular data offloading in hot-spot areas (e.g., stadium during a sport event), information dissemination and data collection in the wireless sensor and Internet-of-Things (IoT) networks, big data transfer between geographically separated data centers, fast service recovery after infrastructure failure, mobile data relaying in emergency situations, or customized communications.

UAV Communications: What Is New

- The integration of UAVs into cellular networks, either as aerial users or as communication platforms, brings new design opportunities as well as challenges.
- Both cellular-connected UAV communication and UAV-assisted wireless communication are significantly different from their terrestrial counterparts, due to
    - the high altitude and high mobility of UAVs, the high probability of UAV-ground LoS channels, the distinct communication quality-of-service (QoS) requirements for CNPC versus mission-related payload data, the stringent Size, Weight and Power (SWAP) constraints of UAVs, as well as the new design DoF by jointly exploiting the UAV mobility control and communication scheduling/resource allocation.

Opportunities and Challenges of Cellular Communication With UAVs



Characteristic	**Opportunities**	**Challenges**
High altitude	Wide ground coverage as aerial BS/relay	Require 3D cellular coverage for aerial user
High LoS probability	Strong and reliable communication link; high macro-diversity; slow communication scheduling and resource allocation	Severe aerial-terrestrial interference; susceptible to terrestrial jamming/eavesdropping
High 3D mobility	Traffic-adaptive movement; QoS-aware trajectory design	Handover management; wireless backhaul
SWAP constraint	–	Limited payload and endurance; energy-efficient design; compact and lightweight BS/relay and antenna design

High Altitude

- Compared with conventional terrestrial BSs/users, UAV BSs/users usually have a much higher altitude.
- For instance, a typical height of a terrestrial BS is around 10 m for Urban Micro (UMi) deployment and 25 m for Urban Macro (UMa) deployment, whereas the current regulation already allows the UAVs to fly up to 122 m .
- For cellular-connected UAVs, the high UAV altitude requires cellular BSs to offer 3-D aerial coverage for UAV users, in contrast to the conventional 2-D coverage for terrestrial users. However, existing BS antennas are usually tilted downward, either mechanically or electronically, to cater to the ground coverage as well as suppressing the intercell interference.
- Although in the urban area, the cellular network can also provide services for users in a high-rise building (e.g., dozens of meters above ground), it may not be directly applicable to support UAV users, which typically need to fly far above the buildings for safety concerns.
- Preliminary field measurement campaigns have demonstrated encouraging results with satisfactory aerial coverage to meet the basic communication requirements by the antenna sidelobes of BSs for UAVs up to 400 ft (122 m).
- However, as the altitude further increases, weak signal coverage is observed, which, thus, calls for new BS antenna designs and cellular communication techniques to achieve satisfactory UAV coverage up to the maximum altitude of 300 m as currently specified by 3GPP.
- On the other hand, for UAV-assisted wireless communications, the high UAV altitude enables the UAV-BS/relay to achieve wider ground coverage compared to their terrestrial counterparts.

High Line of Sight (LoS) Probability

- The high UAV altitude leads to unique air–ground channel characteristics compared to terrestrial communication channels.
- Specifically, compared to the terrestrial, the UAV-ground channels, including both the UAV-BS and UAV-user channels, typically experience limited scattering and, thus, have a dominant LoS link with high probability.
- On the other hand, however, it also causes strong air–ground interference, which is a critical issue that may severely limit the cellular network capacity with coexisting aerial and terrestrial BSs/users.
- For example, in the UL communication of a UAV user, it may pose severe interference to many adjacent cells at the same frequency band due to its high-probability LoS channels with their BSs; while in the DL communication, the UAV user also suffers strong interference from these cochannel BSs. Interference mitigation is crucial for both frameworks of cellular-connected UAVs and UAV-assisted terrestrial communications.
- Furthermore, the LoS-dominant air–ground links also make UAV communications more susceptible to the jamming/eavesdropping attacks by malicious ground nodes compared to the terrestrial communications over fading channels, thus imposing a new security threat at the physical layer.

High 3-D Mobility:

- UAVs can move at high speed in 3-D space with partially or fully controllable mobility.
- On one hand, the high mobility of UAVs generally results in more frequent handovers and time-varying wireless backhaul links with GBSs/users.
- On the other hand, it also leads to a new design DoF via communication-aware trajectory optimization.
- In this case, the UAV’s mobility is no longer modeled stochastically but deliberately designed to improve its communication performance with the GBSs/users.

SWAP Constraints:

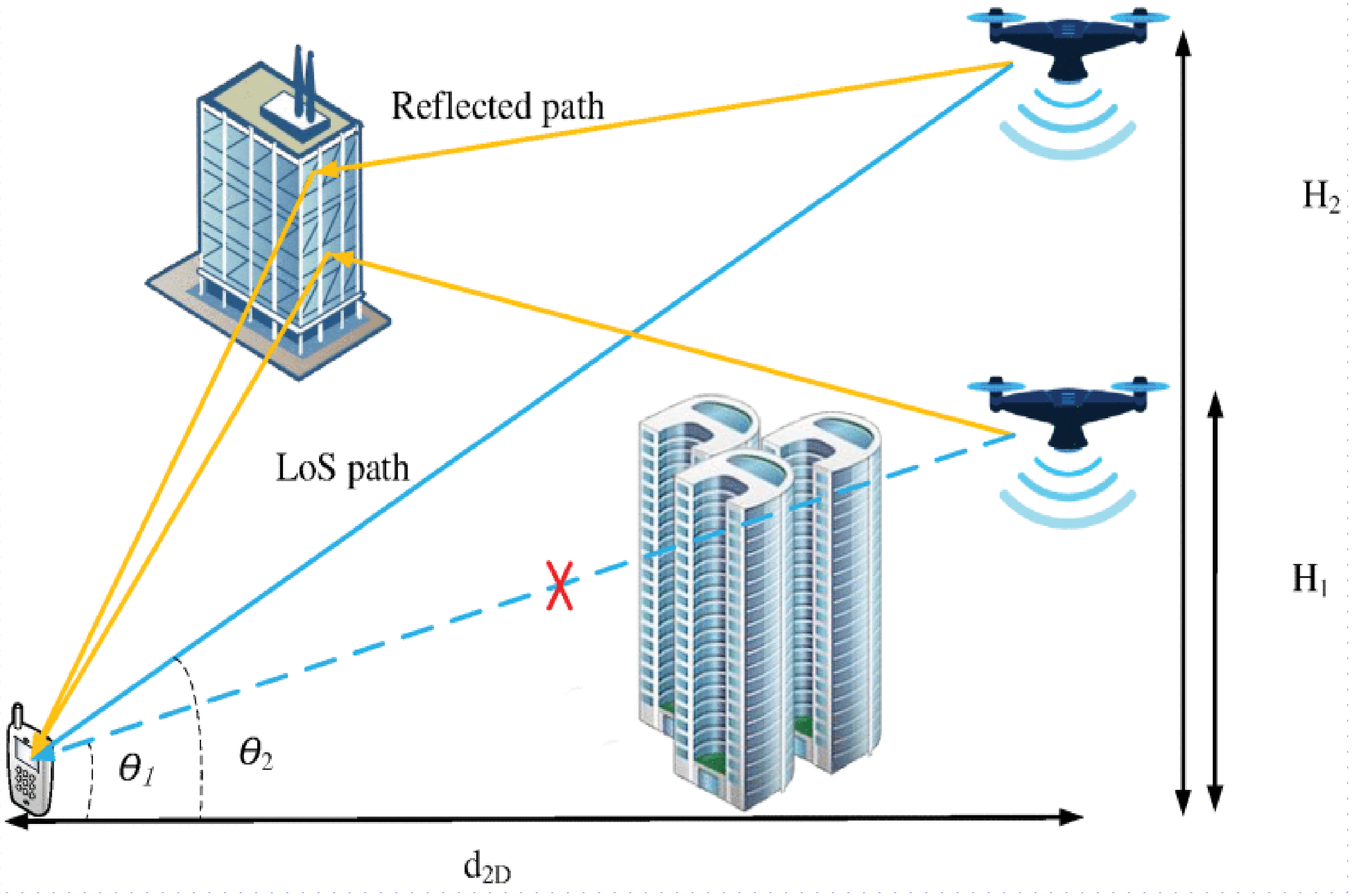
- The SWAP constraints of UAVs pose critical limits on their endurance and communication capabilities.
- For example, in the case of UAV-assisted wireless communications, customized BSs/relays, generally of lighter weight and more compact hardware compared to their terrestrial counterparts, need to be designed to cater for the limited payload and size of UAVs.
- Furthermore, besides the conventional communication transceiver energy consumption, UAVs need to spend the additional propulsion energy to remain aloft and move freely over the air which is usually much more significant than the communication energy (e.g., in the order of kilowatt versus watt) for commercial UAVs.
- Thus, the energy-efficient design of UAV communication is more involved than that for the conventional terrestrial systems considering the communication energy only.

Similarities and differences

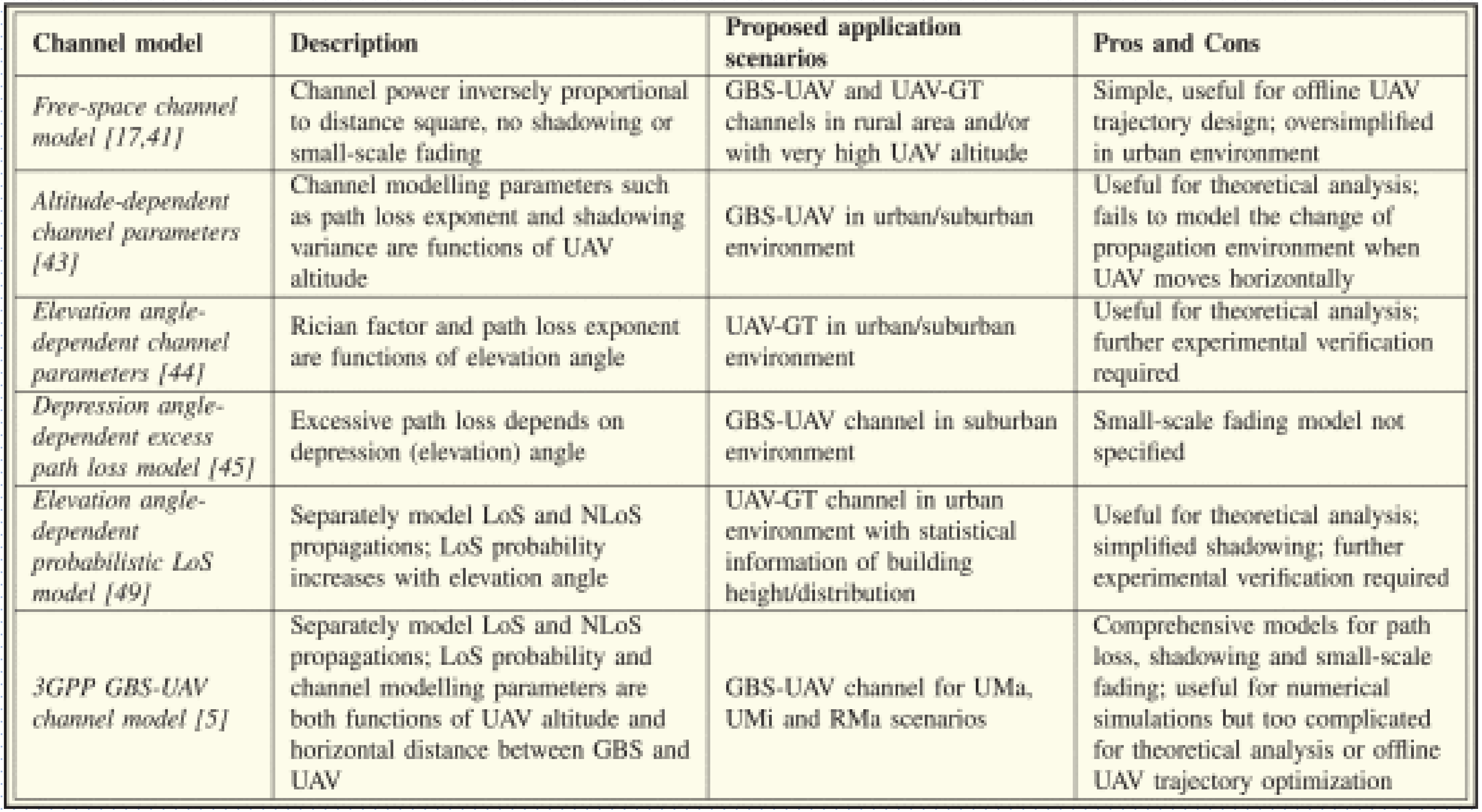
- UAV communications share some similarities with vehicular and aeronautical communications, but they also have some important differences, which generally lead to different considerations on the system design.
- The different altitudes of ground vehicles, UAVs, and aircraft lead to different channel characteristics for their communication links. While vehicular communications usually experience severe small-scale fading due to rich scattering on the ground, aeronautical communications supported by satellites are typically over LoS links due to the relatively high altitude of aircraft.
- The UAV-ground communication channels are more diverse depending on the UAVs' flying altitudes. As such, cellular-connected UAVs generally cause more severe interference to the terrestrial networks than ground vehicles, while aircraft generally do not have a significant impact on the cellular networks.
- In terms of mobility, aircraft have much higher flying speeds than the ground vehicles and UAVs, thus rendering the topology of aeronautical networks more dynamic compared to its counterparts in vehicular and UAV communications.
- The trajectories of ground vehicles are generally constrained by streets and buildings, while an aircraft typically flies by following strictly planned trajectories from initial locations to destinations. In contrast, UAVs are able to move in 3-D space more flexibly in general. As such, the system design in the context of UAV communications (e.g., networking technology, mobility design, and interference mitigation) needs to be carefully studied to exploit the new opportunities as well as addressing the new challenges.

Channel models

UAV communications mainly involve three types of links, namely the GBS-UAV link, the UAV-ground terminal (GT) link, and the UAV–UAV link. As the communication between UAVs with moderate distance typically occurs in clear airspace when the earth curvature is irrelevant, the UAV–UAV channel is usually characterized by the simple free-space path-loss model.

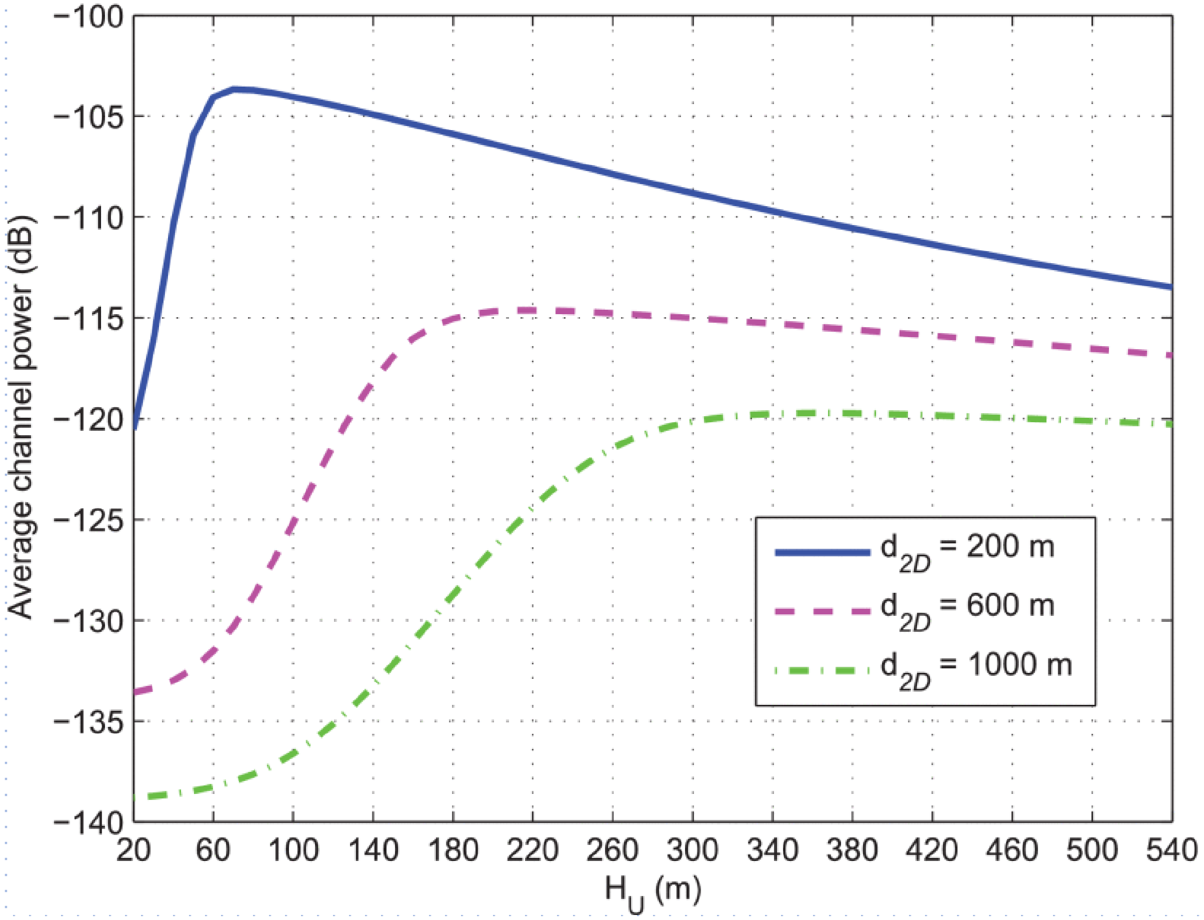


Comparison of the Main UAV-Ground Channel Models

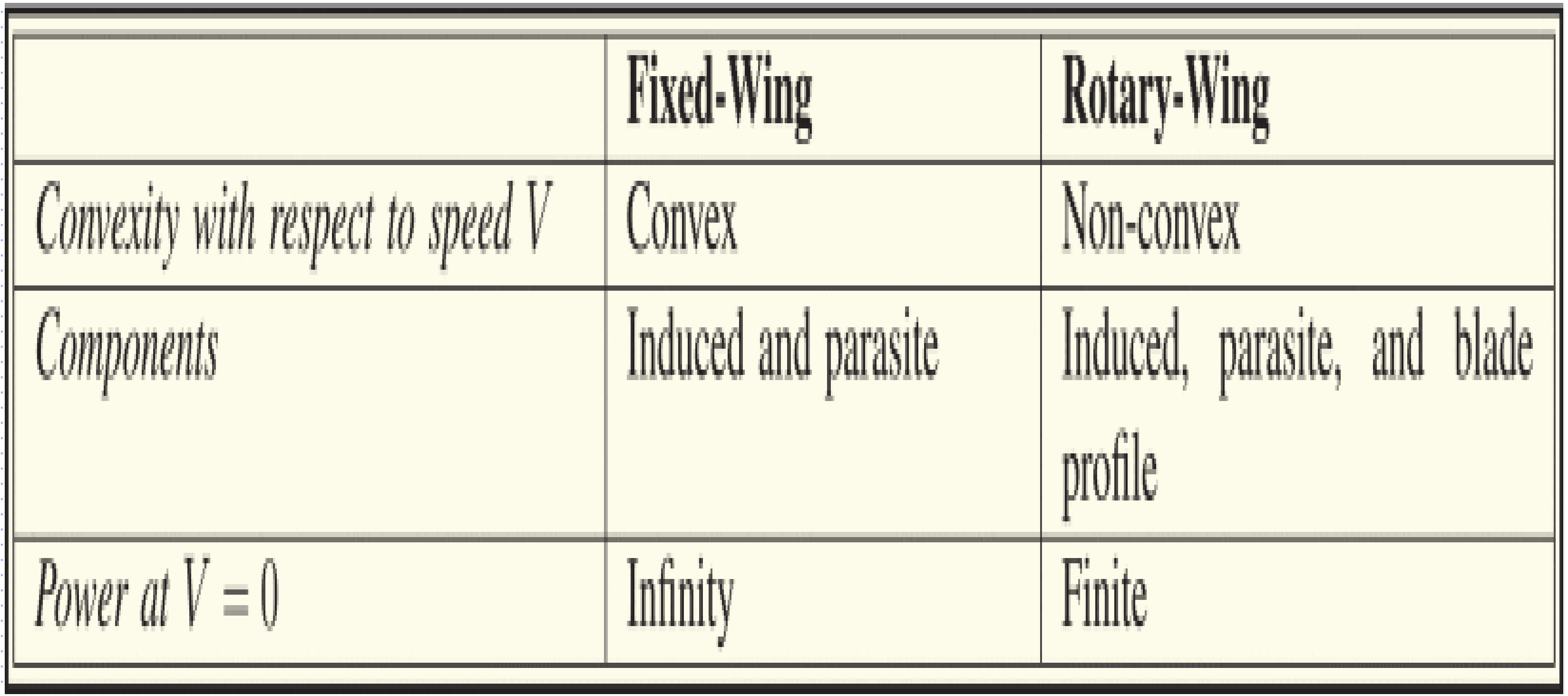


Channel model	Description	Proposed application scenarios	Pros and Cons
Free-space channel model [17,41]	Channel power inversely proportional to distance square, no shadowing or small-scale fading	GBS-UAV and UAV-GT channels in rural area and/or with very high UAV altitude	Simple, useful for offline UAV trajectory design; oversimplified in urban environment
Altitude-dependent channel parameters [43]	Channel modelling parameters such as path loss exponent and shadowing variance are functions of UAV altitude	GBS-UAV in urban/suburban environment	Useful for theoretical analysis; fails to model the change of propagation environment when UAV moves horizontally
Elevation angle-dependent channel parameters [44]	Rician factor and path loss exponent are functions of elevation angle	UAV-GT in urban/suburban environment	Useful for theoretical analysis; further experimental verification required
Depression angle-dependent excess path loss model [45]	Excessive path loss depends on depression (elevation) angle	GBS-UAV channel in suburban environment	Small-scale fading model not specified
Elevation angle-dependent probabilistic LoS model [49]	Separately model LoS and NLoS propagations; LoS probability increases with elevation angle	UAV-GT channel in urban environment with statistical information of building height/distribution	Useful for theoretical analysis; simplified shadowing; further experimental verification required
3GPP GBS-UAV channel model [5]	Separately model LoS and NLoS propagations; LoS probability and channel modelling parameters are both functions of UAV altitude and horizontal distance between GBS and UAV	GBS-UAV channel for UMa, UMi and RMa scenarios	Comprehensive models for path loss, shadowing and small-scale fading; useful for numerical simulations but too complicated for theoretical analysis or offline UAV trajectory optimization

Expected channel power versus UAV altitude in the elevation-angle-dependent probabilistic LoS channel model.

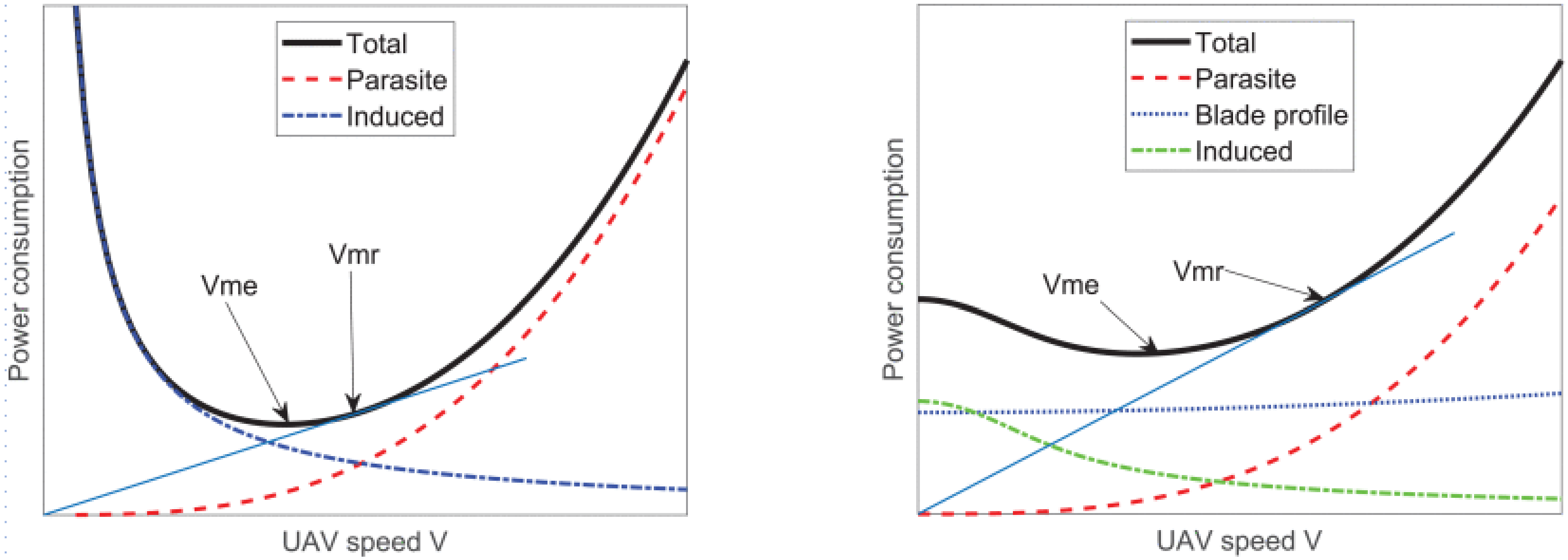


Comparison of Energy Consumption Models for Fixed-Wing Versus Rotary-Wing UAVs



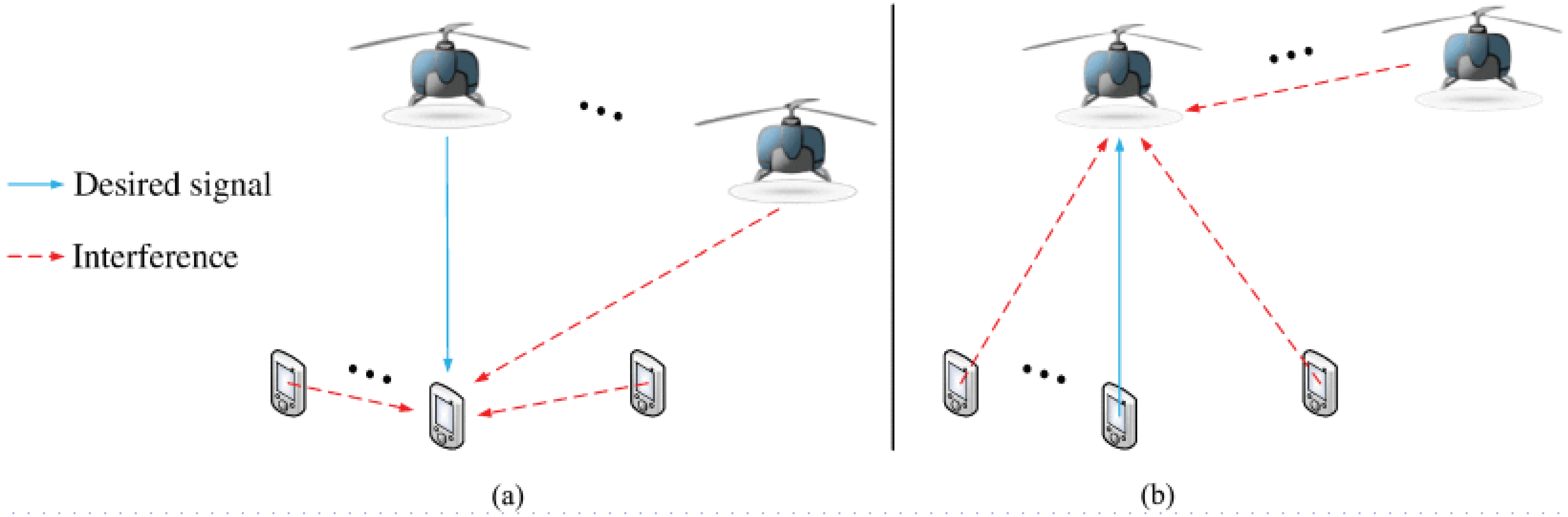
	Fixed-Wing	**Rotary-Wing**
Convexity with respect to speed V	Convex	Non-convex
Components	Induced and parasite	Induced, parasite, and blade profile
Power at V = 0	Infinity	Finite

Typical plots for UAV propulsion power consumption versus speed. (a) Fixed wing. (b) Rotary wing.



(a) (b)

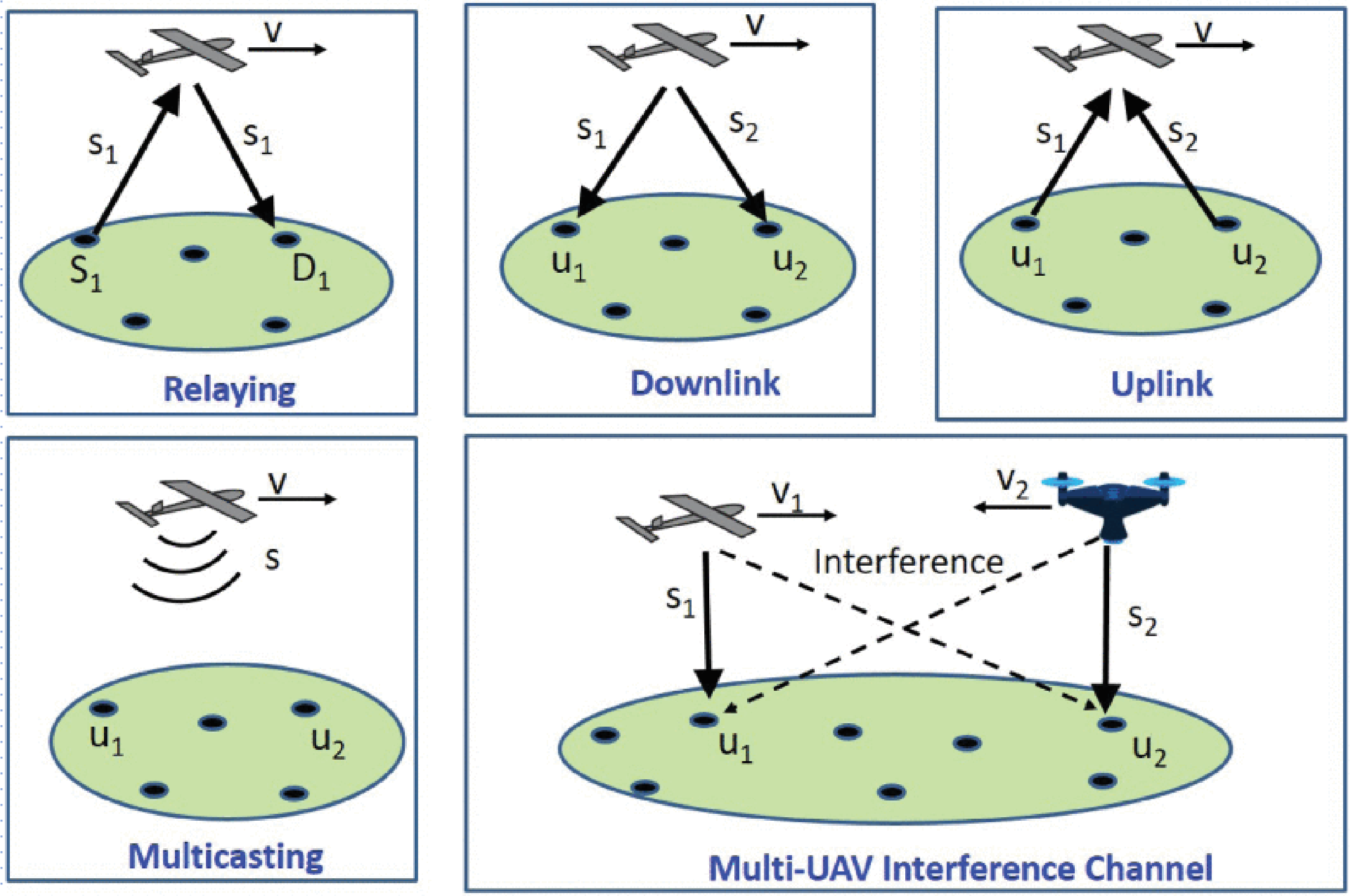
Illustration of the possible interference when the UAV acts as (a) transmitter or (b) receiver.



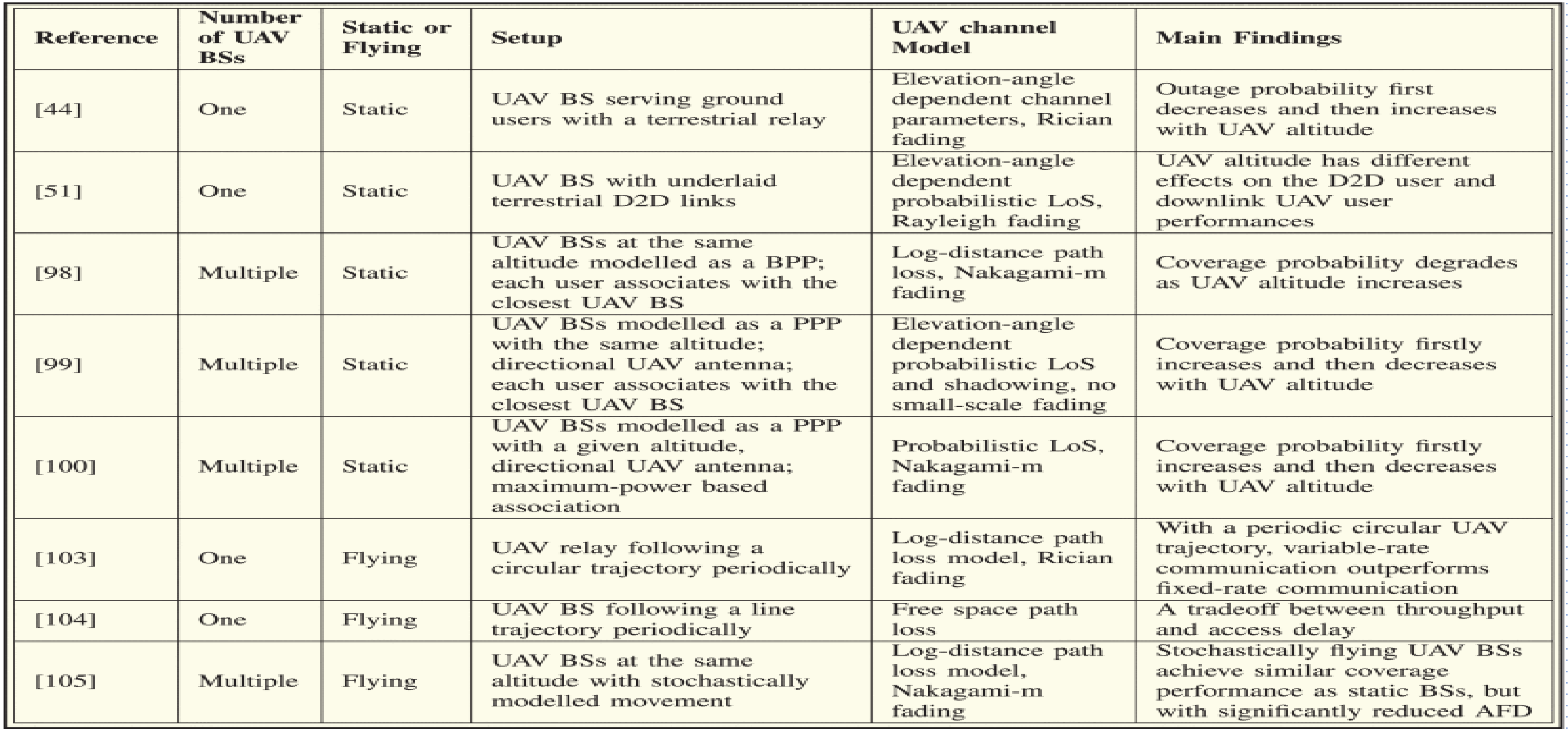
UAV-Assisted Wireless Communications

- UAVs are employed as aerial communication platforms to provide wireless access for terrestrial users from the sky. Under this framework, three typical use cases have been envisioned.
  - **UAV-aided ubiquitous coverage**, where UAVs are used as aerial BSs to achieve seamless coverage for a given geographical area. In this case, UAVs possess the essential functionalities of traditional terrestrial BSs but operate from a much higher altitude and with more flexible 3-D deployment and movement.
    - Applications of this use case include UAV-enabled wireless coverage in remote areas, temporary traffic offloading in cellular hot spots, and fast communication service recovery for disaster relief.
  - **UAV-aided relaying**, where UAVs are employed as aerial relays to establish or strengthen the wireless connectivity between far-apart terrestrial users or user groups.
    - Typical applications include UAV-enabled cellular coverage extension, wireless backhaul, big data transfer, emergency response, and military operations.
  - **UAV-aided information dissemination and data collection**, where UAVs are employed as aerial access points (APs) to disseminate (or collect) information to (from) ground nodes.
    - Typical applications include UAV-aided wireless sensor network and the IoT communications.

Some basic models for the UAV-assisted communications



Summary of Representative Works on Performance Analysis of UAV-Assisted Wireless Communications

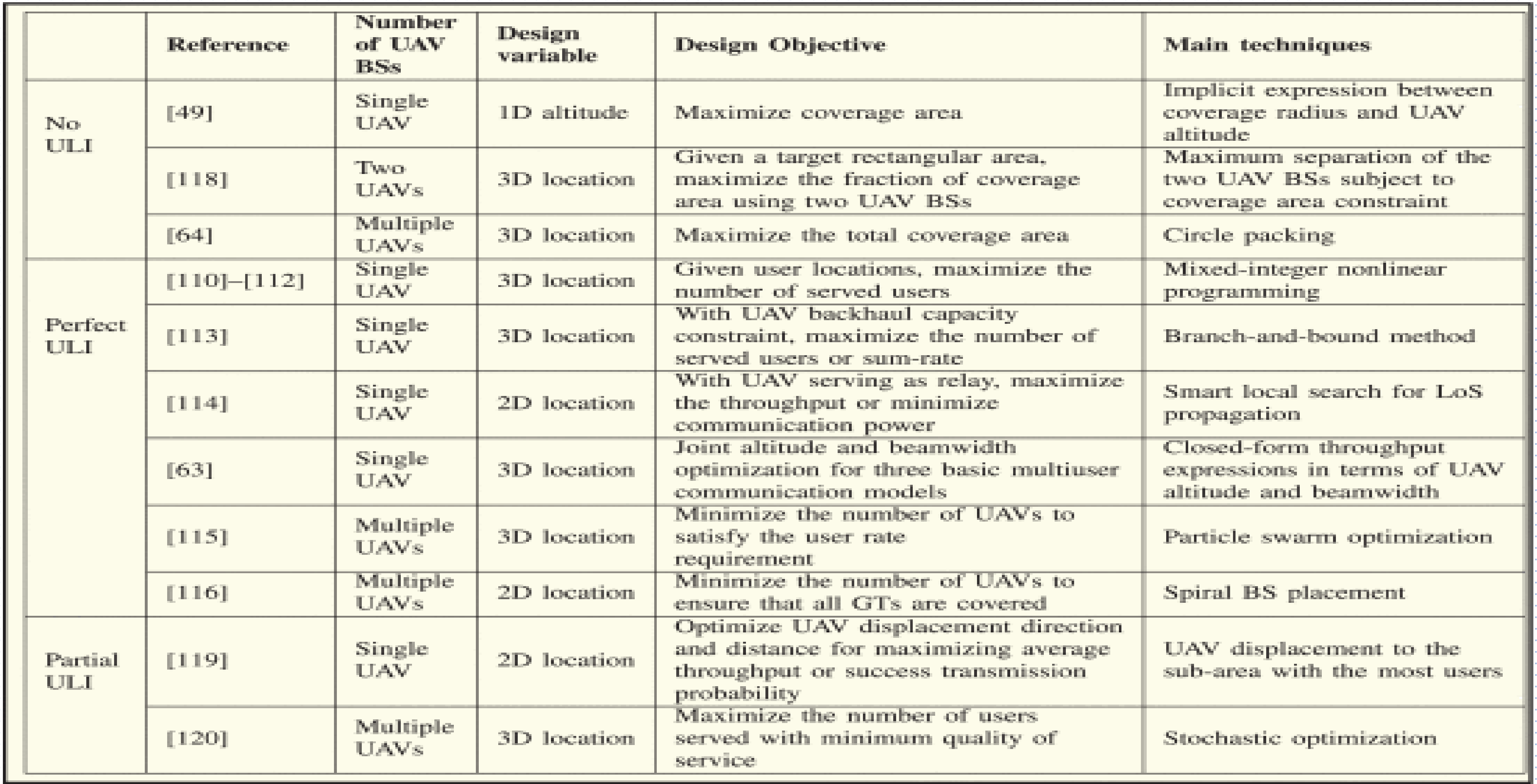


Reference	Number of UAV BSs	Static or Flying	Setup	UAV channel Model	Main Findings
[44]	One	Static	UAV BS serving ground users with a terrestrial relay	Elevation-angle dependent channel parameters, Rician fading	Outage probability first decreases and then increases with UAV altitude
[51]	One	Static	UAV BS with underlaid terrestrial D2D links	Elevation-angle dependent probabilistic LoS, Rayleigh fading	UAV altitude has different effects on the D2D user and downlink UAV user performances
[98]	Multiple	Static	UAV BSs at the same altitude modelled as a BPP; each user associates with the closest UAV BS	Log-distance path loss, Nakagami-m fading	Coverage probability degrades as UAV altitude increases
[99]	Multiple	Static	UAV BSs modelled as a PPP with the same altitude; directional UAV antenna; each user associates with the closest UAV BS	Elevation-angle dependent probabilistic LoS and shadowing, no small-scale fading	Coverage probability firstly increases and then decreases with UAV altitude
[100]	Multiple	Static	UAV BSs modelled as a PPP with a given altitude, directional UAV antenna; maximum-power based association	Probabilistic LoS, Nakagami-m fading	Coverage probability firstly increases and then decreases with UAV altitude
[103]	One	Flying	UAV relay following a circular trajectory periodically	Log-distance path loss model, Rician fading	With a periodic circular UAV trajectory, variable-rate communication outperforms fixed-rate communication
[104]	One	Flying	UAV BS following a line trajectory periodically	Free space path loss	A tradeoff between throughput and access delay
[105]	Multiple	Flying	UAV BSs at the same altitude with stochastically modelled movement	Log-distance path loss model, Nakagami-m fading	Stochastically flying UAV BSs achieve similar coverage performance as static BSs, but with significantly reduced AFD

UAV Placement

- In (quasi-)static UAV communication platforms, the locations of UAVs remain unchanged for the duration of interest.
- For such setups, one important design problem is to determine the UAV locations to achieve the best communication performance.
- Different from the conventional 2-D cell planning with terrestrial BSs of typically predetermined BS heights, the altitude of UAV BS can be flexibly determined, thus leading to new 3-D BS placement problems.
- The unique characteristics of UAV-ground channels also need to be considered for the UAV placement.

Summary of Representative Works on UAV Placement

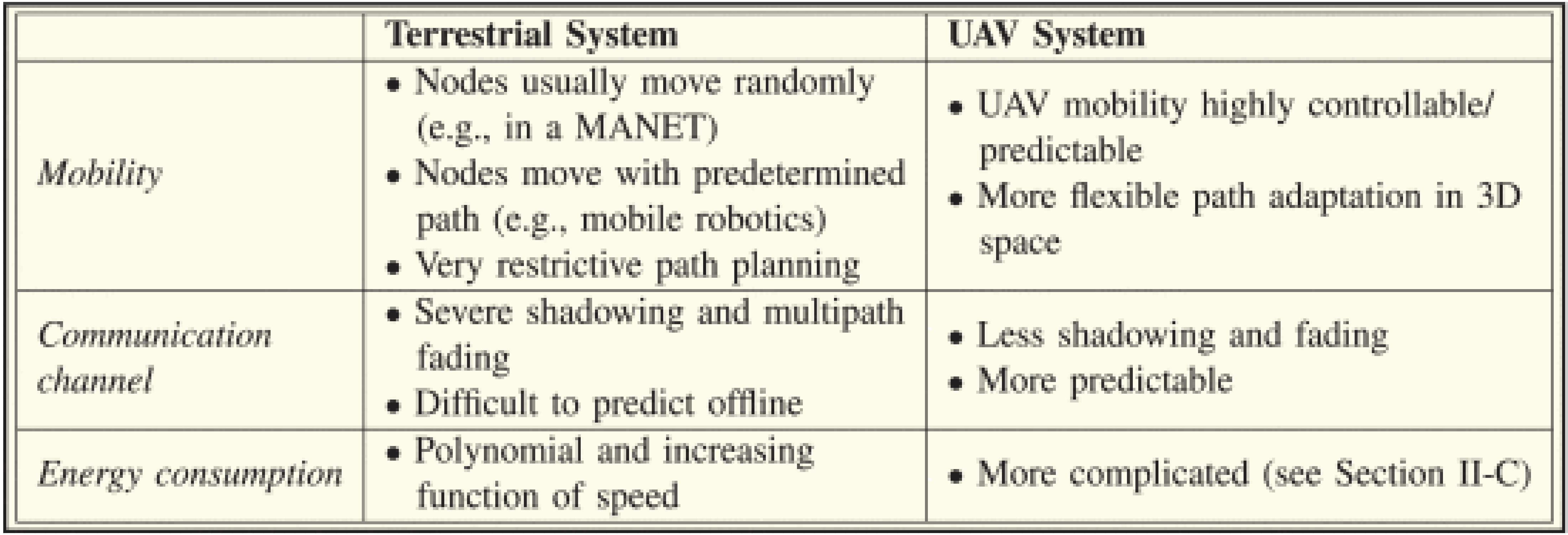


	Reference	Number of UAV BSs	Design variable	Design Objective	Main techniques
No ULI	[49]	Single UAV	1D altitude	Maximize coverage area	Implicit expression between coverage radius and UAV altitude
	[118]	Two UAVs	3D location	Given a target rectangular area, maximize the fraction of coverage area using two UAV BSs	Maximum separation of the two UAV BSs subject to coverage area constraint
	[64]	Multiple UAVs	3D location	Maximize the total coverage area	Circle packing
Perfect ULI	[110]–[112]	Single UAV	3D location	Given user locations, maximize the number of served users	Mixed-integer nonlinear programming
	[113]	Single UAV	3D location	With UAV backhaul capacity constraint, maximize the number of served users or sum-rate	Branch-and-bound method
	[114]	Single UAV	2D location	With UAV serving as relay, maximize the throughput or minimize communication power	Smart local search for LoS propagation
	[63]	Single UAV	3D location	Joint altitude and beamwidth optimization for three basic multiuser communication models	Closed-form throughput expressions in terms of UAV altitude and beamwidth
	[115]	Multiple UAVs	3D location	Minimize the number of UAVs to satisfy the user rate requirement	Particle swarm optimization
	[116]	Multiple UAVs	2D location	Minimize the number of UAVs to ensure that all GTs are covered	Spiral BS placement
Partial ULI	[119]	Single UAV	2D location	Optimize UAV displacement direction and distance for maximizing average throughput or success transmission probability	UAV displacement to the sub-area with the most users
	[120]	Multiple UAVs	3D location	Maximize the number of users served with minimum quality of service	Stochastic optimization

Trajectory and Communication Codesign

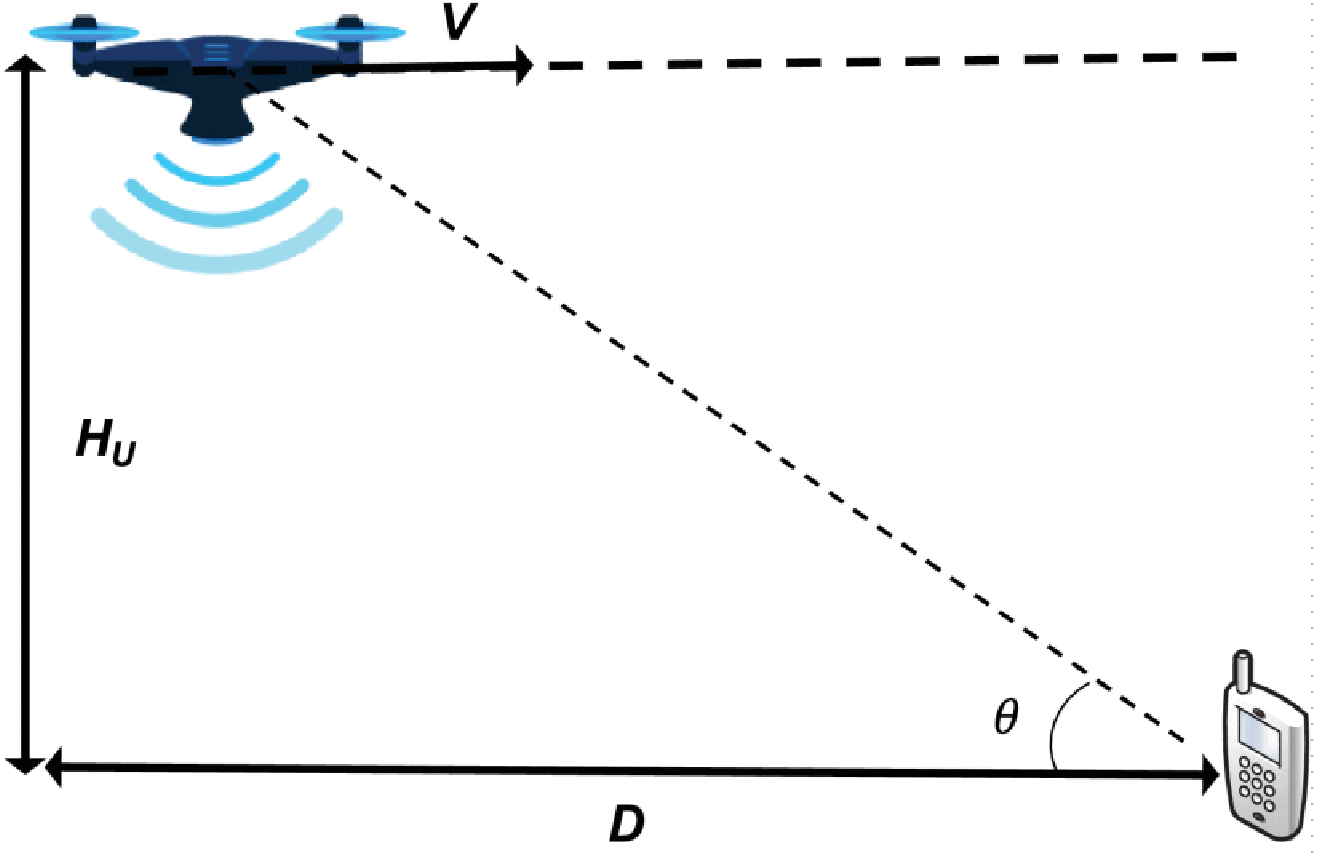
- Compared to conventional terrestrial BSs or quasi-stationary UAV BSs, flying UAV communication platforms offer an additional DoF via UAV trajectory optimization.
- There are some important differences between traditinal systems and the UAV communication systems.
    - First, nodes moving on the ground are usually subject to many obstacles, which greatly limits their flexibility for path adaption. Therefore, most existing works on exploiting ground node mobility assumed either the random mobility model or deterministic mobility along predetermined path. In contrast, UAVs moving in 3-D airspace offer more design DoF in path/trajectory optimization for communication performance improvement.
    - Second, due to the generally rich scattering environment, the wireless channels for ground robotic communications usually suffer from severe fading, which is difficult to be efficiently predicted at any location. In contrast, the UAV-ground communications often contain strong LoS link, making it easier for channel prediction and, thus, facilitating the offline trajectory optimization.
    - Last but not least, robots and UAVs differ significantly in terms of the energy consumption model.

Exploiting Mobility in UAV Versus Terrestrial Communication Systems

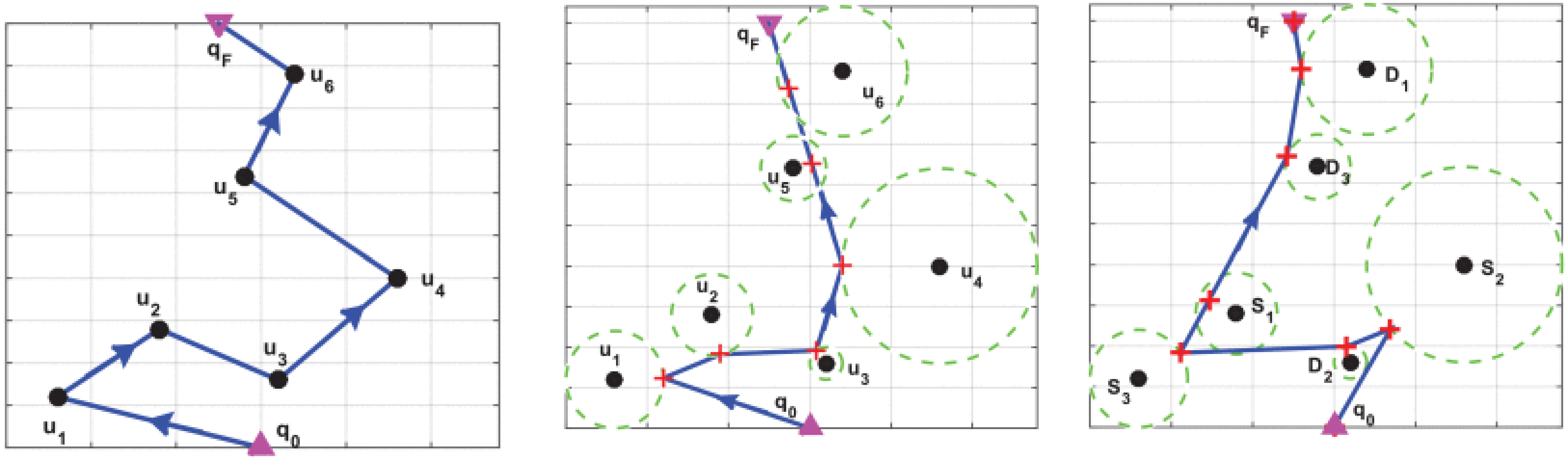


	Terrestrial System	**UAV System**
Mobility	• Nodes usually move randomly (e.g., in a MANET) • Nodes move with predetermined path (e.g., mobile robotics) • Very restrictive path planning	• UAV mobility highly controllable/ predictable • More flexible path adaptation in 3D space
Communication channel	• Severe shadowing and multipath fading • Difficult to predict offline	• Less shadowing and fading • More predictable
Energy consumption	• Polynomial and increasing function of speed	• More complicated (see Section II-C)

Point-to-point link with a rotary-wing UAV flying toward the GT.

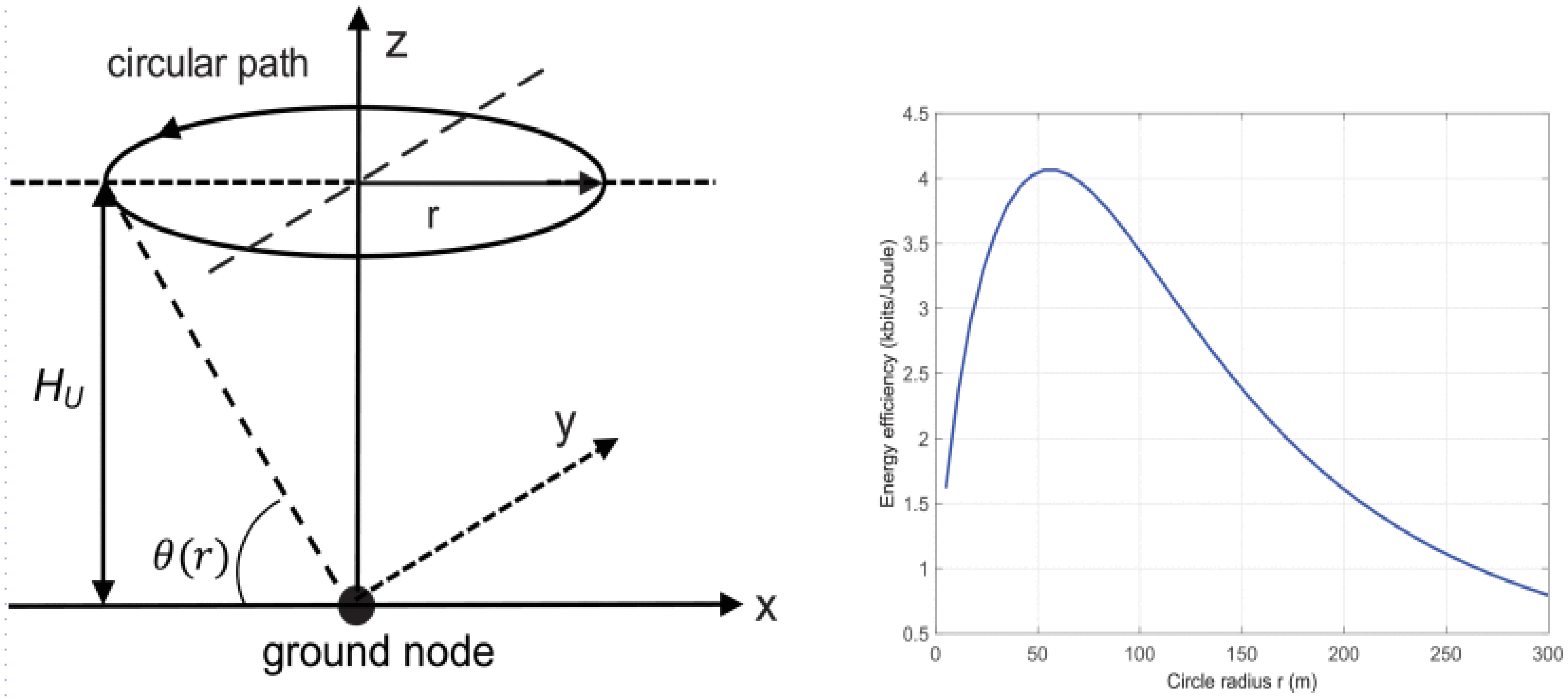


Path planning options



(a) (b) (c)

Energy-efficient communication with a fixed-wing UAV following circular trajectory



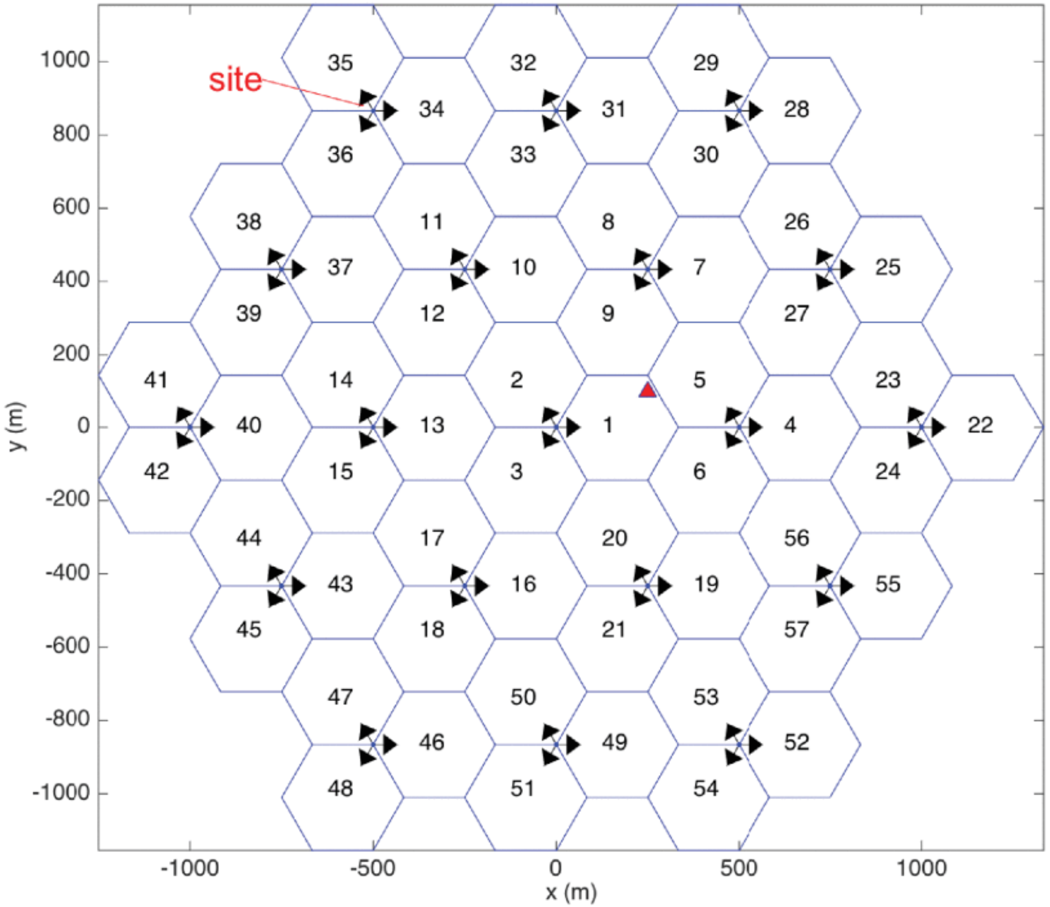
(a)

(b)

(a) Point-to-point link where a fixed-wing UAV follows a circular trajectory with radius r .

(b) Typical plot of energy efficiency versus circle radius r .

Cell layout for numerical simulations of cellular-connected UAV.



Future (istic) directions in UAV communications

- UAV Swarm Communications
- Security
- Intelligent designs
- Caching
- Mmwave communications
- Mobile Edge Computing
- Wireless Power Transfer

A smart agriculture application of UAVs

Co-financed by Greece and the European Union

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Ανάπτυξη και Εφαρμογή Καινοτόμου και Οικονομικού Συστήματος, για τον Ακριβή & Δυναμικό Προγραμματισμό της Άρδευσης και την Επιτήρηση Καλλιεργειών

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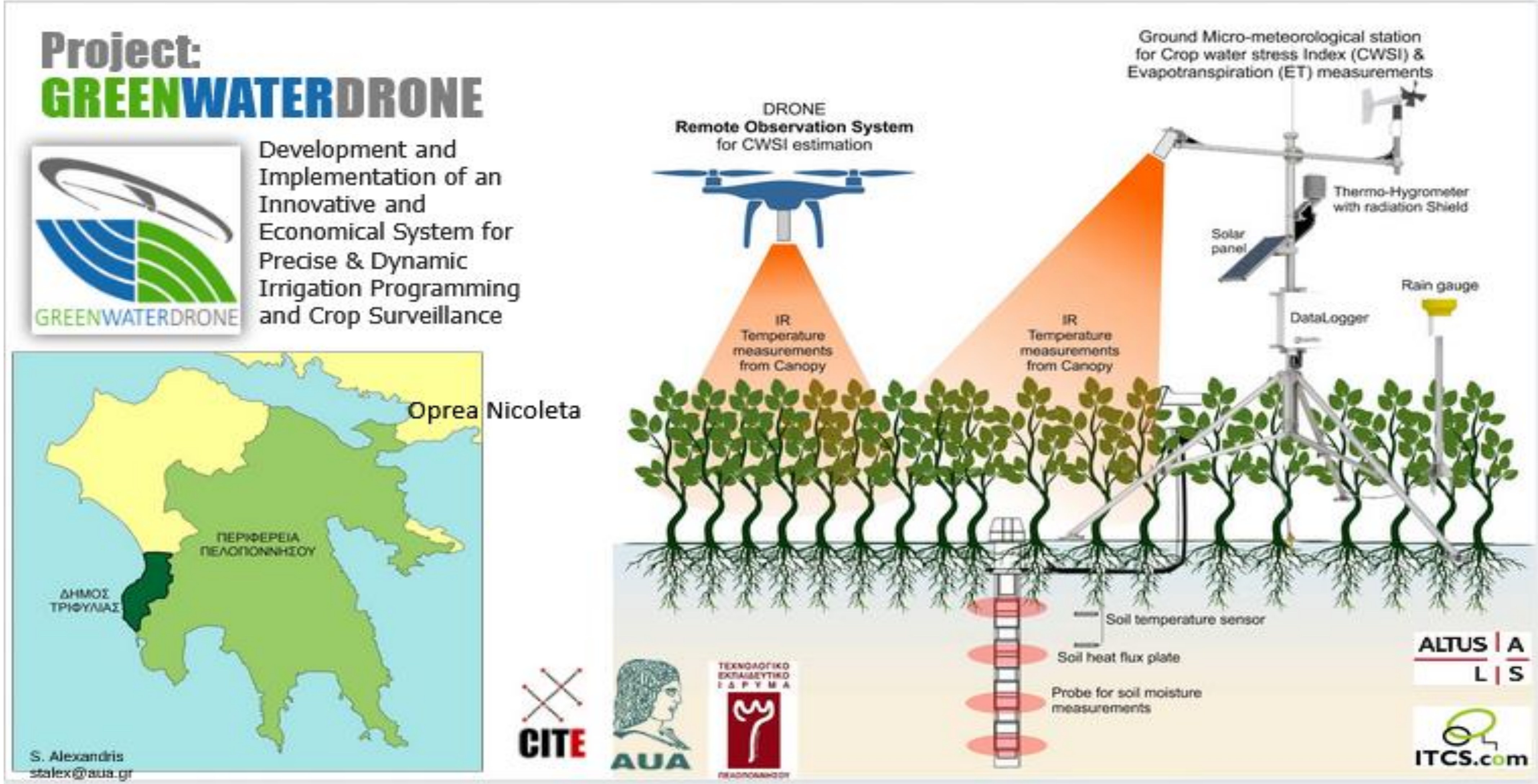

Project:
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Development and Implementation of an Innovative and Economical System for Precise & Dynamic Irrigation Programming and Crop Surveillance

Oprea Nicoleta

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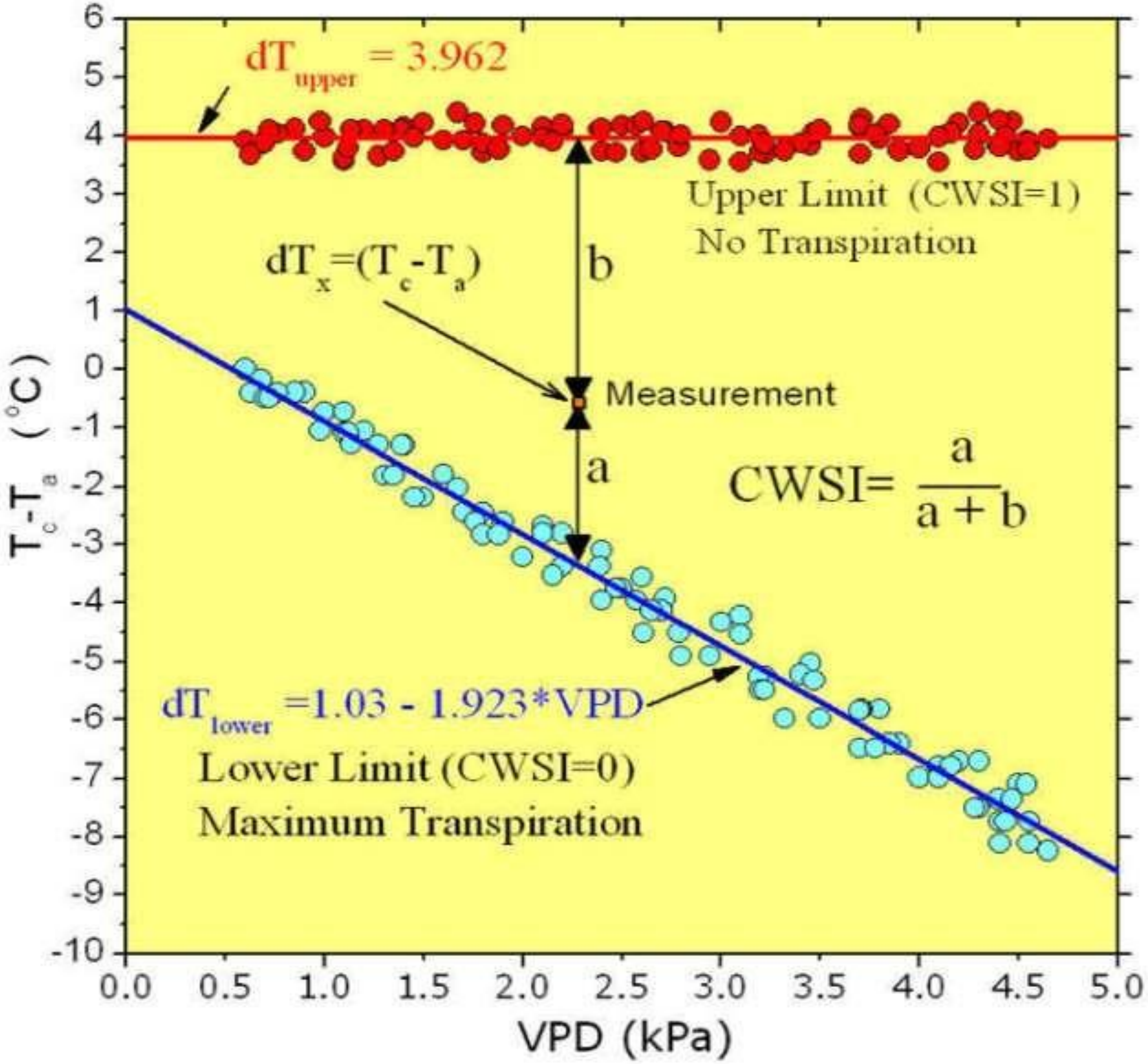
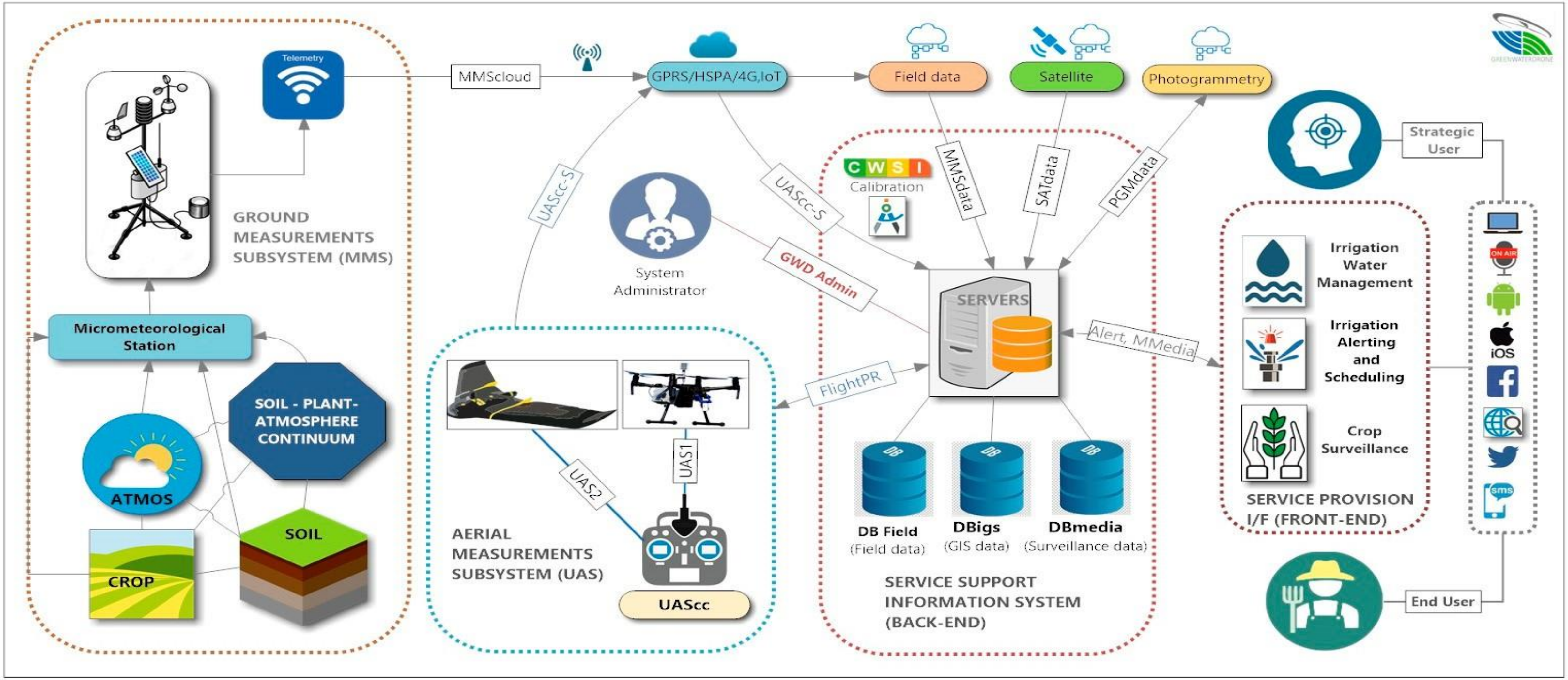
Crop Water Stress Index (CWSI)



Main goals of GWD

- The innovative approach combines real spatial data, such as infrared canopy temperature, air temperature, air relative humidity, and thermal infrared image data, taken above the crop field using an aerial micrometeorological station (AMMS) and a thermal (IR) camera installed on an unmanned aerial vehicle (UAV).
- Following an initial calibration phase, where the ground micrometeorological station (GMMS) is installed in the crop, no equipment needs to be maintained in the field.
- Aerial and ground measurements are transferred in real time to sophisticated databases and applications over existing mobile networks for further processing and estimation of the actual water requirements of a specific crop at the field level, dynamically alerting/informing local farmers/agronomists of the irrigation necessity and additionally for potential risks concerning their fields.
- The supported services address farmers’, agricultural scientists’, and local stakeholders’ needs to conform to regional water management and sustainable agriculture policies.

Physical architecture of the system with the basic physical entities



GWD subsystems

- **The ground measurements subsystem (MMS),** which is applied only during the calibration phase, consists of micrometeorological stations and their integrated/peripheral sensors, which are required to collect microclimatic and soil measurements of the crop field. Data collected from a station is used to calibrate and approximate the CWSI of a specific crop under the local climatic regime for one growing season. Data is communicated to the system over the available mobile WAN infrastructures (2/3/4 G, IoT).

- **The aerial measurement subsystem (UAS)** consists of two types of UAVs.
  - A quadcopter platform UAS1 uses an autonomous microstation to collect raw spatial data from the crop foliage and environment (infrared temperature, air temperature, relative humidity, accurate coordinates, and elevations).
  - A fixed-wing platform UAS2 is required to collect thermal, multispectral, and photogrammetry images over large crop areas.
- Field data collected by the UAS is communicated to the system over the available mobile WAN infrastructures (2/3/4 G, IoT).
- Both scheduled (e.g., during calibration and normal operation) and emergency (e.g., extreme weather conditions) flights are managed by the GWD System Administrator via the FlightPR interface.

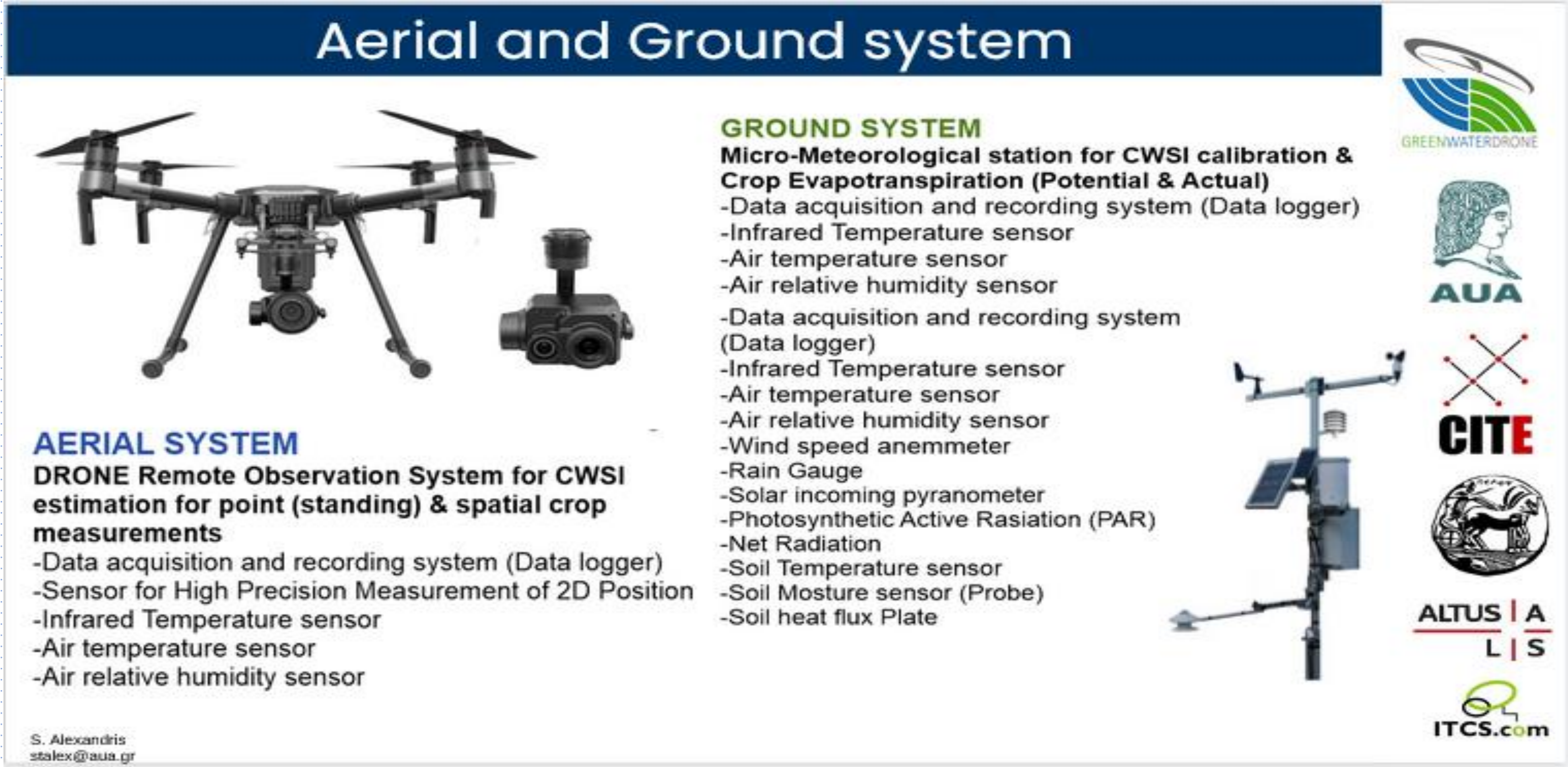
GWD subsystems

- **The service support information system (BackEnd)** implements the crop data management necessary for the storage, classification, management, and updating of field measurements, empirical irrigation data, spatial and crop quality data, field status multimedia, end-user preferences, and interfaces with external services (satellite imagery, photogrammetry applications).
- In addition, it interconnects and supports all other subsystems and is responsible for providing the services of the system (alerting and multimedia content) to all types of supported end users.

- **The service provision I/Fs (FrontEnd)** includes appropriate web interfaces of the system to predefined types of GWD users, such as plain (farmers/agronomists), group (partnerships), and strategic (local/regional authorities) end users, with graded access to the three supported applications through different devices (PCs, smartphones, etc.) and relevant GUIs.

Supported applications

- **Irrigation alerting and scheduling (IRRas):** The plain end user (farmer/agronomist/ farmer partnership) receives alerts in near real time regarding the short-term need to irrigate (or not) a specific crop based on CWSI calculations and empirical irrigation scheduling.
- **Crop surveillance (CS):** The plain end user (farmer/agronomist/farmer partnership) can view on-demand, multimedia content (e.g., photos/video relating to crop condition) of a field or receive alerts in near real time regarding the availability of synchronous video/photos of his crop in the case of a natural disaster or a security issue triggering an emergency drone flight.
- **Irrigation water management (IRRmgt):** The strategic user (agricultural institute, local/regional authorities) may select zones (clusters) on a graphical interface with a map of the area covered by the GWD system (effectively calibrated crops in the area) and obtain irrigation requirements for specific crop patterns and periods, thus enabling the implementation of scenarios for future irrigation water policies.



Aerial and Ground system

AERIAL SYSTEM

DRONE Remote Observation System for CWSI estimation for point (standing) & spatial crop measurements

-Data acquisition and recording system (Data logger)
-Sensor for High Precision Measurement of 2D Position
-Infrared Temperature sensor
-Air temperature sensor
-Air relative humidity sensor

GROUND SYSTEM

Micro-Meteorological station for CWSI calibration & Crop Evapotranspiration (Potential & Actual)

-Data acquisition and recording system (Data logger)
-Infrared Temperature sensor
-Air temperature sensor
-Air relative humidity sensor

-Data acquisition and recording system (Data logger)
-Infrared Temperature sensor
-Air temperature sensor
-Air relative humidity sensor
-Wind speed anemmeter
-Rain Gauge
-Solar incoming pyranometer
-Photosynthetic Active Rasiation (PAR)
-Net Radiation
-Soil Temperature sensor
-Soil Mosture sensor (Probe)
-Soil heat flux Plate

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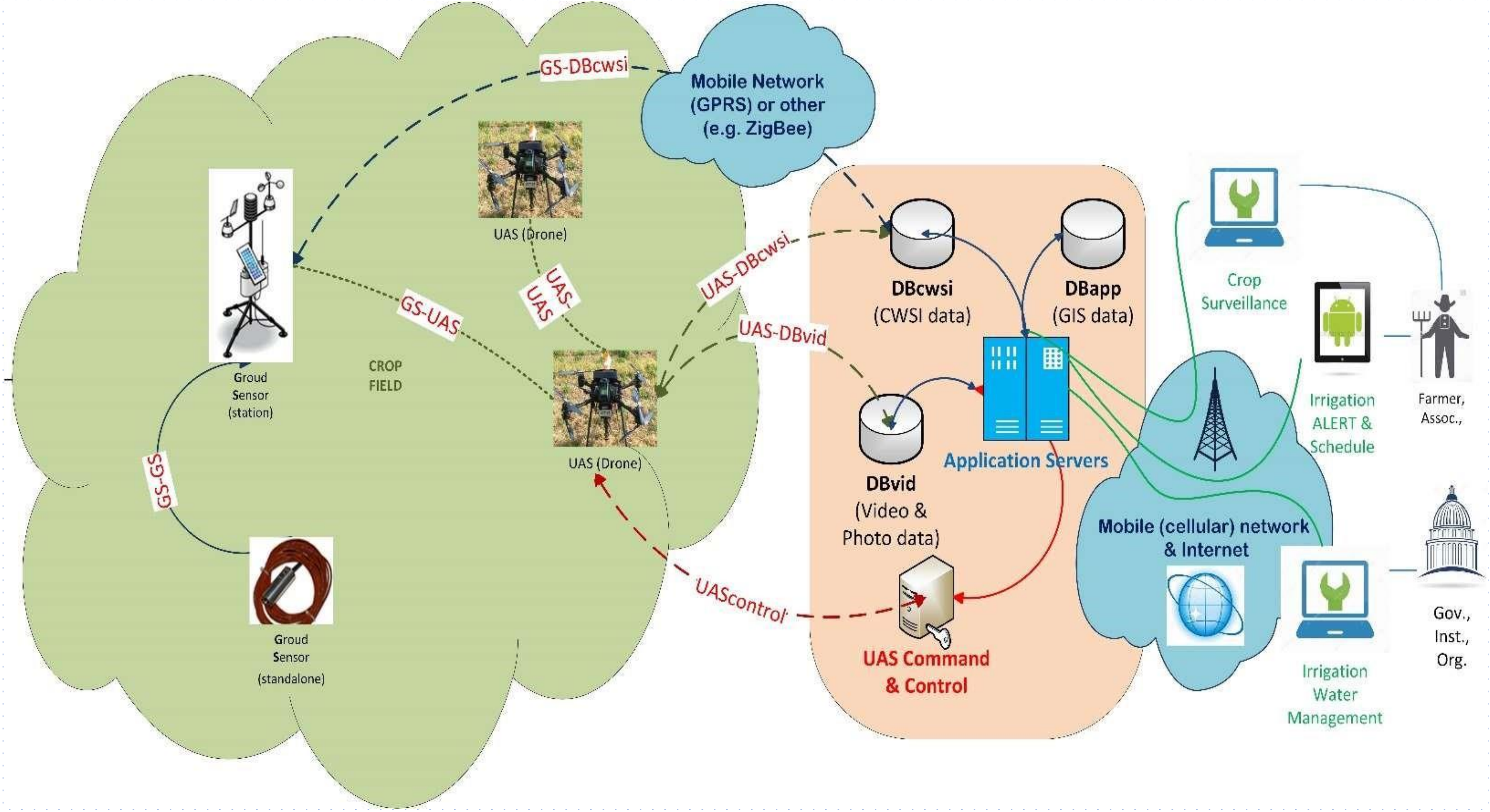
System overview



Experimental Fields

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Micrometeorological Stations

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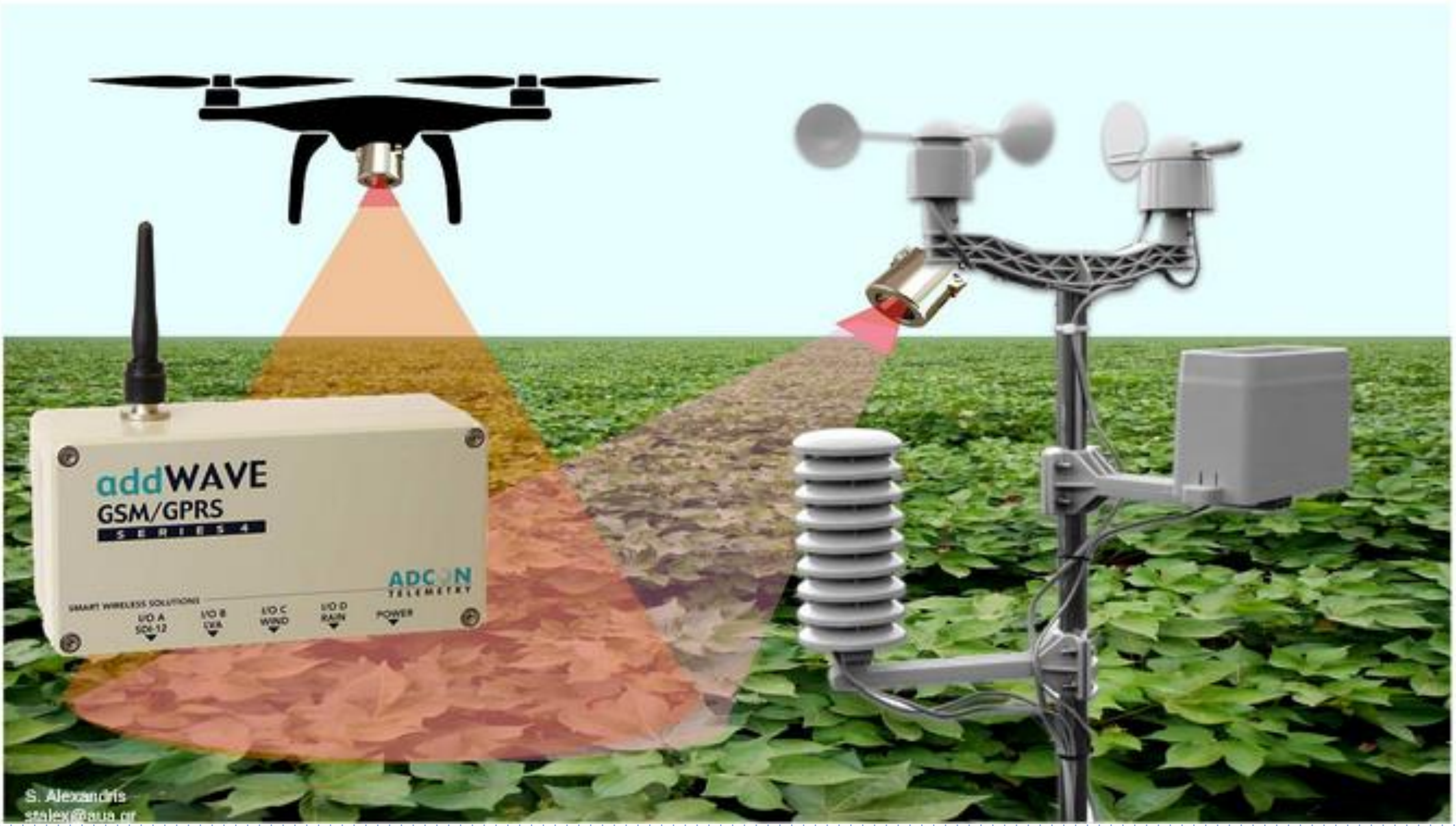
Telemetric system GSM/GPRS



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Experimental field A (Watermelon Crop)

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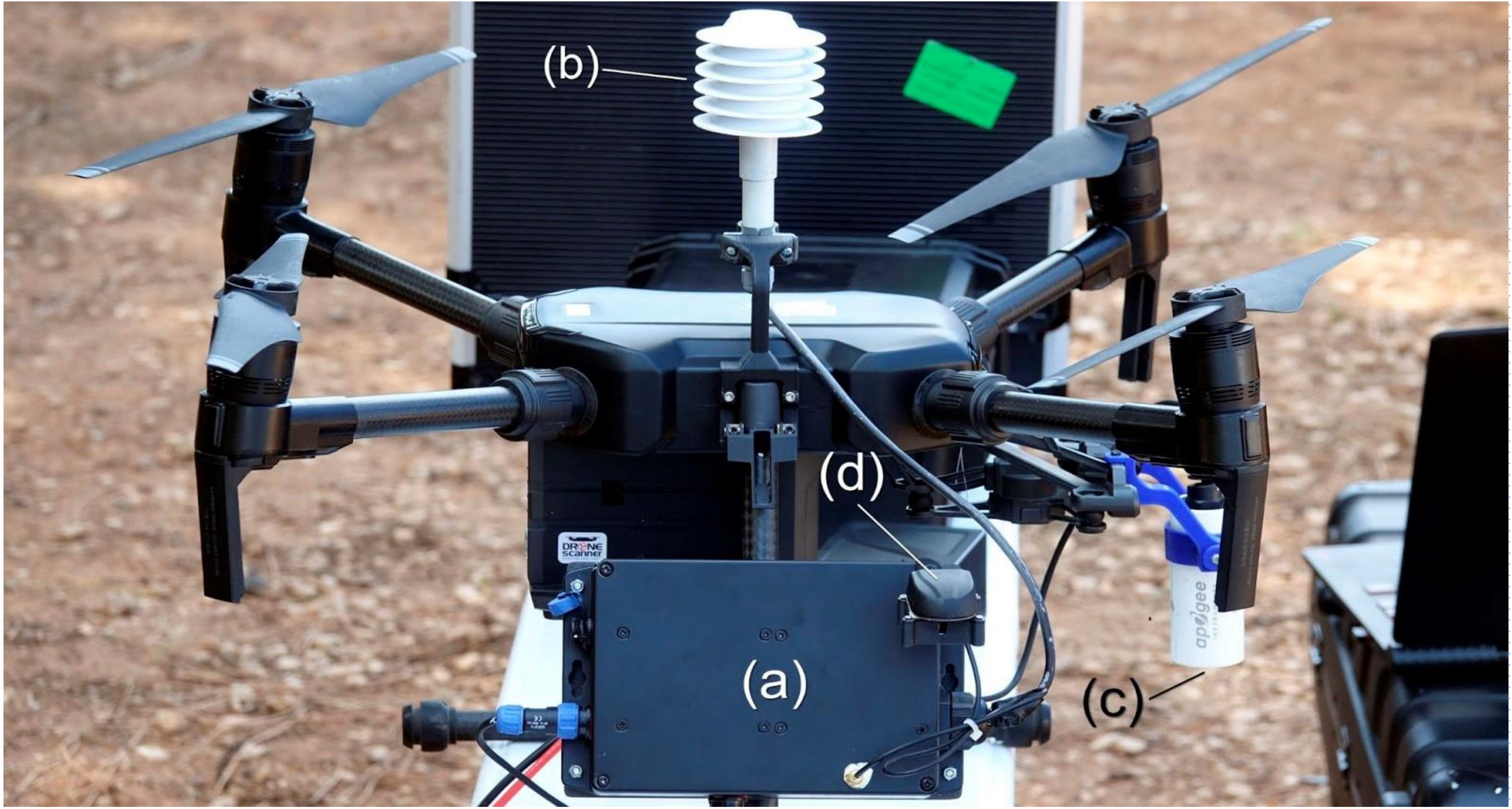

(**a**) Watertight box (data logger Stylitis-12 inside); (**b**) temperature and relative humidity (thermo-hygrometer) sensor in the radiation shield; (**c**) infrared sensor and the mounting base; (**d**) GPS sensor.

Drone Aerial micro-meteo station

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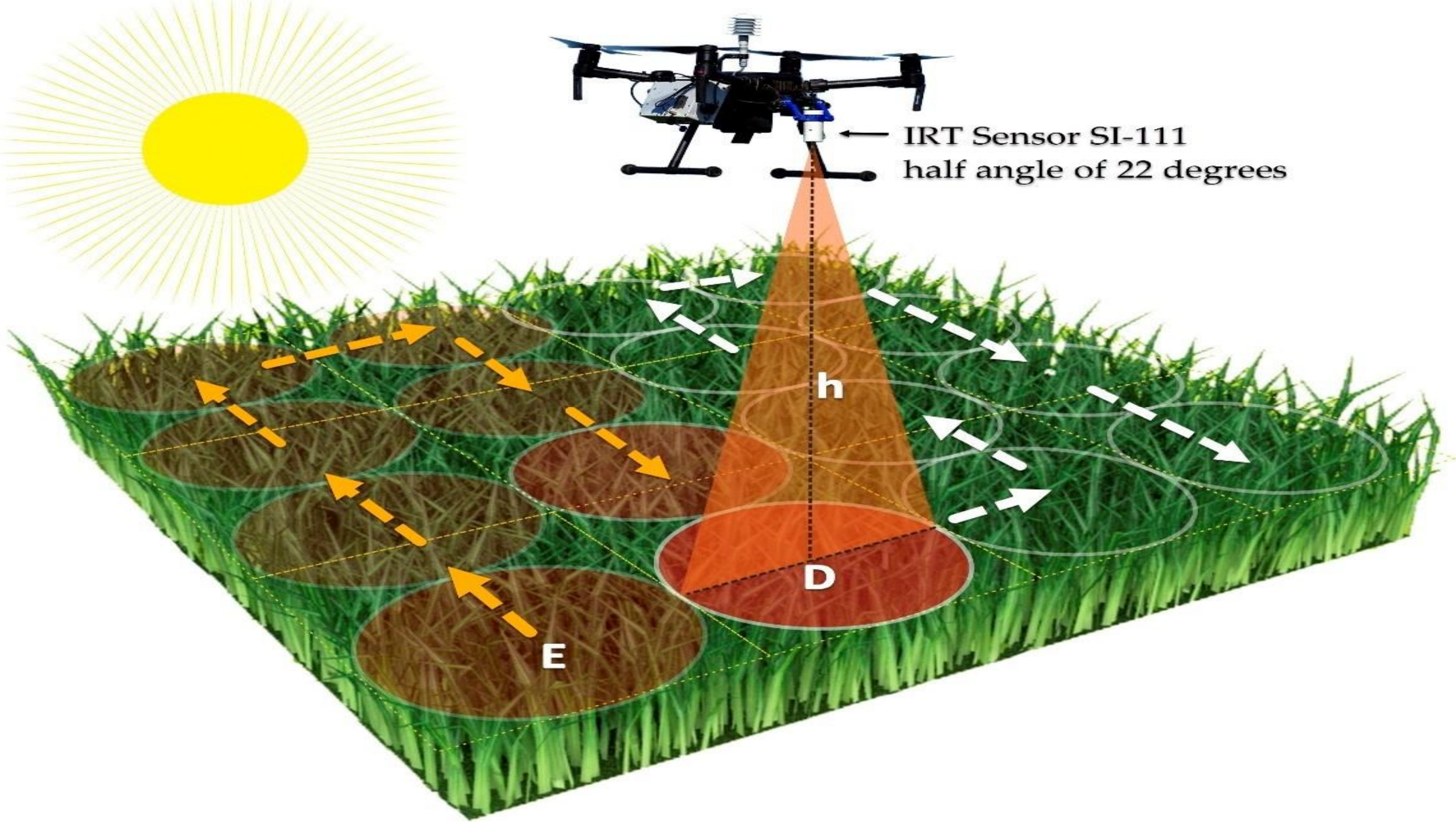
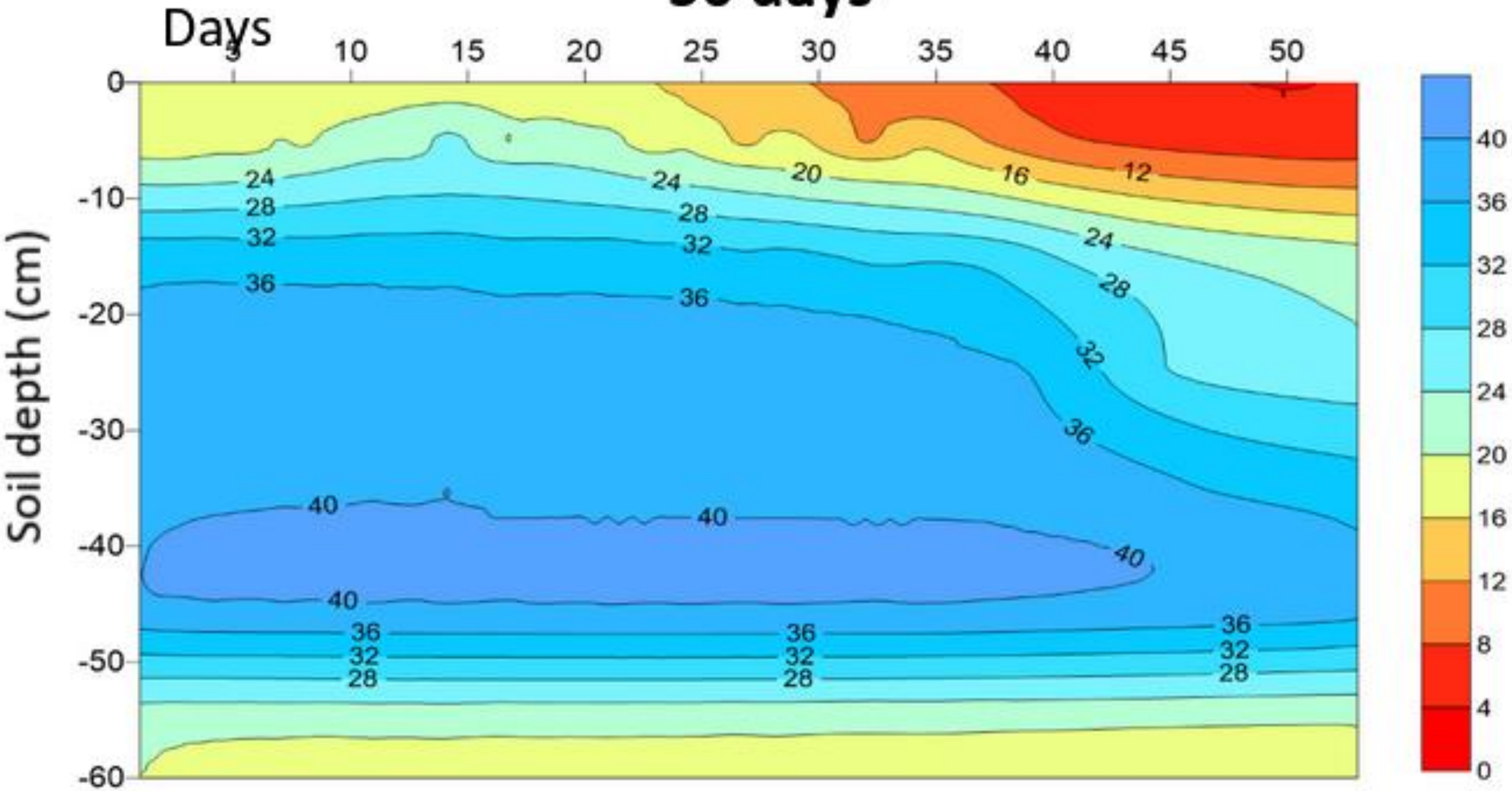


Graphic illustration of the measurement process with an infrared radiometer adapted to a UAV over dense cultivation foliage under a clear sky.
The flight height depends on the sensor type and the characteristics of the crop.
For a specific IRT sensor, the visible surface area is a function of height.

(**a**) The fixed-wing Q100 Datahawk; (**b**) the multispectral Sentera camera; (**c**) the thermal infrared camera Zenmuse XT2.

Field B (potato crop). Soil moisture profile for period of 50 days



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Meteorological sensor Sensors

Thermo-Hygrometer

Wind Direction

Wind Speed

PAR

Net Radiation

Albedometer

Solar Radiation

Infrared Radiometer with Handheld Meter

And Field view Options

Tipping bucket Rain gauge

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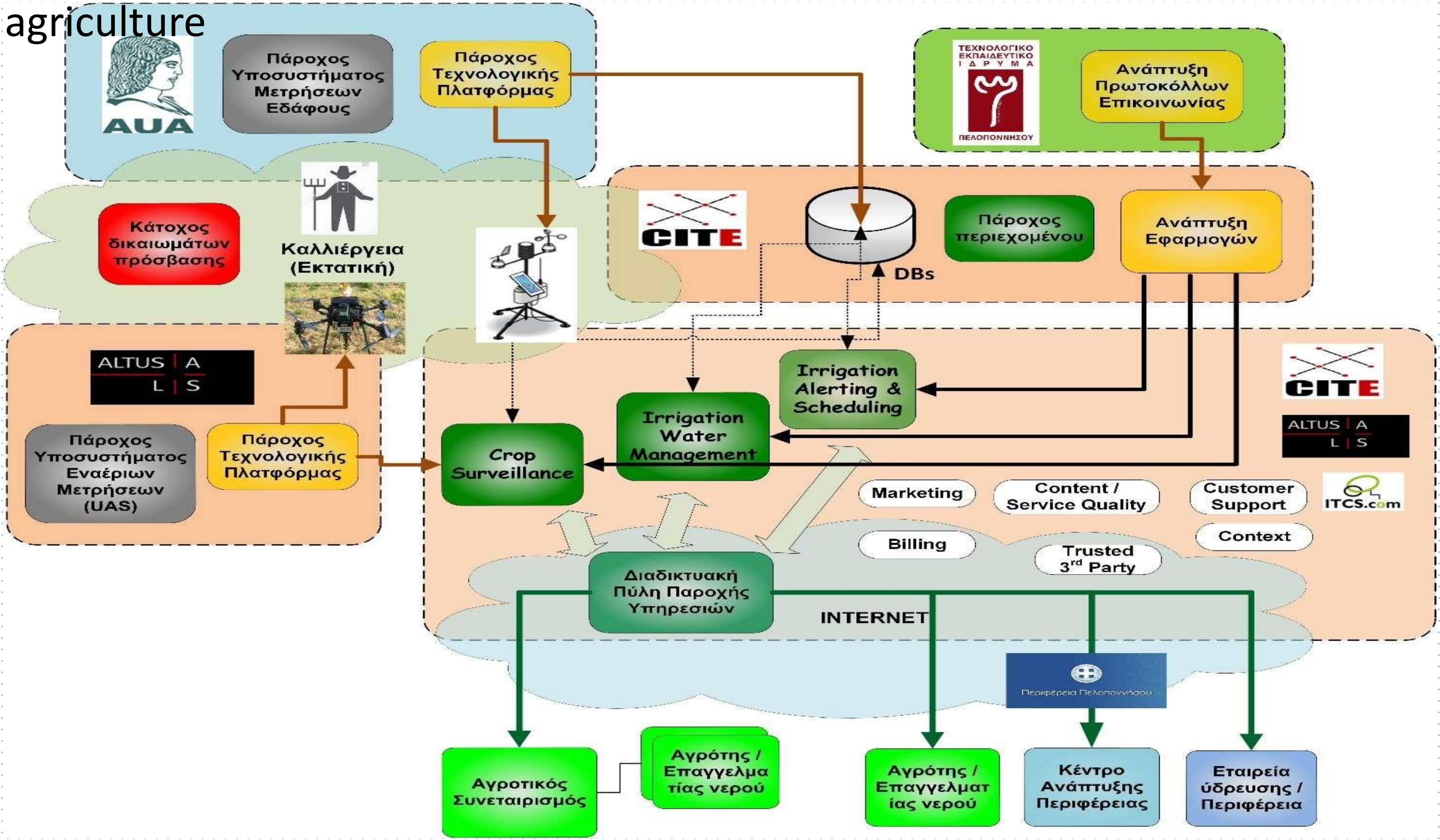
An integrated approach to the concept of smart farming/precision agriculture



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End of the Presentation!!!
Questions???
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Special thanks to all the GWD participants and especially to Prof. Stavros Alexandris (AUA)