

## Survey paper

## An extensive survey on the Internet of Drones

Pietro Boccadoro<sup>a,1</sup>, Domenico Striccoli<sup>a,b</sup>, Luigi Alfredo Grieco<sup>a,b,\*,1</sup><sup>a</sup> Department of Electrical and Information Engineering (DEI), Politecnico di Bari, via Orabona 4, 70126, Bari, Italy<sup>b</sup> Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), 43121, Parma, Italy

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## ABSTRACT

The Internet of Drones (IoD) recently gained momentum due to its high adaptability to a wide variety of complex scenarios. Indeed, Unmanned Aerial Vehicles (UAVs) can successfully be employed in different applications, such as agriculture, search and rescue missions, surveillance systems, mission-critical services, among others, thanks to some technological and practical advantages: high mobility, capability to extend wireless coverage areas, or ability to reach places inaccessible to humans. Moreover, the employment of drones promisingly improves the performance parameters of different network architectures, e.g., reliability, connectivity, throughput, and delay. Nevertheless, the adoption of networks of drones gives rise to several issues related to the intrinsic unreliability of the wireless medium, the duration of batteries, and the high mobility degree, which may cause frequent topology changes. Also security and privacy issues need to be properly investigated. This explains the very large number of works produced in the recent literature on IoD-related topics. With respect to other surveys on IoD-related topics, the goal of the present work is to categorize the multifaceted aspects of IoD, proposing a classification approach of the IoD environment that develops along two main directions. The IoD is initially introduced according to the possible applications and reference operating scenarios. On top of that, this work discussed with its applicability with a dedicated focus on the economical/social implications that the adoption of drones at scale may have. At a macroscopic level, it follows the structure of the Internet protocol stack, starting from the physical layer and extending to the upper layers, without neglecting cross-layer and optimization approaches. At a finer level, all the most relevant works belonging to each layer of the stack are further classified, according to the different issues that propose a peculiar challenges for each layer, and highlighting the most relevant differences with the other surveys present in literature. To provide a deeper insight, the present work embraces many facets of the IoD, with a thorough examination of privacy and security considerations. Finally, a discussion on the main research challenges and possible future directions is carried out, focusing on both open issues and the most promising technologies that deserve to be further developed in the IoD field.

## 1. Introduction

The IoD is defined as a network architecture specifically aimed at supporting communications between autonomous vehicles able to fly and a number of network entities deployed on the ground [1,2]. In the IoD, drones are conceived as smart objects in charge of flying all over a certain area, to carry out a number of different tasks, spanning from patrolling to sensing environmental data, in order to gather data of interest, even in real-time, for any further use. In the IoD architecture, UAVs are conceived as networked objects that can be configured in groups, functionally defined to achieve mission's objectives. Even when they are not configured to form swarms, drones able to communicate among themselves, exchanging data, for example connected with flight coordination capabilities. At the same time, drones are communicating

with a reference ground infrastructure that is in charge of storing and elaborating data for enabling services or providing updated information to remote users connected with dedicated application servers. The reference ground infrastructure is also in charge of controlling the airspace, granting the optimal position of drones and monitoring their activities. Since the ground network infrastructure is conceived as a set of logical nodes with high computational capabilities, tasks coordination and mission plan updates can be delegated, without affecting the limited resources onboard of drones.

The IoD has attracted much interest in the recent literature, due to the flexibility and the adaptability of networks of drones in the most widely differing scenarios, and their ability to enhance the performance of other network architectures. UAVs are becoming more and more

\* Corresponding author.

E-mail addresses: [pietro.boccadoro@poliba.it](mailto:pietro.boccadoro@poliba.it) (P. Boccadoro), [domenico.striccoli@poliba.it](mailto:domenico.striccoli@poliba.it) (D. Striccoli), [alfredo.grieco@poliba.it](mailto:alfredo.grieco@poliba.it) (L.A. Grieco).<sup>1</sup> IEEE Member.

**List of Acronyms**

6G	Sixth-Generation
6lo	IPv6 over networks of resource-constrained nodes
6LoWPAN	IPv6 over Low power Wireless Personal Area Networks
6top	6tisch Operation Sublayer
6TiSCH	IPv6 over the TSCH mode of IEEE 802.15.4
A2A	Air-to-Air
A2G	Air-to-Ground
ACODS	Adaptive Computation Offloading Drone System
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AODV	Ad-hoc On-demand Distance Vector
AP	Allocation Policy
AQ	Autonomous Quadcopter
ASAP	As-Soon-As-Possible Schedule Another Parent
ASN	Absolute Slot Number
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
BDMA	Beam-Division Multiple Access
BS	Base Station
CCN	Content-Centric Network
CCTV	Closed Circuit TeleVision
CEA	Cell Estimation Algorithm
CH	Cluster Head
CIR	Channel Impulse Response
CoAP	Constrained Application Protocol
CoRE	Constrained RESTful Environments
CR	Cognitive Radio
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTD	Conductivity, Temperature, Depth
D2D	Device-to-Device
DAG	Directed Acyclic Graph
DAO	Destination Advertisement Object
DETB	Dynamic Energy & Traffic Balance
DGAC	Direction Gé
DL	DownLink
DIO	Destination Information Object
DNS	Domain Name System
DODAG	Destination Oriented DAG
DP	Dynamic Programming
DRL	Deep Reinforcement Learning
DSSS	Direct Sequence Spread Spectrum
E2E	End-to-End
EASA	European Aviation Safety Agency
ENAC	Ente Nazionale per l'Aviazione Civile
EOF	End Of Frame
ePFC	extended Potential Field Controller
FAA	Federal Aviation Administration
FANET	Flying Ad-hoc NETWORK
FBS	Flying Base Station
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access

FFD	Fully Functioned Device
FIR	Finite Impulse Response
FoV	Field-of-View
FSO	Free Space Optical
G2G	Ground-to-Ground
GA	Genetic Algorithm
GDA	Gradient Algorithm
GIS	Geographic Information System
GPS	Global Position System
GPSR	Greedy Perimeter Stateless Routing
GS	Ground Station
HTTP	HyperText Transfer Protocol
ICI	Inter-Carrier Interference
ICN	Information-Centric Networking
ICT	Information and Communication Technologies
IDFT	Inverse Discrete Fourier Transform
IETF	Internet Engineering Task Force
IIoT	Industrial Internet of Things
IMC	Internal Model Control
IMU	Inertial Measurement Unit
IoD	Internet of Drones
IoT	Internet of Things
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
ISM	Industrial, Scientific and Medical
ISP	Internet Service Provider
ITS	Intelligent Transportation System
JSON	JavaScript Object Notation
KPI	Key Performance Index
KPIs	Key Performance Indices
LA	Learning Algorithm
LAR	Location-Aided Routing
LDRA	Low Delay Routing Algorithm
LLN	Low-power Lossy Network
LLSF	Low-power Lossy Network
LoRaWAN	Long Range Wide Area Network
LoS	Line of Sight
LPWAN	Low Power Wide Area Network
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution-Advanced
LTE-BS	Long-Term Evolution Base Station
LTE-U	Long-Term Evolution-Unlicensed
M2M	Machine-to-Machine
MA	Multiple Access
MAC	Medium Access Control
MANET	Mobile Ad-hoc NETWORK
MTC	Machine-Type Communication
MTC	mission critical Machine-Type Communication
MCU	Micro-Controller Unit
MEC	Mobile Edge Computing
MINLP	Mixed Integer Non-Linear Programming
MPTCP	Multipath TCP
MSPRT	Multi Sequential Probability Ratio Test
MTU	Maximum Transmission Unit
NC	Network Coding

NFP	Networked Flying Platform
NFV	Network Function Virtualization
NLoS	Non-Line of Sight
NOMA	Non-Orthogonal Multiple Access
O-QPSK	Offset-Quadrature Phase-Shift Keying
OFDM	Orthogonal Frequency-Division Multiplexing
OLSR	Optimized Link State Routing Protocol
OS	Operating System
OTF	On The Fly
P2P	Peer-to-Peer
PCC	Path Computation Client
PCE	Path Computation Element
PCEP	Path Computation Element Protocol
PDR	Packet Delivery Ratio
PHY	Physical Layer
PID	Proportional–Integral–Derivative
PLA	PolyLactic Acid
PLR	Packet Loss Ratio
PSO	Particle Swarm Optimization
PSH	Problem Specific Heuristic
PxIMU	Pixhawk Inertial Measurement Unit
QoE	Quality of Experience
QoL	Quality of Link
QoS	Quality of Service
RFD	Reduced Functioned Device
RMM	Random Mobility Model
RMS-DS	Root Mean Square Delay Spread
ROLL	Routing Over Low power and Lossy networks
ROS	Robot Operating System
ROV	Remotely Operated underwater Vehicle
RPL	Routing Protocol for Low-power and Lossy networks
RTT	Round Trip Time
RSMA	Rate-Splitting Multiple Access
RSSI	Received Signal Strength Indication
RSU	RoadSide Unit
RSS	Received Signal Strength
SAIN	Space-Air Integrated Network
SC-FDM	Single Carrier–Frequency Division Multiplexing
SDMA	Spatial-Division Multiple Access
SDN	Software Defined Network
SDR	Software Defines Radio
SE	Spectral Efficiency
SFD	Start of Frame Delimiter
SFO	Scheduling Function Zero
SINR	Signal to Interference-plus-Noise Ratio
SLAM	Simultaneous Localization And Mapping
SNR	Signal-to-Noise Ratio
SPI	Serial Peripheral Interface
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TI	Texas Instruments
TSCH	Time Slotted Channel Hopping
UAS	Unmanned Aircraft System
UASN	Underwater Acoustic Sensor Network
UAV	Unmanned Aerial Vehicle

UAV-BS	Unmanned Aerial Vehicle Base Station
UDP	User Datagram Protocol
UE	User Equipment
UFP	Unmanned Flying Platform
UGV	Unmanned Ground Vehicle
USB	Universal Serial Bus
USV	Unmanned Surface Vehicle
UTM	Unmanned Aerial System Traffic Management
UUV	Unmanned Underwater Vehicle
UWSN	Underwater Wireless Sensor Network
UL	UpLink
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad-hoc NETWORK
VLC	Visible Light Communication
VMS	Variable Message Sign
WG	Working Group
WSN	Wireless Sensor Network

widespread in many fields, due to some technological, tactical and/or practical advantages: (i) high mobility, (ii) easy deployment and re-employability, (iii) real-time monitoring and coordination (strongly dependent on both system architectures and communication technologies), (iv) load transport (depending on the specific cargo application requirements). Drones can be used in areas or to perform tasks that are either not easily accessible by humans or dangerous for human involvement, enhancing the network connectivity, coverage and capacity, especially in combination with other wireless/wired network architectures [1–4]. Given this wide range of functionalities, a number of different applications for the IoD can be enabled. Among them: smart agriculture, search and rescue, surveillance systems, mission-critical services, stock management, sport and training, telecommunications, art and creativity, etc. [3].

Against this, several issues need to be properly investigated in IoD scenarios. First, the wireless medium by its own nature is unreliable: it is prone to errors, attenuations, and multipath propagation, thus bringing to data losses and link interruptions. Even though this is a well-known aspect of wireless communications, this becomes more important when the networked objects are flying by design and moving suddenly from one place to another. This kind of problem has been tackled in literature when referring to Wireless Sensor Networks (WSNs), Mobile Ad-hoc NETWORKs (MANETs), and Flying Ad-hoc NETWORKs (FANETs). Unfortunately, in the IoD, drones are accomplishing several tasks, spanning from coverage enhancement, when they are employed as Flying Base Stations (FBSs), to pattern identification in crowd situations. In these cases, the intrinsic unreliability of the wireless medium suggests that dedicated design efforts must be devoted. In fact, the communication range is often limited, especially in environments with high signal attenuation [5]. The high mobility degree of drones makes this situation even worse, requiring an accurate control and coordination of drones fleets to avoid conflicts, especially in terms of routes and data exchange [6,3].

Power consumption is another critical point in battery powered devices as drones are. This problem is not new to those that study Internet of Things (IoT), since sparing battery and consuming less energy when sensing, communicating, and elaborating data is a mandatory design criterion in that domain. This is motivated by the fact that in the IoT domain, network nodes are supposed to be deployed with low or null maintenance. As a consequence, policies of duty cycling and low transmission power are usually involved in this context. What makes the IoD a more challenging operating scenario is the fact that energy

consumption is not only associated with sensing and communicating but also with movements and flight patterns and mission plans. Further, while IoT devices are often communicating low amounts of data, drones are frequently involved in high traffic volumes. This happens for example when drones are acting as FBSs or supporting video streaming applications. This suggests that onboard memory matters must be faced [7]. Efficient resource allocation should thus be employed to optimize energy consumption, in terms of both the energy spent for data communication and routes of drones [3]. In some application scenarios, where drones are used as relay points to collect and/or deliver data in multi-hop flying networks, cooperation is a mandatory requirement to increase network connectivity, coverage performance, latency and throughput. Moreover, frequent topology changes make much more difficult to implement effective routing protocols that keep a high level of data reliability and network connectivity [8,4,9]. Last but not least, the idea that drones can communicate logically implies some major concerns about security and privacy. Given the constraints in terms of energy consumption and computational capabilities the drones are logically affected by, lightweight cryptography and security solutions are highly recommendable [6]. Overall, the IoD is proposed to allow the development of networks composed by heterogeneous and interconnected drones with proper resource planning to be integrated within third parties businesses and services [10].

The relevance of IoD-related topics to the scientific community to solve the issues described above is testified by the large number of works found in literature, where the IoD paradigm is analyzed in all its multifaceted aspects. The motivation for this survey is to analyze communications aspects, technologies, protocols and architectures in the IoD scenario, detailing as much as possible the analysis of the state-of-the-art research on the topic, at the same time updating and completing the analysis of the other surveys found in literature [4,11,8,6,3,12,5].

For all the reasons mentioned above, and for ease of comprehension, the classification proposed in this work follows, at a higher level, the classical protocol stack, starting from the analysis of all the issues related to the physical layer and going on with the data link layer, the network layer, and the transport and application layers. Nevertheless, there are also cross-layer and optimization approaches that cannot be framed in any of the protocol layers. They have thus been analyzed and discussed in a separate section.

The last part of this work is then focused on a discussion on the main research challenges and possible future directions in the IoD field.

Although researchers and research teams worldwide are concentrated on drones' related topics, all the themes that the scientific community is dealing with appear to be fragmented. As a result, all the works that will be described herein, as well as the survey papers, are only focused on specific aspects, leading to non-structured nor systematic studies. For instance, when discussing the application of drones in real world context, there is a lack of characterization of the operational contexts. Indeed, the social and economical impact is not discussed in detail. At the same time, these aspects are often treated on a regional basis. Moreover, in the context of drones communications, several solutions have been proposed in terms of modulation techniques. Nevertheless, the theme has never been surveyed before. To provide a further example, when optimization approaches are discussed, the proposed frameworks are not as thorough as they could be. For example, it is easy to find papers that optimize both trajectory and energy consumption. Sometimes it is possible to find papers that design the path followed by a drone during a mission without taking into consideration 3D spaces. Hence, while specific aspects are addressed within the other surveys and overviews on the IoD, the purpose of this work is to carry out an organic and thorough analysis, dealing with all the main aspects of the theme. At the same time, this work investigates the applicability of novel technologies, e.g., mmWave and Visible Light Communication (VLC), upcoming networks, i.e., Sixth-Generation (6G), and communication paradigms, i.e., Information-Centric Networking (ICN).

In a nutshell, this work surveys the IoD landscape as hereby resumed:

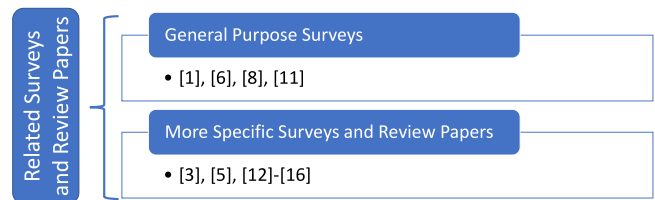


Fig. 1. Related works taxonomy.

- Application fields and/or scenarios are identified and classified.
- All the surveys that are available to date are listed and point-wise analyzed.
- All the relevant references are classified and mapped according to layered structure of the ISO/OSI protocol stack.
- For every layer of the protocol stack, the referenced papers are discussed in detail to point-wise analyze strengths and weaknesses. At the end of each section, a detailed analysis of the main findings is given, together with the lessons learnt.
- On top of the aforescribed classification, this work dedicates efforts in listing and discussing all the papers that address cross-layers evaluations/optimizations/proposals.
- To provide a further insight in the theme, security and privacy aspects are discussed in a dedicated section.
- Lastly, a section is dedicated to a detailed examination of the most promising evolutionary perspectives for unmanned aerial vehicles in the future, with a further focus on the most relevant technologies and protocol stack solutions.

To the best of authors knowledge, this is also the first study on the subject that also considers drone economics, thus discussing the economic impact of the adoption of drones in all the main application fields.

The remainder of this paper is organized as follows: Section 2 proposes a detailed study on the related surveys, describing their classification approach. At the same time, it clarifies the differences between the analytical models and approaches proposed so far and the way this work approaches the IoD, as a whole. Section 3 discusses the applicability of the IoD paradigm in real use-cases. Section 4 focuses on the physical layer, and provides a detailed characterization on connectivity issues as well as channel modeling approaches. Section 5 focuses on data link layer, discussing the related works on resource allocation and data scheduling. Section 6 is dedicated to network layer, paying attention mainly to coordination aspects, routing problems and relaying schemes. Section 7 is focused on the application layer, which includes Quality of Experience (QoE) indicators, computation offloading, task allocation and data collection/distribution. Section 8 analyzes all the papers proposing cross-layer approaches and optimization strategies in several IoD-related aspects, ranging from path planning and collision avoidance to network formation and control, energy efficiency, mobility, network architectures, among others. Section 9 is focused on security aspects and business models, which can be considered as complementary themes when discussing the development of drones as enabling technology towards the IoD. Section 10 summarizes the main findings and discusses the strengths and weaknesses of the analyzed technological landscape. All the considerations made in the surveyed literature pave the way of future research perspectives which are discussed in detail, with specific focus on the open issues and the most promising technologies. Finally, Section 11 concludes the work.

## 2. Related survey and review papers

The main goal of this Section is to analyze all the available survey works on IoD and IoD-related themes. The aim is to better highlight the key contributions of the present work with respect to what is already available in literature. The overall organization of this section is reported in Fig. 1.

## 2.1. General purpose surveys

There are some papers that investigate in detail several aspects related to networks of drones [1,6,8,11].

The first, and probably most important, work on IoD can be found in [1]. It proposes an IoD architecture that aims to solve the problem of airspace allocation and management. Other network architectures are first analyzed, to derive valuable lessons on scalability and fault tolerance to be fruitfully exploited in networks of drones, and at the same time highlighting the main differences with the IoD scenario. The proposed architecture is then introduced, to provide generic services that can be used by different applications where drones are enabled to carry out tasks. Some challenges for effective IoD systems are also explored and discussed, to provide future research directions on the topic.

The integration of UAVs in cellular networks is analyzed in [6]. Several aspects are discussed in detail. First, UAVs types and main features (flying mechanisms, coverage range and altitude, speed, flight time, and power consumption) are addressed. Several standardization studies on channel modeling and characterization aspects are discussed in detail. The main part of this survey focuses on the different challenges and opportunities for UAV-based networks, ranging from the optimization of aerial Base Stations (BSs) location and flying path to the minimization of energy consumption. Different prototyping tests are also surveyed, together with the main aspects of UAV regulations and security issues.

Another interesting contribution is provided by [8]. It proposes a classification of UAVs based on their employability in the contexts of Vehicular Ad-hoc NETWORKS (VANETs) and MANETs, comparing such use cases with networks composed by UAVs only (ad-hoc networks). The contribution also highlights some of the main characteristics of UAV networks, taking into account single-UAV and multi-UAV systems. Networks are categorized based on their topology. A large part of this survey is dedicated to routing approaches. The work is completed with a detailed discussion on strategies for energy efficiency and handover.

In the survey [11] a detailed review of papers on communication technologies is presented for networks of drones in IoT scenarios. Literature is analyzed based on the classification of technologies into long-range and short-range. Long-range technologies are discussed in papers focusing on drones control, connectivity increase, relaying, and in emergency situations or when UAVs are outside the range of direct links. Short range technologies are exploited for different applications like flight control, real-time data acquisition, file transfer, device synchronization, low-power/low-cost communications, and UAV localization [11]. Literature is classified based on some application scenarios, i.e., monitoring activities, management of road traffic and disasters, path planning and routing, data collection mechanisms, almost exclusively referred to hardware (sensors, cameras, RFIDs, etc.) on board the drones. This survey also investigates the literature on network architectures and communication technologies, i.e., WiFi, satellite, WiMax, etc.

Even if each of the works [11,8,6] exhaustively analyzes aspects peculiar of UAV networks, nevertheless the discussion remains confined to specific topics, such as communication technologies in IoT [11], routing and energy efficiency [8], or legislation and security aspects in UAV-assisted cellular networks [6]. As a matter of fact, none of these surveys conducts a wide-range analysis of the main challenges present at different layers of the protocol stack.

## 2.2. More specific surveys and review papers

Even more contextualized to specific IoD-related topics is the analysis carried out in the survey and review papers [3,5,12–16].

The survey [3] focuses on cooperation models for UAV-based networks. Single UAV and multi-UAV systems are analyzed in detail, with specific reference to relaying and routing strategies for cooperative

network formation and coordination. The goal is to provide a detailed insight of the existing models, with their related features, to allow researchers to identify the existing solutions and analyze the performance of both existing and the models proposed. To this end, the available software solutions and simulators that enable cooperation and communications among flying entities forming ad-hoc networks are also compared and discussed, to test the implementation of an UAV-oriented network.

Physical layer aspects in the aerial/ground environment are analyzed in [5], with an emphasis on channel characterization and modeling. This work focuses mainly on the measurement approaches at the basis of the modeling procedures in UAV networks. A classification follows of the different kinds of models, empirical or analytical, through the analysis of the papers on the topic. Empirical studies based on measurement campaigns are described in detail, taking into account several factors like signal frequency, environmental conditions and UAVs main parameters (coverage, height, and mobility).

The paper [12] overviews area coverage problems in UAV networks. The main impacting factors, i.e., coverage capabilities, UAVs mobility and lifetime, network connectivity, and presence of obstacles in the environment, are discussed with specific reference to the coverage types that are classified based on the UAVs motion (hover, fly, stall, etc.) and the network deployment. Other types of constraints in the drones utilization, i.e. energy consumption, coordination among UAVs and path planning problems, are summarily described together with path models adopted to study dynamic coverage problems.

Robotic networks for surveillance purposes are discussed in [13]. A discussion is carried out on the main research directions and challenges of robotics (with a detailed analysis on autonomy issues), with an analysis of the acoustic signal treatment and processing, network protocols and security aspects in underwater communications. This work is interesting because it refers to a very hostile environment for wireless communications, as the underwater scenario is.

The overview work [14] deals exclusively with location optimization algorithms. It makes a classification of the algorithms that can be used for optimizing the position occupied by a certain number of UAVs, especially when they are supposed/asked to act as BS (the so-called Unmanned Aerial Vehicle Base Stations (UAV-BSs)). Different classes of algorithms are analyzed in this survey. They include exact approaches, able to find the global optimum of the optimization problem, as well as heuristic-based approaches, reinforcement learning approaches, or other searching techniques. This kind of classification is useful to solve the formulated problems through Mixed Integer Non-Linear Programming (MINLP) techniques.

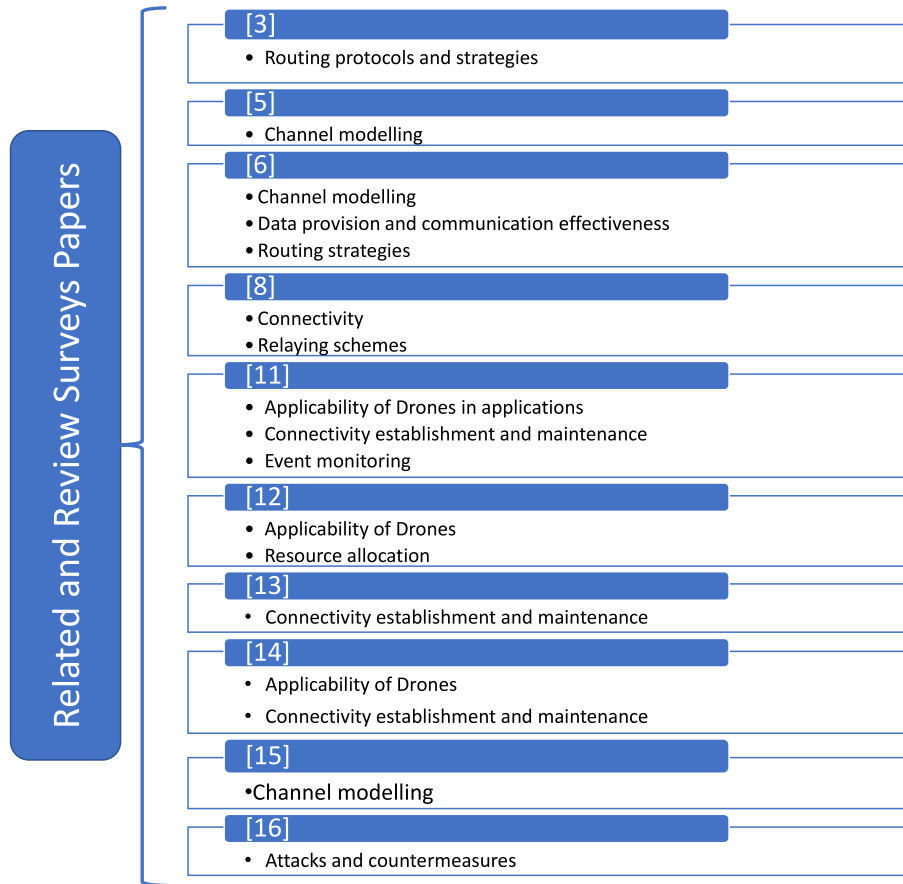
The mmWave technology is analyzed in [15]. It overviews the issues arising from the utilization of mmWave communication in UAV networks. The main research challenges are discussed, especially with respect to channel modeling and estimation/acquisition strategies. The adoption of mmWave in cellular networks is also discussed with reference to aerial-to-ground communication issues that include both the UAV-to-BS and UAV-to-User Equipment (UE) scenarios. Scheduling and sharing of physical (time/frequency) resources among users are taken into account.

The paper [16] analyzes UAVs from a security perspective. It proposes a literature review of attacks that employ an UAV, and the related countermeasures that can be taken through anti-UAV techniques. The first part of this survey is dedicated to the classification of UAVs based on several parameters (like weight, altitude and range, and supported applications). An analysis of UAV regulations in different countries and the most common malpractices using commercial and personal UAVs is also carried out, that arise some security issues. The most relevant contribution of this paper lies in the analysis of the UAVs adoption in military weapon-based attacks, and in the description of UAV monitoring and neutralizing techniques. Monitoring techniques aim at discovering the presence of UAVs. The goal of neutralization techniques is to neutralize the normal operation of the UAV. All the



**Table 1**  
Comparison among the related surveys.

	[3]	[5]	[6]	[8]	[11]	[12]	[13]	[14]	[15]	[16]	This survey
IoD Application Fields					✓	✓					✓
Satellite Communications and 6G											✓
IoD economics											✓
Modulation Techniques										✓	✓
Channel Modeling and Characterization		✓	✓			✓			✓		✓
Communication Technologies					✓	✓			✓		✓
Connectivity			✓	✓		✓	✓	✓		✓	✓
Throughput Evaluation and Optimization			✓								✓
Resource Allocation and Optimization			✓	✓	✓		✓	✓			✓
Scheduling			✓	✓		✓			✓		✓
Cooperative Strategies	✓						✓				✓
Routing Protocols	✓			✓	✓						✓
Relaying Schemes	✓		✓								✓
Quality of Service (QoS) and QoE								✓			✓
Task Allocation	✓				✓						✓
Video Streaming			✓								✓
Data Collection and Distribution			✓		✓		✓				✓
Novel Communication Technologies and Paradigms											✓
Cross-Layer and Optimization Approaches											✓
Events Monitoring and Management					✓		✓				✓
Security and privacy aspects			✓							✓	✓
Drones Identification and Classification										✓	✓
Security in Drone Networks											✓



**Fig. 2.** Summary of the macro-topics covered by the related surveys.

neutralization approaches analyzed in this paper act on the physical radio signal. Finally, some case studies of UAV neutralization are overviewed.

It is noteworthy that papers [3,5,12–16] analyze a specific aspect of the IoD scenario: papers [3,5] refer to the only network and physical layer respectively; the survey [13] deals with surveillance in the underwater environment. The works [14,12] summarily review coverage problems [12] and optimization strategies [14]. The paper [15]

is focused on the research perspectives in mmWave communication technologies. The survey [16] deals with UAVs misuse cases, and the related countermeasures in terms of monitoring and neutralization. Indeed, it refers to a single UAV, totally neglecting networks based on drones' swarms and their interactions with other network entities.

All the themes and topics covered by the discussion so far reveal that there is the need to conduct a wider study on the theme. A study that

aims at creating an homogeneous, harmonized, and integrated discussion on all these aspects. In fact, even though useful, each of the cited references are mainly focused on a subset of the technological aspects of the IoD. In some cases, the cited works are discussing/analyzing specific phenomena. Therefore, a more cross-cutting classification approach is needed. This is achieved by leveraging a thorough layer-by-layer characterization of mathematical problem formulations, technologies employment, and implementation proposals. As an outcome, the challenging issues and open research questions will be characterized in networks of drones, as remarked in Section 1. In Table 1, the surveyed state of the art is proposed, with a detailed overview of the theme that each work describes and tackles. In Fig. 2, a summary of the main topics of all the related surveys described in this section is given. In Fig. 3, the overall organization of the present contribution is shown. Furthermore, for each Section, a detailed representation of the taxonomy will be reported, showing its structure in detail.

### 3. IoD applicability

This Section discusses the applicability of the IoD networking architecture with a detailed analysis of all the application fields that have been proposed so far. To dig deeper in the subject, the employment of drones in the many applications that may benefit from their adoption are dealt with from an economical perspective. The overall organization of this Section reported in Fig. 4.

#### 3.1. IoD application fields

As previously anticipated, drones employability in different operational contexts has been widely discussed so far [1,17–21,10,12,22,7,23,24,11,25–30]. In many cases, the studies propose a detailed analysis of their capabilities, the possibilities they enable, the persistent configurations and, above all, the involved technologies.

In the telecommunications field, drones are of interest because they can be used both in emergency situations and in the ordinary conditions, i.e., management of data traffic. As an application example, let be an event with many connected users who want to send data through their 4G connections, e.g., a concert. In such a situation, the phone cells are typically overloaded. In this scenario, drones can act as mobile BSs, delivering the service with smart and self-adaptive deployment plans to support the load in excess, thus granting connections continuity. These capabilities can also be extremely useful in those contexts where service interruptions and signal losses are due to network outages. In case of environmental disasters, such as earthquakes and floods, the massive use of fleets of drones, while guaranteeing the possibility of timely intervention to restore connectivity, and, at the same time, it guarantees the acquisition of data, i.e., video images or environmental parameters. In non-critical scenarios, several examples of drones employment can be done, such as photogrammetry and aerial survey of both buildings and large wooded areas, as well as in smart agriculture. Here, the detailed analysis of high-resolution images can provide several kinds of information, like, for example, the quantity of pesticides or irrigation, the effects of abundant rain, the quality of the soil, and the presence of diseases. This information allows targeted interventions to save entire crops and improve the quality of production. The employment of drones has been extended in smart mechanism by integrating the Machine-to-Machine (M2M) communications. This enables drones to interact with sensors and service providers. Such a mechanism can be further evolved towards coordination schemes in between the sensor services with its upper layers, which is, in general, a fog and/or cloud environment. In the latter context, distributed intelligence and cooperation among logical nodes becomes of utmost importance to offload the elaboration provided by UAVs.

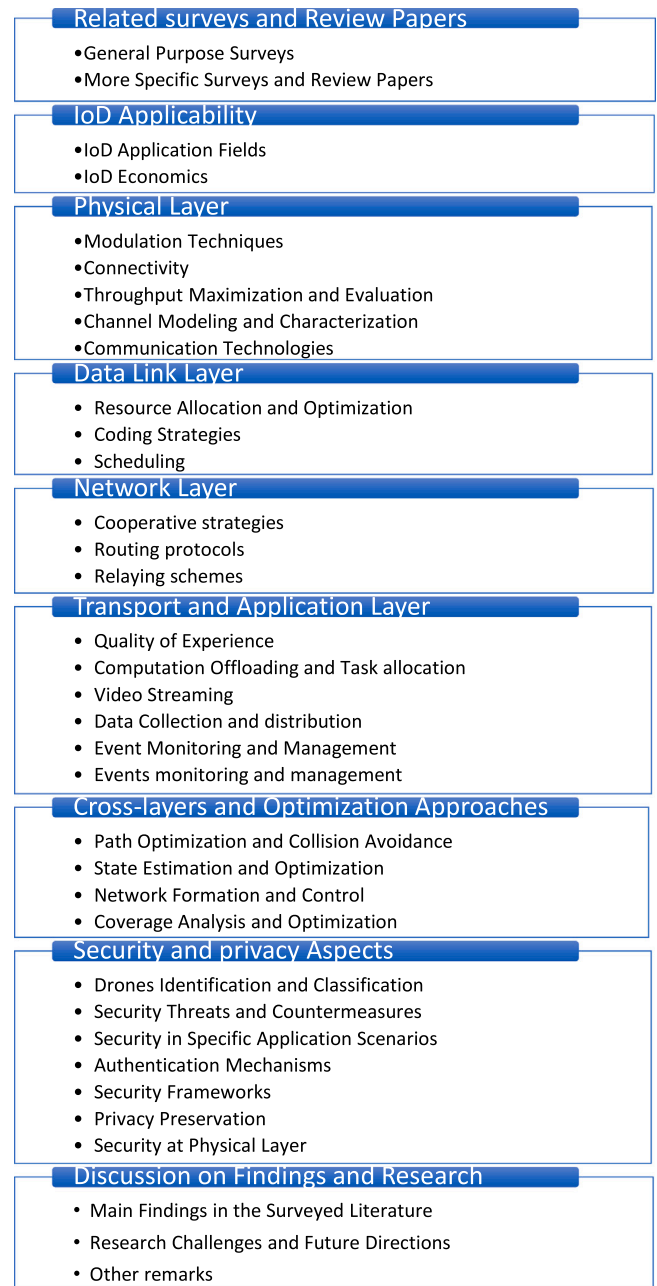


Fig. 3. Overall organization of the present work.

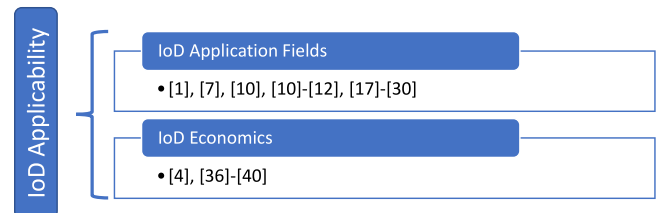


Fig. 4. IoD applicability taxonomy.

In Fig. 5, the reference architecture for the IoD is depicted. In it, a swarm<sup>2</sup> of UAVs is flying over an area of interest. While on

<sup>2</sup> For the sake of simplicity, it is herein assumed that there is only one swarm. In general, complex operating scenarios may involve multiple swarms, with differentiated tasks.

**Table 2**  
Summary of the main applications drones are involved in.

Application area	Activity	Open challenges	References
Law Enforcement	Public Safety Orthographic surveillance	Multiple sensing units Long lasting missions Seamless connectivity	[26,17,19,27,22,11,28,18,23,30]
Civil Engineering	Aerial Photogrammetry Area mapping (GIS) Land development/construction Science and research	Multiple sensing units High quality video imaging	[7,24]
Logistics Tracking	Unmanned cargo Process enhancement Proactive Maintenance	Multiple sensing units Interaction with environment	[26,25,24,17,19,27,22,21,23]
Military Applications	Search and rescue Surveillance Border control	Long lasting missions Multiple sensing units Seamless connectivity Autonomous decision making	[26,17,19,27,22,11,28,30]
Air Traffic Controlling	Traffic control Security Weather forecast ITSs Science and research	Multiple sensing units Seamless connectivity Near Real-Time	[26,25,24,17,27,22,11,18,23,30]
Public Safety	Search and rescue Disaster Management	Real-time tracking High quality video imaging	[1,26,25,24,17,27,22,11,12,21,20,23]
Entertainment	TV series and films Concert and Events live streaming Flight clubs Selfies	High quality video imaging Artificial Vision Objects and Pattern Tracking	[26,25,7,27,22,20,29]
Industrial monitoring Processes enhancement	Smart Agriculture and Pharming Power lines/grids Oil and Gas	Multiple sensing units High quality video imaging Interaction with environment	[1,4,7,11,17,19,20,18,22,28,27]

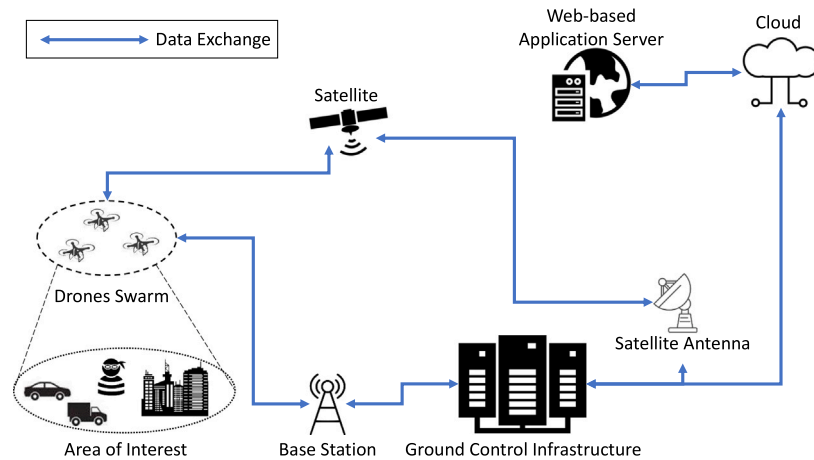


Fig. 5. Reference IoD architecture.

flight, drones are communicating to the to a Ground Control Infrastructure leveraging a certain number of BSs. As suggested by the preliminary studies on 6G technology, drones are communicating with satellites [10,31,25,32–35]. In particular, satellites are mainly communicating to drones to be activated and/or remotely controlled. These control messages are sent by the ground control infrastructure via satellite antennas. The whole set of information regarding the mission plans, the achieved mission goals and, eventually, remote control are handled by web-based applications in a distributed fashion leveraging cloud computing. In order to enhance the data transmission rate and the system capacity, 6G network has led a key role in pioneering the introduction of system intelligence using Artificial Intelligence (AI) [33].

As clearly comes out from this description, the IoD architecture must be considered as in a general-purpose fashion. In particular, the main claim of the IoD is that the network architecture is extremely versatile and able to meet several requirements at the same time. To clarify this, some of the main references of the present work are reported in Table 2, where the application fields are classified together with the roles that

the drones are covering [10]. A detailed discussion of these points will be given in the remainder of the present work.

### 3.2. IoD economics

Beyond the novelty, and possible innovation, that drones may lead in the wide context of civil applications, UAVs represent a promising perspective in several industrial segments [4,36–40]. The economic impacts associated to the wide employment and integration of UAVs at scale is certainly going to have impacts on job creations. At the same time, industries will be able to cut costs from more effective means of transportation and distribution. The applications may vary for several reasons. First of all, the technological readiness of drones is continuously increasing in terms of performances. For instance, drones are able to fly regardless of the payload: in fact, at the time being, UAVs may be (i) in charge of moving variable-sized payloads, (ii) equipped with cameras (e.g., photo or video), (iii) sensors, and (iv) radars. As for flight time and autonomy, drones are more and more able to fly for



longer periods of time, thanks to enhanced battery and energy supply systems.

The work presented in [40] discusses the possible economic impact of the introduction of drones in multiple applications. Starting from what is stated in [41], and further confirmed in [42,43,38], the employment of drones at scale would bring \$80 billion by 2025. This is motivated by the fact that a plenty of interesting functionalities that drones may expose when employed [44], such as improving public support given their intrinsic autonomy. Moreover, security can be enhanced according to the fact that social and economic impacts can be the result of the fact that surveillance or search and rescue activities can be carried out almost on their own by the drones. Another interesting contribution is [45], in which the main focus is on smart agriculture and smart farming technologies. This work discusses the details about precision application technologies, which implies the need for technologies able to work with variable-rate. The rationale for this variability may be either application dependent or context dependent. For example, data acquisition related to crop monitoring when diseases or irrigation problems are detected may lead to sudden intervention, thus saving entire production sectors. At the same time, precision irrigation and weeding has been widely recognized as one of the leading pillar of smart farming. Irrigating on demand and constant monitoring of soil humidity can be enabled by the analysis of aerial images. [46] provides similar forecasts, but in the UK market. Even though regulations and production sectors are different from other countries, what this study has in common with others is the fact that they share the same opinions in terms of the drones' role. Defined as *game-changer*, drones are expected to improve industrial processes at scale by £42 billion by 2030. The study discusses the role of technology in saving lives in harsh environments and in the case of hard working condition, providing concrete examples in case of utilities and oil and gas plants. The detailed analysis carried out in this contribution envisions several strategic fields in which the impact of drones is expected to be of paramount importance. In particular:

- Public and Defense, Health, technology.
- Technology, media and telecommunications.
- Construction and manufacturing.
- Financial, insurance, professional and administrative services.
- Transportation and logistics.
- Agriculture, mining, gas and electricity.

In a nutshell, drones may have direct impact on [37]:

- Consumer applications, thus including individuals, non-commercial and non-professional. A forecast on drones shipment for this sector indicates a total of 29 million units by 2021.
- For enterprise drones, Business Insider Intelligence expects shipments to reach 805,000 in 2021 with a five-year Compound Annual Growth Rate (CAGR) of 51% from 102,600 in 2016.
- Government drones fall into two categories: military and public safety. Among the two, the former market can be considered as the most mature. The U.S. military has been using drones for combat since 2001, and it rapidly expanded its drone fleet to more than 7000 by 2012. The Department of Defense budget in 2016 allocated \$2.9 billion for more than 50 new drones for combat and surveillance, according to the Bard Center for the Study of Drones.

Industrial players may significantly cut costs and/or improve operations for the enterprises that will introduce or adopt them. As for the industrial applications that will mostly benefit from the introduction of drones, the most significant impacts will be on [37]:

- Infrastructure (45.2B \$).
- Agriculture (32B \$).
- Security (10B \$).
- Media and Entertainment (8.8B \$).

- Telecommunications (6.3B \$).

As for delivery, it has been estimated that there could be an increment on transportation speed ( $\sim 50\%$ ), a positive effect on environmental impact (lower by almost 50%), increased control over package delivery flow ( $\sim 40\%$ ), and safety ( $\sim 30\%$ ) [39]. Service provisioning may be related to systems and methods for delivering mail and goods using UAVs.

To sum up, the number and kind of fields that may benefit from the employment of drones are so numerous that their potential impact in automating and optimizing processes can only roughly be foreseen. At the same time, as happens every time a groundbreaking technology becomes available, the massive employment of drones may radically change every business not only in terms of time-to-market for products but, even more, in terms of process design and optimization. As a final remark, the potential of a new technology is usually threatened by fragmented laws and legislative frameworks. A dedicated discussion will be carried out later on in the present work.

#### 4. Physical layer

This Section discusses all the technological aspects and research challenges connected to the Physical Layer (PHY). In particular, the main topics of interests are: (i) Modulation techniques, (ii) Connectivity, (iii) Throughput maximization, (iv) Channel modeling and characterization, and (v) Communication technologies. The Section closes up highlighting the lessons learned on this theme. The overall organization of this Section is reported in Fig. 6.

##### 4.1. Modulation techniques

There are some papers that analyze modulation techniques in the context of UAV communications [47,48]. They are discussed in the following subsections.

###### 4.1.1. Signal quality enhancement

The analysis of modulation schemes are the contributions [47,48]. A modulation technique that increases the efficiency of the data link between UAVs is investigated in [47]. The analyzed modulation scheme is the Single Carrier-Frequency Division Multiplexing (SC-FDM), which has the important goal to fulfill long-range communication and long battery life requirements for networks of UAVs. This scheme is already known in uplink communications for Long-Term Evolution (LTE) systems, but in this study it is contextualized to UAV communication, by comparing its performance with the classical Orthogonal Frequency-Division Multiplexing (OFDM) modulation scheme. Performance analysis is carried out in terms of transmission power optimization, bit error rate and pulse shaping. An analysis of the OFDM modulation is considered in [48], to propose a noise suppression method for UAV communications. The discussed method filters electromagnetic impulse noise at receiver side; then, it performs OFDM demodulation to suppress noise. The problem is tackled analytically, using models for the various electromagnetic pulses to analyze their influence on the OFDM-based communication. The electromagnetic pulse suppression strategy is, hence, presented: it relies on a module that performs the separation of noise from the signal before OFDM demodulation, that acts in combination with a dual antenna method to reduce the bit error rate and increase the quality of the received pictures.

##### 4.2. Connectivity

Connectivity is a topic widely analyzed in literature, as testified by the works [49–76]. They are mainly focused on: (i) analysis and optimization of coverage and resource allocation, (ii) relaying and routing, (iii) cooperative networks, (iv) path planning and position optimization and (v) connectivity issues in specific application scenarios, as described in what follows.

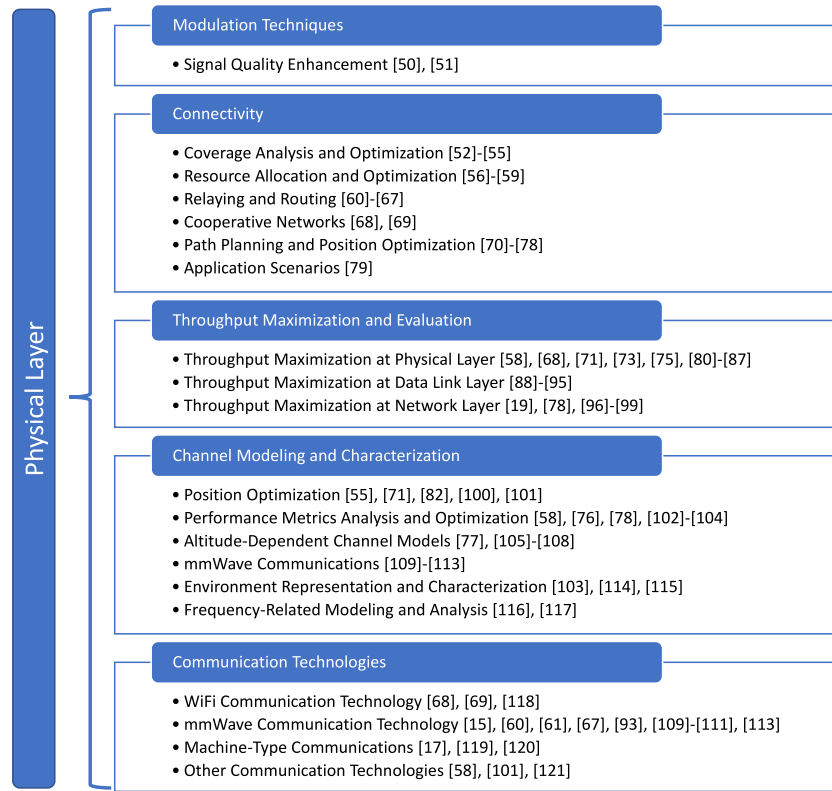


Fig. 6. Physical layer taxonomy.

#### 4.2.1. Coverage analysis and optimization

A connectivity analysis can be fruitfully exploited to study coverage performance of networks of drones in different contexts; this is the approach followed by the works [49–52]. The work [49] proposes a coverage analysis that takes into account connectivity between UAVs and ground users. In this work, UAVs at low altitudes provide services to users falling into a coverage area whose shape is influenced by the UAVs' directional antennas. The coverage analysis is carried out on a statistical base as a function of the main UAV parameters, among which, the Line of Sight (LoS), as well as NLoS, connection (as graphically represented in Fig. 7) interference between UAVs and ground users. A similar approach is followed in [50], where a coverage probability analysis is carried out in a multi-UAV scenario. In particular, here UAVs provide service to a ground receiver. The analytical expression takes into account both LoS and NLoS components, and aims at carefully capturing the influence of the dominant interferer on the receiver, with respect to the other interference contributions from the rest of UAVs. Another coverage study in a network that includes UAVs with relay functionalities is developed in [51], where the connection probability is studied in conjunction with coverage capabilities, for different types of traffic. LoS and NLoS connections are modeled statistically also in [52], to study the coverage performance of small cells of drones providing wireless access to ground users. The probability of LoS and NLoS connections are used to analyze the drones altitudes that maximize the coverage extension and minimize the transmission power.

Even though drones' connectivity can be considered as a peculiar aspect of the physical layer, it also impacts on other layers of the protocol stack. For this reason, connectivity has been discussed in several studies proposing strategies for resource allocation and optimization, relaying and routing, cooperative networks, path and position optimization, and analyzing specific application scenarios.

#### 4.2.2. Resource allocation and optimization

The works [53–56] take into account connectivity in the framework of resource allocation and optimization strategies. In these works, the probabilities of both LoS and NLoS connections are used to theoretically describe Air-to-Air (A2A) and/or Air-to-Ground (A2G) links. Several factors are considered to model the link connectivity, like the environment, placement and density of buildings, and relative positions of UAVs and users. In [53], the model is exploited to develop a resource allocation algorithm in a cache-enabled UAV-based network, that optimally allocates the spectrum bands so that the queue stability of users and their bandwidth requirements are satisfied. In [54], the link connectivity model is exploited to maximize the average number of bits received by ground users, subject to constraints on the UAVs' maximum flight times, granting fair resource allocation. In the work [55] both LoS and NLoS path loss models are exploited to implement an algorithm that increases the throughput of a public safety network which leverages, at the same time, the unlicensed LTE spectrum of UAVs and the Wi-Fi spectrum of ground access points. The goal is to balance the load on the basis of the link quality of users.

#### 4.2.3. Relaying and routing

In the works [57–64] connectivity is analyzed in the context of relaying and routing strategies. The work [57] proposes a solution to increase the connectivity among devices adopting mmWave communication, through mobile relaying. To this end, the optimal position of the mobile nodes is found so that the link quality is maximized, and the communication range is increased accordingly. In the work [58] the loss of connectivity is analyzed to justify the importance of an accurate prediction of node movements for an efficient design of the routing strategy. The proposed routing algorithm includes a feature that predicts the movements of the mobile node, to increase the message delivery ratio and reduce delay in case of short-lived connectivity. The work [59] models the connectivity between two nodes, in terms of expected connection time, to build a routing protocol that dynamically

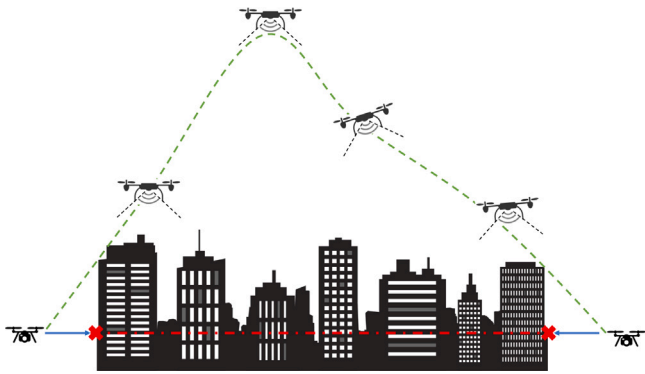


Fig. 7. NLoS communications enabled by drones.

updates the routing path based on the prediction of the connection times of drones. In [60], a route recovery strategy is proposed that exploits UAVs as relays interconnecting terrestrial networks in disaster scenarios. The route recovery over damaged networks is based on a topology discovery algorithm that identifies clusters of nodes, and the relative cluster heads, depending on their connectivity capabilities. In the routing protocol developed in [61] the most connected path is found to route data between vehicles of a VANET and UAVs assisting them. The path depends on the traffic density and the degree of connectivity on the road. An extension of the same protocol developed in [61] is proposed in [62]. The latter considers both routing between UAVs and vehicles and routing among UAVs. The UAVs' connectivity is a requirement of the layered network architecture presented in [63]. The routing algorithm proposed in this work aims at minimizing latency while maximizing the Packet Delivery Ratio (PDR). The connectivity information is exploited to improve the routing performance. A connectivity model is developed in [64] to analytically describe the channel conditions of the back-haul links in 5G cellular networks that leverages the mmWave spectrum. The dynamic blockage of back-haul links is modeled in a network with UAVs acting as relay nodes. This aspect is part of a more complex analytical framework that captures also the mmWave propagation characteristics and the UAVs mobility, to dynamically reroute data depending on the variable channel conditions.

#### 4.2.4. Cooperative networks

The works [65,66] analyze connectivity among drones in cooperative networks. In particular, [65] proposes a distance control algorithm that finds the optimum distance among drones. Here, UAVs are cooperating in data transfer tasks, to guarantee the stability of the wireless connection and, consequently, of drones' communication. The continuity of the connectivity is the main focus of the work [66], that proposes a network infrastructure, composed by drones that exchange data with ground users, to manage critical events. The goal is to guarantee the service continuity by preserving the connectivity among UAVs in case of nodes replacement. To this end, a modification of the Optimized Link State Routing Protocol (OLSR) protocol, already known in literature, is proposed.

#### 4.2.5. Path planning and position optimization

There are several works that analyze connectivity to develop path planning and position optimization strategies [67–75]. The work [67] proposes the use of flying back-haul hubs to extend the coverage area in a 5G network. The hubs optimal location is wisely established, by solving an optimization problem, to provide connectivity between the core network and the ground BSs. Also the algorithm proposed in [68] aims at finding the optimal position of UAVs used as BSs to provide connectivity to ground users. The algorithm makes use of a theoretical channel model that describes the connectivity of the A2G links as a function of the propagation paths and the main features

of the antenna arrays. Another path planning algorithm that takes into account connectivity can be found in [69]. This work studies the connectivity of a wireless network of balloons with UAVs acting as relays. The connectivity requirement is expressed as a function of the probability of the link outage among balloons. Depending on this, the proposed path planning algorithm finds the optimal UAVs positions that maximize the network connectivity. A path planning and resource allocation scheme that models connectivity in cellular-connected UAVs is found in [70]. In this work, analytical expressions of connectivity are used to model the interference level of the UAVs on the ground network and compute the optimal paths of UAVs that minimize it, together with the transmission delay and the time that the UAVs employ to reach their destination. An approach that takes into account connectivity of both A2A and A2G links is found in [71], where connectivity constraints are introduced to study the path planning problem for an aerial sensor network connected to ground Long-Term Evolution Base Stations (LTE-BSs). The connectivity constraints are expressed in terms of the outage probability of the link, which depends on the relative distance between aerial and ground nodes through A2A and A2G links. Based on this, the connectivity constraint is derived, which depends on the minimum link capacity. The work [72] develops a mobility model of a fleet of UAVs, where each UAV must keep the connectivity with its neighbor, taking also into account residual energy level and area coverage as decision criteria for the path planning procedure. In [73] the LoS probability is used to derive the coverage probability of an UAV providing service to ground users. The approach is similar to what developed in [50], but, in this case, the focus is not only on connectivity and the coverage probability expression is used to compute the optimal UAV position that maximizes the coverage area and coverage lifetime. The work [74] proposes a connectivity model between UAVs and ground nodes. Connectivity is modeled in terms of the outage probability of the terrestrial-aerial communication link, and the optimal UAV height that maximizes the coverage area in presence of fading is found, accordingly. In [75] the probabilities of LoS and NLoS connections are used for a theoretical model of A2A and/or A2G links. This model is used to design a network formation algorithm that guarantees the connectivity between each UAV of the aerial network and a gateway node through, at most, one path.

#### 4.2.6. Application scenarios

The approach proposed in [76] differs from all the others described above, since the link connectivity is related to the users QoE. Specifically, the LoS connectivity, derived in terms of probability of connection loss, is exploited to model the transmission links in a network of UAVs. The goal is the optimization of the users QoE, that in this case depends on the user data rate, delay, and device type.

### 4.3. Throughput maximization and evaluation

This Section describes all the works proposing strategies for throughput optimization and evaluation, in different IoD scenarios and at different layers of the protocol stack (physical, data link and network layer) [65,77,78,68,79,70,80–84,55,73,85–94,19,95,75,96].

#### 4.3.1. Throughput maximization at physical layer

As expected, the majority of the works on throughput maximization and evaluation are focused on the physical layer of the protocol stack [65,77,78,68,79,70,80–84,55,73].

Some of the most significant contributions of the theme deal with position and path optimization strategies of UAVs [65,77,78,68,79,70,80,81]. More specifically, in [65] throughput performance is studied to show the effectiveness of a distance control algorithm, with the goal of guaranteeing the stability of the wireless connection in A2G links in case of drone replacement in the network. The proposed algorithm dynamically changes the position of drones so that a minimum throughput requirement is satisfied. The work [77] proposes a strategy for

throughput maximization in a UAV-based wireless network where a single UAV is used as BS to serve ground users. The proposed strategy simultaneously optimizes the UAV path and the scheduling times of users communications. The solution of the optimization problem aims at maximizing the minimum throughput over all users, while guaranteeing fairness among them. The same network scheme of UAV-aided cellular network is proposed in [78]. In this architecture, the UAV offloads the ground BS and serves the UEs at cell edge. The goal of this scheme is the maximization of the minimum throughput of the UEs, and it is achieved by jointly optimizing the UAV trajectory, resource allocation, and the partitioning of users between the UAV and the terrestrial BS. The issue of aggregate data rate maximization in the DownLink (DL) channel is tackled in [68]. In this work, an approach is proposed that optimizes the hovering locations of UAVs acting as flying BSs to maximize the DL aggregate rate, exploiting UAVs mobility and beam-forming techniques. This goal is obtained through a search algorithm, that finds the hovering locations with a low interference leakage, that maximize the Signal-to-Noise Ratio (SNR) of the ground users. The work [79] considers a wireless network where UAVs act as relay. In this scenario, an algorithm is proposed that exploits the LoS information to find the optimal UAV positions that maximize the end-to-end throughput. These positions are found by means of a model that takes into account the signal propagation properties of the A2G channel. The computational complexity of the proposed algorithm is shown to be low, if compared to other UAV algorithms of position optimization. The work [70] proposes a path planning algorithm for a network of cellular-connected UAVs. The problem is modeled as a dynamic game among UAVs, in which each UAV learns the optimal path and the transmission power along the path, that optimizes the latency and the rate per ground user. To this end, the achievable data rate per user is modeled as a function of the channel characteristics, and the UAV path is planned so that the interference of UAVs on the ground network and the transmission latency are both minimized. Allocation of resource blocks assigned to each user is managed accordingly, so that the per-user data rate is increased. In the work [80] an algorithm is proposed that optimizes the direction and distance of an UAV acting as a BS, depending on the amount of randomly moving users in a sector of the served cell. The users throughput is derived as a function of the SNR; the optimal UAV position is then computed so that the average throughput is maximized in the cell. The latter aspect is also the goal of the work [81], even though the considered scenario here involves a multihop UAV network. The network model proposed takes into account parameters related to the observation area and signal attenuation due to obstacles. These parameters are exploited to derive an analytical expression of the upper bound of the throughput. The optimal locations of UAVs that maximize this bound are found accordingly.

Some papers analyze throughput for the optimization of spectrum efficiency [82,83]. More specifically, in [82] an optimization algorithm is proposed that takes into account data rate. The algorithm aims at maximizing the spectrum efficiency and energy saving of an UAV that relays data between two Ground Stations (GSs), by jointly optimizing the time allocation of data to be received and forwarded, and the UAV speed and trajectory. The expression of the maximum instantaneous throughput is derived for the links between the GSs and the UAV and is used to maximize efficiency with a two-folded scope: spectral and energy. An approach for energy efficiency and throughput improvement can be found in [83]. In this work, a study on the adaptive modulation is carried out for networks of Unmanned Aircraft Systems (UASs) collecting data from some sensor nodes. Based on the analysis of the impact of the UAS trajectory on the modulation scheme, a problem is formulated that maximizes the throughput per energy of UASs, while preserving fairness among transmissions between sensor nodes and UASs. The proposed solution exploits an approach based on the game theory.

An analysis on the impact of the link quality on system throughput is found in the works [84,55]. In [55], a study is carried out on the use of

unlicensed spectrum for UAV-BSs communications in a heterogeneous network with Wi-Fi ground Allocation Policies (APs), to investigate the enhancement of achievable throughput in emergency situations. To this end, a game theoretic approach is proposed, and the related algorithm configures UAV-BSs transmissions to balance the load between UAV-BSs and ground APs. The solution found takes into account the users link quality and the loads of UAV-BSs and APs, aiming to ensure a satisfactory throughput for all the users. The work [84] studies the impact of the characteristics of the wireless link on the system throughput in a UAV-to-ground link. Several parameters are chosen, i.e., antenna orientation, UAV height, yaw and distance between the UAV and the ground access point, for experimental evaluation of throughput performance.

The paper [73] analyzes rate and coverage performance for UAV-based communication with Device-to-Device (D2D) links. To this end, an analytical model for the system sum-rate is first discussed as a function of the UAV height and number of users, in a scenario of a single static UAV transmitting data to a D2D network. Rate performance are derived as a function of Signal to Interference-plus-Noise Ratio (SINR), UAV altitude and density of D2D links. Lastly, it is also show the existence of an optimal UAV altitude and a users density that maximize the rate.

#### 4.3.2. Throughput maximization at data link layer

Several works analyze throughput at link layer, even though the discussion of the proposal is carried out at physical layer [85–92].

In some papers, the throughput analysis is carried out in the framework of VLC systems [85–88]. In [85], an analytical model is developed for the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. It considers the relationship between the physical and MAC layers of the protocol stack. In this context, the paper shows that the multi-packet reception capability of the VLC system, i.e., the capability to decode multiple packets coded with orthogonal sequences, reduces packets collisions and increases the number of simultaneous transmissions, also increasing throughput. A throughput evaluation is carried out in [86]. The goal of this paper is to develop an IEEE 802.15.7 simulation module for ns-2, based on an accurate modeling of the physical layer and of the CSMA/CA protocol at MAC layer. The mean throughput of a system composed by a coordinator servicing 12 nodes is derived, to validate ns-2 simulation results and compare the module performance with a Markov-based analytical model present in literature. A theoretical study of the IEEE 802.15.7 standard that takes into account throughput is found in [87]. The study is conducted at Medium Access Control (MAC) layer, through theoretical analysis and computer simulations. More specifically, a Markov chain is used to model the MAC layer with the use of the beacon frame and CSMA/CA. In this context, closed-form expressions are derived for the main performance metrics, including throughput. The model is then validated through simulation. Also the work [88] evaluates throughput performance at MAC layer in a VLC system where two nodes are in reciprocal Field-of-View (FoV), and one of them continuously transmits data to the other. The MAC layer throughput is evaluated as a function of the frame payload (at a fixed distance) and the nodes distance (with a fixed frame payload). Throughput evaluations are carried out in two configuration scenarios, single-hop (direct communication between two nodes) and two-hop (three nodes, with one node forwarding packets at network layer between the other two).

Access schemes at MAC layer for throughput improvement are discussed in the works [89,90]. A radio access scheme thought for multi-UAV networks with relaying capabilities is proposed in [89], to increase throughput. This work proposes a modification of the classical Long-Term Evolution-Advanced (LTE-A) frame structure, together with a scheduling algorithm that dynamically changes the ratio of DL and UpLink (UL) subframes, to increase the efficiency of relay communication and, thus, the network throughput, especially in cases of longer distances. The work [90] discusses the integration of mmWave



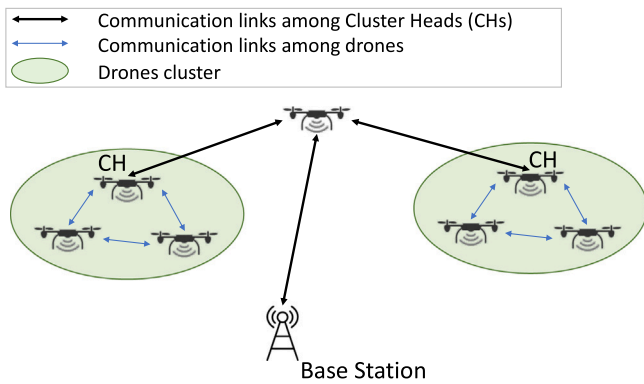


Fig. 8. Communications among clusters/drones swarms and Base Station thanks to relay node.

communications in last-generation UAV-based cellular networks. This work mainly focuses on the design of a multiple access scheme that, in combination with multiplexing techniques and beam-width selection strategies, improves the system throughput in presence of concurrent transmissions.

Resource allocation schemes for throughput optimization are discussed in [91,92]. In [91], a priority-based frame selection scheme is proposed, to optimize throughput and energy saving. This scheme can be exploited to improve the efficiency of data delivery in a sensor network that adopts a single UAV. The framework comprises the frame selection scheme, another scheme that adjusts the CSMA/CA contention window at MAC layer, and a routing protocol that selectively transmits frames based on their priority and the relative distance between nodes. A throughput-aware resource allocation algorithm is proposed in [92]. The model is suitable for data transmission between an UAV and GSs. In this work, the effective throughput is used as requirement to optimally allocate communication resources, expressed as time slots, for communication between the UAV and GSs. Throughput is computed as a function of different parameters, i.e., allocated time slots, modulation scheme and coding rate. The model aims at increasing the minimum throughput, as derived from the solution of the optimization problem.

#### 4.3.3. Throughput maximization at network layer

Throughput is also considered in some papers discussing issues at network layer [93,94,19,95,75,96].

A couple of works focus on relay schemes for throughput improvement [93,94]. In [93], throughput maximization is discussed for multi-hop networks with clusters of relays, as illustrated in Fig. 8. The goal of this work is to find the optimal deployment of relay nodes, in terms of number of hops and clusters locations, that minimize the outage probability, together with the optimal number of relays that maximizes the throughput. The work [94] proposes a relaying scheme that schedules transmission so as to minimize energy consumption, at the same time maximizing the network throughput in presence of bit errors. To this end, an optimization algorithm is proposed, together with a simplification that provides a sub-optimal scheduling solution in a much faster way, at the same time guaranteeing throughput improvements.

Novel routing schemes that take into account throughput are developed in [19,95]. A geographical routing (also referred to as geo-routing) scheme is implemented in [19]. The solution is known by literature and adopted in UAV-based systems. If compared to the classical implementations, the goal of the proposal is to increase throughput and decrease delay. The core of the proposal is a modification of the frame structure at physical layer of the geo-routing scheme with contention-free capabilities, that reduces overhead, as well as reducing delay and increasing throughput. A throughput stability analysis is

found in the work [95]. This work proposes a centralized routing protocol for a fleet of UAVs, that exploits the information coming from a ground control system to keep connectivity among drones and throughput stability, while shortening the route update times.

Network architectures that take into account throughput are found in [75,96]. The proposal discussed in the work [75] is a scheme in which UAVs act as a flying back-haul network connecting ground BSs. The flying network is dynamically formed by choosing the A2A and A2G links and the network topology that maximize a given utility function, through a network formation game approach. The chosen utility function considers the achievable data rate, the number of relayed packets, and delay in both DL and UL directions. A hierarchical network structure is proposed in the work [96], that provides a stable throughput and extends the network lifetime. It is composed by satellites, airships and UAVs. Based on an estimation of the weather conditions, a topology control and routing algorithm are proposed, that distribute the traffic load among the network nodes so that bottlenecks of link capacity can be avoided. In this way, an acceptable performance in terms of network lifetime and average throughput is guaranteed, for different weather conditions.

#### 4.4. Channel modeling and characterization

This section describes all the works related to channel modeling and its analytical description together with the most relevant techniques for characterizing the communication medium in use by drones [97,52,98,68,79,73,99,75,55,100–102,74,103–111,100,112–114]. Different models are presented aiming at mathematically describing several aspects of IoD communication scenarios, that are described in what follows.

##### 4.4.1. Position optimization

Some works analyze the communication channel for UAV position optimization [97,52,98,68,79]. Specifically, the works [97,52] refer to the A2G channel. An A2G channel model is employed in [97] in a network of UAV-BSs. This work proposes a position optimization algorithm, that maximizes the UAV lifetime. In particular, this model is exploited to find the optimal UAV hovering altitude that minimizes the transmission power, and that contributes to find the optimal position of UAVs in a 3-Dimensional space. In this scenario, the A2G channel model is used to compute the average path loss as a function of the environment, the carrier frequency and the type of the link (LoS or NLoS). A channel model is presented in [52] to study small cells of UAVs acting as aerial BSs. More specifically, the A2G channel model is developed, including LoS and NLoS paths and the related path loss. The probabilities of LoS and NLoS connections are derived. Further, those values are characterized in terms of average path loss, which depends on both the UAV height and the coverage radius. This channel model is exploited to find the optimal UAV altitude that maximizes the ground coverage area, and study the coverage performance of UAV-BSs. A channel model is adopted in [98] to propose a solution that minimizes the energy of micro-UAVs in cognitive radio systems. The goal of this work is to find the optimal drone position, and power level, that minimize the UAVs energy consumption. To this end, path loss and channel gain are analytically derived, to model A2G and Ground-to-Ground (G2G) channels. These models are then exploited to solve the joint optimization problem of power allocation and drone positioning. A narrow band channel model is introduced in [68] to study the optimal hovering locations of UAV-BSs to provide wireless connectivity during time-limited events. The model used for the wireless link is expressed as the sum of different propagation paths with different gains from UAVs to users. This model is then used to find the optimal UAVs positions that maximize the user SNR. To this end, an antenna array is adopted; this solution is of interest since it introduces the contribution of beam-forming to the SNR improvement and locations optimization. The same approach of [68] is used in [79], where channel models are



exploited to find the optimal UAV position that maximizes the end-to-end throughput, but without a pointwise knowledge about the whole radio map of the signal strength. To this end, two different channel models are employed: an A2G channel model between the BS and the UAV that exploits the only LoS propagation, and the channel between the UAV and the user, that instead models the path loss exploiting both LoS and NLoS propagation.

#### 4.4.2. Performance metrics analysis and optimization

Channel modeling is tackled for analysis and optimization of other performance metrics in [73,99,75,55,100,101]. In [73,99], the A2G channel is modeled to optimize coverage and rate performance in UAV networks. As known by literature, the model used in these works takes into account three different groups of signals: LoS, reflected NLoS, and reflected signals that cause multipath fading. Similarly to several other works on the topic, LoS and NLoS links are modeled separately to derive the received signal power at users locations. Based on this procedure, the goal of [73] is to analyze the coverage and rate performance in a UAV-aided network in presence of D2D links, while the work [99] aims to derive the optimal coverage probability and deploy multiple UAV-BSs with directional antennas. Other theoretical approaches that model the A2G channel for analysis and optimization of performance metrics are found in [75,55,100]. The work [75] takes into account both A2A and A2G channel models to design a multi-hop backhaul network composed by UAVs. The A2G channel is modeled statistically, through LoS and NLoS links that take into account the higher attenuation due to diffraction and shadowing. The only LoS link is instead considered for the A2A links. These models are then exploited to evaluate the SINR of the A2G link, and the SNR of the A2A link, to derive the achievable end-to-end rate and design the UAVs network formation accordingly. The same approach to the A2G channel modeling adopted in [75] is found also in [55], where the channel is modeled statistically, through LoS and NLoS path loss. The goal of the work is to balance the load between UAVs and Wi-Fi ground Access Points during emergency situations, based on the users link quality. The path loss model is exploited to compute the received SINR that, together with the load balancing requirement, determines the best association between the user and the BS. Differently from the studies mentioned above, the work [84] focuses on A2G channel measurements to characterize path loss exponents in the UL and DL channel, in two different environmental scenarios. Several parameters are considered in the field experiments: antenna orientation, UAV height, yaw and distance. The impact of these metrics on the Received Signal Strength (RSS) and throughput is evaluated. A channel model is adopted in [101], that proposes a strategy for optimization of resource allocation so that the transmission delay of packets in an UAV-based cellular network is minimized. Part of this study is dedicated to the communication channel model based on non-LoS paths with Rayleigh fading. This model is then used to derive the power received at destination node, that is exploited to derive the transmission rate first, and then the mean packet arrival rate and transmission delay, that are optimized by solving an optimization problem.

#### 4.4.3. Altitude-dependent channel models

Some works develop channel models that take into account the influence of UAVs altitude [102,74,103–105]. The works [102,74] propose an A2G channel model to study the effect of the altitude of an UAV-BS on some performance parameters, i.e., power, capacity gain [102], path loss and scattering [74]. The optimal UAV height is found that brings to the best trade-off between the optimal values of these parameters, through an extension of the A2G channel model that takes into account the UAV height in path loss and fading. The validity of the proposed model is tested also for low-altitudes UAVs. The work [103] focuses on the analysis of A2A channel features. Its goal is to extend the Rice model, which is usually involved in theoretical characterization of the A2A channel. Such studies are usually conducted by

varying the UAV altitude, to provide a more accurate description of the multipath effect. Based on real RSS measurements, an estimation of the main Rice model parameters that describe the fading and multipath effects is derived, in dependence of the UAVs altitude. The Rice channel model is extended accordingly. Modeling of the propagation channel for low-altitude UAVs is the goal of [104]. The UAV communication channel is studied through narrow-band and broadband measurement campaigns carried out in a suburban area, capturing the main channel characteristics: path loss, fading, power delay profile, multipath components, and root-mean-square delay spread. This work carries out an analysis of the A2G channel characteristics for low UAVs heights. The work [105] is entirely focused on channel models. Its primary goal is to model the path loss exponents of the radio link between an UAV acting as UE, and the cellular network. The proposed model takes into account the height of the UAV, which is exploited to model both the path loss exponent and the shadowing effect. The model is validated in a real scenario, using a UAV connected to two different LTE networks.

#### 4.4.4. mmWave communications

Channel modeling and characterization are developed for mmWave communications in [106–110]. A2G channels for UAV communication in the mmWave band are the main topic in [106]. The goal of this work is to analyze the main characteristics of the A2G channel in different scenarios, each under different mmWave propagation conditions. Simulations are used to study the channel characteristics between a fixed ground station and a UAV that moves along a linear trajectory at a constant velocity. The height of the UAV varies to test and study different conditions. The most suitable model for the RSS behavior is derived accordingly. In the work [107] channel modeling is discussed for mmWave communication in UAV cellular networks. Channel characteristics are illustrated, discussing the most relevant issues of mmWave propagation, in terms of propagation loss, scattering, multipath components, and reflections around the UAVs. The most suitable channel model is then chosen to derive beam-forming vectors for different users. mmWave channel for DL transmission is studied in [108], in a network of UAVs connected to cellular BSs. The model takes into account the multipath and the angles of departure, the height and horizontal distance of the UAVs from the BSs, the transmit antenna structure at the BS (composed by an antenna array), and the path loss of the DL channel. The LoS component of the paths is considered as predominant in this model, that is not suitable for low UAVs altitudes. The goal is the evaluation of energy efficiency in multiple access schemes for mmWave DL communications. The work [109] analyzes the coverage performance of cellular networks assisted by UAVs in mmWave communications. To this end, a channel model is introduced. It is designed as to exploit only the LoS component of the links between UAVs and mobile terminals. Due to the adoption of mmWave technology, the model takes into account the possibility that the LoS signal is blocked by obstacles. Also small scale fading and shadow fading effects are considered, through probability distributions. This model is exploited to define the strategy of user association and a cooperative clustering scheme for UAVs that maximize the coverage performance of the network. The characteristics of a mmWave channel in UAV communications with an antenna array are investigated in [110]. The channel is characterized thanks to the Inverse Discrete Fourier Transform (IDFT) to obtain an analytical description of the channel behavior in the discrete time domain. The main parameters of this description are estimated to provide a channel tracking method that takes into account angle information, Doppler shift and UL/DL channel gains.

#### 4.4.5. Environment representation and characterization

Some papers exploit channel models in specific environmental scenarios [111,100,112]. An algorithm to learn the channel characteristics between a UAV and a ground user is proposed in [111]. To this end, the radio channel is characterized through a propagation model based

on a representation of obstacles whose configuration is stored into a map, together with other channel parameters. These data are used to estimate and reconstruct the channel propagation characteristics based on a reduced set of measurements, with relatively small prediction errors in the radio map reconstruction. In [100] an A2G channel model is described and used for UAV-BSs providing wireless service to ground users. As discussed in other works [75,55], the probability of LoS link between the UAV and the user is evaluated, as a function of the environment and the horizontal and vertical distances between the UAV and the user. Based on this, the path loss is modeled and used to evaluate the conditions in which the ground user can be served by the UAV. A type of A2G channel model that takes into account detailed information (i.e., shapes, intersections and heights of buildings, reflection, diffraction, propagation mechanisms, etc.) is presented in [112]. Its main goal is to accurately characterize the path loss characteristics of the links between UAV-BSs and users, to derive a model suitable for altitudes both lower and higher than the buildings heights. The model parameters are optimized, based on the UAV altitude, so that the root-mean-squared-error is minimized.

#### 4.4.6. Frequency-related modeling and analysis

A couple of works deals with the specific problem of characterizing the channel in the frequency domain [113,114]. The work [113] proposes a technique to estimate and compensate the Inter-Carrier Interference (ICI) for high speed UAVs. Based on the analytical expression of OFDM symbols, the channel matrix estimation is performed in the frequency domain, to accurately estimate the Doppler effect and the amplitude of all paths. A classification framework that takes into account both spatial and spectral information is, then, adopted, to correctly evaluate the received data, and the channel estimation and equalization method. A theoretical channel characterization is proposed in [114] to equalize channels that present selectivity in both time and frequency domains (the so-called double-selective channels). In this work, doubly-selective channel equalization is studied for the transmission of continuous phase modulated signals, that usually present a high computational complexity. The goal is to present new equalization techniques that simplify the equalizers, even at a cost of approximations. To this end, the channel impulse response is characterized through a causal Finite Impulse Response (FIR) system.

### 4.5. Communication technologies

The right choice of the wireless technology used for drones' communication (LTE, Wi-Fi, VLC, WiMax, etc.) is of paramount importance to optimize the communication performance of networks of drones. It depends on many factors, thus including the type of the UAV tasks, their duration, the environment, drones' mobility, communication range, limitations on transmitted data or energy consumption: technologies like cellular networks, WiMax, and satellite communications guarantee a wide coverage area, high transmission bandwidth, high throughput and reliable connectivity, but are energy-consuming and often introduce high delays. Counterwise, technologies like Bluetooth and Zigbee have an extremely low power footprints, data degradation, implementation costs and delays, but also a low transmission bandwidth, throughput, and are more subject to interferences caused by obstacles. All these aspects are covered in the works [115,65,66,57,108,90,58,64,106,107,110,15,17,116,117,98,55,118].

#### 4.5.1. WiFi communication technology

WiFi technology is explicitly addressed in the papers [115,65,66]. The work [115] mentions the Wi-Fi technology to build an ad-hoc network and implement a communication protocol for high-quality video transmission between drones sensing an area and mobile devices. The proposed protocol introduces an ad-hoc routing protocol that allows three drones to work together in the same network and expand the sensing area. Wi-Fi is also used in [65], to implement a distance control

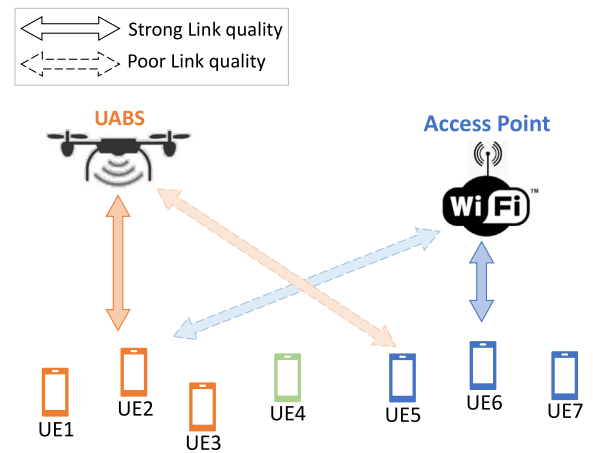


Fig. 9. Cellular technology aided by an Unmanned Aerial Base Station (UABS) combined with Wi-Fi to provide connectivity to User Equipments (i.e., users).

algorithm, that finds the optimal distance between two UAVs that maximize the stability of the wireless communication, and minimize the number of UAVs utilized to cover a given area. In [66] Wi-Fi is chosen as the most suitable technology for an A2G communication network composed by UAVs and ground users, as illustrated in Fig. 9. The goal of this study is to keep a service continuity when a UAV is replaced because of limited battery lifetime. The choice of Wi-Fi is motivated with its ease of deployment, the use of unlicensed spectrum, and the need to support applications with different values for throughput in the same network.

#### 4.5.2. mmWave communication technology

Several works analyze the mmWave technology for UAV-aided networks [57,108,90,58,64,106,107,110,15].

The mmWave technology is introduced in the work [57] to propose a strategy for an UAV to find automatically and accurately its optimal relay position, so that data can be forwarded in short time. mmWave communication advantages (very high frequency and increased bandwidth, short wavelength that allows beam-forming) and disadvantages (attenuation in free space propagation, blocking effect due to obstacles and objects) are described in detail, to justify the need of wide employment of the relaying technique in mmWave communications.

The adoption of mmWave in UAV-aided cellular networks is investigated in [108,90,58]. In [108,90] multiple access schemes are discussed for mmWave communications. The mmWave channel model is introduced in [108] to evaluate the energy efficiency of different multiple access schemes in a cellular-connected network that uses UAVs. The paper [90] proposes a multiple access scheme design for 5G mmWave UAV networks acting at both the PHY and MAC layers, where concurrent transmissions are multiplexed into a single beam so that interference in the single beam is transformed into concurrent transmissions, and interference among adjacent beams is reduced. In [58], different aspects related to the mmWave technology are investigated: (i) the channel propagation characteristics, (ii) the implementation of beam-forming techniques that account for channel variations, (iii) the impact of the Doppler effect due to UAVs mobility, (iv) and the adoption of spatial-division multiple access for mmWave to increase the network capacity. Some algorithms for optimization of UAVs mobility are also considered, to avoid signal blockage. Finally, the relationship between UAV positioning and user discovery is discussed, to analyze the reciprocal impact of one over the other.

The mmWave technology is exploited in [64] to model backhaul links in UAV-assisted networks in urban environments, with UAVs once again acting as relay nodes. This work develops a mathematical model that takes into account the multipath propagation and the blockage

effect of the mmWave backhaul link, as well as the mobility of both signal blockers (humans, objects, etc.) and UAVs. These phenomena are accurately modeled by using the 5G New Radio technology, which is a backhaul architecture with reconfiguration capabilities that dynamically reroutes data to alternative paths, to increase connectivity and data reliability. The study of mmWave backhaul performance is conducted in both spatial and temporal domains.

The main goal of [106] is to characterize the mmWave A2G channel used by UAVs communications through simulations. Two mmWave bands are chosen for simulation, analyzing the RSS and Root Mean Square Delay Spread (RMS-DS) of Multipath Components (MPCs) for different UAV heights and environments (urban, suburban, rural, and over sea). Simulation results are also exploited to build a channel sounder.

Training and tracking strategies for mmWave UAV communications are presented in [107,110]. The design of beam-forming codebooks with different beam widths is proposed in [107]. It starts from the analysis of the channel propagation characteristics, to fasten the beam-forming training and tracking phases. The impact of the Doppler effect due to UAVs mobility is investigated, also carrying out an analysis of spatial-division multiple access schemes and signal blockage events. Moreover, a channel tracking strategy is presented in [110]; based on the analysis of the mmWave UAV channel with a beam squint effect, the proposed channel tracking method exploits the information on angle and Doppler reciprocity to obtain the channel state information exploiting only one pilot symbol, and reducing the feedback overhead.

#### 4.5.3. Machine-type communications

The works [17,116,117] analyze different technologies for Machine-Type Communication (MTC) in UAV networks. In [17] they are mentioned to discuss D2D communications in public safety applications scenarios. This work is mostly a review paper on the recent advances in D2D technology, and tackles the issues of device discovery, D2D clustering and relaying, and Vehicle-to-Vehicle (V2V) communications. In this context, together with the D2D technology as standardized by 3GPP rel.13, to increase coverage capabilities in critical situations, several other technologies are discussed. The latter are considered as candidates since they allow D2D communication in unlicensed spectrum: Wi-Fi, Bluetooth, and ZigBee [17]. All the aforementioned technologies also propose interesting advantages in terms of high data rates, low latencies, and implementation costs. Moreover, they are widely adopted on mobile phones and devices, in general. The paper [116] focuses on mission critical Machine-Type Communication (MTC) and investigates some connectivity options like D2D links and drone-assisted networks to satisfy the MTC requirements. Specifically, LTE technology is combined with Wi-Fi for D2D communications between mobile devices and UAVs, to increase connectivity and data reliability. In addition, the mmWave technology is studied in the scenario of small cells of drones that act as Access Points to increase the network coverage where the performance of the LTE network is poor. The technologies introduced in [117] are used to describe the main specifications of localization techniques in a M2M network composed, among others, by drones. The main goal of this paper is to propose a mathematical model that describes the structure of the M2M network able to adopt agents for efficient localization of nodes.

#### 4.5.4. Other communication technologies

Other communication technologies can be found in [98,55,118].

The Cognitive Radio (CR) technology is analyzed in [98] and it is proposed as a promising solution to mitigate the main issues in spectrum utilization of the other wireless technologies (Wi-Fi, Bluetooth, or cellular communications) for UAV-based applications. The CR technology allows to access the spectrum in an opportunistic way, by sensing it through advanced radio techniques, and to transmit data over bands that are not utilized by other transmissions. It also allows the simultaneous usage of the same spectrum to serve different users,

without exceeding an interference threshold. This paper proposes an energy-efficient optimization strategy, that finds that optimal UAV location and transmission power level so that a UAV can send data using the CR technology, while respecting the data rate threshold of the spectrum owner.

The work [55] investigates the possibility of using the Long-Term Evolution–Unlicensed (LTE-U) technology for communication among UAV-BSs, to increase throughput by exploiting the unlicensed spectrum. In critical scenarios, UAV-BSs make use of LTE-U to fill coverage gaps due to the damaged infrastructure that adopts Wi-Fi. The goal of this hybrid infrastructure is to quickly deploy an on-the-fly cellular network able to fill the gap of throughput requirements of the damaged Wi-Fi ground network, through a game theoretic approach that selects the radio access technology technique that achieves load balancing among LTE-U UAV-BSs and Wi-Fi APs.

Optical wireless communication is studied in [118] for the so-called Free Space Optical (FSO) communication systems. The latter exploits the optical signal for high data rate communications over relatively long distances. This paper focuses on FSO systems where UAVs act as relays. The study is conducted by assuming that relays are buffer-aided, and they can move in the space (i.e., they are not stationary), and evaluates the impact of these two assumptions on the FSO system performance. Two application scenarios are also discussed and validated through simulation by taking into account the outage probability as performance metric.

#### 4.6. Comparison with other surveys

Several topics related to the physical layer are discussed in the surveys [12,3,5,11,8,15]. Connectivity is discussed in [12,3]. Nevertheless, in both these works the analysis is only related to coverage strategies and in some specific application scenarios or network architectures. Some works deal with throughput maximization and evaluation, i.e., [3,5,11]. The related analysis mostly refers to routing strategies, even though some insights are provided for hybrid network architectures [5,11]. A throughput analysis is also provided in [8,5] but without analyzing novel strategies for its optimization. Channel modeling and characterization is partially discussed in [5,15]. Nevertheless, in the survey [5] the channel analysis and modeling is tightly bounded to measurement systems for the A2G links of low-altitude UAV networks and platforms. Similarly, in the review work [15] channel characterization is studied with the only reference to the mmWave technology, pointing out the most significant challenges and opportunities related to this topic. Together with the work [15], also the survey [11] analyzes and classifies in detail the most widely used communication technologies for IoD scenarios. The drawback of the approach followed in [11] is that this survey neglects other newer technologies, such as mmWave or VLC.

If compared to the surveys mentioned above, the value added of this survey is to enhance and complete the analysis on the topics already covered by them, also adding topics that have not been discussed. More in detail, in the present survey the connectivity issues are also related to proposals for resource allocation and optimization, relaying and routing, cooperative networks and path planning and optimization strategies. A more complete throughput analysis is carried out at network layer, with a dedicated focus on optimization strategies, while covering other aspects at physical and link layers. Channel modeling and characterization is described with reference to position (including the height of the UAV) optimization strategies, adding the discussion on frequency-related modes, and collecting and describing more papers that propose an analytical representation and characterization of the environment. Communication technologies are broadly discussed, including mmWave, CR, LTE, FSO and MTC systems. Finally, papers on the theme of modulation techniques, which are not covered by all the other surveys, have been introduced and described in detail.

#### 4.7. Lessons learned

Important lessons emerge from the analysis of the physical layer aspects covered in the IoD papers.

The modulation techniques analyzed for UAV-based networks are not novel by themselves. The main novelty lies in their application in the context of FANET. As known in fact, drone detection and classification is a very important issue for UAVs, especially to face security issues, and this task can be accomplished by detecting the modulated signal at physical layer as testified by some of the surveyed papers. Efficient modulation techniques borrowed from other wireless network systems like LTE also help to increase the efficiency of the transmitted signal, with respect to noise reduction and transmission power optimization.

The analysis of drones' connectivity and channel modeling are tightly bounded together, and are both important to increase coverage performance, to optimally allocate resources at different layers of the protocol stack, and to increase the path reliability in routing, path planning and position optimization strategies. Nevertheless, connectivity and channel models and schemes tend to be not so accurate because they cannot take into account several aspects at the same time, for example, the presence of obstacles in urban environments, signal dispersion and interferences, height and mobility of drones. Thus, some of the conclusions are only valid under simple hypothesis. Furthermore, the optimization problems for resource allocation, path planning and routing algorithms bring to solutions that are computationally expensive, or suboptimal.

The analysis and the optimization of throughput allows to increase the system performance in data exchange and to optimize different metrics in IoD systems (mutual distance, positions and paths of drones, spectrum and energy efficiency, network topologies). With respect to this theme, in most cases, the throughput optimization translates into solving an optimization problem. Unfortunately, the obtained solutions are computationally expensive, or found approximately, or only valid in over-simplified scenarios and/or conditions. Furthermore, throughput maximization is counterbalanced by a higher energy consumption, which can become a serious drawback for battery-powered drones.

Performance of networks of drones can be increased also by choosing the most appropriate communication technology, depending on several factors like the specific environmental scenario, type and duration of tasks, communication range and energy consumption of drones, among others. Several works on this topic are mainly review papers; the most interesting aspects raised by papers on this topic lie in the exploitation of peculiarities of the chosen technology to optimize specific transmission aspects, such as spectrum utilization, data rate, and distance of nodes.

### 5. Data link layer

In this Section, some relevant issues at link layer are discussed. They are mainly focused on two different aspects: (i) the allocation and optimization of resources, and (ii) data scheduling. The Section closes up highlighting the lessons learned on the theme. The overall organization of this Section is reported in Fig. 10.

#### 5.1. Resource allocation and optimization

Papers on resource allocation at link layer are mostly focused on the optimization of different performance metrics, such as PDR, packet error probability, bandwidth, delay, throughput, and energy efficiency.

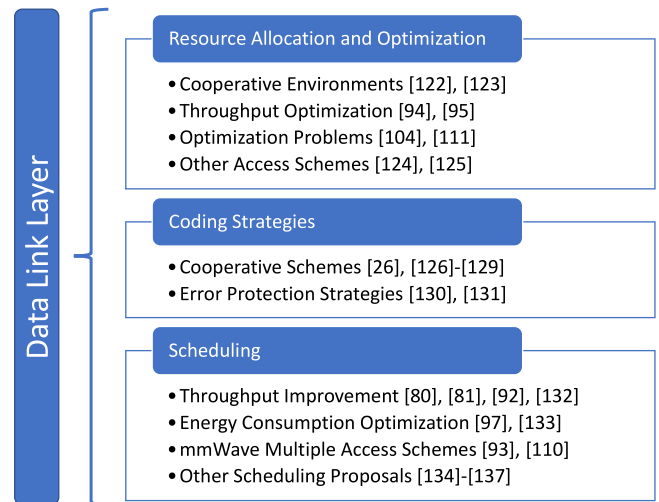


Fig. 10. Data link layer taxonomy.

##### 5.1.1. Cooperative environments

Schemes at MAC layer in cooperative environments are proposed in [119,120]. A packet loss tolerant algorithm is proposed in [119] to mitigate the communication disruption and help improving cooperation in networks of robots. The proposed algorithm aims at accomplishing a specific task despite link losses, guaranteeing cooperation and coordination among wireless networked robots. The network of robots is composed by one leader and several followers, and the goal of the algorithm is to set position, velocity and control of the followers so that they are always able to follow the leader. Depending on the amount of packet loss, the control input is periodically corrected to reduce the error, or bias, that each robot accumulates in the link with the other robots. A MAC protocol is proposed in [120] to reduce the packet error probability in WSNs where a UAV collects data from sensor nodes. The proposed protocol is part of a data collection scheme that exploits cooperation between a UAV and different sensor nodes. In this protocol, sensor nodes are allowed to transmit data on the basis of a polling signal that gives them the chance to transmit data, which can belong to the single sensor or come from cooperative sensor nodes that collect data from other nodes. The MAC protocol manages also the construction of the cooperative sensor node list, and establishes which data must be retransmitted through the chosen cooperative sensor node.

##### 5.1.2. Throughput optimization

Schemes for throughput optimization are presented in [91,92]. A data acquisition framework is proposed in [91] to increase the efficiency of data gathering in UAV networks. The main goal is the optimization of the system throughput through a scheme that assigns different priorities to UAVs in different areas. To this end, a modification of the contention window mechanism at MAC layer is proposed, that lowers the range of the contention window sizes to areas with high priority, and increases it for lower priority areas. This approach allows reducing packet collisions and losses, especially when the UAV moves in the forward direction. A resource allocation method is presented in [92] for a wireless network composed by UAVs and GSs. Exploiting the Time Division Multiple Access (TDMA) scheme, resources are allocated in the communication channel between the UAV and the GS by taking into account mission-specific and environmental requirements. The beforehand knowledge of the UAVs throughput, that depends on the UAV specific mission, is exploited in the TDMA-based allocation scheme, to derive the optimal allocation of the different time slots and respect the throughput requirements of each UAV. Two different priority degrees of the UAVs are also considered in the time slots assignment.



### 5.1.3. Optimization problems

The mechanisms proposed in the works [108,101] bring to constrained optimization problems that can be solved through standard methods and/or approximations with reduced computational complexity. Several Multiple Access (MA) schemes are analyzed in [108] for mmWave UAV cellular-connected networks, with respect to energy efficiency. Two specific MA schemes, i.e., Rate-Splitting Multiple Access (RSMA) and Non-Orthogonal Multiple Access (NOMA), are analyzed in detail and optimized to maximize the energy efficiency for mmWave DL transmissions, taking into account real propagation patterns from antenna elements in last-generation wireless networks. The energy efficiency optimization problems for both the MA schemes are computationally very expensive, so an approximate algorithm is proposed to provide a solution. The work [101] proposes a resource allocation mechanism that has the objective of minimizing the mean packet transmission delay in a cellular network with UAVs placed in a 3D multi-layered structure. Delay is first derived analytically through a queuing system that models the mean packet arrival rate. Then, it is minimized by solving an optimization problem that allocates spectrum and power for each layer in a two-layer UAV network, through standard procedures.

### 5.1.4. Other access schemes

Other access schemes for resource optimization are developed in [121,122]. The goal of the access scheme proposed in [121] is the optimization of the accuracy in the medium access procedure. The proposed scheme helps an UAV when joining an ad-hoc UAV network by correctly identifying the MAC protocol without demodulating the property field MAC header, which can be very difficult in particular situations (i.e., when channel attributes strongly change due to interferences). The identification of the MAC protocol is performed adaptively through machine learning methods that include a classifier, the latter is able to identify MAC protocols according to features extracted from the channel attributes, improving the access accuracy.

The paper [122] proposes a MAC layer protocol that optimizes the data transmission by sharing the information on the reciprocal position among UAVs. This information is useful to reduce the packet overhead at MAC layer, and to exchange control packets between neighboring nodes with the goal of increasing the effectiveness of mutual communication between drones and pointing directional antenna of transmitting UAV towards the UAV receiving data, so that the link can be established quickly, the delay in data reception is lowered and the throughput can, hence, be increased.

## 5.2. Coding strategies

Some papers analyze and propose coding strategies at link layer for UAV-based networks [123,124,26,125–128]. Most of the surveyed papers on this topic analyze Network Coding (NC) [123,124,26,125,126]. NC is a technique that aims at saving time and bandwidth resources when trying to recover information from packets transmitted at link layer. It relies upon the principle that a transmitted packet includes kind of “repair information” for previously sent packets. The destination node uses this received repair packet in combination with previously received packets already stored in the receiving buffer, to recover the original information contained in the previously received packets. This concept can also be extended to multi-hop environments, since the information in a repair packet can be properly encoded so that it can be exploited by multiple nodes. The advantage of NC techniques is that the transmission time of a repair packet is usually much smaller than the time needed for an independent transmission of several packets, thus saving time and bandwidth, and increasing spectral efficiency [26].

### 5.2.1. Cooperative schemes

In the context of UAV-assisted networks, NC is usually exploited in combination with cooperative techniques in multi-hop scenarios [26,123–126]. Cooperation is a topic peculiar of the network layer (as pointed out in Section 6.1); nevertheless, the NC techniques analyzed in these contributions are developed at link layer. Network coded scenarios are tackled in [26]. This work proposes a strategy to improve the QoS in UAV-aided networks that transmit high-quality video streams. QoS is evaluated in terms of reduced delay and increased throughput. In this context, NC acts in combination with an application layer ARQ protocol, and relies on a cooperative technique where several nodes adopt a broadcast transmission of packets. Each node stores multiple packets, and performs an XOR operation among them to build a single coded packet. On top of that, the packet is forwarded to a destination node which, in turn, decodes the packet XORing it with the packets already stored, thus increasing the spectral efficiency. The works [123,124] focus on a drone acting as a relay node in Network Coded Cooperation (NCC) for wireless networks. The adoption of an UAV as relay node gives a higher degree of freedom in terms of mobility. As a relay node, the UAV receives packets from different sources, in different time slots, performs NC over all the received signals, and transmits the coded packet to all the destinations. Based on the statistical distribution of the fading channels linking the sources, the UAV and the destinations, the contributions of these paper are related to a formulation that leads to analytically deriving expressions for: the network coded noise and its variance, the overall SNR at destination node, and the rate [123], as well as a closed-form expression for the outage probability and the impact of drone height on the outage probability [124]. Cooperative multi-hop networks of drones are analyzed in [125,126] for data exchange by means of NC. An Instantly Decodable Network Coding (IDNC) technique is proposed in these works, whose goal is to reduce the energy consumption and delay due to the NC operations in a cooperative multi-hop network. This problem is modeled through a cooperative game theoretical approach [125,126]. The NC metrics, such as decoding delay, completion time, delivery time and rate, are considered in the optimization problem and contribute to partition the network into coalition groups that take into account energy efficiency, together with delay. The main contribution in [125] is to define a scalable, low-complexity approach for the cooperation in the IDNC game that takes into account energy consumption. This approach is further enhanced in [126] by decentralizing the dynamic choice of the transmission power by each of the network nodes; furthermore, the stability of the cooperative game is studied, demonstrating its convergence to a stable coalition structure.

### 5.2.2. Error protection strategies

Other coding strategies are useful to protect information from errors and noise, as testified in papers [127,128].

A packet coding strategy is adopted in [127] for delay constrained applications transmitting video over fading channels. The proposed scheme makes use of the so-called cross-packet coding strategy, that is based on several transmissions of the same information message occurring from the moment of message availability to the message decoding deadline. During this period, the subsequent retransmissions of the message are coded with different code rates, so that additional protection bits in subsequent retransmissions can contribute to increase the probability of successful decoding of the message. Differently from the conventional cross-packet coding strategies, the proposed scheme does not consider any feedback and does not remove protection bits related to the previous transmissions, so to reduce the retransmission delay and keep a low frame error rate.

A convolutional denoising encoder is exploited in [128] to reduce noise due to the drone flight and the wind when transmitting recorded audio signals in UAV sensor networks. It makes use of convolutional neural networks that are trained with datasets obtained by mixing drone flying and wind noises with speech signal. The time–frequency features of the speech signal are extracted and used to eliminate the noise contribution from the target speech.



### 5.3. Scheduling

Scheduling of information exchanged among drones is another challenge usually tackled at link layer. Papers on this topic schedule the data transmission so that specific metrics, i.e., successful data rate and throughput, energy consumption and interference among drones, can be optimized.

#### 5.3.1. Throughput improvement

Scheduling at link layer can be useful to optimize communication throughput, as testified by [89,77,78,129].

A radio access scheme thought for improving relaying capabilities in a multi-hop UAV-based network is proposed in [89]. In this scheme, the number of DL and UL subframes scheme is dynamically changed by first changing the structure of the frame, and then scheduling the UL and/or DL subframes allocation in the frame to each node, so that the throughput of the communication links is improved also for relatively long distances between the communicating nodes.

A UAV-aided network is studied in [77,78] where a UAV is used as a flying BS to serve a group of ground users. A scheme is proposed in [77] that maximizes the minimum average throughput among all users by jointly optimizing the scheduling of data sent by users and the UAV trajectory, given a periodic/cyclical TDMA scheme of fixed period. The optimization problem is solved through an iterative algorithm that alternatively optimizes the user scheduling and UAV trajectory at each iteration, and whose convergence to the optimal solution is proven to be guaranteed. The same network scenario is also presented in [78], but with the addition of a ground BS to the UAV and the ground users. The performance metrics optimized in [78] are the same of [77] (average throughput and UAV trajectory), with, in addition, the users partitioning between the UAV and the ground BS.

Throughput optimization in UAV swarm networking is proposed in [129]. An UAV smart network is composed by multiple heterogeneous UAV swarms. In the proposed scheme, communication among UAVs relies on the novel 5G New Radio technology, that allows packet delivery with a reduced energy consumption through beamforming. As first step, the throughput optimization is formulated in terms of a max-min throughput approach aiming to maximize the minimum throughput, for both full-duplex and half-duplex modes. Based on this, an optimal scheduling approach is proposed, that allocates the transmission time for each connection to maximize the number of connections among swarms and minimize collisions between the UAVs beams, thus achieving throughput maximization. This optimization is applied to each swarm and among different swarms.

#### 5.3.2. Energy consumption optimization

Also the energy consumption can be reduced through effective scheduling, as illustrated in [94,130]. The scheduling algorithm is proposed [94] optimizes the energy consumption in cooperative networks of drones with relaying capabilities. At the same time, it guarantees a target rate of successfully received packets. The goal of the algorithm is to schedule the transmitted packets so that the energy consumption is minimized, at the same time guaranteeing a target bit error rate. The problem is solved by means of integer programming techniques, even if its solution is NP-hard. A suboptimal algorithm is then proposed to reduce the computational overhead due to the problem complexity. A packet scheduling strategy is proposed in [130] for UAV-aided WSNs, where multiple UAVs relay data from a WSN sensor to a ground BS. The proposed scheme aims at saving energy in presence of lossy channels, and at increasing the UAVs lifetime. The scheduling mechanism relies on the channel quality indications reported by the UAVs to the BS, which in turn establishes the optimal subset of packets that each UAV must send to the BS, so that a target packet success rate is guaranteed, also minimizing the maximum energy consumption of all the UAVs. Since the optimization problem is NP-Hard and very expensive for a computational point of view, a suboptimal solution is proposed that achieves a faster convergence.

#### 5.3.3. mmWave multiple access schemes

The works [107,90] study users scheduling in multiple access schemes for UAV communications adopting the mmWave technology. A study on Spatial-Division Multiple Access (SDMA), or Beam-Division Multiple Access (BDMA), in mmWave communications is carried out in [107]. The scheme is based on a BS equipped with multiple transceivers, and each UE is equipped with a single transceiver, so that multiple users can transmit over a single beam and the achievable rate can be boosted. The main challenges of such a scheme are described, i.e., how to wisely schedule different users into a group, and allow different groups to access simultaneously the BS while minimizing the reciprocal interference. Multiple access for mmWave communication in UAV-aided 5G networks is analyzed in [90]. The proposed scheme takes into account the transmission of multiple highly directional beams that are peculiar of mmWave communication, allowing access to different users for each beam, both for UL and DL links. The goal of the scheme is to adapt the beamwidth to the channel quality indication and transmission requirements of users, to establish the best user grouping strategy that selects the users that have to concurrently transmit data in a single beam. The proposed algorithm aims at improving the overall system throughput.

#### 5.3.4. Other scheduling proposals

Other scheduling proposals at link layer are found in [131–134]. [131] discusses a scheduling scheme that takes into account bandwidth requirements during both upload and download phases as a function of services requests to provide dedicated tradeoffs. The simulated solution is a priority-based service scheduling scheme able to increase service quality while granting fresh data. As a consequence, the average request serving latency.

The paper [132] proposes different data collection algorithms in a wireless sensor network assisted by an UAV. The goal of the algorithms is to increase the efficiency of data collection by taking into account transmission data rate and contact duration time between the sensors and the UAV. Based on synchronization and join messages between the sensors and the UAV, contact duration time, data rate and available time slots are derived. This information is then exploited to schedule the assignment for the time slots available to the single sensor to transmit data. The effectiveness of the algorithms is evaluated with respect to number of collected packets and fairness in data transmission among sensors.

In [133] a fault detection and scheduling mechanism is studied for a drone that exchanges information from different sensors through a communication network. The focus of this study is the transmission of information on fault detection in drone motors. To this end, the scheduling mechanism proposed in this work aims at preserving the medium access, while enhancing the accuracy and rapidity of information exchange among the different parts of the system. Communication constraints and the possibility of packet drops are taken into account too.

The paper [134] proposes an algorithm that maximizes data collection in a UAV-enabled mobile sensor network composed by a UAV and several ground mobile nodes. Depending on the topology-based parameters that characterize the network (i.e., UAV height and velocity, mobile nodes position and velocity), the proposed algorithm jointly maximizes the number of collected packets at link layer and the number of nodes that can successfully send a packet to the UAV. The solution of this optimization problem is a scheduling technique that optimally selects the frames to be sent by the nodes, so to enhance the transmission opportunities of the nodes with shorter contact duration with the UAV. The algorithm is also tested in a real experiment scenario.

#### 5.4. Comparison with other surveys

The surveys that discuss link layer aspects for drones' communications are found in [8,3,13]. In [8] the surveyed papers on data link layer are analyzed with a dedicated focus on energy consumption aspects. The classification of the related approaches is based on the way energy is saved, which nevertheless is not the only issue of UAV communication at link layer. Link layer approaches are mentioned in [3] for the formation of UAV ad-hoc networks. In this work, the main challenges, i.e., synchronization among nodes, delays, resource reservation, access management and error control, and modified MAC protocols, are summarized, citing only one paper that overviews them. So, unfortunately, no detailed discussion is carried out in [3] on this topic. In [13] some link layer issues are addressed with respect to the cooperative robotic networks. They are mainly related to the severe limitations of signal propagation, that require the design of new MAC protocols. Some works on the most promising approaches are discussed, ranging from the well known TDMA, Frequency Division Multiple Access (FDMA) or Carrier Sense Multiple Access (CSMA) schemes, together with Medium Access Collision Avoidance (MACA) and hybrid schemes, with an additional analysis on the amount of control information for channel reservation. The main drawback of this classification is that it only refers to cooperative robotic networks that operate in underwater environments, and the surveyed works mentioned in [13] do not basically propose any novel technique at MAC layer.

If compared to the papers mentioned above, the main goal of this Section has been to integrate and further develop their analysis, presenting all the most recent approaches discussed for UAV networks in a broader range of link layer related topics.

#### 5.5. Lessons learned

The analysis of the proposals discussed in this Section allows to acquire important knowledge on the pros and cons of resource optimization and scheduling strategies at link layer, as well as coding strategies. Almost all of the proposed algorithms reduce packet losses and increase throughput. These major enhancements are important to improve the performance of communication links, especially in critical scenarios. Nevertheless, significant modifications to MAC layer protocols are needed (i.e., the variation of some protocols parameters, additional prediction/estimation algorithms or metrics, etc.), that can create interoperability problems with the UAV-based networks that adopt the classical link layer protocols. Relevant integration efforts are, hence, needed. Cooperative schemes are also useful to improve communication efficiency and reduce packet losses at MAC layer, but they introduce a data overhead needed to share information in the cooperative nodes. This complicates the implementation of scheduling mechanisms needed to decide which node must transmit the information, when, and at what frequency. Tight synchronization mechanisms are another critical point that raises in this scenario. Another consideration is that the optimality of resource allocation and scheduling often translates into finding the solution of complex optimization problems, whose convergence is not guaranteed, and that can be solved only at the cost of simplifications that, nevertheless, bring to suboptimal solutions. Coding strategies are helpful to increase the efficiency of the communication link, in terms of time and bandwidth saving, and increased spectral efficiency. They are always associated to cooperation strategies, to increase QoS metrics in cooperative networks. The drawback of this strategy is the additional time needed to decode packets, and the increased computational complexity for encoding and decoding operations, if compared to the simple packet retransmission. This explains why the research efforts are actually focused on low-complexity techniques, that can scale well in networks with a large number of UAVs.

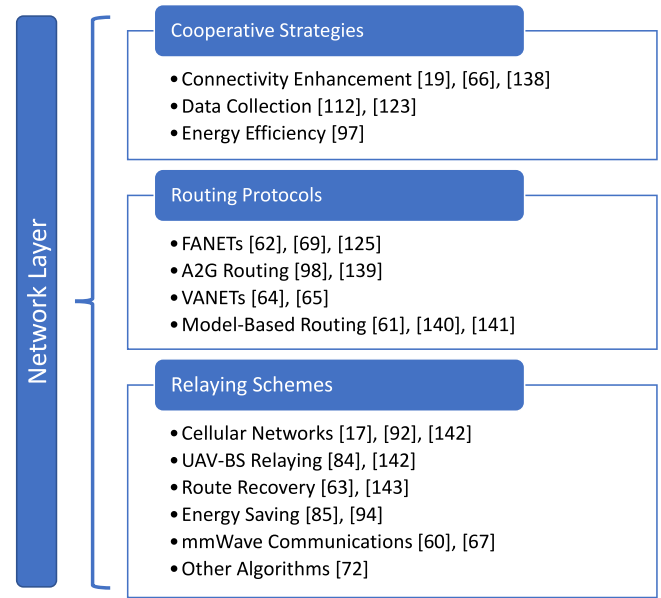


Fig. 11. Network layer taxonomy.

## 6. Network layer

The present Section focuses on: (i) cooperative strategies, (ii) routing protocols, and (iii) relaying schemes. The organization of this section is reported in Fig. 11.

In particular, this Section aims at discussing all the main aspects and issues related to the network layer of the IoD i.e., all the proposals and strategies in multi-hop flying network scenarios.

### 6.1. Cooperative strategies

Cooperative strategies are discussed in [135,63,19,120,109,94] to optimize different metrics, i.e., connectivity [135,63], energy efficiency [94], data collection [120], coverage performance [109], and throughput [19].

#### 6.1.1. Connectivity enhancement

An architecture for ICNs that uses moving routers is proposed in [135]. An UAV that acts as a Content-Centric Network (CCN) router is used to deliver contents between physically disjoint networks. The goal is to exploit the flexible capabilities of CCN routing, i.e., the utilization of content caches and content names, to improve communication performance at network layer. At the same time, connectivity to disjoint networks is provided thanks to the capability of the router to move autonomously. The scheme is also extended by proposing a communication architecture which uses different UAV-based routers to cooperatively process routing among disjoint networks.

A low latency routing algorithm is presented in [63], for a UAV-based cooperative network providing IoT services. The algorithm is suitable for large scale networks of UAVs, where the latency of the classical routing algorithms developed in literature increases and the connectivity decreases because of high interference and delay, together with the rapid topology changes due to the high mobility of UAVs. The Low Delay Routing Algorithm (LDRA) developed in this paper exploits the cooperation among UAVs that have relaying capabilities. It uses only partial information on UAVs location and connectivity, distributing the different data flows by optimally choosing the relay UAVs, so that latency is minimized.

A contention-free geo-routing scheme is developed in [19] to decrease latency and increase throughput in UAV-based systems. The

scheme is based on a cooperative relaying strategy, where multiple nodes concurrently transmit the same frame towards the destinations. In the first hop of the routing scheme, a source transmits a frame into the network, and nodes closer to the destination relay concurrently the frame. Thanks to the OFDM transmission, the multiple copies of the same frame more easily bring to a successful frame decoding. In the second hop, each receiver decides whether to forward the frame or not, based on both the position information provided by transmitters of the previous hop and the positive progress towards the sink. Due to the concurrent transmission of multiple nodes, the communication range and throughput increase, and latency decreases.

#### 6.1.2. Data collection

A cooperative scheme is studied in [120] for efficient data collection in WSNs that use UAVs as relay nodes. Even if the main focus of this work is the proposal of a MAC protocol as described in Section 5.1, a cooperative architecture is also proposed for the data collection system. The scheme is based on a model where an UAV collects data from sensors along its flight path and provides them to cloud servers. The servers have complete knowledge of sensor nodes positions and data, and generate the flight paths of the UAV, sharing them with the same UAV. In the proposed scheme, the UAV requests the retransmission of missing data from cooperative sensors, which are collected in a list.

The cooperative scheme proposed in [109] aims at increasing the coverage performance of UAV-aided cellular networks where the UAVs act as BSs caching the most popular contents and providing them to mobile terminals, so that the ground BSs are offloaded. UAVs are grouped into cooperative clusters, to provide cached contents to a group of mobile terminals. Transmission of the cached content by the UAV in the cluster is possible only if some requirements, i.e., the amount of energy to feed communication modules, the presence of the requested content in the UAV cache and the maximum connection capacity of the UAV, are respected.

#### 6.1.3. Energy efficiency

Energy efficiency is the main focus of the cooperative relaying scheme proposed in [94]. The proposal is based on the adoption of a swarm of UAVs that relay data coming from remote sensors to a ground BS, to overcome the presence of lossy channels, save energy and extend the UAVs lifetime. The scheme is based on a relaying cooperative protocol that exploits the information on the reception quality reported by the UAVs to the BS. Accordingly, the BS schedules the packet load to be transmitted and the Adaptive Modulation and Coding (AMC) scheme for each UAV, to find the best trade-off between the success rate of packet transmission and the energy consumption. The optimization problem is NP-hard and mathematically intractable; thus an approximated solution is proposed that decouples the processes of energy optimization and AMC selection.

### 6.2. Routing protocols

There are many works that propose routing strategies in UAV-based networks [122,59,66,95,136,61,62,137,58,138], for different application scenarios and network architectures.

#### 6.2.1. FANETs

Papers [122,59,66] develop routing strategies for FANETs. Different communication protocols are proposed in [122] in the FANET scenario. Among them, a routing protocol is presented, which exploits a reinforcement learning approach. Specifically, it takes into account the UAVs positions in the routing policies, updating them by means of a reward function that depends on the network utility, so that the optimal paths can be chosen that minimize the delay in data delivery. The main advantages of the protocol are that a global knowledge of the network is not needed, and that the protocol has capabilities to continually evolve for self-optimization purposes.

A predictive routing protocol is proposed in [59] to tackle the main challenges in FANETs, i.e., UAV speed, connection loss, network topology changes, etc. The protocol is based on a predictive 3D estimation of the expected connection time between two adjacent intermediate nodes with directional transmission, with a continuous update of position and speed information to improve prediction accuracy. When the estimated connection time is close to expire, an alternative path is chosen during data transmission, to guarantee service continuity. The adoption of omnidirectional transmission and beamforming is also allowed; the former to increase the connection among nodes, and the latter to increase the transmission distance and reduce the packet collisions and the set-up time of the routing paths.

A modified routing mechanism to evaluate the impact of drone replacement in FANETs is proposed in [66]. The main goal of this work is to study how to replace dynamically drones in a FANET without degrading the overall network performance, and taking into account the network main characteristics, i.e., its dynamic variation in time, its support for heterogeneous traffic, and its limited lifetime. In the last part of this paper, after a description of the most used routing protocols in FANETs and their classification into reactive and proactive protocols, a modification of the proactive routing protocol chosen for the analysis is proposed, that adapts a protocol attribute to the battery charge of the node, so that the connection during handover between UAVs because of battery depletion can be maintained.

#### 6.2.2. A2G routing

In [95,136] routing strategies are developed in Air-to-Ground (A2G) environments. The paper [95] proposes a centralized routing protocol for networks of UAVs controlled by a Ground Control System (GCS). In the proposed scheme, all the drones are managed by the GCS, which is the component demanded to collect and manage control-related information from drones, including their routing tables. Such an approach avoids the continuous exchange of periodic information on the link cost values among UAVs (the GCS can extract this information from the geographic information of UAVs). Furthermore, the disconnection time of the network due to the UAVs mobility can be minimized because the GCS knows the schedules of drones mobility and can predict the topology changes. The protocol is implemented using real UAVs and GCS.

Two different opportunistic routing protocols are developed in [136] in a scenario where a UAV moving at a predefined height and speed provides connectivity to different mobile sensors, that move in the same direction with different speeds. Opportunistic routing is suitable for scenarios with a changing network topology, because of its capability to increase throughput. In both the proposed protocols nodes that want to transmit data but are not in the UAV communication range, choose the neighbor nodes in the UAV range that can act as packet forwarders, to increase the PDR. In the first proposed protocol, a source node transmits packets to all the neighbors in its range, while in the second it transmits packets to the forwarder with the highest velocity. The PDR increase comes at a cost of an increased delay and routing overhead, if compared to the direct connection between source nodes and the UAV.

#### 6.2.3. VANETs

Routing protocols for VANETs are developed in [61,62]. For sake of better clarity, Fig. 12 provides an illustrative example of a UAV-assisted VANET where routing operations and protocols are applied. In a nutshell, drones are herein assumed to monitor a road as part of an ITS. Once a situation of interest is detected, i.e., an accident, the ground control infrastructure is in charge of providing updated information to all the vehicles on the road. Thanks to the employment of Variable Message Sign (VMS) systems, and leveraging Vehicle-to-Infrastructure (V2I), all the road users can be promptly notified about the dangerous situation and, at the same time, the closest available UAV can be relocated, when needed. As will be discussed later on in this

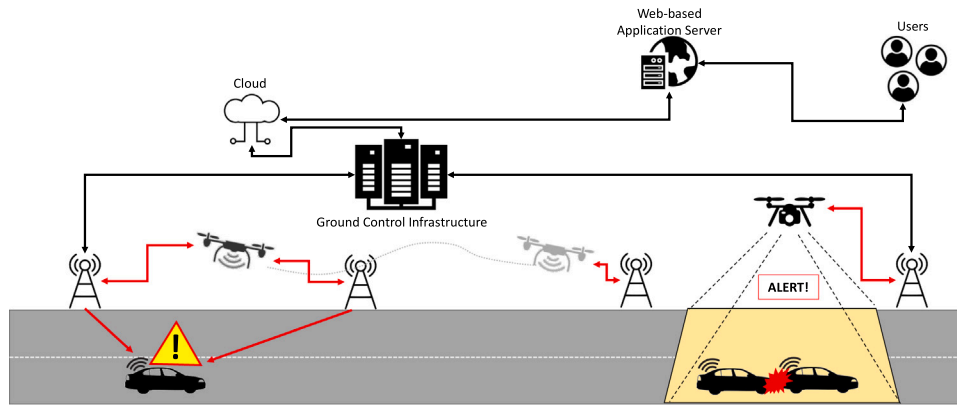


Fig. 12. Drones in a ITSs scenario with connected vehicles.

section, ITSs are also using Vehicle-to-Vehicle (V2V) communications. In fact, connected cars and direct links between the drones and the vehicles may be used to simplify messages exchange, thus lowering latencies and improving communication effectiveness.

The routing protocol developed in [61] aims at increasing the reliability of data delivery for UAV-assisted VANETs in urban environments. The proposed protocol is based on the information exchanged between UAVs and vehicles on the traffic density and the connectivity of the vehicles. Based on this, the UAVs can decide their location to relay data in the points of the network where connectivity among ground vehicles is missing because of the presence of obstacles which are present in typical urban environments. Accordingly, vehicles can choose to use UAVs as forwarders if there are no available paths in direct vehicle-to-vehicle communications.

A routing protocol that finds the shortest end-to-end connected path in VANETs is proposed in [62]. It takes into account the high mobility of vehicles and the frequent changes in the network topology due to unpredictable movements of vehicles. The proposed protocol exploits heterogeneous communications through the cooperative interaction between an ad-hoc network of UAV and a VANET. The goal of the UAV network is to restore communication links that fall down because of the presence of obstacles in the urban environment. To this end, two different protocols are used: the first, more delay-tolerant, exploits the global knowledge of the UAVs about the connectivity status of the road segments to route data between UAVs and ground vehicles; the second, more reactive, routes data among UAVs only when needed.

#### 6.2.4. Model-based routing

The routing protocols proposed in [137,58,138] are based on analytical models. A routing protocol for networks of UAVs is proposed in [137]. It exploits an application layer functionality that predicts future trajectories of UAVs and that is integrated in a routing protocol already known by literature, to improve connectivity in the UAV-based network and reduce packet losses. Different mobility models and exploration algorithms are used for comparison between the proposed protocol and other known routing protocols.

A routing framework for hybrid space/air networks is proposed in [58], to mitigate the high bit error rates and long delays that can occur because of the mobility of nodes and the varying network topology. The framework exploits a routing algorithm based on a hybrid time-space graph, that is described by two subgraphs. The first subgraph describes deterministically the space network. The second subgraph aims at predicting the contact time and contact probability among the UAVs of the air network, and for this reason it is based on a semi-Markov prediction model. The graph is transformed into a state-space graph to establish the optimal next hop, depending on a forwarding rule that can exploit UAVs in the air network or satellites in the space network as relays. The goal of the proposal is to improve the message delivery ratio, the end-to-end-delay and the power consumption.

The routing algorithm proposed in [138] exploits 3D cubes as partitioning regions to forward data among UAVs. More specifically, data are relayed by choosing only one UAV as relay node per region. The optimal path among different cubes is chosen based on the maximum successful transmission probability derived from an analytical model. Then, the most appropriate UAV that relays data in each cube is selected by jointly considering again the successful transmission probability and the UAVs mobility. The goal of this routing algorithm is to improve the end-to-end delay, jitter, and PDR.

#### 6.3. Relaying schemes

UAV-based relaying schemes are presented in [17,139,89,140,60,141,81,91,82,69,57,64].

##### 6.3.1. Cellular networks

Papers [17,139,89] exploit drones as relays in cellular networks. The review paper [17] analyzes D2D communications in different application scenarios. Part of this work is focused on the utilization of drones as D2D relays, to extend cellular network coverage especially in extraordinary conditions when the ground BSs can be damaged or switched off in critical scenarios (like catastrophes, network damage, etc.). In such situations, drones transfer the signal from far BSs to mobile devices, filling coverage holes. This paper does not go into deeper details on the implementation of D2D relaying functionalities. The same topic is described also in [139], that tackles the wireless coverage issue in case of disasters or incidents in public safety wireless networks. This work proposes a multi-hop D2D scheme that extends network coverage wherever ground relay is not possible. The proposed scheme jointly finds the optimal UAV position and the resource allocation, in time or frequency domain, so that the data rate of each hop in the path from the BS to the mobile device is maximized.

A radio access scheme is proposed in [89] for multi-hop relay networks composed by UAVs. This scheme increases the efficiency of relay communications between an observation UAV transferring data to a ground BS exploiting UAVs as relay nodes. This study is based on the assumption that the time-division relaying technique exploited in LTE-A can be suitable to increase the efficiency of relay communications among UAVs, in terms of both reduction of mutual interference among UAVs and communication order by the relay node to transfer data from the observation UAV to the BS, especially for long distances. Since the existing LTE-A scheme is not suitable for UAV-based relaying because of some limitations in the frame structure, this work proposes a LTE-A access scheme that increases the relay communication efficiency over long distances, taking also into account the UAVs height.

Also the solution presented in [139] exploits a relay UAV, called Floating Relay (FR), to dynamically and adaptively provide additional coverage in a macrocell served by a ground BS to tackle the issue of an



increasing traffic volume in the macrocell. The discussion focuses on some important aspects like frequency reuse, interference between FR cells and the macrocell and among FR cells, bandwidth allocation for the backhaul network, and coverage capabilities.

### 6.3.2. UAV-BS relaying

Other relay schemes exploiting UAVs for data transmission to a ground BS can be found in [141,81]. The relaying scheme proposed in [141] is conceived for image transmission in an UAV-based network. In this work, some survey UAVs transmit sensed images to a BS through a relay UAV. The scheme is based on a planning model that computes the best set of relay points where the relay UAV can meet the survey UAVs, that minimize the average traveling distance of the relay UAV. Then, a reinforcement learning approach is used to find the optimal time to visit each point. This technique exploits a reward function based on the rate of image acquisition. The proposed solution avoids the need of any collaboration between survey UAVs and the relay UAV, and reacts to the varying network traffic to improve the quality in end-to-end delay and frame delivery ratio.

Similarly to [141], the paper [81] focuses on a scheme where a relay UAV forwards data collected from multiple observation UAVs to a ground BS. The observation UAVs cover a wide area. Depending on the main parameters that influence the network performance, i.e., signal attenuation and obstacles, a formula for the upper bound of the throughput in the network is derived, together with the optimal location of the relay UAV that maximizes the upper bound of the throughput.

### 6.3.3. Route recovery

Relaying is adopted for route recovery schemes in [140,60]. A relay scheme is proposed in [140] that aims to solve the problem of jamming attacks in VANETs. The scheme exploits an UAV that relays data from vehicles to RoadSide Units (RSUs) placed at fixed locations. If the RSU serving the vehicle is in a heavily jammed area, the UAV becomes in charge of relaying data to another RSU with better channel conditions. The UAV decides whether or not to relay data from the vehicle to another RSU which is far from the jammer, depending on the channel quality in the direct link between the vehicle and the serving RSU. The interaction between the UAV and the jammer is studied through an anti-jamming relay game approach, derived from the game theory. Reinforcement learning techniques are also used to derive the optimal relaying strategy of the UAV without knowing the jamming model.

A route recovery scheme is proposed in [60] in ad-hoc networks where UAVs act as relays. The scheme is based on probe packets sent by the UAVs to discover the route topology and stitch partial paths so to avoid network holes in damaged networks. Based on the captured topology, an algorithm for optimal UAVs deployment is adopted, which minimizes the UAVs traveling time and distance and avoids duplicate coverage. It is exploited to decide how to replace the network holes through UAVs. To this end, an algorithm is adopted that dispatches a reduced number of UAVs, allowing an improvement of routing performance both on local and global scales.

### 6.3.4. Energy saving

The relay schemes proposed in [91,82] are focused on energy saving. A relaying strategy is proposed in [91] as part of a routing algorithm aiming to save the energy consumption in a UAV-aided WSN for data acquisition. The routing algorithm is based on a priority-based scheme, that takes into account the UAV mobility. More specifically, sensors are classified into frames, each one with an assigned transmission priority, so that sensors in more urgent areas transmit their packets with a higher priority. Sensors of a frame are further grouped into clusters, choosing a Cluster Head (CH) that transmits gathered data to the UAV. The proposed routing algorithm aims to deliver data from sensors to the CH by choosing the optimal relay node with the better

channel quality and the shorter distance from the CH, so that the energy consumption from source to destination can be saved.

The relaying scheme proposed in [82] makes use of a single UAV that helps two ground stations without any direct connection to reach each other by following a circular trajectory. The goal of the proposed scheme is to maximize the spectrum and energy efficiency by jointly optimizing the time allocation of the UAV relaying, its speed, and its trajectory. The solution of this optimization problem reveals a trade-off between the energy consumption for the propulsion of the relay UAV and the maximization of energy and spectrum efficiency of the whole system.

### 6.3.5. mmWave communications

The works [57,64] propose routing schemes for mmWave communications. Mobile relays in mmWave communications are studied in [57]. A relay method suitable for mmWave communications is proposed, to bypass obstacles and/or increase the communication range. In this scenario, an UAV acting as relay adjusts dynamically its path based on real-time measurements of the link quality of different mmWave beams. In this way, the UAV is able to dynamically choose its optimal position accurately and in a short time, despite the unpredictability and varying nature of the wireless link. The proposed scheme is also enhanced to multiple relays that can also use directional beams to extend the communication range.

A methodology for dynamic rerouting in networks exploiting mmWave technology is presented in [64]. The proposed methodology is applied to mmWave backhaul links that dynamically reroute depending on the channel conditions, to improve the flexibility and reliability of the backhaul solution. Dynamic routing is possible thanks to UAVs that work as aerial relay nodes, so that the negative effect of occlusions and signal blockage due to obstacles can be reduced. The methodology presented in this work considers the influence of some components, like the signal propagation model and the blockage probability of the mmWave links due to obstacles typical of urban environments, and the UAVs mobility.

### 6.3.6. Other algorithms

The relaying algorithm proposed in [69] is applied in a wireless backhaul network composed by balloons. Some UAVs are used as relays to increase the network reliability, which fluctuates because of the limited control on the balloons mobility that can bring to temporary link failures. The proposed algorithm aims to plan the UAVs paths and schedule all of them so that the network reliability is maximized. The path planning algorithm is developed for the single UAV and also for multiple UAVs, supposing to know the availability prediction of the links among balloons and the traffic matrix of the network.

## 6.4. Comparison with other surveys

The network layer has been widely studied in the past literature, and related papers mainly discuss on cooperation, routing and relaying aspects at network layer of UAV-based networks. The survey papers that cover this topic are [3,11,8]. The work [3] analyzes different aspects of the network layer, ranging from cooperative networks, routing and relaying strategies. It carries out an exhaustive analysis of frameworks, models and approaches applied to multi-UAV cooperative systems, data routing and relaying strategies. Routing strategies are analyzed in [11] for networks of UAVs. In this work only data routing is analyzed in detail, presenting the most significant protocols in MANETs and VANETs. The survey [8] discusses the applicability of the most important types of routing protocols, whether static, proactive, reactive, hybrid or geographic, to the MANET scenarios. Networks prone to delays and disruptions are also analyzed, discussing the suitability of other kinds of routing protocols in this more challenging context. With this well-articulated background in mind, the main goal of the network layer analysis carried out in this section has been to update the discussion of network layer strategies in [3,11,8] through a detailed survey of the most recent literature on this topic.



### 6.5. Lessons learned

Multi-hop strategies at network layer have been proposed in many papers on networks of UAVs. The surveyed works discussing cooperation among drones testify that cooperation is a good solution to increase connectivity among separate networks, to increase the effectiveness of routing algorithms and the energy efficiency, and to reduce latencies in data exchange. Except for the papers proposing simplified scenarios, these improvements translate into optimization problems, whose optimal solution comes at a cost of high computational effort.

As expected, routing strategies are one of the main issues at network layer. This holds true also for networks of drones, where many challenges peculiar of FANETs (i.e., UAVs mobility, fast changes in networks topology, error-prone communication channels, etc.) must be tackled. To this end, the proposed approaches make use of strategies ranging from proactive and predictive techniques, to centralized architectures, analytical models, and information on UAVs position, velocity, etc. The key-aspect of such proposals is the optimal choice of the UAVs as data forwarders, so that the above-mentioned challenges can be effectively managed without degrading the network performance (in terms of PDR, delay, and routing overhead). Lessons learned from the analyzed works demonstrate that the joint optimization of all these parameters is extremely difficult, and the most suitable routing strategy is strongly context-dependent.

Another important lesson is learnt from the analysis of the relaying schemes proposed. They are adopted for different purposes, i.e., extension of coverage and communication range, interferences reduction in G2G multi-hop communications, energy efficiency, throughput optimization, and defense against jamming attacks. Studies in this direction show that relaying can be effective especially in environments subject to interferences from external sources (physical obstacles, jammers, etc.) or intrinsic to the specific short-range communication technology, as mmWave is. Most of the problems presented in the surveyed works are tackled by finding the optimal number and positions of relay nodes; but, once again, the optimization problems suffer from the same drawbacks highlighted for cooperation strategies.

## 7. Transport and application layer

The Transport and Application Layers have been conceived as independent. It is worth noting that, in most cases, transport layer is taken for granted. This is motivated by the fact that many applications are designed focusing on the expected performance level and, hence, QoS and QoE Indicators are used. Accordingly, no survey paper so far investigated application layer in detail. Indeed, several references start from the concepts of Network Function Virtualization (NFV), Software Defined Network (SDN) and/or distributed computing schemes to propose innovative schemes that demonstrate offloading possibilities in specific applications. At times, applications are conceived as solutions released on top of consolidated telecommunications technologies. In those cases, the protocol stack is not discussed in detail, nor it is modified. This happens frequently when LTE, 4G, or 5G communications or, more in general, consolidated networking solutions are involved. Overall, many scientific contributions rely on the Internet model, which involves Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). Therefore the transport layer is not among the major concerns and is assumed to be TCP- or UDP-based. For all the scientific contributions that will be discussed in this section, a focus on the transport layer will be provided whenever the solution is different from the two cited above.

The present Section proposes application layer-related contributions, mainly connected to: (i) QoE, (ii) Computation offloading, (iii) Video Streaming, (iv) data collection and distribution, (v) events monitoring and management, and (vi) task allocation. The Section closes up highlighting the lessons learned on the theme. In Fig. 13, the overall organization of the present Section is summarized.

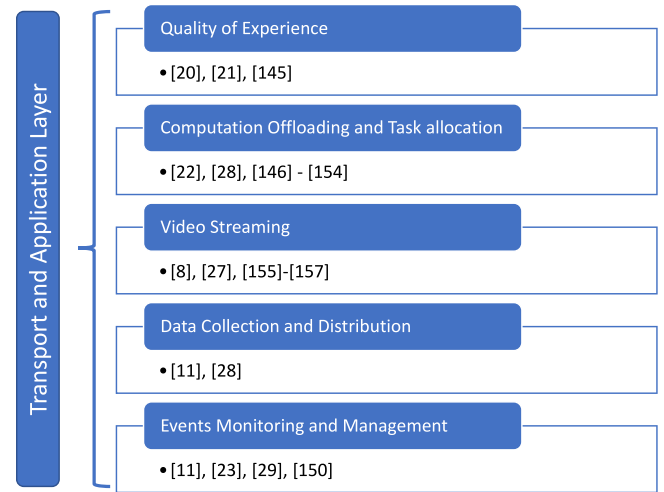


Fig. 13. Transport and application layer taxonomy.

### 7.1. Quality of Experience

In the IoD context, the network is specifically designed to transmit images and video recordings. For some applications, a very low latency may be highly required (i.e., real-time monitoring). In some other cases, instead, ultra high quality is needed. This heterogeneity leads to the definition of QoE indexes, which may enable several possibilities.

One of the most thrilling perspective in research for mobile telecommunication networks is represented by the possibility to employ UAVs as mobile BSs. In fact, with the possibility to mount a base station on top of an aerial platform, BS planning and deployment can be sensibly simplified. At the same time, this possibility may significantly improve methodologies for coverage area optimization. Further, mobile BSs could be helpful in solving several problems connected to base station capacity and inter-cell interference, which are among the major stakeholders when studying cellular networks. Those problems are tackled by a number of contributions proposed so far, and in particular, [21] demonstrates the strengths and weaknesses of the employment of a deterministic approach to analyze these problems. Specifically, this work analyzes the aforementioned parameters with a variable threshold for the received power. Accordingly, an optimal altitude and power consumption model is derived for aerial BSs in different environments which mainly refer to sub-urban, urban and densely populated urban environments. Among the main outcomes, a channel model for A2G communications is obtained.

Granting QoE does not specifically mean to improve a specific application and/or functionality. In fact, QoE analysis can also be used to design advanced coordination functionalities. In [20], QoE is considered in the context of heterogeneous networks, where mobile BSs are mounted on top of UAVs. In this work the flight plan is the output of a dedicated QoE-aware algorithm, based on the Q-learning approach. The simulation results proposed by this contribution testify that the flight plan diversification improves the overall QoE of the users. In the work [142] drones are configured in FANETs covering area where the fixed (i.e., ground) network infrastructures are hard to reach. The proposal tackles the lack of standardized routing protocols for FANET applications to allow efficient communication between devices thanks to an adaptive routing protocol based on fuzzy logic, demonstrating its added value in terms of both QoS and QoE.

### 7.2. Computation offloading and task allocation

The tasks that drones can carry out may involve more than one drone at a time. This means that drones may be organized in swarms or

clusters. Several contributions so far investigate the tasks that drones can handle suggesting that swarms may be a preferable choice when the application (or reference scenario) may benefit from the increased coverage capability a drone can offer. Even though a swarm of drones may represent an interesting opportunity, each of them is still limited in terms of computational power and energy resources. Such limitation suggests an optimization of the task list of the drones, for example by balancing the load of tasks among the swarm components. In this fashion, [143] proposes an opportunistic solution to provide computational offloading for a swarm. The scheme leverages the IEEE 802.11ac communication technology and is based on an artificial neural network with a prediction module specifically designed to provide updated decisions on whether it is preferable to keep the task list of a drone, or offload it. The method aims to be time-effective in deciding whether to offload tasks to other clusters or not.

The same problem is discussed in [144], where different swarms are supposed to have different task assignment lists. In particular, whenever one of the clusters is more heavily charged with respect to another, the proposed scheme opportunistically decides to carry out the offloading to another cluster, with respect to a number of different parameters and costs. The effectiveness of the scheme lies into an increased drone lifetime and a shorter response time.

The paper [22] deals with the problem of delay mitigation for video streaming applications, which is of great relevance in the context of cellular networks, especially in high traffic conditions. The proposal of this work is the design of algorithms and criteria for offload selection and drone positioning. This goal is reached by adopting UAVs that carry lightweight commercial micro-cells with small form factor, so to better handle congestion for macro-cells.

The problems of complex and time-consuming calculations to be carried out during a mission, together with the limited resources typically available on-board the UAVs, are discussed in [145,146]. Here, computation offloading strategies are, once again, proposed as feasible solutions to mitigate the issues related to over-exploitation of constrained resources. The approach proposed in [145] is referred to as Mobile Edge Computing (MEC) and is based on the game theory, with a focus on a sequential game involving drones, BSs and edge servers acting as players with computation tasks. The contribution demonstrates the existence of a Nash Equilibrium and designs an offloading algorithm to derive possible tradeoffs between energy consumption and achievable delay. In [146], the problems related to temporary overloading of the network are solved relying on Deep Reinforcement Learning (DRL) techniques.

In the context of surveillance systems, [147] discusses the theme of safety-related applications in hazardous locations. The proposal leverages the concept of computational offloading by proposing an Adaptive Computation Offloading Drone System (ACODS) solution, that is based on a response time prediction module for providing task offloading decisions. Task offloading management is achieved via a Multipath TCP (MPTCP) algorithm, a solution already known in literature, that is based on the use of multiple interfaces to communicate and transfer the packets. The adoption of the MPTCP performance of the network is improved in terms of reliability, throughput, and delay.

Drones are employable in a number of industrial-grade applications, as argued in [28]. In this case, the discussion proposes an interesting point of view on the IoT scenario, by proposing an application that provides predictive maintenance to energy distribution systems through the employment of UAVs with visual capabilities combined with a 5G network infrastructure. In particular, thanks to the 5G communication network, massive capacity, zero delay, elasticity and optimal deployment can be reached in scenarios with a massive deployment of IoT devices for broadband and mission critical services.

Drones' employability has been discussed also in fog computing and MEC. In the former case, drones are conceived as enablers for distributed offloading of intensive computation tasks to an edge/cloud server [148,149]. For this reason, the paper [148] proposes a game

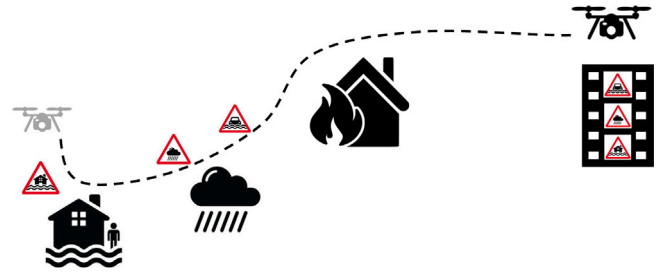


Fig. 14. Drone gathering video streaming signals in environmental relevant scenarios.

theoretical approach in which drones are the players and the cost function to be minimized is a combination of energy overhead and delay. Thanks to this approach, drones can detect, identify and classify objects and/or situations dealing with intensive tasks such as pattern recognition and video preprocessing.

Due to the limited computing resources of drones swarms, it is usually difficult to handle computation-intensive tasks locally, hence the cloud based computation offloading can be adopted as a solution. This becomes of greater relevance as long as low latency and high reliability are required. The proposal in [150] is based on fog computing for a swarm of drones. Here, latency and reliability are taken as constraints of an optimization problem where the energy consumption is the optimization target function to be minimized.

Both MEC and 5G cellular network are exploited in [151] for mission planning optimization of UAV-BSs. The edge of the 5G network is provided with a softwarized Flight Control System (FCS) component that offloads the UAV from computationally demanding tasks, thus increasing its energy efficiency and easing the real-time processing of the flight data collected by the UAV sensors. A real testbed is implemented to verify the effectiveness of the proposed solution in real flight conditions.

### 7.3. Video streaming

Drones employability in both civil and military applications include several possibilities such as search and rescue, coverage, and aerial imaging in different environmental scenarios, as illustrated in Fig. 14. Once the drone is flying, gathering images and videos may not be as useful as it could be in video streaming contexts. This aspect may become more and more challenging when referring to a swarm of drones. In this case, coordination among the swarm is not simply beneficial, but becomes a need.

Several contributions so far describe the existing communication and routing protocols, including Ad-hoc On-demand Distance Vector (AODV), Location-Aided Routing (LAR), and Greedy Perimeter Stateless Routing (GPSR) protocols [8]. These solutions have been deeply investigated in order to identify their limitations when applied to networks that include drones or swarms of drones.

According to the specific application scenario, the main requirements and characteristics may vary. At the same time, it might happen that drones are asked to fly over multiple areas of interest, which leads to the need for designing optimized trajectories to coordinate the flight of the swarm in a continuous way. Video streaming based on drones employability may be sensibly enhanced by leveraging multicast wireless video streaming to transmit data. In particular, video multicast streaming using IEEE 802.11 poses challenges of reliability, performance, and fairness under tight delay bounds [27]. The latter assumption is strengthened by the fact that “ready-to-fly” consumer drones use a fix-bitrate technique to encode video, for example, 1080p or 4K resolution, which provides poor performance in high mobility conditions where the communication channel may be subject to sudden and relevant fluctuations. In this work, a dedicated section is dedicated

to multi-homing. Since a multi-homed network is defined as a network connected to multiple Internet Service Providers (ISPs), the proposed approach helps avoiding connection failures. To reach this goal, it is necessary to integrate different layers of both the network and the transport layers in Internet Protocol version 4 (IPv4) and Internet Protocol version 6 (IPv6) networks.

Video streaming may also be conceived not only as application enabler but as a method for handling and controlling network traffic and design. As a matter of fact, such a consideration enables interesting perspectives in terms of variable traffic demands, application heterogeneity, and application requirements. The contribution presented in [152] proposes a dynamic cloud service placement to handle real-time video streaming and control commands for a drone that is controlled by a remote user. In this case, the main aim is to first grant, and then improve, the QoE for streaming services provided by drones using UDP. A similar problem is faced in [153], where the drone is remotely controlled and the high demands in both the UL and DL directions are thoroughly characterized in terms of QoS.

Another situation of relevance for video streaming and real-time surveying is data gathering from disaster-struck regions, as discussed in [154]. In fact, in all cases where the ground network infrastructures are damaged, drones may offer rapid deployment for data source recovery. Without loss of generality, the simple deployment may be ineffective without an adequate energy management strategy. The case study discussed in this work envisages a scenario in which drones operate alongside the wireless network infrastructure to establish a LoS link for communication while investigating a power allocation strategy for the BSs. As a result, the work highlights that it is of outmost importance to incorporate the multi-tier heterogeneous network, so to extend the network coverage in such challenging scenarios.

#### 7.4. Data collection and distribution

Thanks to the high mobility of drones, their employability has been discussed in a number of applications, such as service delivery, pollution mitigation, farming, and rescue operations. On the theme, [28] proposes something similar to what discussed in [11]. In [28], in fact, UAVs are proposed as a value-adding utility to IoT devices and networks in the context of MTCs. The contribution represents an interesting survey of all the UAV-based architectures that can enhance smart sensors, cameras, actuators, and, more in general, IoT devices since they enable a brand-new perspective: an eye in the sky.

Data management is not only a matter of efficient upload (like happens in data gathering applications). In fact, [18] argues that a high rate, but also cost-efficient, easy-to-deploy, and scalable, backhaul/fronthaul framework, is of great importance in the context of 4G/LTE/5G communications and wireless networks. In this work mobile BSs are conceptualized as Unmanned Flying Platforms (UFPs). This definition is motivated by the fact that UAVs are only one of the kinds of flying platforms that can be used in this context. In particular, flying platforms may be drones or balloons. To provide advanced communications services in FSO, the proposal in [18] investigates the feasibility of a framework that involves backhaul/fronthaul traffic flows between access and core networks via point-to-point links.

#### 7.5. Events monitoring and management

In [11] the employment of UAVs is discussed to demonstrate their countless reference applications for public protection and disaster relief operations, but also for commercial and governmental services. Some good examples are surveillance and reconnaissance, public safety, homeland security, forest fire monitoring, environmental monitoring, security and border surveillance, farming, or even Internet delivery, architecture surveillance, goods transportation.

Fortunately, not all the scenarios and applications investigated in the scientific literature are related to dangerous or extreme situations.

In particular, network capability could be ineffective/insufficient for temporary high loads. The contribution [29] deals with high-action sports game played on a large field. In such events, the idea of using networked drone cameras to gather real-time data can be considered as a great intuition, still challenging. In the design phase, it clearly emerges that distributed approaches yield sub-optimal solutions, an assumption that is motivated by the lack of coordination. Still, a centralized approach to coordination may imply round-trip latencies of several hundreds of milliseconds. For this reason, the contribution proposes a fog-networking based architecture that aims at coordinating a network of drones to capture and broadcast the sports game, with a tradeoff between coverage and streamed video bitrate. Here, latencies are mitigated by a centralized controller that leverages a predictive approach to upcoming locations in order to re-assign the UAVs to new locations, when needed. The work shows that relay nodes are able to boost throughput while working in real-time.

On the same theme, the work proposed in [147], and already discussed in this section, can be mentioned once again since the proposal may contribute to highly advanced, and safe, surveillance of hazardous locations.

The paper [23] proposes a cloud-based system that is able to remotely control and manage all the operations carried out by drones and, more in general, robots. As for the UAV, the system uses UDP, TCP, Universal Serial Bus (USB) and serial. When UDP and TCP are used, data are forwarded to client applications through dedicated Websockets. The framework is able to operate in a wide range of commercial applications, under real-time constraints and below visual LoS conditions. Still, the proposal is facing security problems and future research directions involve both transmission and coordination tasks.

#### 7.6. Lessons learned

This section is focused on all the technological aspects connected with application layer. However, several scientific contributions discussed have shown a peculiar influence, and non-negligible impact, on QoS parameters such as latencies and PDR (or, complementary, Packet Loss Ratio (PLR)). These quantities have, in fact, a close link with the QoE parameters that can be used in quality assessment of streaming services, especially video. With respect to path planning, the impact on the application layer is relevant. In fact, optimizing the path that drones are programmed to follow during their mission has a significant impact on the optimization of onboard resources, with a consequent extension of mission longevity. Similar considerations can be referred to the optimization problems connected to resource handling and data exchange capacity.

The dedicated study of the problems related to the application layer demonstrates that mobility is a key enabler for different applications in several scenarios. In particular, it is possible to guarantee local and temporary offloading thanks to the repositioning of the drones, both in the case of mobile BS deployment and when drones are part of a swarm. In the case of mobile BSs, they can be re-deployed even when a replacement is necessary. Thanks to these functionalities it is possible to think about adaptive, temporary and optimized coverage based on the needs of the application scenario. Some case studies have shown that the typical Key Performance Indices (KPIs) that are used to measure QoE and QoS can become input variables to objective functions and algorithms specifically dedicated to the design and optimization of routing. The latter represents an important frontier in the design of drone networks, especially when large swarms are involved. At the same time, a softwarization-based approach could be used to create customized solutions tailoring the specific application needs.

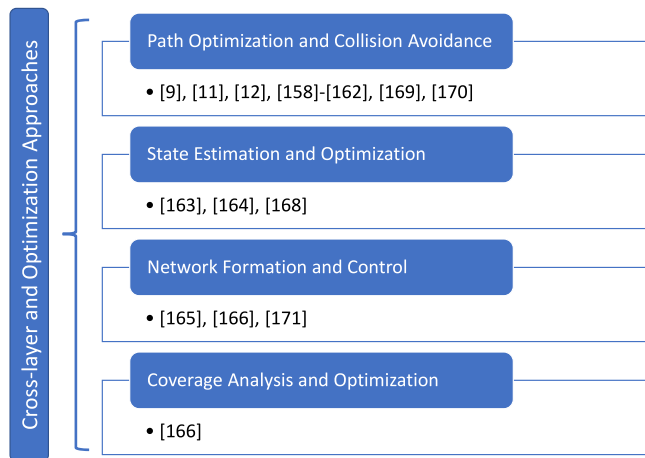


Fig. 15. Cross-layer and optimization section taxonomy.

## 8. Cross-layer and optimization approaches

This Section is specifically dedicated to the details on the following aspects: (i) Path optimization and collision avoidance, (ii) State estimation and optimization, (iii) Network formation and control, and (iv) Coverage analysis and optimization. All the aforementioned topics are peculiar to the application layer. Nevertheless, the optimization processes include aspects and parameters encompassing other layers of the stack, from channel models, signal energy, energy efficiency, throughput and connectivity/coverage requirements at physical layer [155–163], or resource scheduling at data link layer [164,165,160], and this justifies the cross-layer nature of these studies. Hence, no survey paper so far investigated these problems as a whole.

The Section closes up highlighting the lessons learned on the theme. Fig. 15 summarizes the overall organization of the present Section.

### 8.1. Path optimization and collision avoidance

When discussing drones missions and task list, the specification of the main criteria for path design becomes of critical importance. Some of the most relevant problems related to path design and optimization criteria have been widely and extensively discussed in [11,9], and [12]. Since those works are surveys, a deeper insight on the theme of optimizing the path a drone flights over has been discussed in many other works. For example, the problem of understanding which is the optimal trajectory has been studied in the context of UAV-enabled wireless power transfer systems, as proposed in [155]. In particular, this study discusses the UAV maximum speed, which is generally constrained by physical layer aspects, even if the optimization occurs at application layer. This limitation leads to the design of complex hover-and-fly trajectories, which, still, deserve to be optimized. The proposal applies convex programming optimization technique to solve the problem.

Path optimization is a leading trend in research, since power and energy consumption are among the major stakeholders in UAVs characterization. On this theme, qualitative modeling for energy footprint optimization are widely discussed in several studies, such as [156–159,166], as associated to trajectories design. Those works are pretty similar since the whole set of parameters involved in all of them is almost the same. Still, they share the wider objective of finding out the minimum energy consumption, the bits allocation (i.e., for each task) and the shortest, yet most efficient, trajectories. Those parameters resulted to be simultaneously optimized. Anyway, the proposed models are in the need to be verified over wide swarms flying over long distances, while keeping coordinated flight conditions steady.

Another interesting work on the theme of trajectory design and path optimization is presented in [157]. It assumes that the UAV flies

horizontally with a fixed altitude while exchanging data with a ground infrastructure. While on flight, the drones are supposed to communicate with the reference ground infrastructure in an energy-efficient way, that is granted thanks to the compliance to several KPIs, thus including the required throughput and the overall energy footprint. The work derives the contributions due to mechanical propulsion thanks to a theoretical model. The obtained framework is used to design multiple trajectories and iterates the application of the algorithm to demonstrate its versatility. A similar goal is reached in [158,159], where the proposal envisions a framework with an UAV-based network for communication in post-disaster areas. In this scenario, a single UAV replaces a damaged base station collecting information from users. In the proposal [158], the UAV trajectory is optimized taking also into account the UAV height, so that the UAV uplink throughput during flight is maximized and energy consumption is minimized. This goal is reached by formulating an optimization problem based on a Constrained Markov Decision Process (CMDP). It exploits several models, i.e., UAV mobility, channel, data size and energy. The proposed algorithm is able to find the best trade-off between system throughput and energy consumption, also avoiding collisions with obstacles located in the area with geographical constraints. The approach followed in [159] is quite different, even if the scenario is the same. The single UAV acting as a relay delivers the UEs packets to a functioning ground base station before the UEs buffer overflows and packets are lost. In this paper, a scheduling method is proposed, where the UAV selects the most suitable UE to provide connectivity during flight, so that the UE packet drop rate and energy consumption are minimized, and the overall UEs communication time is increased. This goal is reached by means of a data-driven learning method for the UAV, that makes use of a Deep Neural Network (DNN) to train the UAV. The theme of complex trajectory design is discussed in [166] too. Here, the mission envisions frequent turnovers between hovering phases and altitude variations. Among the most relevant advantages of the proposed model there is its wide applicability to multi-copters.

In [164] an energy-efficient scheme is proposed to include multiple variables for the optimization, such as the energy budget of each UAV, the number of tasks that each drone has to accomplish, and the type of data exchanged, together with the UAVs reference speed. Here, both uploading and downloading phases are handled relying on MEC solutions.

The study presented in [167] discusses the problem of hybrid delivery employing Truck-drones. In particular, this work frames an optimization problem related with the connection between the payload size and the energy spent while moving it over certain trajectory. Moreover, the proposed framework includes the possibility that No-Fly zones are within the mission plan. Even though the invasion scenario only includes a single truck and a single drone, multiple vehicles are clearly among the future research perspectives. Even more so because the problem can be complicated with different scales or shapes of no fly zones, in which case fleet coordination becomes mandatory.

### 8.2. State estimation and optimization

Several works deal with the drones' state estimation with the precise aim of identifying methods to minimize energy consumption, rather than designing trajectories or maximizing the area covered during the mission.

The ability to communicate state information is discussed in [165], a proposal that aims at achieving the maximization of users throughput in a three-dimensional space where dangerous conditions are verifying. The mathematical formulation of the problem includes several parameters, such as the overall throughput, the remaining battery capacity for each UAV in a swarm, and several others. Those variables are modeled on a multi-period graph. Something similar is done in [160], a contribution that formulates an optimization problem to specifically address



natural disaster scenarios in real-time conditions with relay-assisted UAVs.

State estimation represents the starting point of the study proposed in [161], in which multi-objective optimization algorithms are proposed. Their aim is to allocate tasks and plan paths for multiple UAVs forming a swarm. The proposal leverages the Genetic Algorithm (GA) approach to minimize the time in which the mission gets completed and includes area coverage and communication path. As a such, the problem also embraces network connectivity aspects. The solution can be fine-tuned to prioritize coverage or connectivity according to mission commitments.

### 8.3. Network formation and control

Two major survey contributions discussed network formation and control-related aspects in the context of the IoD, for instance [3] and [8]. A detailed analysis of those themes have been extensively discussed in the form of optimization problems in [168,162,163]. In particular, [168] discusses network formation as the result of an optimal task assignment problem. The formulation leverages the coordinated nature of a swarm of drones that are communicating through A2A links. Together with network formation thanks to the cooperation among multiple drones, efficient mission plans are constantly generated and updated to refine the obtained results. Similarly, [162] proposes UAVs-enabled wireless communications between multiple ground nodes that are subjected to specific requirements, such as throughput, energy consumption optimization, and limitations on communication-related energy expenditure. The proposal models propulsion power in close correlation with physics-related phenomena. The model reaches the energy minimization objective as a results of a non-convex problem. Therefore, the preliminary fly-hover-communicate assumption is empowered with a more sophisticated design criteria that includes the hovering location and duration, together with the flying trajectory design.

In the same field, another possibility is related to BS offloading and coverage area enhancement, as in 5G wireless communication systems [163]. Another interesting application is aided relaying, with UAVs providing reliable wireless connectivity between users or user groups in adverse environments.

### 8.4. Coverage analysis and optimization

An interesting research perspective is the BS offloading and coverage area enhancement, as in 5G wireless communication systems [163]. UAVs are often involved in information dissemination and/or data collection. In these cases, drones are arranged to fly over a certain area of interest and gather data. Here, aided relaying envisions UAVs providing reliable wireless connectivity between users or user groups in adverse environments. This use greatly reduces the overall energy consumption at the end-node level, thus extending the network lifetime.

### 8.5. Lessons learned

Many lessons can be learned from the cross-layer approaches discussed in this Section. All the presented topics (path and trajectory optimization and design, state estimation and optimization, and network formation and control) are of great importance to exchange data among UAV and/or between UAV and GS, while optimizing different metrics like energy consumption, connectivity, throughput, delay in data exchange, task accomplishment, overall mission time, connectivity, and coverage area. Especially the minimization of energy consumption pushes such optimization strategies, because of the positive implications on the increase of the flight time, battery duration and amount of data delivered to destination.

Nevertheless the metrics to be optimized are too many and often in contrast each other, so trade-offs have to be reached especially when

the optimization strategies are implemented through multi-objective algorithms which are intrinsically much more computationally complex with respect to their single-objective counterparts. Very often, and as usual, simplifications are introduced to make these algorithms more computationally tractable, but with the risk of oversimplifying real application scenarios. Another weak point resides in the high mobility of drones, that brings to continuous and frequent changes in the network topology and connectivity. Accordingly, also the state information (position, velocity, etc.) must be continuously updated to recover from unavoidable mismatches between the estimated state and the real one, and this increases the overhead in exchange of control information among drones and/or with GSs.

## 9. Security and privacy aspects

This Section discusses security and privacy related topics that are of relevance in the context of the IoD. Similarly to other Sections, this one closes up highlighting the lessons learned on the theme. In Fig. 16, the overall organization of the present Section is summarized.

UAVs can be considered as complex flight control computer-aided systems with, at least, one sensor. UAVs are programmed, off-line, before take off, or controlled, on-line, to fly over a specific pattern, for example within a facility. During this period of time, the drone is supposed to receive sensor data, thanks to on-board units, apply some processing routine to the sensor data, as to detect an unacceptable level of difference in data features, determine a new flight instruction for the vehicle based on the processing. Afterward, the new flight instructions are sent for controlling the flight of the vehicle.

According to the reference context, several security aspects may be involved. Conventionally, commercial surveillance systems are managed by humans, that regularly check in at guard stations and make observations. Surveillance systems have progressed into closed-circuit television monitoring, and more recently integrated systems have been developed to include video cameras installed at strategic locations in a facility. These video cameras are in communication with a centralized remote monitoring facility, and operators visually sweep the facility from the monitoring center. Upon discovery of suspicious activity, the operator can engage in a response plan. A surveillance solution has been employed by the military through surveillance unmanned aerial vehicles, commonly referred to as drones. Military surveillance drones are capable of flying over large areas such that video surveillance can be achieved. Military surveillance drones are very expensive and address surveillance of very large outdoor areas. Even though civil applications may be characterized by surveillance tasks, there is a difference between military drones and civil ones. Indeed, military drones are not practical for businesses that want to maintain security at a single location or small group of locations such as a warehouse or a manufacturing facility.

In [169,10], the leading theme is security in the context of the communications among drones. The main concern on the theme is related to the security and the privacy of the data exchange processes.

### 9.1. Drones identification and classification

Modulation schemes are studied in some papers to identify and classify drones [170–172]. These contributions aim to identify drones on the basis of modulated RF signals [171,172] and classify them based on their unique features [170]. The method proposed in [171] aims at preventing UAVs from unauthorized flights over reserved areas. The solution proposed to tackle this problem is to use SDN to process the UAVs control signals. On the basis of a detailed analysis of the UAVs control methods, that rely on different modulation techniques, this study proposes a simple detection technique through measurement campaigns that are conducted on the field. Two different commercially available UAVs are used to extract the main features of their control signals through a SDN. Another UAV detection technique is proposed



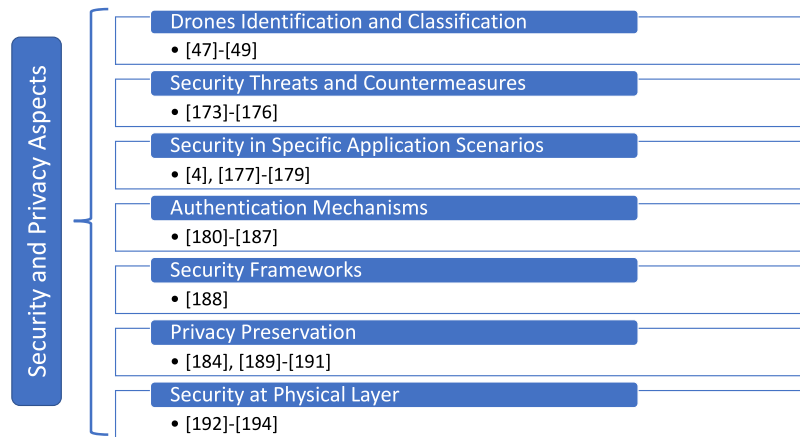


Fig. 16. Security, privacy and business models taxonomy.

in [172], for drones identification purposes. The paper carries out an analysis of the radio communication between the UAV and the remote control, as related to a specific type of drone. The radio communication channel is studied with reference to the number of channels adopted, their frequencies, the frequency utilization method and the modulation technique. This last aspect is used to study how the communication is maintained between the UAV and the remote controller through a signal analysis. A classification method for UAVs based on the analysis of the RF signal is proposed in [170], to avoid security and privacy issues and preserve public safety. Drone pilots are identified through the analysis of RF signals captured from the drone controllers, in presence of wireless co-channel interference, namely, Wi-Fi and Bluetooth. The methodology adopted to detect the UAVs is first described, testifying the robustness against false alarms and missed target detection. The RF features are extracted to classify the controller signals of UAVs. A RF fingerprinting technique is proposed, able to capture the unique characteristics (the “fingerprint”) of each UAV controller. The proposed approach is then compared with different Machine Learning algorithms, to testify its effectiveness for UAV classification.

## 9.2. Security threats and countermeasures

Some papers on security in drone networks are mainly focused on the description of the security threats and the related countermeasures in drones communication [173–176]. The importance of cyber-security in UAV-based networks is highlighted in [173]. The main goal of this work is to describe the main security threats involving networks based on UAVs. To this end, the main challenges for networks of drones are first presented, among which the need to verify the identity of a drone in some application scenarios, proposing a classification of the drone based on its functionalities, range, altitude, endurance, etc. This classification is the starting point to describe the main attacks and security threats that can be carried out on drones, which testifies how easily a UAV can be attacked, and its functionalities can be compromised. The network architecture is described, highlighting the main security threats as referred to each part of the network. Finally, a risk assessment scheme is proposed, that contains integrity, confidentiality and availability. The necessary steps to provide security for drones are considered as concluding considerations of this study. More focused on secure communications among drones is the study carried out in [174]. The security-related risks are addressed, especially focusing on the “taking over control” type of attack. It is a software centric type of attack that exploits the vulnerabilities of the standardized communication and control protocol. To this end, the possible approaches adopted to carry out attacks on the protocol vulnerabilities are discussed in detail, also highlighting that they can be easily exported to other communication protocols. Then, some recommendations are made to improve

the security of drones operations. They mainly consist in a strong limitation of the secret information disclosed during the binding phase, an extension of the binary string that represents the secret information exchanged, and the adoption of cryptographic methods, that are not actually present in the UAVs communication protocols. Other vulnerability issues are described in [175], with reference to a specific type of drone provided with video stream capabilities. This paper raises a warning flag from the privacy and resource accessibility points of view, which should absolutely not be set free in communication networks of any kind. This work focuses on the well known security vulnerabilities like an unencrypted Wi-Fi network connection and the management of the linux-based operating systems running on the drone by a user. This study also shows how the drone can be hacked, illustrating some possible attack scenarios that exploit the port scanning to carry out a combination of attacks that can take the full drone control. Then, some operations are described to secure the WiFi connection of the drone and its operation with the official smartphone app or third-party software. The work [176] discusses security of UAVs, but considering holistically the interactions among UAV systems from the point of view of attack methods and threats. The study is conducted from the perspective of a common security analysis among different systems, and the related security challenges to be tackled. The main goal is to derive a general security model, which can be exploited in different UAV-based systems, and that can analyze the security problems. The security analysis at the basis of the model is carried out by addressing both attacks at several layers of the stack, and potential threats, and analyzing security from the point of view of aerial, ground, marine and space unmanned systems. A summary of the security issues for the different systems paves the way to a discussion on the main security challenges for unmanned systems and the future directions that can be taken to tackle them.

## 9.3. Security in specific application scenarios

Papers [177–179,4] contextualize the UAV security analysis to specific application scenarios. The security aspect is addressed in [177], specifically referred to drone-assisted public safety networks. Drones can be fruitfully employed in public safety networks, where the supported services aim to protect people and environments from a wide variety of threats, because they enhance the communication capabilities of such wireless networks, since they can reduce coverage gaps and network congestion. Nevertheless, security is of great importance in this context, because sensitive data and/or critical information can be transmitted among drones. This contribution analyzes the most relevant security threats and the related countermeasures, that cover all the aspects of data confidentiality, integrity, availability, authenticity, privacy preservation and non-repudiation [177].

Another scenario, the smart farming environment, is considered in [178] to study security and privacy issues related to the use of IoT and communication technologies involving the use of UAVs, that are subject to cyber-security threats and vulnerabilities. This is mainly an overview paper, whose goal is first to provide an overall description of the communication architecture in the smart farming landscape, at different protocol layers. Then, the security and privacy issues are identified, in terms of security, privacy, authentication and authorization, and compliance with regulations. Cyber-attacks are then presented and classified into data, network, supply chain, and other relevant attacks. In parallel, the current research in cyber-security is discussed, describing also the main contributions and weak points of the works on this topic. Finally, the most interesting research challenges are addressed, that cover different areas ranging from network security to supply chain, artificial intelligence, machine learning, access control and information sharing [178].

Security plays a very important role also in military applications. For example, drones are widely used in the context of counter-terrorism [179]. Here, the concept of security is strictly related to the ability of inspecting active theaters of war. The conventional wisdom on drone warfare holds that drones are considered secure if, and perhaps only if, they have a high effectiveness in striking and disabling terrorist organizations. Nevertheless, the legitimacy of their employment is still under discussion. In fact, there is a diffused willingness to mitigate the strategic use of drones, at least under recognized standards and norms.

#### 9.4. Authentication mechanisms

Authentication mechanisms in networks of UAVs are described in [180–187]. The papers [180–182,184,186,187] are entirely focused on authentication mechanisms in UAV-based networks. More in detail, the works [180–182] propose mutual authentication mechanisms based on the so-called Physical Unclonable Functions (PUFs) that represent the unclonable, unique physical identity of a device, depending on its own hardware characteristics. In particular, [180] leverages a mutual authentication protocol between UAVs and a ground station. This mechanism aims at overcoming the traditional cryptographic techniques which are inefficient in networks of UAVs, because of their tight resource constraints, together with the nature of the wireless medium that is “open” by its own nature. Based on PUFs, a challenge–response pair is unique, and is used to authenticate the UAV to the ground station, through the well known time-based one-time password algorithm. It is used to exchange the challenge–response pair between the UAV and the station in the initial phase of the proposed algorithm, that is developed in such a way to avoid an adversary to overhear, duplicate, corrupt, or alter authentication data. Another approach based on PUFs is found in [181]. This work proposes a mutual authentication protocol for UAV-based networks in surveillance areas. PUFs are exploited to generate secret keys in real-time, being also able to secure UAV networks that rely on the SDN paradigm, protecting them from UAV tampering attacks. In such scenario, three different entities are defined: a “mini-drone” that accomplishes surveillance tasks, a “ground station”, a trusted entity that collects data, and a “leader drone” that acts as a relay between the mini-drones and the ground station. The proposed mutual authentication protocol protects the communication between leader drones and the ground station as a first step, and between mini drones and leader drone, as a second step. In each authentication round, two unique session keys are generated, one between the leader drone and the ground station, and the other between the mini drone and the ground station. Furthermore, thanks to the PUF-based mechanism, challenge–response key pairs generated are not stored in the UAV memory. The simplicity of computations makes the proposed protocol lightweight and suitable for real-time protection of SDN networks that employ UAVs. The PUF-based authentication scheme developed in [182] extends what presented in [180,181] by supporting also authentication among UAVs. More specifically, the

protocol is able to establish a secure session between an UAV and the ground station first, and then between two UAVs. Proof of the main security features such as mutual authentication, anonymity and forward secrecy is provided, together with the security proof against the most common types of attacks (like masquerade, man-in-the-middle, replay, cloning, de-synchronization and tampering attacks). All this, with reduced computation, communication, and storage costs. In a similar way to what previously discussed, the peculiarities of the IoD are taken into account by the work presented in [187], where data exchange between mobile users, a drone working a server and the remainder IoD infrastructure. Even though the operating context is similar, [186] focuses on an efficient privacy-aware scheme specifically designed for authenticated key agreement. The peculiarity of the contribution is that fact that no secret keys are store within the devices, still granting the desired security features.

Another discussion on authentication vulnerability in consumer WiFi drones is found in [183]. This work proposes a security assessment that illustrates how to manipulate a WiFi drone by a software suite, and without the need for additional hardware equipment that can carry out jamming or eavesdropping attacks, like for example a Software Defines Radio (SDR). The assessment procedure show that a deauthentication attack can be effectively carried out; it is a kind of Denial of Service (DoS) attack where a malicious entity launches deauthentication packets to a wireless access point (AP), making the AP believe that they come from a real client, thus taking down the drone. The drone vulnerabilities are assessed by standardized assessment models. Some prevention strategies are also discussed, like the adoption of encryption protocols and best password practices. The work presented in [185] is an important contribution that tackles both privacy and security from a technological point of view, for example securing transmission and reception activities. More specifically, a mechanism for secure communications in UAV-based networks is proposed. It supports key agreement, user authentication, non-repudiation, and user revocation, and all this in one algorithm. This mechanism is then exploited to build a secure communication protocol for UAV-based applications, which aims at maximizing the energy efficiency. The performance of the proposed scheme is evaluated in a real testbed.

#### 9.5. Security frameworks

A security management framework is proposed in [188], which aims at automating the orchestration, configuration and deployment of lightweight Virtual network Security Functions (VSF) in Mobile Edge Computing (MEC) nodes, that are placed on-board UAVs. Different factors are considered to optimize the security orchestration. The contribution of this work is manifold. First, a MEC architecture is proposed and implemented. With this background, the orchestration mechanism is provided, to manage security in UAV networks, and taking into account different metrics and conditions for the VNF placement on UAVs, like operating capacity, battery, atmospheric conditions, computing resources (RAM, disk, CPU), and network metrics. The applicability of the proposed solution is then evaluated in a real testbed and use case, testing the performance of the framework from both the MEC node and the UAV points of view.

#### 9.6. Privacy preservation

Privacy is also a critical issue in the IoD environment, as described in [189,184,190,191]. This aspect is developed in [189]. This paper discusses the security challenges from the legal point of view, starting from the assumption that the legal framework for UAVs is very complex in the EU scenario. The main goal of this paper is to point out the key open issues in the legal field, that include public security legislations, telecommunication law, rules on product liability, criminal and insurance law, privacy and data protection. An overview of the new EU rules is first provided, describing the approach followed by the EU

to guarantee security and safety for aircraft operations in the sky. The open issues on the security topic are then addressed, synthesized into privacy preservation, telecommunications and cyber-security breaches, registration of UAVs and the identifiability of their operators and pilots, liability and enforcement regulations. The resulting picture confirms the complexity of the legal framework that necessitates harmonization and clarification of rules [189].

A major privacy concern is directly linked to the idea that drones are moving all around urban and suburban areas, impairing privacy of the people, especially in case of amateur drones. This is the theme developed in [184], where different safety, security and privacy threats are discussed in the deployment of amateur UAVs. The main goal of this review paper is to illustrate the state-of-the-art studies on this topic. A framework is then proposed, that exploits cognitive IoT to provide amateur drone surveillance with a higher level of intelligence through cognitive tasks, i.e., sensing, data analytics, knowledge discovery and intelligent decision making [184]. A case study is also provided, where detection of both authorized and unauthorized drones is provided, to check the correct operations that the various types of drones can carry out.

The contribution [190] specifically addresses privacy issues of IoT in both civilian and military architectures and a certain number of security and privacy requirements. The main contribution of this paper is to study the IoT architecture and its main security and privacy requirements. To this end, the main security and privacy challenges in the IoT scenario are described, that range from the privacy leakage, that occurs when sensitive data are collected by unauthorized drones, to data sharing in the cloud that can be readable by third-parties, and malicious interference in control sites that occurs whenever a drone can be managed, controlled in all its movements by an attacker to compromise a system. For all these issues, solutions are proposed aiming at protecting the privacy of sensitive data. They consist of authentication solution for privacy protection to lightweight cryptography protocols for security and privacy protection in case of stored data. A lightweight data protection protocol is also proposed for data stored in a cloud server. It is based on the well-known Identity-Based Encryption (IBE) protocol, but it is made lightweight to adapt it to the resource-constrained drones. Finally, future research directions are also suggested to tackle the main security challenges explained above.

Drones are also widely used also in commercial applications, and this raises concerns about the related privacy and safety issues arising from a domestic employment of drones. This is the main goal of the work [191], that carries out an exhaustive review of the state-of-the-art literature on drones thought for commercial uses, but focusing on the so-called “tecnoethical” aspects, i.e., the study of the impact of drones technology on ethics. Social and ethical concerns are studied in different key-areas, also providing insights on the state of the public knowledge on commercial drones, but seen from an ethical point of view. Finally, this paper points out also the need to increase the level of attention towards the potential negative ethical consequences in the use of commercial drones.

### 9.7. Security at physical layer

Some papers tackle the security aspect in UAV networks from the physical layer perspective [192–195]. From this point of view, an interesting research topic about security is jamming, as testified in [192,193]. In [192] jamming is discussed as a kind of attack in optical UAV network architectures. The jamming attack is presented as a kind of Denial of service (DoS) attack, where the attacker sends intentionally and interference signal in the communication link between UAVs exploiting the FSO link. A technique for jamming attack detection is proposed, able to detect the presence of jamming signals in combination with the transmitter signals. A countermeasure approach is also presented, allowing to recover the transmitted signals in presence of a jamming attack. Another solution to the problem

of jamming is presented in [193] for UAV-aided cellular systems. This paper proposes a UAV relay scheme based on the Reinforcement Learning (RL) approach, that exploits the RL and transfer learning to optimize the relay signal power against jamming, without knowing the network topology and the models of message generation and jamming signal. The proposed scheme estimates the received jamming power, the condition of the links between jammer, UAV and the base stations. From these estimations, the UAV chooses the best relay policy that improves the network resistance towards jamming attacks. Neural network is exploited to learn from past UAV relay experiences in similar cellular anti-jamming communication systems. Performance bounds, including bit error rate and computational complexity of the proposed relay scheme, are derived through simulation. A more general description of physical layer related security is carried out in [194], where eavesdropping and jamming attacks are taken into account in wireless networks including UAVs. Eavesdropping and jamming attacks are first described from two different points of view. In the first, UAV-ground communications are analyzed as more subject than terrestrial communications to eavesdropping and jamming attacks by malicious ground nodes. In the second, malicious UAVs can be more effective in carrying out eavesdropping and jamming attacks to terrestrial communications, if compared to malicious ground nodes. Starting from these premises, countermeasures are proposed to secure A2G communications from terrestrial eavesdropping and jamming, and to secure terrestrial communications from UAV eavesdropping and jamming.

Covert communications are analyzed in [195] for A2G networks. Covert communication is a kind of physical layer security, that provides a more sophisticated level of encryption for wireless networks. The main goal of this work is to investigate covert communications for UAV-assisted networks. To this end, two case studies are presented in which covert communication can be enhanced, i.e., UAV-assisted multi-user data dissemination and jamming-assisted UAV covert communication. The main challenging issues and research directions related to this topic are also discussed.

### 9.8. Lessons learned

In the military context, both the role and employment are under discussion nowadays, since a regulation is highly wished from many players. Turning from the military to the civil context, the considerations connected with privacy are due to lack of legislation. Privacy concerns are partially justified by the possibility that data tracking, and propagation problems may emerge. For example, in case a drone captures a frame with private information, it should be discarded or somehow censored. This is still an open issue for the future. Sometimes, the problems are related to the fact that not all the countries are using same regulations and/or laws on the theme. It is noteworthy that, according to the regional legislation, any government agency/body could impose limitations to drones’ employment in beyond controlled, monitored use.

## 10. Discussion on the main findings and future research perspectives

The aim of this Section is to discuss the detail of the main findings of the whole analysis carried out so far. At the same time, in this part, the present contribution is specifically focused on the main lessons learned from the surveyed literature. Particular attention is devoted to the strengths of the main results found and the related issues. Fig. 17 summarizes the contents of the present Section.

### 10.1. Discussion on the main findings in the surveyed literature

The analysis of UAVs connectivity demonstrates an extremely wide set of possible technologies involved for creating both A2A and A2G links. In terms of channel modeling and connectivity analysis, several

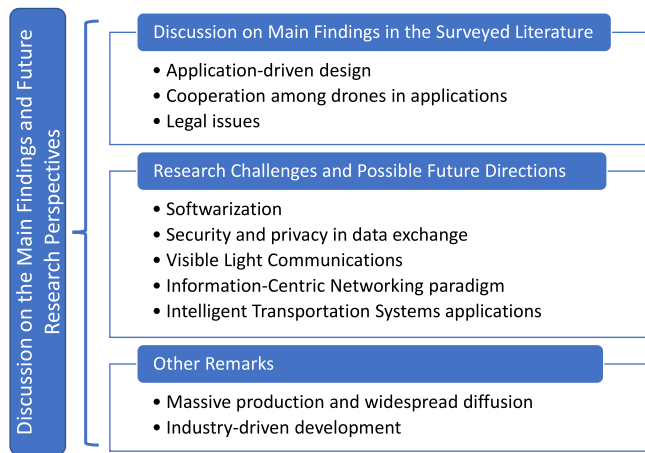


Fig. 17. Security, privacy and business models taxonomy.

studies show that there is a tight bound between the two aspects. Several proposals aim at creating reliable mathematical formulations that include as much aspects as possible, in terms of statistical variability and signal fluctuations in the communication channel. They are very useful to analyze the increase in coverage performance, the optimal allocation of resources at different layers of the protocol stack, and the improvements in path reliability for routing, path planning and position optimization strategies. Although the presented contributions are valuable, connectivity and channel models suffer from multiple problems, mainly connected to real-world operating conditions, such as NLoS conditions and/or presence of obstacles. To solve such issues, the most promising solution seems to be the choice of the most suitable communication technology, that matches the specific application needs.

At data link layer, the current state of the art suggests that drones may benefit from significant modifications to MAC layer. For example, cooperative schemes are useful to improve communication efficiency. Synchronization is another important point that arises from the analysis carried out. To reach optimal resource allocation, scheduling is widely considered as the most promising strategy, especially in densely populated scenarios in which drones are configured in swarms.

Network layer-related problems are, once again, strictly related to enhancements in connectivity; drones are proposed as relaying units to strengthen existing networking solutions.

Turning to application layer considerations, the solutions that have been investigated so far demonstrate that applications may strongly benefit from the adoption of cooperation among drones, as suggested in lower layers solutions. Some of the most interesting works show the suitability of drones for advanced applications in continuous monitoring of widely distributed phenomena, with surveillance among others. What emerges as a clear perspective of the employment of drones is the fact that the inspection of difficult access areas is sensibly simplified. Almost all of the referenced works on this topic agree that the quick on-site deployment of inspection system composed by one or more drones generates crucial benefits.

The analysis and optimization of throughput has been discussed as a way to increase the performance of communication systems in the context if both A2A and A2G links for data exchange, and to optimize different metrics in IoD systems (mutual distance, positions and paths of drones, spectrum and energy efficiency, network topologies). In such context, the throughput optimization in most cases translates into solving an optimization problem, whose solution is computationally expensive, or found approximately, or only in simplified scenarios. Furthermore, throughput maximization is counterbalanced by a higher energy consumption, which can become a serious drawback for battery-powered drones. Given the formulations of the optimization problems

proposed for resource allocation, the currently available technological landscape seems to be a sensibly limiting factor, in terms of onboard energy availability and computational capabilities.

Despite the wide agreement on the fact that drones may sensibly enhance all the processes in which they may be involved, some legal issues are clearly arising. In fact, there is a relevant lack of legislation in many countries to allow a massive employment of networks of drones as enabling technology. Moreover, some of the biggest players in this market argue that legislation should be somehow homogeneous and harmonized across borders, thus allowing industrial players to act on a worldwide scale.

## 10.2. Research challenges and possible future directions

In this section, the main research challenges and possible future directions in the IoD field are discussed.

As for communications among drones, the main trends are related to the extension of the covered area and the employability of communication protocols to guarantee a target QoE in both A2A and A2G. In the 5G perspective, it could be useful to standardize communications and creating homogeneous frameworks and platforms that provide real integration among heterogeneous technologies, rather than pushing on performance (e.g., increasing the data rate or decreasing latencies). This process is often referred to as *Softwarization*. It is worth noting that a similar phenomenon is taking place in the IoT world., where a number of examples and dedicated studies are specifically focused at integrating the existing IoT technologies rather than developing new ones [196–199]. Specific attention is devoted to the security aspects of such interactions [200], thus proposing innovative solutions based on Blockchain and smart contracts [201].

Another example can be found in the application of VLCs and ICN technologies to drones. Some works have already contributed on the VLC topic [85,202,203,87,86,88,204–206], especially for what concerns the analysis of the IEEE standards [85], modulation schema and light patterns at physical layer [203], MAC layer analysis and performance of network topologies [87,86], simulation software [86,88], applications of the VLC system architecture [204,206] with its strengths and weaknesses [205], and related performance evaluation [202]. It would be very interesting, as a future research direction, to investigate the possibilities of application of this novel technology to the IoD field.

As said, another interesting research line that definitely deserves attention is the application of ICN in the context of the IoD [207]. In particular, what clearly emerges from the study of the related state-of-the-art, is that the application of the ICN in the context of ITSs seems not to be already as mature as it could [208,209]. As a matter of fact, the authors believe that this may represent a limiting factor since the ICN architecture proposes one of the best solutions to support communications over users, especially in mobile-by-design scenarios [210,211]. Among the main reasons that make this of relevance, there is the increasingly emerging limitation of the host-centric nature of the Internet, as known today. Indeed, there is a continuous request for seamless mobility, coming from users of different nature, and pushing to the limit the Internet capabilities. The proper support to intrinsic mobile scenarios becomes necessary in those cases in which the handover is frequently verified. The latter is, in fact, an extremely well-known problem in the telecommunications world as, in a mobile scenario, the user remains connected to the network, and does not experience any discontinuity of service, if, and only if, the coverage is acceptable. Since the global connectivity cannot be granted with a single access point (i.e., a single cell in the case of cellular networks), the problem of the handover arises when the user moves from one access point to another. In the case of cellular networks, this happens when the user moves from one cell to one of the neighboring ones. The intrinsic mobility that characterizes ITSs systems, both from the points of view of users and drones producing data, places serious constraints on sustainability. It is worth noting that routing problems also arise in



these cases, because of the need to realize in real-time which access point is the UAV connected to, and both in DL and UL. If the routes are not known, the UAV will experience a loss of connectivity and information exchange. The ICN communication paradigm, leveraging the Publish-Subscribe communication scheme, represents a good candidate for granting QoS design criteria, such as communication latencies, PLR, resilience, and throughput. The joint analysis of even some of these aspects, combined together in ITS applications, could be an interesting challenge for the future research.

Another research challenge in drones' communication concerns security and privacy in data exchange. Strictly related to privacy is the legislation issue. Legislative interventions could also be of importance on the theme of privacy, even if some problems have still to be solved [184]. In particular, one of the concerns is related to the idea that drones moving all around urban and suburban areas could impair privacy of the people. To the best of the authors knowledge, very few works analyze these aspects: the work [185] treats these themes from a technological point of view, for example securing transmission and reception activities. The contribution [190] specifically addresses privacy issues of the IoD in both civilian and military architectures and a certain number of security and privacy requirements. The work [175] raises a flag from the privacy and resource accessibility points of view, which should absolutely not be set free in communication networks of any kind. Nevertheless, research efforts could be made in this direction to further analyze and improve these aspects.

### 10.3. Other remarks

Drones can be fruitfully employed in an ever growing number of emerging applications, where groups of cooperative, mobile and highly functional machines fulfill complex tasks autonomously to reach a common goal. As a key part of the IoT paradigm, UAVs networks are following an evolutionary step, rapidly evolving from networks of "smart" objects to networks of "social" objects [212], acting autonomously with other objects depending on their mutual social relationships, discovering and providing services and information in a trust-oriented fashion. All this, well beyond the relationships among the objects owners. Nevertheless, to fully exploit this high degree of automaticity and "social intelligence", further research efforts are needed, in two main directions. First, an accurate design of the parameters that characterize the social relationships is needed, to avoid false or bad friendships among UAVs. Second, the information exchange and the cooperation among UAVs should avoid attacks that can destroy the friendship relationships and the ability to operate autonomously by network of drones [212]. Again, security, and especially trustworthiness, is a high-priority aspect to be carefully considered in IoD, as testified by the research works on this topic analyzed in Section 9.

Interesting solutions may be proposed and developed at scale if promising technological paradigm were investigated. In this fashion, the joint adoption of IoD and ICN can be proposed as a key enabler for synergistic cooperation in both military and civil applications.

Some other considerations are related to technology and to the massive production and widespread diffusion of autonomous vehicles, even more so in industrial applications. It is well known that there is a close relationship between costs and the development of a technology [213]. In this context, advanced industrial countries select, and apply without costs, all the innovations that are more immediately useful and have a short Time-to-Market. As the general level of capital accumulation rises, more capital-intensive technologies become economical. Since industrialization is driven by technology applicability, and considerably boosted by rapid prototyping, the need for a drone to carry out part of industrial process monitoring or supply chain support/optimization depends on both its cost and its accessibility. The consideration can be completed by reasoning on the legal aspects of the question. Since there is not a unified legislation on the usage of unmanned vehicles, the seamless employability is still far from now. In a global economical

context, this means that a firm or an industry may find economical and legal barriers to their welcoming attitude towards drones. In all the analyzed works, these aspects have been neglected, but they surely represent a value added in future research on the IoD theme. On the same theme, it is worth mentioning that *data owner* and *data ownership* are to be clarified/unified. In this context, the General Data Protection Regulation (GDPR) already gave some indications. Indeed, they need to be further specialized, since drones are a recent frontier in technological advancement and technology is usually evolving faster than law.

## 11. Conclusions

This work aims at providing a thorough overview on the research activities on the IoD networking architecture. To this end, the available scientific literature has been thoroughly investigated and studied in detail and classified to identify the current research trends.

At a first level of analysis, the proposed classification scheme follows the Internet protocol stack, starting from the physical layer, going up towards the application layer, without neglecting cross-layer approaches. At a finer description level, for each layer of the stack the papers have been further classified and described, based on the proposed approach.

While describing the challenges that threaten the IoD diffusion, this work also presents the current open issues, in order to draw future research directions. The analysis demonstrates that consistent design efforts have been devoted to specific aspects at the different layers. For instance, several mathematical models/frameworks have been proposed to improve communication range, or reliably model the wireless medium, at physical layer, or even efficiently routing for synchronization. Some works propose cooperation and network formation as an efficient data exchange strategy.

Promising results have been discussed in those works that focus on one of the aforescribed problems and try to deal with it as an optimization problem. This is even more evident when the IoD-related problems are solved together in combined optimization approaches, such as energy consumption and trajectory design, or path planning and routing optimization.

At the same time, novel proposals and design methodologies were surveyed to discuss the effects of the introduction of 5G and 6G-compliant technologies, such as mmWave and VLC. Even though the discussion is still ongoing, further efforts could be useful to establish new requirements even in critical operating conditions.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Pietro Boccadoro** received the Dr. Eng. degree (with honors) in electronic engineering from "Politecnico di Bari", Bari, Italy, in July 2015. From Nov. 2015 to Oct. 2017, he collaborated as a researcher with Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT) at Politecnico di Bari and collaborated to research activities for the H2020 BONVOYAGE project. He is IEEE Member since 2017. In 2021 he got his Ph.D. in Telecommunications. He has been constantly involved as a Technical Program Committee member of many prestigious conferences. He is also serving as a Reviewer for many prestigious Journals. From 2021 he is R&D Software Engineer at Nextome.



**Domenico Striccoli** received, with honors, the Dr. Eng. Degree in Electronic Engineering in April 2000, and the Ph.D. degree in April 2004, both from the Politecnico di Bari, Italy. In 2005 he joined the DIASS Department of Politecnico di Bari in Taranto as Assistant Professor in Telecommunications. Actually he teaches fundamental courses in the field of Telecommunications at Department of Electrical and Information Engineering (DEI) of Politecnico di Bari. His scientific interests span different aspects of Telecommunications networks, including wireless technologies (NB-IoT, 5G/6G, NR, etc.), bandwidth allocation, multimedia systems, Call Admission Control schemes, scheduling techniques, QoS/QoE in mobile wireless networks (WSN, 5G, etc.).



**Luigi Alfredo Grieco** received the Dr. Eng. degree (with honors) in electronic engineering from "Politecnico di Bari", Bari, Italy, in Oct. 1999 and the Ph.D. degree in information engineering from "Università di Lecce," Lecce, Italy, on December 2003. From Jan. 2005 to Oct. 2014, he held an Assistant Prof. position at the "DEI - Politecnico di Bari". From March to June 2009, he has been a Visiting Researcher with INRIA (Sophia Antipolis, France), working on the topic of Internet measurements. From Oct. to Nov. 2013, he has been a Visiting Researcher with LAAS-CNRS (Toulouse, France) working on Information Centric Networking design of M2M systems. From Nov. 2014 to Dec. 2018, he has been an Associate Professor in Telecommunications at Politecnico di Bari (DEI). Since Dec. 2018, he is a Full Professor in Telecommunications at Politecnico di Bari (DEI). He authored around 200 scientific papers published in venues of great renown that gained more than 10000 citations (source: Google Scholar). His current research interests include: Industrial Internet of Things, Information Centric Networking, and Nano-communications. He is the Founder Editor in Chief of the Internet Technology Letters Journal (Wiley) and served as EiC of the Transactions on Emerging Telecommunications Technologies (Wiley) from mid-2016 to 2019. He also serves as associate editor the IEEE Transactions on Vehicular Technology journal (for which he has been awarded as top associate editor in 2012, 2017 and 2020). He has been constantly involved as Technical Program Committee member of many prestigious conferences. Within the Internet Engineering Task Force (Internet Research Task Force), he contributed (as author of RFC 7554) new standard protocols for industrial IoT applications (new standard architectures for tomorrow ICN-IoT systems). From Jan. 2019, he is Founding Member and Subarea-Chair of the IEEE SIG on Intelligent Internet Edge. In 2020 he has been nominated scientific coordinator of the IoT4.0 Lab.