A Vision and Framework for the High Altitude Platform Station (HAPS) Networks of the Future

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Abstract

A High Altitude Platform Station (HAPS) is a network node that operates in the stratosphere at an of altitude around 20 km and is instrumental for providing communication services. Precipitated by technological innovations in the areas of autonomous avionics, array antennas, solar panel efficiency levels, and battery energy densities, and fueled by flourishing industry ecosystems, the HAPS has emerged as an indispensable component of next-generations of wireless networks. In this article, we provide a vision and framework for the HAPS networks of the future supported by a comprehensive and state-of-the-art literature review. We highlight the unrealized potential of HAPS systems and elaborate on their unique ability to serve metropolitan areas. The latest advancements and promising technologies in the HAPS energy and payload systems are discussed. The integration of the emerging Reconfigurable Smart Surface (RSS) technology in the communications payload of HAPS systems for providing a cost-effective deployment is proposed. A detailed overview of the radio resource management in HAPS systems is presented along with synergistic physical layer techniques, including Faster-Than-Nyquist (FTN) signaling. Numerous aspects of handoff management in HAPS systems are described. The notable contributions of Artificial Intelligence (AI) in HAPS, including machine learning in the design, topology management, handoff, and resource allocation aspects are emphasized. The extensive overview of the literature we provide is crucial for substantiating our vision that depicts the expected deployment opportunities and challenges in the next 10 years (next-generation networks), as well as in the subsequent 10 years (next-next-generation networks).

Index Terms

Sixth Generation (6G) Networks, High Altitude Platform Station (HAPS), Super Macro Base Station (SMBS), Vertical Heterogeneous Network (VHetNet).

Abbreviations

3D	Three Dimensional
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
AI	Artificial Intelligence
AR	Augmented Reality
BER	Bit Error Rate
BS	Base Station
CAV	Connected Autonomous Vehicle
CIR	Carrier-to-Interference Ratio
DoF	Degree-of-Freedom
eMBB	enhanced Mobile Broadband
ERAST	Environmental Research Aircraft and Sensor Technology
FBMC	Filter Bank Multicarrier
FSO	Free Space Optical
FTN	Faster-Than-Nyquist

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HAPS	High Altitude Platform Station
ICAO	International Civil Aviation Organization
ICI	Inter-carrier Interference
IoE	Internet of Everything
IoT	Internet of Things
ISI	Inter-symbolic Interference
ITS	Intelligent Transportation System
ITU	International Telecommunications Union
ITU-R	ITU Radiocommunication Sector
JAXA	Japan Aerospace Exploration Agency
LAPS	Low Altitude Platform Station
LEO	Low Earth Orbit
LOS	Line-of-Sight
LTE	Long-Term Evolution
MBMS	Multicast Broadcast Multimedia Services
MCU	Micro Controller Unit
MEC	Mobile Edge Computing
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MLSE	Maximum Likelihood Sequence Estimation
NAL	National Aerospace Laboratory
NFV	Network Function Virtualization
NLOS	Non Line-of-Sight
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
NTN	Non-Terrestrial Network
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio Frequency
RL	Reinforcement Learning
RNN	Recurrent Neural Network
RR	Radio Regulation
RRM	Radio Resource Management
RSS	Reconfigurable Smart Surface
RSSI	Received Signal Strength Indicator
SD-ABN	Software Defined Airborne Backbone Network Architecture
SDN	Software Defined Network
SEFDM	Spectrally-Efficient Frequency Division Multiplexing
SI	Swarm Intelligence
SINR	Signal-to-Interference-plus-Noise Ratio
SISO	Single-Input Single-Output
SLL	Side-Lobe Level
SMBS	Super Macro Base Station
SNR	Signal-to-Noise Ratio
SWAP	Size, Weight, and Power
TR	Technical Report
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UN	United Nations
URLLC	Ultra Reliable Low Latency Communication
VHetNet	Vertical Heterogeneous Network
VR	Virtual Reality
WRC	World Radiocommunication Conference

I. INTRODUCTION

In the state-of-the-art Sixth Generation (6G) network architecture, a vision of a three-layer Vertical Heterogeneous Network (VHetNet) is under discussion. This vision is consistent with the Third Generation Partnership Project (3GPP) activities regarding Non-Terrestrial Network (NTN), as defined in Technical Report (TR) 38.811 [1][1]. The three layers consist of a satellites (space) network, aerial network, and terrestrial network [3], as shown in Fig. 1. A High Altitude Platform Station (HAPS) is an integral component in the realization of the vision of VHetNets.

A HAPS is a network node that operates in the stratosphere at an altitude of around 20 km. Due to the unique properties of the stratosphere, a HAPS can stay at a quasi-stationary position and contribute significantly to the goal of ubiquitous connectivity. HAPS-related research activities can be traced back to 1990s through numerous research perspectives [4]. This research showed promise for the advancement of ubiquitous connectivity, with a particular focus on rural areas and disaster relief applications. In what follows, we go a step further by showing how the use of HAPS systems can catalyze advanced mobile wireless communication services with ultra-wide coverage and high capacity.

Recently, HAPS has been discussed as a viable aerial network component due to the evolution in communications technologies and advances in solar panel efficiency, lightweight composite materials, autonomous avionics, and antennas. As costs are time-dependent and more cost-effective technologies and materials are emerging, the use of HAPS systems will become more economically feasible in the future networks. With the development of advanced materials and the realization of necessary technological leaps, it is expected that new enablers will gradually materialize in coming years. These research trends have resulted in HAPS being actively considered to be a feasible technology for the future of wireless communication networks. Although the choice of energy source was considered as a fundamental issue in HAPS research, solar power coupled with energy storage has been regarded as the primary means of providing energy for HAPS systems since they have large surfaces suitable to accommodate solar panel films [5]. Moreover, because of its low-delay characteristics in comparison with the emerging satellite networks, a HAPS can provide wireless services directly to the users of terrestrial networks [6].

With ongoing disruption in wireless communication designs (e.g., data-driven designs) and emerging use cases (e.g., on-demand distributed machine learning platforms and data centers), HAPS systems have become more appealing for their potential benefits. From this perspective, a stand-alone balloon providing Internet access to a remote area is a limited example of what is possible. The era of portable data-centers, intelligent signal boosters, flying macro base stations, and machine-learning platforms capable of intelligent decision-making for a massive number cargo drones and flying cars has arrived. In effect, we envision the future with a massive constellation of HAPSs, termed as a *HAPS mega-constellation*[2] (analogous to a satellite mega-constellation), enabling high capacity network access, computation offloading, and data analytics tools, to millions of users/devices not only in suburban areas but also in dense urban areas, as shown in Fig. 1. As depicted in this figure, we can summarize our proposed framework as follows:

1) The HAPS layer, performing as a large-scale intelligent entity, enables fast, reliable, and efficient long-distance communication between satellites, bypassing the need for the installation of millions of ground and offshore relay stations [10]. It can also function as a distributed data-center for recording the orbital paths of satellites, monitoring conjunction alerts, and calculating the probability of a collision between satellites. The availability of such information in a timely manner for different satellite companies is vital for the preservation of the functionalities of the satellite mega-constellations. In addition, satellites help the HAPS layer in improving the handoff performance.
2) The HAPS layer is responsible for managing the mobility of a swarm of Unmanned Aerial Vehicle (UAV) by providing edge intelligence, offloading heavy computations, and handling large-scale sensing and monitoring, which are useful for cargo delivery and monitoring systems. The communication platform is expected to smoothly handle diverse communication requirements, such as Ultra Reliable Low Latency Communication (URLLC) and enhanced Mobile Broadband (eMBB) communications.
3) The HAPS layer provides fast Internet access and wireless communication services, such as IoT and distributed machine learning, to urban, suburban, and remote areas, reducing the reliance on terrestrial and satellite networks.

Due to these capabilities, we envision that the use of HAPS systems can be a remedy to the architectural problems that will be encountered as the use of aerial components increases in wireless networks. The use of HAPS systems as new wireless access platforms for future wireless communication systems has great potential, and its associated promises are detailed in this paper.

A. Survey and Overview Articles on HAPS

Several overview articles have been published on the use of HAPS systems as communication platforms. [11] provided a summary of the essential technical aspects of HAPS systems, including possible architectures and cell formations as of 2005. A summary of current and potential applications as well as past field trials along with open technical issues was given in

[1] In this document, the terminology as defined by the International Telecommunications Union (ITU) is used [2].

[2] According to ITU recommendations, a HAPS should have a wide footprint of about 500 km in radius [7]. A network of few multiple HAPS can extend the coverage to serve a whole country. For example, a HAPS constellation of 18 nodes is estimated to be sufficient to cover all of Greece, including all of its islands [8], and a constellation of 16 HAPS nodes are held to be sufficient to cover Japan [9].

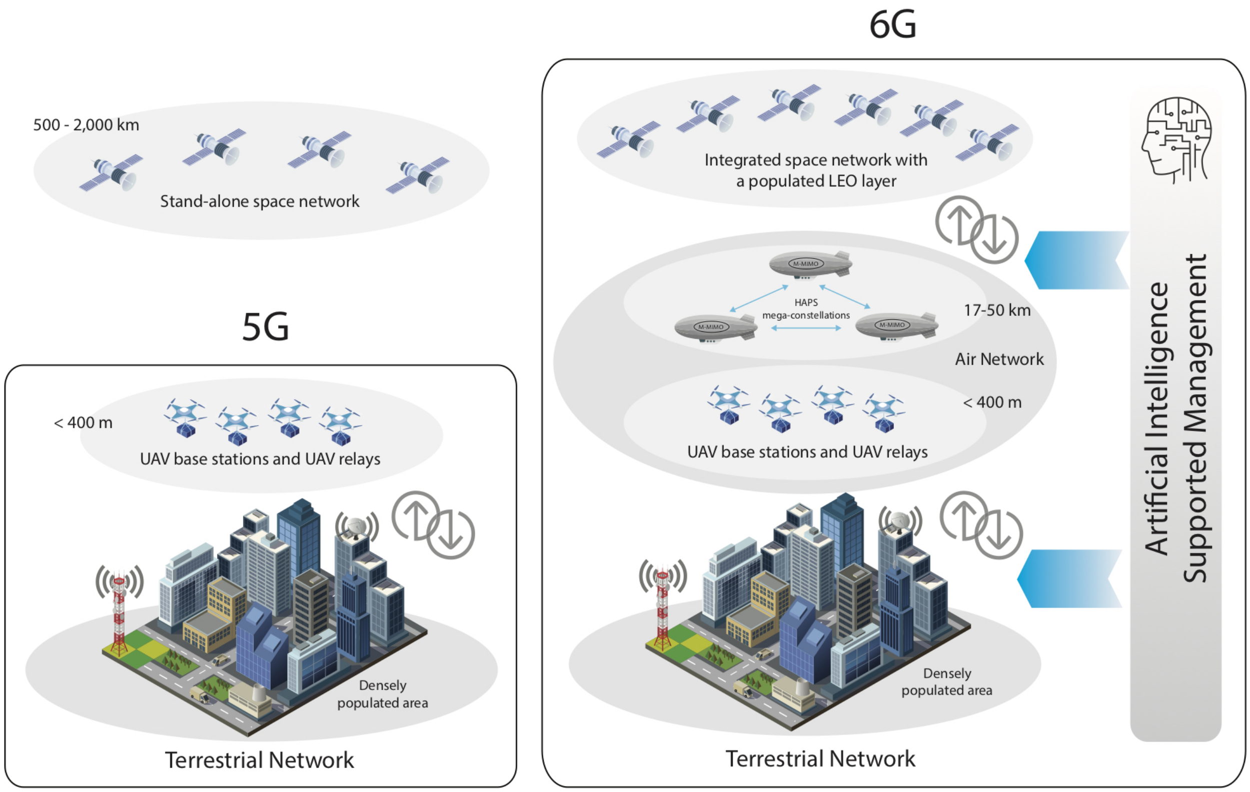


Fig. 1: An overview of the transition from 5G to 6G. A fully integrated Vertical Heterogeneous Network (VHetNet) is envisioned in 6G.

[12]. The commercial and research project deployments of HAPS systems as of 2009 was provided in [13]. The literature on the use of optical communications in HAPS platforms was presented in [14]. The authors of [15] provided an overview of HAPS related activities at past World Radiocommunication Conference (WRC) of the International Telecommunications Union (ITU), until 2010. [16], published in 2011, presented an overview of possible architectures for using HAPS systems to provide global connectivity. [17] provided a survey of the technological changes as of 2016. The books [18], [19] demonstrated the use of HAPS nodes as either a stand-alone or complementary part of a terrestrial network. [20] described the integration of the satellite systems and HAPS systems, paving the way for hybrid terrestrial-satellite communication systems. Findings from experimental studies from the HeliNet project were presented in [21]. The work in [22] demonstrated that HAPS accommodates a suitable system for wide-area synthetic aperture radar (SAR) imaging in a microwave remote sensing. An overview of the channel models for HAPS and satellite systems for both Single-Input Single-Output (SISO) and Multiple-Input Multiple-Output (MIMO) antenna systems was given in [23]. The book [24] provided an in depth overview of the channel models in HAPS and satellites. Although the works described above provided overviews of past and suggested use cases, their main focus was on the use of HAPS systems in sparsely populated areas or areas with underdeveloped infrastructure.

With respect to UAV communications, which mainly cover low to medium altitude platforms, there are many survey and tutorial articles that extensively overviewed the related literature[3]. Among them, [27] provided a comprehensive tutorial of the subject, reviewed recent developments, and highlighted important open issues. The authors extensively discussed the problem of joint rate allocation and trajectory design in UAV systems. They also comprehensively overviewed channel modeling in UAV systems, including UAV to ground and BS to UAV configurations. A review of recent developments in UAV communications from a 5G perspective is given in [25]. The authors also discussed several problems in UAV trajectory design as they pertained to communication requirements and the limited battery life of UAVs for IoT applications. Also, [26] comprehensively overviewed the use of mmWave communications in low-altitude platforms. [28] surveyed the literature on UAVs from a cyber-physical

[3]It is worth noting that while 3GPP technical reports, e.g., TR 22,829, use the term "UAV" for low-altitude vehicles with altitudes of roughly up to 150 m, the general literature sometimes uses this term for broader applications that range from low to medium and occasionally to high altitude platforms [25], [26]. In this paper, we stick to the ITU definition, unless otherwise noted.

system perspective by reviewing the three components of communication, computation, and control platforms in a versatile UAV system. However, acknowledging distinctive traits of HAPS nodes in comparison to UAVs, these literature is not relevant to the scope and subject of this paper. For examples, important issues in UAV communications, among them the trajectory design with respect to limited energy on board, the management of temporary, small-scale, and on-demand service providers or computational platforms for terrestrial networks, and the control and management of swarms of UAVs have very different scales in HAPS systems. Instead of providing communication/computation service to a hand-full of users on demand, we now face the prospect of doing so for a coverage area of 60 km to 400 km. Additionally, we now face the problem of preserving the functionality of HAPS systems for a couple of months and preferably years.

The literature on HAPS have progressed in a limited scale in the period between 2015 to 2018. Yet in 2018, along with possible research directions, a revival on the literature can be observed. A fresh view on the literature is given in the survey paper [29]. Therein, the authors discussed how the coverage of a HAPS can be extended by several orders of magnitude compared to conventional use-cases, e.g., from 60 km coverage radius to about 500 km coverage radius. Different communication techniques, such as resource allocation, MIMO communications and advanced antenna systems, and handoff were listed as main enabling factors and many relevant papers were reviewed accordingly. We should note that [29] mainly considered communications issues of HAPS systems almost related to 3G/4G technologies, while this work attempts to position HAPS systems in the era of 5G and beyond by covering various applications of HAPS systems for large-scale communications, intelligent relaying, computation offloading, and distributed machine learning. Furthermore, [29] often did not explicitly distinguish between UAVs and HAPS systems to the extent that many developed ideas for the former were implicitly assumed to be (automatically) transferable to the latter, which, as discussed above, may not be valid or precise. From a technological viewpoint, the use of HAPS in [29] is mainly restricted for the single-station applications for remote areas and disastrous situations. By contrast, our main goal in this work is to shed light on undiscovered potentials of the HAPS, where, in particular, dense-urban areas can greatly benefit from. As the current research literature does not address the use of HAPS systems in densely populated metropolitan areas, the literature does not fully reflect the potential of stratospheric platforms. For an overview of the surveys and books on HAPS systems refer to Table I.

B. Contributions and Outline

The aim of this article is to present promising research directions and a comprehensive overview of the current literature. Although the use of HAPS systems can extend beyond functioning as an essential networking component (e.g., they can also be used for component wide-area synthetic aperture radar (SAR) imaging in microwave remote sensing [22]), in this paper we mainly discuss communication, computation, and networking aspects towards the HAPS-mega constellations, as depicted in Fig. 2. We distinguish between next-generation and next-next-generation deployment scenarios by looking to the future over the next 10 and 20 years, respectively. Our main contributions are as follows:

- Presenting use-cases of HAPS systems and introducing the *HAPS-mounted Super Macro Base Station (SMBS)* as a promising and cost-effective solution for addressing traffic demands in the 5G and 6G eras. Unlike conventional macro BSs, the envisioned HAPS-mounted SMBS not only enhances coverage and capacity, but also supports data acquisition, computing, caching, and processing in a plethora of application domains.
- Describing recent advancements in HAPS energy subsystems and the latest technological innovations for communications payload. At the same time, we highlight the evolution of HAPS network architecture in accordance with the development of components of HAPS systems.
- Introducing the use of *Reconfigurable Smart Surface (RSS)* in the communications payload of HAPS systems and discussing their potential use cases and the benefits of such an integration.
- Providing a detailed review and discussion of the Radio Resource Management (RRM) and interference management schemes reported in the HAPS literature in the past 20 years. This includes a discussion of power control schemes, such as techniques that take into account mobility, multicasting, and computational power for edge computing over HAPS. Channel/sub-channel allocation and spectrum sharing as well as joint power, sub-channel and time allocations are discussed. Antenna and interference management are provided, including cell shape adaptation, coordinated multipoint transmission and platform diversity, massive MIMO for HAPS, as well as a discussion of motivations for virtual massive MIMO over a HAPS mega constellation.
- Proposing suitable waveform designs and multiple access techniques for HAPS communication links, where potential technologies such as Faster-Than-Nyquist (FTN) signaling, Spectrally-Efficient Frequency Division Multiplexing (SEFDM), Filter Bank Multicarrier (FBMC), and Non-Orthogonal Multiple Access (NOMA) are also extensively discussed.
- Addressing mobility management by discussing both inter-HAPS and intra-HAPS handoff algorithms used in HAPS systems and some critical issues that need to be considered in future HAPS systems. We also highlight existing techniques in HAPS network management and how HAPS networks can benefit from the application of softwarized techniques, such as network slicing, software defined networks, and network function virtualization.
- Describing the unique role of Artificial Intelligence (AI) and Machine Learning (ML) in design, topology management, handoff, and resource allocation in HAPS communication systems.

TABLE I: An overview of survey papers and books on HAPS systems

Reference	Year	Focus	Description
[11]	2005	Wireless architecture	• Summarizes the technical aspects and potential architectures of HAPS deployment. • The survey is based on old use-cases of HAPS systems.
[12]	2007	Project deployments	• Summarizes the main concepts of HAPS technology, applications and field-trials.
[18]	2008	Wireless architecture (Book)	• Introduces the main concepts for HAPS as an alternative for telecommunications services.
[13]	2009	Project deployments	• Description of the developments of HAPS projects and main potential applications.
[14]	2010	Optical links	• A review of the technologies, studies, and field-trials for HAPS optical communication links.
[15]	2010	Spectrum management	• A review of technical studies for HAPS developments in past meetings of the WRC and the ITU-R recommendations for HAPS systems.
[16]	2011	Wireless architecture	• An overview of possible scenarios in which HAPS can be interconnected with terrestrial and satellite networks.
[23]	2011	Channel model	• A survey of measurement campaigns and modeling approaches for HAPS and satellite communication links.
[19]	2011	Wireless architecture and communication links (Book)	• Describes the basics of HAPS systems and the technological requirements for utilizing HAPS for broadband communications. • It also presents a roadmap for HAPS constellations in future networks.
[17]	2016	Project deployments	• An overview of the historical development of HAPS technology, including discussions of technological advancements.
[25], [26]	2019	Wireless architecture and communication links	• These surveys discuss the future applications and challenges of aerial platforms and their use in mmWave communications. • These studies are mostly focused on low-altitude vehicles (UAVs).
[29]	2020	Wireless architecture	• Considers the use of HAPS with legacy technologies, 5G, and beyond 5G applications. • Sparsely populated, under-served areas are considered.
This manuscript	2020	Wireless architecture, and use-cases	• Presents a vision and framework for HAPS networks including discussion of various use-cases. Also, general requirements, design issues, and important parameters regarding each use-case are elaborated. • The latest advancements in HAPS systems as well as the promising technologies and techniques for HAPS communication links are discussed with a synergetic perspective. • Highlights the potential of AI/ML to facilitate/empower the design, topology management, handoff, and resource allocation aspects. • Discusses important challenges and open issues.

- Elaborating on various challenges that the widespread implementation of HAPS may encounter in coming years. We categorize the challenges and open issues two groups, next-generation (next 10 years) and next-next-generation (10-20 years), and provide numerous examples of each group along with tentative solutions and possible roadmaps.

This article is organized as follows. In the next section (Section II), we describe next-generation HAPS use-cases. In Section III, we focus on aviation and spectrum regulations that aim to harmonize the worldwide usage of HAPS. In Section IV, we describe the main components of a HAPS communication system and its onboard subsystems, while highlighting prominent past and recent projects. The channel models that characterize the performance limits of the HAPS nodes are presented in Section V. Section VI provides a comprehensive perspective on radio resource management and interference management of HAPS nodes from an overall network performance perspective. The handoff management of HAPS nodes, in accordance with the existing terrestrial networks is detailed in Section VII. In Section VIII, we outline the network management perspective. The indispensable role of AI is detailed in Section IX. In Section X, in addition to the next-generation networks' needs, the open issues that need to be addressed in the in the next 20 years, and the associated challenges, are listed. Finally, we present our conclusions in Section XI.

II. Promising Use-Cases for HAPS Systems in Next-Generation Networks

HAPS systems have promising advantages over satellite communications, as summarized in Table II. These advantages will make them an indispensable component for next-generation wireless networks. Conventional wireless communication services provisioning using HAPS systems are limited to rural and remote areas to provide broadband access as an alternative to terrestrial systems and for disaster relief [29], mainly targeting areas with low user densities. However, communication

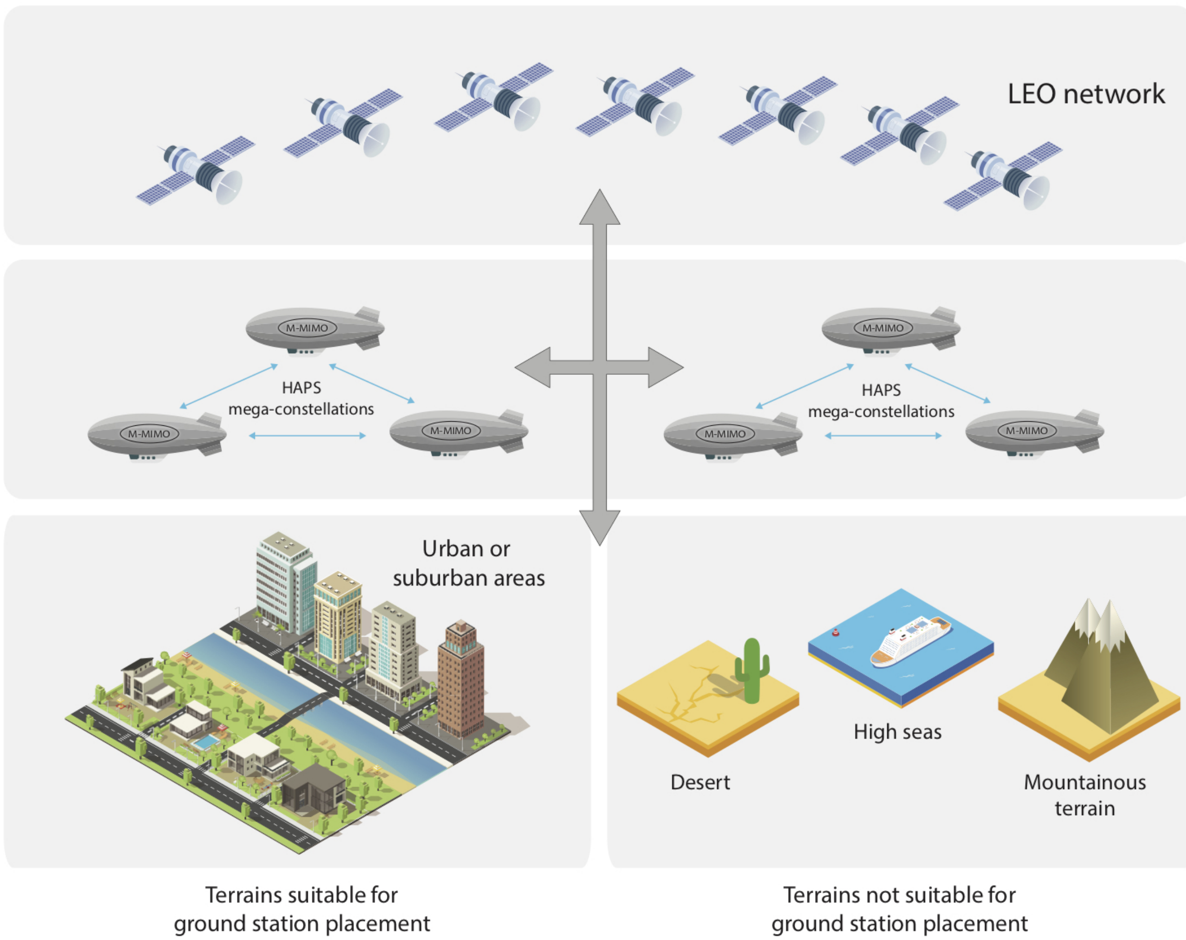


Fig. 2: The vision of HAPS mega-constellations over the next 20 years, bridging space and terrestrial networks over densely populated urban centers, providing connectivity and computation even over terrains that are not suitable for ground network architectures.

TABLE II: Complementary features of HAPS systems compared to Low Earth Orbit (LEO) satellite

Advantage	Description
Low altitude deployment with favorable channel conditions	◦ HAPS constellation deployments are expected to be at a low altitude when compared to LEO satellites located from 350 km to 2000 km, leading to a favorable link budget and a high Signal-to-Noise Ratio (SNR) for the downlink providing a coverage advantage. Considering the uplink connectivity, the relatively low path loss enables the use of UEs as the terminals which have limited transmit power levels, without the need for specialized ground stations.
Almost stationary positions	◦ LEO satellites can cross over continents within several minutes due to their high speeds. As a result, some of the capacity of LEO satellite communication is wasted while they pass over oceans and underpopulated areas. By contrast, the relatively stationary position of HAPS systems prevents a waste of capacity. ◦ The stationary position of the links avoids the introduction of a significant Doppler shift.
Smaller footprint with a large surface volume	◦ A HAPS system has a smaller footprint compared to LEO that provisions a higher area throughput. Due to its large volume, a HAPS is suitable for MIMO and massive-MIMO deployments. Aided by multi-antenna arrays, HAPS systems can generate highly directional 3D beams with narrow beamwidths that improve the SINR for all users. ◦ The larger volume of HAPS systems can be equipped with huge solar panels and energy storage systems. Due to advancements in solar panel efficiency and energy-storage, HAPS systems can stay airborne for a long period of time with minimal energy consumption.
Reduced round-trip delay	◦ Due to a lower altitude, a HAPS system corresponds to a round trip delay of 0.13 to 0.33 ms which makes them a good option for low-latency applications, such as URLLC. Hence, a HAPS constellation-based communication system can overcome the inherent high-latency problem of satellite networks.
Deployment and maintenance advantages	◦ The costs and risks of deployment are lower in the case of HAPS systems compared to LEOs. Moreover, HAPS systems are easier to bring back to earth once they finish their mission, while satellites are not recoverable.

TABLE III: Features of the envisioned HAPS systems compared to conventional HAPS

Aspect of comparison	Conventional HAPS	Envisioned HAPS
Application scenarios	Rural and remote areas, emergency cases.	Urban and suburban areas in addition to remote areas.
Population density	Applicable only to regions with low user density.	Suitable for areas with high user density.
Goals	Extending the coverage of a terrestrial network.	Maximizing the achievable capacity to cover a lot of users. Guaranteeing low latency for mission-critical applications.
Functions	Providing connectivity for ground users.	In addition to connectivity, supporting computation, control, and caching. Connecting UAV and satellite mega-constellation nodes.
Target use-cases	Broadband coverage, Internet access, natural disaster recovery, and environment monitoring.	Internet of Things (IoT) applications, intelligent transportation systems, high-stake cargo drones, high-capacity Augmented Reality (AR)/Virtual Reality (VR) applications, temporary unpredictable events, computation offloading, and filling coverage gaps.
Coexistence	As an alternative to terrestrial networks.	As a complement to terrestrial and satellite networks.
Network type	Related to 3G/4G technologies.	Related to the 5G and beyond era.
Deployment	Single HAPS in isolation to provide coverage and capacity.	Multiple HAPS systems forming a network to provide coverage and capacity.

services in urban and suburban areas are heavily concentrated with an ever-increasing demand. The HAPS-based wireless access architecture we envision presents a compelling alternative to terrestrial network densification due to the possibility of using one platform for multiple applications, as detailed below. Table III summarizes the features of our envisioned HAPS systems over conventional HAPS systems.

A. HAPS-Mounted Super Macro Base Station (HAPS-SMBS)

A macro BS is a crucial component in wireless access architectures to provide coverage and support capacity. Currently, the concept of network densification through small cell deployments has been widely acknowledged in 4G, Long-Term Evolution (LTE), and 5G standards to address the requirements of coverage and capacity in terrestrial networks [30]. However, the communication needs of metropolitan areas are constantly increasing, and small cell deployments are not up to the task of matching this ever-increasing demand [31]. Although network coverage and capacity can be improved through the addition of UAV-mounted BSs, their Size, Weight, and Power (SWAP) constraints limit the lifetime and coverage area of UAV BSs. Also, the mobility of UAV BSs introduces a fast on/off restriction, where the BS needs to be activated/deactivated very rapidly.

Compared to UAVs, HAPS systems, which are inherently quasi-stationary, have a larger footprint, more computational power, and better LOS communication links. A HAPS-mounted SMBS (HAPS-SMBS) can therefore be regarded as a powerful platform to enhance connectivity. HAPS-SMBS systems, however, are not alternatives to terrestrial BSs; instead, they are a complementary solution for network management and control. The use of HAPS-SMBS systems to support a terrestrial communication network introduces agility and enables rapid capacity improvement solutions in an intelligent manner to address high and variable traffic demands. With this agility in network design, average user demands can be met with a terrestrial network, and rapidly changing or unpredictable user demands can be addressed by a complementary HAPS-SMBS. Due to a larger volume, the application of massive MIMO techniques can be exploited in a HAPS-SMBS to provide improved channel capacity. Also, the use of multiple coordinated HAPS-SMBS systems, equipped with multi-antenna arrays, can enable further flexibility of the extremely precise beams through a distributed MIMO set-up. The coordinated use of multiple HAPS-SMBS systems is also envisioned for metropolitan areas. It should be added that, unlike conventional macro BSs, HAPS-SMBS systems not only enhance coverage and capacity, but also serve as computational platforms. They function as intelligent frameworks to enable communication, computation, and caching while exploiting the power of machine learning algorithms. With these features, the potential benefits of a HAPS-SMBS can be substantially greater than a conventional macro-BS. We envision that future HAPS-SMBS architectures will support data acquisition, computing, caching, and processing in diverse application domains, as exemplified in Fig. 3, and detailed below. These potential use cases have been recently presented in [32], however their overall general requirements to access the feasibility of deployments have not yet been discussed. In this article, we discuss the requirements in terms of design and technical analysis to attain these use cases with the goal of revealing their full potential.

B. Use-Cases for HAPS-SMBS Systems

1) HAPS-SMBS systems to support IoT services: It is expected that HAPS will play a key role in supporting diverse Internet of Things (IoT) applications [33]–[35]. The ever-increasing proliferation of IoT technologies presents substantial challenges to the research community in terms of addressing connectivity, reliability, and latency requirements of a massive number of connected devices. In this context, current infrastructures and methods of designing wireless access architecture are rather limited and incapable of supporting these highly demanding wireless systems and services. The wide footprint of HAPS systems is ideal for providing greater coverage to a high number of IoT devices each with low-rate links. In addition, IoT devices might be located in areas where there is no terrestrial network coverage (e.g., forests, mountains, oceans, etc.). HAPS-SMBS

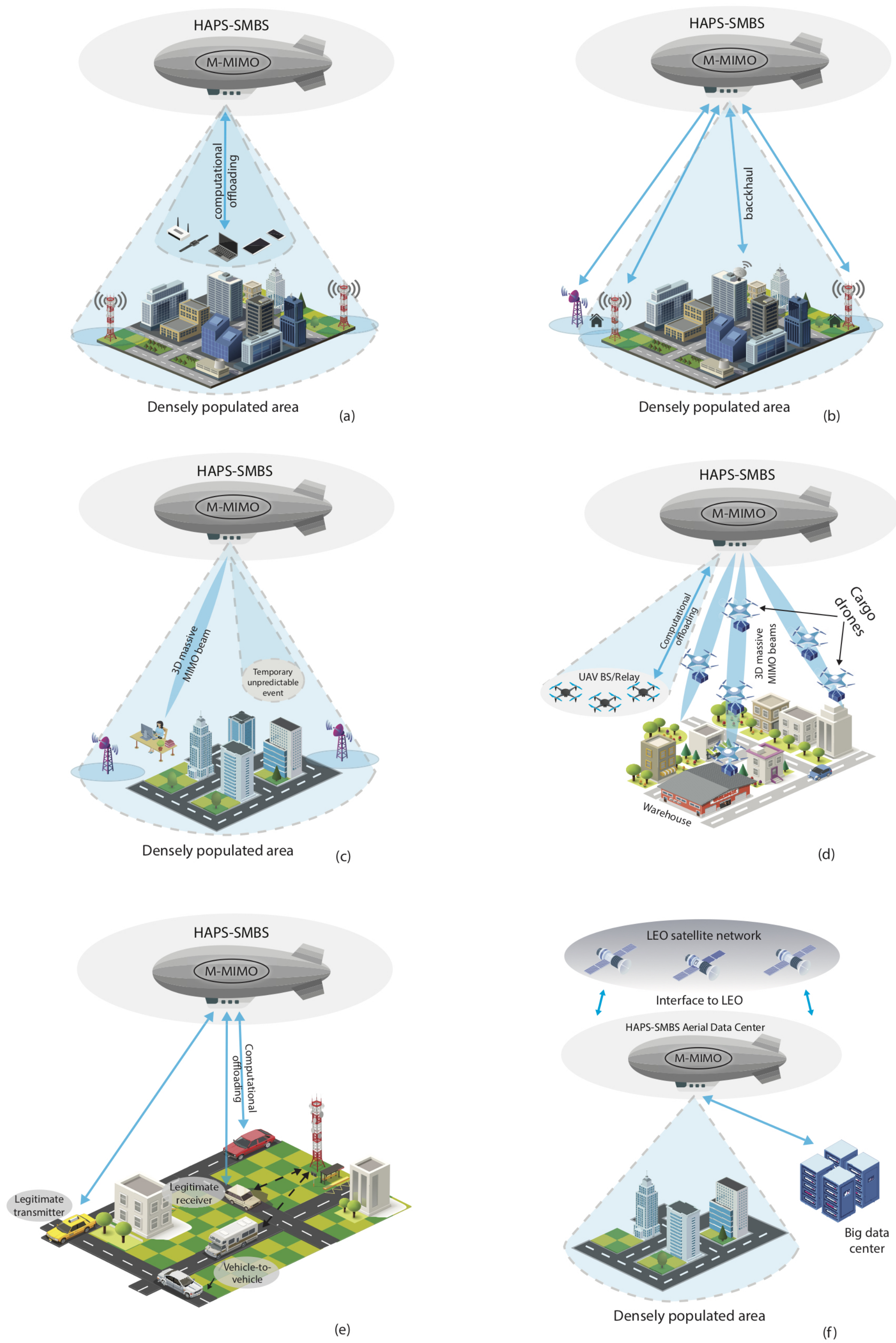


Fig. 3: (a) A HAPS-SMBS delivering IoT services. (b) A HAPS-SMBS backhauling small and isolated BSs. (c) A HAPS-SMBS covering unplanned events and filling coverage gaps. (d) A HAPS-SMBS supporting and managing aerial networks. (e) A HAPS-SMBS supporting intelligent transportation systems. (f) A HAPS-SMBS acting as an interface with LEO satellites and as an aerial data center.

systems, therefore, are an attractive solution to complement terrestrial networks to collect data from IoT devices and provide reliable uplink connections for them in a seamless, efficient, and cost-effective manner, as shown in Fig. 3(a).

To support IoT devices on the ground from HAPS-SMBS, a natural question that will arise will be that of the required transmission power of such IoT devices to communicate directly with a HAPS-SMBS located at least 20 km away. This becomes even more accentuated for some particular applications with IoT devices that are expected to function over a time span of decades without requiring batteries to be recharged or replaced. Among other things, the required transmission power of devices is proportional to the required received SNR to guarantee the QoS, which is inversely proportional to the transmission rate. As IoT devices transmit data at a very low bit rate when they are on (note that devices may occasionally turn on and stay off for long periods of time), IoT devices with low data transmission rates are therefore capable of communicating directly with a HAPS using low transmission power.

Instead of handling massive machine type communications (mMTC) that we have in terrestrial networks, however, we need to handle mx-MTC ($x >> 1$) in the case of a HAPS-SMBS due to its large coverage area. This will introduce many unprecedented challenges due to the need to design efficient multiple access techniques for the simultaneous transmission of a massive number of devices. System designers may also need to strike a balance between reducing packet collisions which reduce the need for frequent packet re-transmission attempts—given the very strict energy consumption limit of some devices and/or the strict delay requirements of some applications—and the reliability requirements of mission-critical applications, which may call for re-transmission of the packets.

2) HAPS-SMBS systems for backhauling small and isolated BSs: Although fiber optic communications remain a superior option for backhaul connectivity, installing fiber for backhauling small cell BSs may not be an efficient solution for many environments due to its high-cost [36]. A cost-effective backhauling solution is the use of wireless microwave links, and this is already a well-accepted approach. Also, the combination of the wider channel bandwidths of mmWave bands and MIMO digital beamforming with high gain advanced antennas makes mmWaves a viable solution for in-band backhauling [37].

Although the distance between a HAPS and a ground femto-BS can be between 20 km and 200 km (depending on the coverage footprint of the HAPS), the communication link is almost LOS dominant (with pathloss exponent of around 2) with moderate shadowing/fading fluctuations due to a lack of scattering. Therefore, a rule of thumb calculation suggests that a small-BS with a 3D distance of 200 km from the HAPS could gather almost the same average power gain that it would receive from a macro-BS but with a distance of 1000 meters. As our vision advocates the use of HAPS systems for metropolitan areas, industrial areas, and even mega-cities, the coverage footprint of a HAPS could be as small as 20-50 km. These figures become more promising, however, for a femto-cell situated at a distance of 50 km from a HAPS while receiving an average signal power similar to that of a macro-BS at a distance of about 100 meters. Furthermore, we should note that as femto-BSs are stationary and HAPS systems are quasi-stationary the establishment and maintenance of such links is less demanding since beam tracking and beam adjusting are less necessary. As a result, the extra communication delay imposed by long distances between HAPS systems and femto-BSs can be compensated for with occasional events of beam adjustment/establishment (compared to terrestrial networks).

When compared to terrestrial communications, mmWave communication links from a HAPS to ground femto-BSs may suffer from rain/cloud absorption losses (proportional to $10^{cr/H}$, where H is the HAPS's altitude, r is the distance between the ground and HAPS, and c (dB/km) is a factor absorbing the rain/cloud effect [38]). This extra loss may not be an issue given that a HAPS can compensate for these negative effects by allocating higher transmission power and harnessing higher directional antenna gain due to possibility of installing very large 3D antenna arrays. Additionally, as we also mentioned before, the link is not subject to severe shadowing/fading fluctuations, which could boost the average received power by about 10-20 dB compared to the counterpart links in terrestrial communications.

On the other hand, the de facto solutions are mmWave or macro-wave communications from macro-BSs. Macro-wave communications are versatile and thus present the first option. However, it suffers from high signal attenuation given that macro-BSs are currently down-tilted and the fact that inter-cell interference is quite dominant. Hence, if possible mmWave communications combined with massive MIMO communications should be considered in order to manage the inter-cell interference. Note that to ensure the quality of mmWave communications due to maneuverability of UAV-BSs, the Macro-BS should always stay in the communication view of the UAV-BSs. Such a requirement, nevertheless, could be limiting and complicates the mobility management of the UAV-BS, as instead of optimizing the mobility of UAV-BS merely for the best performance for the ground users or the provisioned service (shortest path for package delivery), one needs to include the backhaul communication requirements into account. On the other hand, via backhauling from HAPS such issues are basically trivial as the mobility management can become only a matter of the quality of the service that the UAV-BS is providing. However, one should note that compared to the backhauling for the ground femto-BSs, the matter is more involved as constant beam-tracking is required due to the mobility of UAV-BSs.

Inspired by recent advances in HAPS systems and FSO [39], [40], outdoor small cell BSs can be backhauled through HAPS-SMBS. Note that FSO links are vulnerable to weather conditions. In the case of cloudy, rainy, and foggy conditions, the quality of FSO links could substantially deteriorate. Hence, as FSO links are generally more robust in clear weather conditions, robust solutions to effectively deal with various weather conditions should be investigated. One straightforward solution might be to boost the robustness of the FSO backhaul links by considering hybrid mmWave Radio Frequency (RF)/FSO technologies

[39]–[42], as depicted in Fig. 3(b). While this solution is feasible and has immediate merits, one should note that since mmWave communication may have smaller spectral efficiency compared to FSO, the backhaul data rate between a HAPS-SMBS and a ground station could be affected. As a result, apart from early detection for automatic switching between technologies, sophisticated resource allocations and 3D beamforming may be necessary.

3) HAPS-SMBS systems to cover unplanned user events: In case of unexpected and temporary events which are difficult to predict, such as flash crowds, wireless networks might require additional support to maintain ubiquitous connectivity [43], [44]. Such events normally happen in crowded cities and can lead to network congestion. UAV mounted BSs have recently gained much attention for boosting wireless capacity and offload traffic from congested terrestrial BSs during such events [45]. Compared to UAV mounted aerial BSs, which have SWAP constraints, HAPS-SMBS systems provide greater capacity for ground users due to their large platforms, massive-MIMO capabilities, and higher transmission power. Hence, the envisioned HAPS-SMBS architecture can address the demands of unpredictable events by increasing relevance between the distributions of supply and demand, as shown in Fig. 3(c).

To cover such temporary unplanned user events, HAPS-SMBS systems can be used opportunistically. Alternatively, these events can also be covered through over-engineering terrestrial networks. In this case, the expenses of HAPS-SMBS operations may be compared with the expenses of over-engineering a terrestrial network. Despite revenues, providing connectivity to these scenarios is important to avoid serious losses and poses challenging demands such as high data rate. Nevertheless, as massive-MIMO is among the most disruptive technologies to provide capacity improvement in ground networks, the promise of this technology in HAPS-SMBS systems needs to be investigated. Also, other capacity improving techniques such as NOMA, mmWave, beamforming, and any combination of them in HAPS scenario need to be revisited. In general, advanced big data solutions are required to predict the occurrence of temporary events (along with some estimations with regards to the volume of produced traffic per geographic area and unit time) in order to properly provide resources including bandwidth, power, and computational capacity.

4) HAPS-SMBS systems as aerial data centers: HAPS-SMBS systems will also be able to operate as aerial data centers to support agile computational offloading. As an example, Augmented Reality (AR) applications may require high computational capabilities. In this regard, efficient computational offloading will be a necessity [46], [47]. As HAPS-SMBS systems can have more computational power than user terminals (e.g., UAV nodes or ground users), may be useful for providing different levels of computational services. Moreover, due to its high position, HAPS-SMBS can provide better coverage with LOS links, avoiding the possibility of disconnection while offloading data. As aerial data centers, HAPS-SMBS systems can also provide a back-up computational facility.

To envision a flying data center, HAPS-SMBS systems should have enough power from solar panels to support additional computation. This requires the investigation of how much power a HAPS-SMBS will require to support additional computation and how much solar power can be harvested. Also, cooling is an important requirement of data centers. The atmospheric temperature at a HAPS' operating altitude is quite low (on average in the range of $[-15^oC, -50^oC]$ [48]), so we might not need too much energy for cooling as we can use the naturally low temperature around the HAPS. In addition, the size of HAPS-SMBS data center will be limited by the onboard payload capacity. Moreover, one of the important design issues in data centers is to reduce the response delays. Analyzing data in the sky will reduce response delays and decrease the burden on air-to-ground communication links.

5) HAPS-SMBS systems to fill coverage gaps: HAPS-SMBS systems can supplement existing terrestrial networks by filling coverage gaps in a cost-effective manner. Coverage gaps are encountered when terrestrial UEs are faced with an insufficient Signal-to-Interference-plus-Noise Ratio (SINR) from a terrestrial BS due to a physical obstruction [49]. Such blockage effects become more severe for mmWave cellular networks and may have a higher negative impact on user associations.

To handle this problem, a HAPS-SMBS requires to steer a beam in the targeted direction. When compared to UAV BSs, the advantage of using HAPS-SMBS systems is their large platform size and ability to perform 3D beamforming [50] with massive MIMO that allows to create disjoint narrow beams for each user in the 3D space. In addition, a HAPS-SMBS system can provide a permanent service rather than the temporary service of UAV BS. This use-case is also shown in Fig. 3(c). Nevertheless, the creation of very narrow beams with higher capacity and accurate beam steering directions should be investigated for HAPS-SMBS systems to UEs. This can be problematic due chiefly to the long distances between users and HAPS-SMBS systems, as CSI estimation/feedback may render unaccepted delay and therefore outdated beamforming solution. As a result, beamforming and resource allocation needs to be less sensitive to accurate/up-to-date knowledge of the channel. In effect, solutions that rely more on the long-term behavior of the channel, for example, statistical CSI needs to be developed.

6) HAPS-SMBS systems for supporting and managing aerial networks: Enhancing the computational capabilities of UAVs is becoming more important in order to maintain the critical tasks at UAVs. However, due to their SWAP constraints, UAVs have limited onboard computational resources [51], [52]. A HAPS-SMBS system can be suited with powerful processors that can enhance the computation power of UAV networks elements with limited resources as a complement of terrestrial networks. The larger coverage area of a single HAPS-SMBS enables data collection from large portions of the aerial network which reduces the dependency on terrestrial stations that are already overcrowded in most urban areas. Moreover, the effect of interference would be much higher in ground base stations compared to HAPS-SMBS systems for such computational offloading for UAVs.

In addition, using Machine Learning (ML) algorithms, HAPS-SMBS can control and manage the UAV network intelligently with minimum dependence on terrestrial-based control, as exemplified in Fig. 3(d).

To control and manage UAV networks from HAPS-SMBS systems, seamless connectivity of UAV nodes with the HAPS-SMBS systems will be guaranteed. HAPS-SMBS systems should guarantee reliable and wide connectivity with relatively low latency. In addition, in the near future, in densely-populated urban areas thousands of cargo-UAVs are expected to be flying around daily. To ensure their safe operation, a massive amount of data about them will need to be continuously collected and analyzed. For this, on-board processors with enough power and cooling support will be required.

7) HAPS-SMBS systems for supporting intelligent transportation systems: The full-scale introduction of the Intelligent Transportation System (ITS)/ Connected Autonomous Vehicle (CAV) paradigm will be the most powerful automobile revolution in history [53]. Recent advances in sensors, high-end computational units, and the introduction of in-car wireless communication capabilities have paved the way for CAV that will enable unprecedented scenarios for road transportation [54]. Nowadays, automakers are spending billions of dollars to promote the idea that CAVs can greatly reduce road accident rates and create a safer society. However, such breakthroughs will certainly create new challenges for the design and implementation of CAV infrastructure. For example, CAVs will need to support services such as interacting with drivers, cooperating with other vehicles, offering decision-making support and strategies for traffic control and management. Also, CAVs will need to recognize their surroundings, plan a route, and control vehicular motion without any human input. But wide-scale data fusion and processing are necessary for such CAV applications [55]. Interestingly, a HAPS-SMBS can play a key role in providing the ubiquitous coverage for this ITS/CAV paradigm. Since vehicles may be limited in their computational processing capabilities, they may need to offload data [56], [57]. Due to their large coverage areas and significant computational capabilities, a HAPS-SMBS can be used for data offloading with minimal communication delays. Moreover, HAPS-SMBS systems can provide coverage in rural and remote areas, which is essential for travailing on highways and using trains, flights, or ships (Fig. 3(e)).

To support such operations, information from vehicle sensor nodes will need to be forwarded to the HAPS-SMBS that then will either act as a relay, forwarding the received signal to a terrestrial gateway, or will process the received data on board and send it back to the vehicles with further instructions. This choice requires optimal planning in the distribution of data offloading and computing services in terrestrial and HAPS networks taking into account the delays of both communication and computation. Some other design issues for this system would be to support high QoS levels (delay, packet error, outage probability) for vehicle-to-HAPS-SMBS telecommunications links in order to ensure reliable and fast message exchanges and guarantee transport and safety applications.

HAPS-SMBS systems can also provide coverage for cargo drones that are likely to disrupt the retail industry in the near future. Usually, cargo drones are supported through terrestrial networks [58]. The use of cargo drones is currently being promoted by mega-retailers to carry courier packages. For instance, cargo drones can be used for Amazon's prime air drone delivery service and the autonomous delivery of emergency drugs [59]. In this scenario, a large number of cargo drones will constantly be flying and filling the skies, and hence 3D highways are to be expected in support of the cargo package distributions using these drones. A single HAPS-SMBS can be used to provide coverage for a high number of cargo drones in major cities.

In this use-case, HAPS-SMBS systems should ensure reliable connectivity and safe operations for cargo-drones in the airspace, probably involving a combination of both radio-based and vision-based solutions. This requires the provision of communications channels of high reliability and low latency for many cargo-drones in a large geographical areas. Furthermore, as HAPS-SMBS systems can provide a computational platform for path-planning and navigation in accordance with supply-chain requirements, sophisticated solutions for massive computational offloading are required.

8) HAPS-SMBS systems for handling LEO satellite handoffs and providing seamless connectivity: The high speeds of LEO satellites necessitate frequent handoffs at terrestrial gateways [60], which is undesirable. Fortunately, HAPS-SMBS systems can cover many satellites simultaneously due to its wide upper footprint. Therefore, to provide seamless LEO satellite connectivity to aerial and terrestrial networks, a HAPS-SMBS system can serve as an interface to manage the handoff in the LEO satellite network, as shown in Fig. 3(f). In this scenario, the frequent handoffs of LEO satellites will be handled by HAPS-SMBS systems. Also, if ground users are able to communicate with the HAPS-SMBS interface directly, then there is no need for users to accommodate special devices for communication with LEO satellites.

There are two types of links in this system: user-to-HAPS links; and HAPS-to-LEO satellite links. The link between a user and a HAPS-SMBS can be realized through RF links, whereas FSO links would be a better choice for HAPS to LEO connections. The achievable performance improvement of the aforementioned architecture can be realized through link budget analysis. An improvement in the link budget can be translated reducing the transmit power as well as the cost and size of the user terminal. However, to establish reliable and uninterrupted connections between ground/aerial users and LEO satellites through HAPS-SMBS systems, HAPS-SMBS systems need to learn the mobility patterns of the LEO satellites in order to predict their handoff, then establish a connection to a coming satellite before losing the current connection. In this regard, machine learning approaches will play a significant role in learning these mobility patterns. It should also be noted that as new satellite constellations are added to current satellite communication systems, ML solutions will need to be flexible enough to handle continual environmental changes. Alternatively, one may also require the incorporation of satellite tracking system/data—gathered and processed in order to predict any possible collisions among satellites—into the model in order to compensate for the relatively sudden change in the orbital movements of some satellites.

III. Regulatory Aspects

The regulation in the aerospace industry is crucial for the safe and harmonious operation of HAPS supported networks. International Telecommunications Union (ITU) Radio Regulation (RR) defines HAPS as a network element that operates between 20 km and 50 km and at a specified, nominal, fixed point relative to the Earth [2]. ITU Radiocommunication Sector (ITU-R) F.1569 indicates that there is a local minimum in the wind speed of around 20 km to 25 km, targeting to minimize the required propulsion power for keeping the HAPS nodes stationary [61]. In the recent deployments, HAPS have been frequently deployed at 17 km or 18 km altitude [17]. Different countries determine the different maximum altitudes of controlled airspaces, and a typical value is 20 km [12]. Although at the borderline between the controlled and the uncontrolled airspace, regulations of HAPS need to be carefully designed for safe and secure operations, and currently there are limited studies addressing HAPS safety [62]. The recently founded industry consortium, HAPS Alliance[4], also works in areas of aviation and commercialization to build a strong HAPS ecosystem.

The regulation activities are mostly limited by the ITU-R and International Civil Aviation Organization (ICAO). ITU-R regulates the spectrum aspects of HAPS while ICAO, a United Nations (UN) specialized agency, governs the safety aspects of HAPS and relations with civil aviation activities. The licensing and control of airspace lies within the jurisdiction of national civil aviation authorities, and rules vary from country to country.

A. Aviation Regulations

ICAO defines two distinct HAPS classes: unmanned free balloons and the unmanned aircraft. Accordingly, an unmanned free balloon is defined as a non-power driven, unmanned, lighter-than-air aircraft in free flight, whereas an unmanned aircraft is defined as an aircraft intended to operate with no pilot on board [63]. Although the regulatory guidance is still developing, regulations associated with these two classes have significant differences. The main difference is that balloons are excluded from real-time management. The regulations are applied according to the specifics of each development. For example, the Google Loon Project, terminated in January 2021, was included in the unmanned free balloon category. Yet due to the increasing computational capabilities along with an effective propulsion system, even balloons can be managed in real-time with smart approaches, as noted by [62].

Current aviation regulations are monitored according to the rules of the national civil aviation authorities. Yet, large-scale HAPS deployments are envisioned to be conducted by an international consortium. To catalyze successful large-scale HAPS deployments, an international set of rules and regulations are needed to control licensing and operations. Addressing this concern, Liu and Tronchetti [64] proposed the categorization of near space, from 18 km to 100 km, as exclusive utilization space along with a corresponding set of rules. This solution may avoid the uncertainty associated with the international legal status of near space.

B. Spectrum Regulations

ITU has been working to support and integrate HAPS nodes in communication networks since 1997. Based on technical investigations, as reported in recently published reports, including F.2471 [65], F.2472 [66] and F.2475 [67], it is concluded that a bandwidth of 396 MHz to 2969 MHz is needed for ground-to-HAPS links. A bandwidth of 324 MHz to 1505 MHz is determined as necessary for the HAPS-to-ground links. At the World Radiocommunication Conference in 2019 (WRC-19), which aimed to revise the regulatory framework for HAPS and non-geostationary satellite systems, it was agreed to append the 31 - 31.3 GHz, 38 - 39.5 GHz bands for HAPS usage, in addition to the already dedicated 47.2 – 47.5 GHz and 47.9 – 48.2 GHz bands for worldwide usage. These bands will be used in addition to the previously dedicated International Mobile Telecommunications (IMT) bands in the 2 GHz and 6 GHz bands. Furthermore, 21.4 - 22 GHz and 24.25 - 27.5 GHz frequency bands can be used by HAPS in the fixed services in Region 2, which covers the Americas, including Greenland, and some of the eastern Pacific Islands. The potential of using mmWave bands in HAPS networks has been noted in [68] and dates back to 2000, in the High Altitude Long Operation Network (HALO) concept. In addition to the presence of quite limited ambient interference, the use of mmWave bands also introduced inherent advantages associated with small antenna sizes and small array sizes, which can serve as an advantage, as opposed to the inherent high path loss of these bands. An overview of the designated frequency bands is provided in Figure 4. As we can see there, the frequency bands cover L, S, C, K, Ka, and V bands, some of which also serve other applications. For example, the L-band and S-band allocations are also dedicated for terrestrial IMT services. These frequency bands will not only serve disaster relief missions but they will also be used to address the increasing connectivity demands of end-users by providing commercial broadband services. The ITU regulations also limit the interference of communication services on earth observation sensors in radio astronomy stations. WRC-19 provided recommended requirements for the maximum transmit equivalent isotropic radiated power (EIRP), antenna radiation

[4]https://hapsalliance.org/

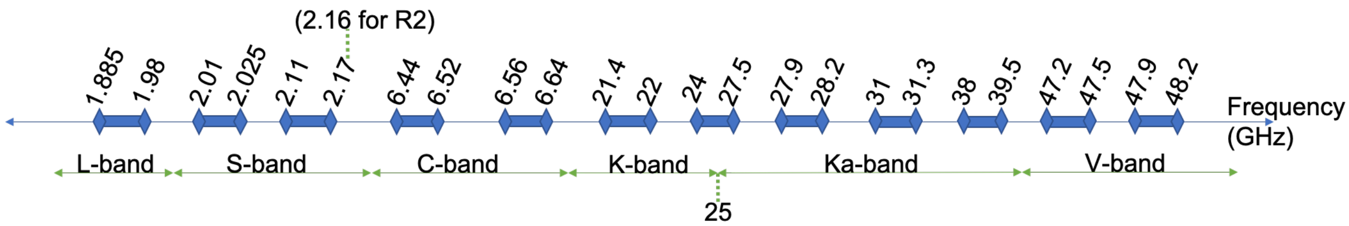


Fig. 4: An overview of the spectrum bands dedicated for HAPS.

pattern, power flux density (PFD) limits, the separation distance between radio astronomy station to limit the interference, and the nadir of a HAPS platform [69].

IV. The HAPS System

In this section, we present a general view of the HAPS communication system along with its onboard subsystems, as illustrated in Fig. 5. In particular, we discuss in detail the recent advancements in both energy and communications payload subsystems. Moreover, the characteristics of different types of HAPS along with the classification and key features of the most popular HAPS projects are highlighted.

A. System Components

A HAPS is located in the stratosphere[5], a layer of the Earth's atmosphere. This layer has unique properties, which makes it suitable for HAPS deployment. It is almost free from any weather disturbance, such as lightning or thunderstorms. Because of the absence of clouds in this layer, solar energy can be effectively utilized without atmospheric pollution. Moreover, the stratosphere is safe for deployment as it is above the altitude of commercial air traffic. Due to these intrinsic features of the stratosphere, two different types of stratospheric platforms (aerostatic and aerodynamic) can be deployed to stay in a quasi-stationary position above the Earth for extended durations, as we will be explain in the following subsection. In general, a HAPS communications system consists of two parts: a non-terrestrial part and a terrestrial part part.

1) Non-terrestrial Part: This part includes all the main relative network components in the air or the space as well as the essential onboard subsystems for an effective HAPS deployment and successful communication system. Generally, it consists of two segments:

- *Onboard subsystems:* They mainly consist of three subsystems; *flight control subsystem*, *energy management subsystem*, and *communications payload subsystem*. The goal of the flight control subsystem is to handle the stabilization of the platform, control its mobility, and point it toward the targeted direction. To achieve these, sensors to measure altitude and direction of HAPS, a computing unit for decision making, and actuators to carry out the desired movement and orientation, are required. Moreover, the flight control unit manages the interface between the platform and the ground control station. This is performed by the telemetry, tracking and command signals, which reports the health of the platform, and provides an important two-way flow of information between a HAPS and its ground control station [18]. The energy management subsystem handles the energy generation and storage process, and it regulates the energy consumption of other subsystems. The communications payload subsystem is responsible for managing the communications between the HAPS and other entities. Based on the mission of the HAPS and the targeted applications, different equipment and technologies can be incorporated in the payload. Further details of the energy and payload subsystems will be discussed in the subsections IV-C and IV-D.
- *Non-terrestrial networks:* This segment represents all the non-terrestrial communication nodes in the aerospace domain that are potentially involved in the HAPS communication systems, as depicted in Fig. 5. A HAPS might be connected with other HAPS and form a constellation [70], [71], or it could be a part of a network with different layers of satellites [20], [72]. Moreover, the HAPS layer might be connected with various types of Low Altitude Platform Station (LAPS)s, such as UAVs base stations or relays (UxNBs), or it might serve a swarm with diverse kinds of UAV users (UAV-UEs) [39].

2) Terrestrial Part: This part represents the ground elements of the HAPS communication system. It can be divided into three segments:

- *Control station:* This manages the communication operations between HAPS and different types of users. Also, it orchestrates the communication links and manages the resources between multiple HAPS nodes and other non-terrestrial

[5]The lower edge of the stratosphere is about 20 km near the equator. At mid-latitudes, it reaches around 10 km, and at the poles about 7 km. The speed of winds in the stratosphere can exceed those in the troposphere, reaching near 60 m/s in the southern polar vortex.

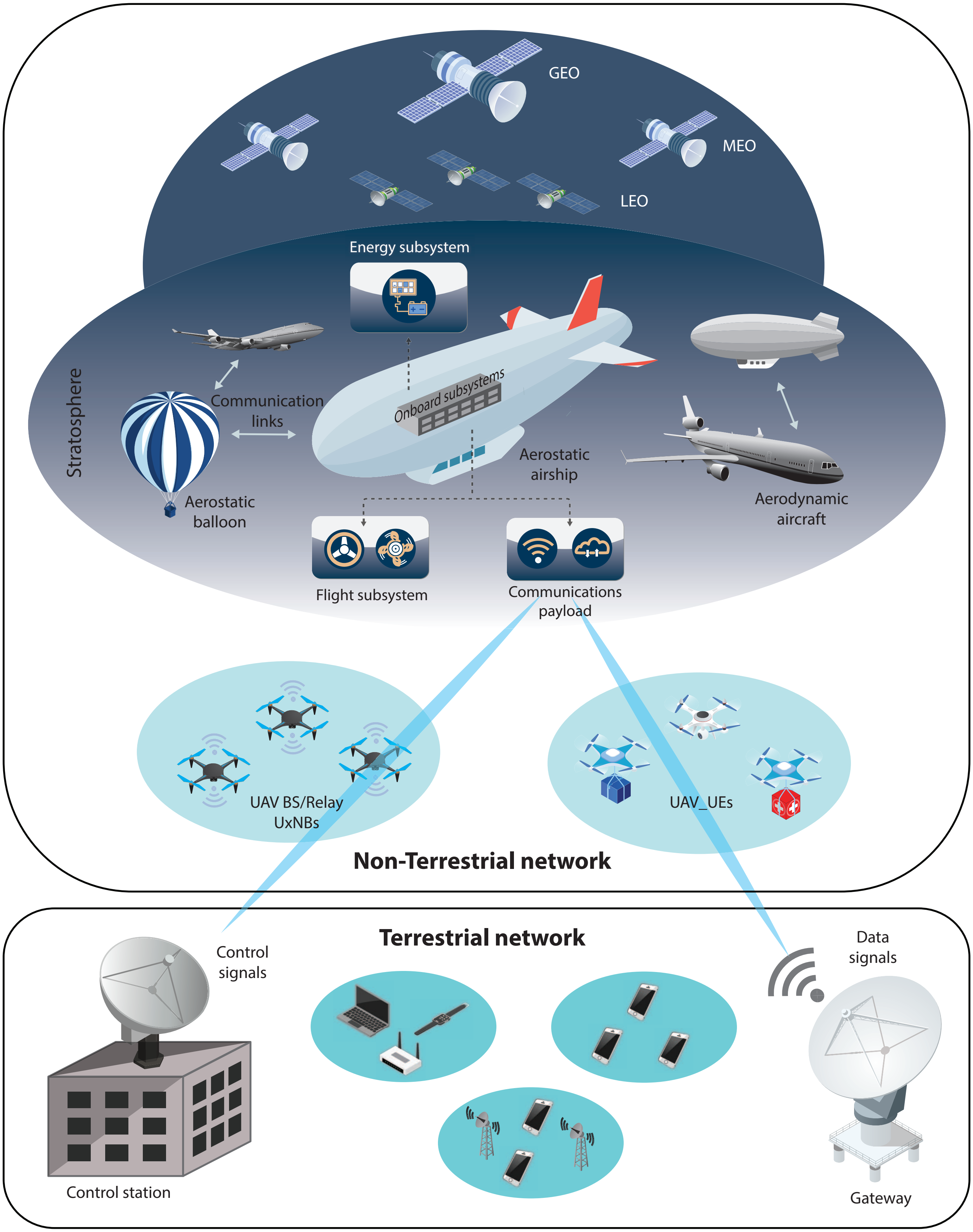


Fig. 5: A general view of the HAPS system and its main components.

or terrestrial networks. Moreover, the control station handles the takeoff/landing process, monitors remotely the position of the HAPS and controls its direction to maximize the antenna efficiency and enhance the performance.

- *Communications gateway:* It connects the HAPS to the core network through a wired backhaul infrastructure. Depending on the HAPS payload and the type of terrestrial network, a HAPS may either communicate directly with terrestrial users, or the data information may be exchanged through the communications gateway. The control station and communications gateway could be either co-located within the same building facilities or have separate locations. They basically consist of amplifiers, processing units, and antennas. Antennas that are typically used have parabolic dish reflectors to guarantee high directivity gain.
- *Terrestrial networks:* This segment includes all the terrestrial nodes or users involved in the HAPS communication systems. This includes terrestrial BSs and different types of users, such as mobile users and IoT sensors.

B. Types of HAPS and Related Projects

Generally, HAPS nodes can be classified into manned or unmanned aerial platforms. In the 1960s, jet-powered manned HAPS were developed, such as the as B-57 Canberra and Lockheed F-104 [73]. Most of these manned HAPS systems were considered for meteorology, scientific purposes, or military applications. The Proteus is an example of a manned HAPS designed for telecommunication usage. However, typical communications applications require prolonged support, and it is difficult for human pilots to fly for extended durations in the harsh stratospheric environment. Therefore, unmanned HAPS nodes are more popular and preferable for communications.

Depending on the underlying physical principle that provides the lifting force for the HAPS, they are classified as aerostatic (a.k.a. lighter than air) platforms or aerodynamic (a.k.a. heavier than air) platforms. While aerostatic platforms make use of buoyancy to float in the air, aerodynamic platforms use dynamic forces created by the movement through the air [16], [29]. Aerostatic platforms appear in two shapes, balloons and airships, and they make use of a lifting gas in an envelope for providing buoyancy to float in the air [16].

Balloons are usually unpowered platforms and they can be tethered to easily control their flights. However, tethered balloons in the stratosphere have been abandoned due to air-safety constraints, and currently tethered HAPS are mostly restricted to a maximum altitude of 2 km. Google Loon was an example of balloons intended for communication proposes. These are made made from large size sheets of polyethylene equipped with antennas and solar panels, and they can stay in the stratosphere for over 100 days. Loon's early experiments were conducted in 2011, and successful WiFi and LTE connections have been realized through Loon since 2013 [74].

Airships are typically powered platforms with propulsion systems which can stay in the stratosphere for several months or years [11]. Although the immense size of airships creates dynamic drag during flights and imposes significant challenges for takeoff and landing, airships offer great flexibility in terms of payloads and power generated using solar cells [16]. Aerodynamic HAPS uses electric motors and propellers as a propulsion system. In contrast to aerostatic platforms, aerodynamic aircraft have limited payload capacities and a higher resistance to strong winds and turbulent conditions [18]. Moreover, an aerodynamic HAPS has to move forward and circle around the intended area of coverage to maintain its quasi-stationary position. Also, they require large wingspans (35 to 80 m) for lifting due to the reduced air density at their operating altitudes. As a result, the radius of the circular movement will be very large, which requires adjustments in antennas pointing and communications beams.

Both aerostatic and aerodynamic HAPS have their advantages and disadvantages. The differences are in deployment costs, coverage areas, payload capacities, endurance level, positioning control, and flight duration. The intended use-case or mission objective plays an important role in determining the best HAPS option [11], [16]. For instance, an aerodynamic HAPS might be more preferable for unplanned events or emergency situations due to their reduced deployment costs [18], flexibility in take-off/landing and mobility control. By contrast, an aerostatic HAPS might be more appropriate for longer-term use cases, such as supporting cargo drones, autonomous vehicles, and computation offloading due to their large payload capacities and high energy generation capabilities. However, station-keeping is more difficult and challenging for aerostatic platforms when there are strong winds and turbulent conditions.

Table IV lists some popular past and recent projects along with their classification and key features. As we can see, in most cases, each HAPS project adopts a certain type of platform, but perhaps a hybrid type of HAPS that combines the advantages of both aerostatic and aerodynamic types is needed for near-future applications. In this regard, both projects Loon and HAPSMobile signed a long-term strategic relationship in 2019 for advancing both types of aerostatic and aerodynamic HAPS systems [74].

C. Energy Management Subsystem

Managing the energy supplied to and consumed by a HAPS is an essential task and impacts flight duration and deployment costs. Since using a HAPS system for communications is generally a prolonged operation, careful energy management is required in order to make HAPS-based solutions feasible and cost-effective.

TABLE IV: Classification and description of popular HAPS examples

Project /Product	**Type**	**Company/ Organization**	**Country**	**Project period**	**Description / Important features**
SHARP [75]	Aerodynamic	Communications Research Centre (CRC)	Canada	1980-1987	○ It is the first HAPS powered by microwave beams from the ground. ○ It was envisioned to operate at an altitude of 21 km providing telecommunications within a diameter of 600 km. ○ It demonstrated successful communications for a one-hour flight duration. ○ After several successful trial flights, the project was ended because of a large drawdown in the CRC budget.
Pathfinder, Centurion & Helios [76]	Aerodynamic	AeroVironment for NASA Environmental Research Aircraft and Sensor Technology (ERAST)	United States	1994-2003	○ The aim of the project was to develop the technologies of solar aerodynamic HAPS. ○ In 2002, Pathfinder Plus demonstrated the world's first HAPS at an altitude of 20 km, from which it provided high-definition TV (HDTV) signals, 3G mobile voice, video and data, and high speed internet connectivity.
(SkyNet) [11], [17], [18]	Aerostatic-(Airship)	(National Aerospace Laboratory (NAL)) Currently: (Japan Aerospace Exploration Agency (JAXA))	Japan	1998-2005	○ The objective was to support future communications with high-speed links. ○ The project consisted of several airships positioned at an altitude of 20 km. ○ Each airship would have about 200 m length and could operate for up to 3 years covering a radius up to 100 km. ○ Due to funding issues, the project was terminated after the successful completion of several phases of the project.
CAPANINA [77]	Aerostatic-(Balloon)	Communications Research Group at the University of York	United Kingdom	2003-2006	○ The goal of the project was to test the feasibility of HAPS for improving broadband access in Europe, particularly for rural communities. ○ It was the first trial to use FSO links for HAPS. ○ It demonstrated successful communications with a rate of 1,25 Gbps at an altitude of 23 km providing coverage over a radius of 64 km.
X-station [78]	Aerostatic-(Airship)	StratXX	Switzerland	2005-Now	○ It supports different communication technologies such as TV, radio, mobile telephony, VoIP, and remote sensing. ○ A set of 3 X-stations can be used to provide local GPS services for an area of up to 10^6 km^2. ○ Each X-station can maintain an altitude of 21 km and cover up to 1,000 km diameter. ○ It uses solar energy and batteries and supports a payload of 100 kg and flight durations of up to one year.
Elevate [79]	Aerostatic-(Balloon)	Zero 2 Infinity	Spain	2009-Now	○ It is a transportation service to lift payloads in the stratosphere for testing and validation of new HAPS technologies. ○ Its STRATOS vehicle can carry up to 100 kg for about 24 hours flight duration at an altitudes between 18-22 km. ○ The company provides different options in terms of altitude, duration, and payload mass based on customer requirements.
Loon [74]	Aerostatic-(Balloon)	Subsidiary of: (Alphabet Inc.) Previously: (Google X)	United States	2011-2021	○ Its mission was to connect people everywhere using a network of HAPS. ○ It was the most mature project whose fleet constituted a meshed network managed by Loon SDN, which provided service to over 300,000 users. ○ Last design was able to fly up to 312 days at an altitude around 18-23 km, with a 40 km coverage radius. ○ In 2019, Loon's balloons accomplished over one million flight hours, flying for a total of around 40 million km.
Zephyr S [80]	Aerodynamic	Airbus Defense and space	United Kingdom	2013-Now	○ One of its goals is to connect isolated people across the globe. ○ It has logged the longest continuous flight duration of any aerodynamic HAPS with a maiden flight of over 25 days. ○ It can broadcast at 100 Mbps with a payload of up to 12 kg and can fly continuously for 100 days. ○ It has a 25 m wingspan, can maintain an altitude above 18 km, and it is fully powered by solar energy, with secondary rechargeable batteries providing 250 W maximum payload power.

Table IV: (Continued) Classification and description of popular HAPS examples

Project /Product	Type	Company/ Organization	Country	Project period	Description / Important features
Aquila [81]	Aerodynamic	Facebook	United Kingdom	2014-2018	○ The aim of the project was to provide broadband coverage for remote areas with an 80 km radius and 90-day flight duration. ○ It was intended to fly at altitudes of 27 km during the day, dropping to 18 km at nights. ○ After several successful tests, the project was ended to work with partners like Airbus.
Stratobus [82]	Aerostatic- (Airship)	Thales Alenia Space	France	2014-Now	○ One of its goals is to provide 5G telecommunications. ○ Its length and width are about (115 m x 34 m), and it can carry up to 450 kg payload for a 5-year mission with annual maintenance. ○ It is positioned at an altitude of 20 km and can cover up to 500 km in diameter. ○ It is expected to be on the market in 2021.
HAWK30 [83]	Aerodynamic	HAPSMobile	Japan	2017-Now	○ Its objective is to connect mobiles, UAVs, and IoT nodes around the world. ○ It has a wingspan of 78 m, deployed at an altitude of 20 km, and can provide a 100 km coverage radius for several months.
PHASA-35 [84], [85]	Aerodynamic	BAE Systems and Prismatic	United Kingdom	2018-Now	○ It is designed for a variety of services including 5G communications. ○ It has a payload capacity of 15 kg and can remain airborne continuously for up to one year.. ○ It can maintain an altitude of 17-21 km with a payload power capacity of 300-1,000 w, and it can cover a radius of up to 200 km.

1) HAPS Energy Sources: There are three types of energy sources that have been used for HAPS operations: conventional energy sources (e.g., fuel tanks and electrical batteries), energy beams, and solar energy. HAPS supplied by conventional energy sources have a very short flight duration of about 48 hours and require frequent landing for refueling [19]. The use of conventional energy sources is suitable as a temporary solution or in an emergency situation. Alternatively, energy beams from the ground can be used to supply a HAPS energy system. This idea was proposed in the 1980s using microwave beams [86], [87]. An example of this is the SHARP project [75], which consists of a large ground antenna system for transmitting a large diameter of microwave beams. Such HAPS energy systems use collectors that consist of numerous rectifier antennas to convert the received energy to DC power. Similarly, laser beams can also be used as an energy source. Several experiments were conducted in Japan and the USA using laser-beam powered HAPS. However, due to the high power irradiation risks posed by both microwave-powered and laser-powered platforms, these are not regarded as safe solutions [19].

Solar energy, on the other hand, is a renewable energy source and a safe option for powering HAPS, and it is the main energy source considered by most HAPS projects. Solar energy is appropriate for HAPS for two basic reasons. First, HAPS operate above the clouds, where natural solar energy is abundant. Second, HAPS are typically huge platforms that can have large solar panels to generate large amounts of energy. Solar-powered HAPS typically have secondary energy sources to power the HAPS functions during nights or in winter. These secondary sources, which may include electrical batteries or hydrogen fuel cells, are recharged by the solar energy during the daytime. Accordingly, a control unit in the HAPS energy subsystem is required to manage operations between primary and secondary energy sources. Effective HAPS solar energy designs have been widely investigated in the literature along with analyses of harvested solar energy and cooperation strategies between solar energy systems and secondary energy sources [88]–[91].

Several recent studies have introduced methods for improving the solar energy conversion efficiency [92]–[94]. MicroLink Devices, a leading company in producing solar arrays for satellite and HAPS, manufactures high-efficiency solar sheets with powers exceeding 1.5 kW/kg. These ultra-thin and lightweight sheets can achieve 37.75% solar energy conversion efficiency, which is highest record compared to any other solar cell technology [95]. On the other hand, for the secondary sources, the values of the energy density of Lithium-ion batteries in early HAPS studies were around 100 Wh/kg [11]. However, the current commercial state-of-the-art Lithium-ion batteries have 250 Wh/kg [96]. Fuel cells, which are the other alternative energy storage system, have advanced greatly: in 2009, the state-of-the-art fuel cells were around 400 Wh/kg [97]; current fuel cells have an energy density of 1600 Wh/kg [98].

2) HAPS Energy Consumption: Generally, HAPS energy is consumed by the two subsystems: the flight control and the communications payload subsystem. The energy consumed by the flight subsystem includes the consumption for the stability and propulsion power, and the consumption caused by controlling the HAPS altitude and direction. Also, the platform's type and its features, such as weight and size, impacts the flight system energy consumption. Since aerodynamic platforms require a continuous circular movement, they have generally higher energy consumption [11], [16], [19]. In addition, as the size and the weight of the platform increases, more energy is required for the flight system. Since aerodynamic HAPS also have a relatively smaller size than airships, the solar energy they generate is less than that of airships. Consequently, their capacity for payload power is relatively small. The remainder of the energy generated is consumed by the payload for the communications operations, which chiefly depends on the type of communications payload and the communication techniques. In general, as more active components and computation processes are included in the payload, they get heavier and consume more energy.

D. Communications Payload Subsystem

1) Active Payload: The active payload generally includes antennas, transponders, low-noise power amplifiers, frequency converters, IF processors, and filters. The payload type is dependent on the intended application and use-cases. Typically, a HAPS payload can be either as a relay station (HAPS-RS) or as a full base station (HAPS-BS) [4]. More active components and higher processing capabilities are associated with a HAPS-BS, which accordingly requires more energy consumption and can necessitate larger and heavier communications components. While a HAPS-BS can fully process signals and serve users directly, a HAPS-RS requires an intermediate station to process the users' signals. Thus, a HAPS-RS involves an increase in the round-trip delay. On the other hand, as discussed in Section I-B, HAPS can be equipped with a BS with superior caching, computing, and communication capabilities, capabilities (i.e., a HAPS-SMBS) for serving dense urban environments. However, the advanced and powerful capabilities of a HAPS-SMBS come with the added costs of payload weight and the energy this consumes. Therefore, careful analysis of the intended use-case with the chosen platform type and its payload size and weight capabilities as well as its energy consumption are of paramount importance for a successful and cost-effective HAPS deployment. Sub-optimal mechanisms that trade computational costs, and therefore consumed energy, for the performance in a controlled manner should be developed. Note also that as HAPS systems are expected to supplement and coexist with terrestrial networks, one can also properly share required computational loads across HAPS systems and terrestrial networks.

2) Passive payload- HAPS-RSS: HAPS deployment for wireless applications is profit-driven. The platform's weight, energy efficiency, and flight duration play an important role in determining HAPS deployment costs. Although it is possible to equip a HAPS with advanced communication, caching, and computing functions, it might not be profitable in some scenarios: for instance, where the role of a HAPS would be limited to relay signals, or if it only targeted a limited number of users in remote areas. In such situations, a cost-effective HAPS deployment would require all of these features, including low energy consumption, a light payload, and reliable communications for extended flight duration. To this end, using passive Reconfigurable Smart Surface (RSS) in HAPS systems would be beneficial. RSS has recently gained a lot of attention in the research community and has emerged as a new technology—indeed, as one of the driving technologies of 6G networks [99]–[101]—to support wireless communications. It is shown in [102] that using RSS can increase the received SNR and by doubling the number of RSS units, the SNR quadratically increases. Also, as demonstrated in [103], RSS can substantially improve data rates.

An RSS consists of a thin layer of meta-surfaces that can be used to deliberately manipulate the phases and directions of incident waves in a controlled manner and, therefore, smartly reflect and refract the signals to the targeted directions. Due to its lightweight and flexible structure, it can be designed in thin films to coat different surfaces [104]. Moreover, using digital meta-materials [105], the manipulation of the electromagnetic waves can be digitally controlled. To manipulate high-frequency signals, e.g., Gigahertz (GHz) and Terahertz (THz) bands, tunable materials such as liquid crystal [106] and graphene [107], [108] are used. Experiments conducted in [109] confirmed that dynamic control of high-frequency signals is feasible. Also, [110] showed that using graphene patches with meta-surfaces can effectively control the wavefront of THz signals with the advantages of adjusting phases up to $180°$. Due to the great potential of the RSS and their special features, industry efforts have started to utilize this technology for different wireless applications. For instance, NTT DOCOMO in collaboration with Metawave demonstrated that by using RSS at 28 GHz, data rate can be increased by approximately ten times [111]. The company Greenerwave currently manufactures an RSS applicable for frequency ranges of up to 100 GHz [112].

More recently, researchers started investigating the integration of RSS in different aerial platforms [113], [114]. The idea of equipping or coating the HAPS with RSS (HAPS-RSS) was first introduced in [114]. Two possible scenarios for utilizing HAPS-RSS are illustrated in Fig. 6: Backhauling signals from rural areas to the gateway and inter-HAPS communication links. In such scenarios, a ground control station is responsible for sending the required configurations allowing the onboard RSS controller to configure the RSS to manipulate and direct the signals to the targeted direction.

The HAPS-RSS resembles the function of HAPS-RS, but the former has additional advantages, as detailed in [114]. For instance, several recent studies have indicated that the capacity achieved through RSS is comparable to that achieved through radio relays [102], [115], [116]. As the performance of RSS supporting wireless communications is strongly dependent on the number of reflectors[6] and given that HAPS are typically large platforms, it is possible to accommodate a large number of reflectors, which will enhance the spectral efficiency. Also, an RSS can support full-duplex communications without suffering from high noise or residual loop-back self-interference, which are the typical limitations of relays [102], [116]. On the other hand, using RSS, the communication payload energy consumption of HAPS declines to the required power for the RSS controller. A recent experiment demonstrated that the configuration of each reflector unit consumed 0.33 mW [117]. As a result of the reduction in the platform's weight and consumed energy, the flight duration of the HAPS could be prolonged, which led to lower maintenance and deployment costs. Studies show that an RSS-assisted communication system could be 40% more energy efficient than a relay-assisted system [115]. Thus, HAPS-RSS can be regarded as an energy-efficient and cost-effective solution.

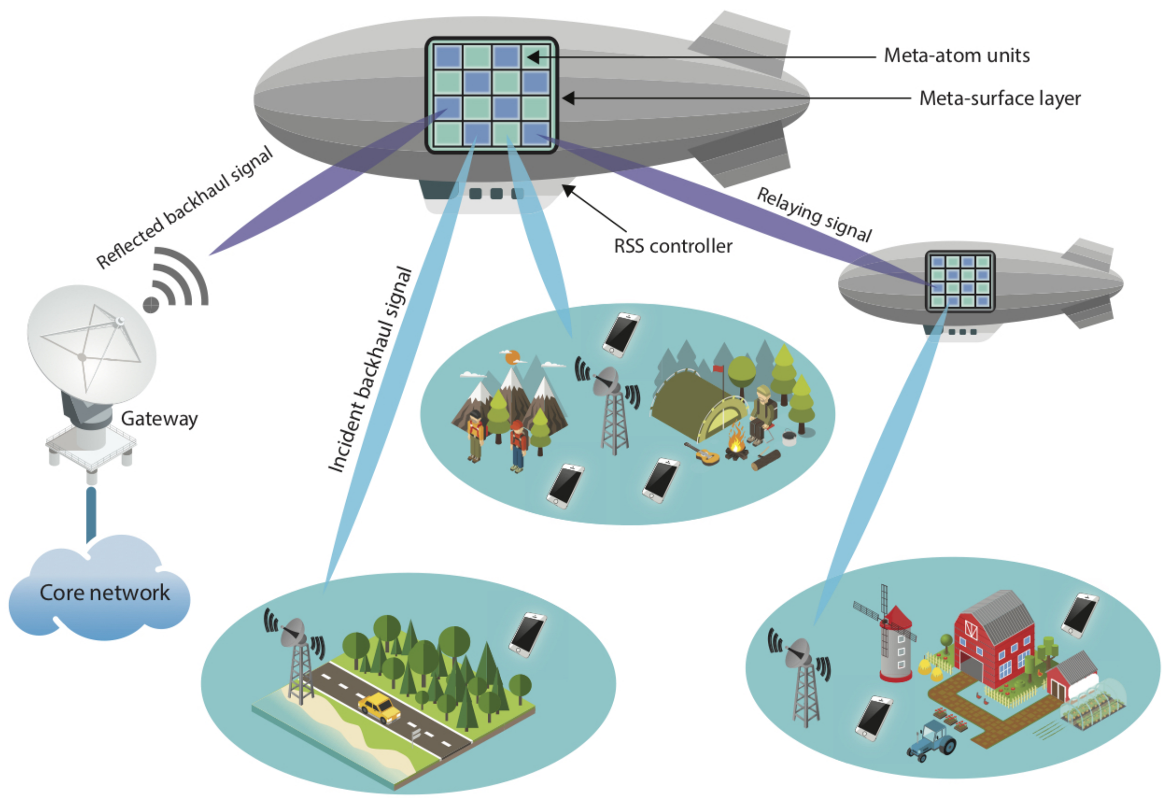


Fig. 6: HAPS-RSS for relaying signals and supporting backhaul from remote BSs.

Despite the advancements in HAPS systems discussed in terms of various platform types, features, onboard energy systems, and communications payloads, several requirements need to be addressed before the HAPS can be deployed to support the novel envisioned use cases. These requirements are dependent on the intended use-cases. In situations where the HAPS are used to tackle the connectivity demands of temporary large events or flash crowds, fast deployment is necessary, and therefore an aerodynamic HAPS might be most suitable in such cases. However, considering the huge data demands of such scenarios, this would require the aerodynamic HAPS to have relatively high payload capabilities. Fortunately, this is feasible with recent progress in HAPS projects. For example, the recent aerodynamic HAPS "PHASA-35" has a payload power capacity of up to 1,000 W [84], [85], which indicates the great potential for supporting a huge number of users with high data rate requirements. On the other hand, utilizing HAPS for IoT services, supporting ITS/CAV, or as data centers require HAPS with capabilities for prolonged flight durations as well as higher power, communication, caching, and computation. In these cases, the choice of the platform needs to be carefully considered. Airships, with their intrinsic features, particularly their immense size and high payload capacities, have the potential to accommodate such heavyweight and high energy consumption payloads. For instance, the Stratobus airship, expected to be deployed late in 2021, can accommodate a payload of 450 kg with a power rating of 8 kW for a 5-year mission [82]. In addition, the envisioned use-cases typically demand a constellation of HAPS. Building

[6]The dimensions of each reflector unit are typically between $[\lambda/10, \lambda/5]$, where λ is the wavelength [104].

such constellations will require cost-effective and energy-efficient inter-HAPS communication links. The HAPS-RSS with its passive nature can be utilized to support the required multi-hop links in a cost-effective manner.

V. Channel Models for HAPS Systems

To understand the full potential that HAPS networks can offer, a deep understanding of the channel models is necessary. This has been addressed by several studies. An extensive overview of channel models, including their extension from HAPS to satellite models was given in [23]. Although a recent survey of HAPS channels is not available, there are numerous studies for modeling the channels of lower altitude platforms, such as [118]. However, since scatterers are more present on the ground than in the stratosphere, channel characteristics show significant deviations, hence extra caution is needed when selecting the suitable channel model. An overview of the current channel models is given below.

A. RF Channel Models

1) Empirical-Statistical Models: The initial studies of HAPS channels are adaptations from land-mobile satellite channels. A high-resolution time series provided by the data form German Aerospace Centre (DLR) was first presented in 1991 in [119], where the authors used the land mobile satellite channel to model the link via a digital two-state Gilbert-Elliott structure. This model was then used to assess the performance of the proposed HAPS channel models. An overview of the satellite channel models applicable to HAPS systems were first noted in [120]. Studies of channel modeling in stratospheric telecommunication systems started with the modeling of atmospheric effects on system performance [121].

2) Non-Geometric Stochastic Models: The first study that considered the impact of multi-path (i.e., small scale) fading in the presence of terrestrial scatterers in HAPS channels was [122], where the authors derived a channel model for the 2 GHz band. Since attenuation due to rain is negligible in this band, it was not considered in the analyses. The authors considered an ellipsoid channel model by placing the transmitter and the receiver as foci. The scatterers were assumed to be uniformly positioned along the ellipsoid.

A statistical model for mixed propagation conditions for land mobile-satellite systems was presented in the ITU-R Recommendation P.681-11 [123], along with the duration, state distributions and the transition probabilities. The combination of the line-of-sight, slight shadowing and the total obstruction conditions for the HAPS channel models using a semi-Markov studied was proposed in [124] and extended to tapped-delay lines in [125]. The impact of these state switches on the error performance was noted. [126] presented a statistical model for jointly estimating the statistical time-series and power spatial delay profile for HAPS-MIMO channels. A model comparison was also provided with the data provided by DLR [119], using the corresponding first order statistics.

3) Geometry-Based Stochastic Models: The first study that proposes a geometry-based stochastic model (GBSM), specifically a geometry-based single-bounce (GBSB) model, was introduced in [127], where the authors presented a 3D scattering model for a stratospheric multi-path fading channel for isotropic and non-isotropic scattering environments. The spiral and temporal correlation functions were provided and the required antenna separation distance was derived. The authors in [128] studied the impact of the channel model on the capacity expressions that could be obtained in HAPS communication channels. This work was then extended in [129], where the elevation angle of the platform, the array orientation and configuration, the Doppler spread, and the distribution of the scatterers were considered for non-isotropic scattering environments using a 3D geometry-based single-bounce reference model for Ricean fading channels. It was observed that the model parameters had a significant effect on the space-time correlation, and that the corresponding impact needed to be taken into account in the array designs. [130] defined a 3D GBSB sum-of-sinusoids (SoS) principle-based statistical simulation model for HAPS-MIMO channels using the framework of the reference model in [129]. Its wideband extension was presented in [131].

Considering the relay channel use-case of HAPS nodes between two terrestrial nodes, a geometry-based modeling of MIMO M-to-M relay-based channels was presented in [132]. An extension of the [129] model for low altitude air-to-ground UAV communication channels was introduced in [133]. The main difference between the low-altitude versus high altitude channel lies in the probability of the line-of-sight presence. Furthermore, at high altitudes, the air node encounters no local scatterers.

4) Non-Stationary Models: A birth-death process-based non-stationary LOS component appearance and disappearance was presented in [134], where the authors detailed the derivation of the multi-user spatial correlation function and extended the use-cases to multi-user HAPS environments. A non-stationary 3D MIMO GBSM was investigated in [135], where the authors modeled the appearance and disappearance of multi-path components using a two-state continuous-time Markov process. Closed form expressions of survival probabilities were derived. Long distance and small-scale time-variant parameters were also considered to model the non-stationary aspects of the MIMO channel. The Space-Time Correlation Function and the Doppler Power Spectral Density expressions were presented. A dual polarized MIMO channel model for HAPS systems was studied in [136], where spatial correlation and polarization correlation expressions were also provided.

The dynamic evolution of an LOS component in 3D models was investigated in [137] by a two-state continuous-time Markov chain. Closed-form expressions are derived for the survival probabilities of the LOS components using Chapman-Kolmogorov equations along with the corresponding space-time correlation function.

5) Air-to-Air Channels: Air-to-air HAPS scenarios have also been considered in the literature. The authors in [138] introduced a 3D non-stationary geometry-based scholastic model for air-to-air channels using a 3D Markov mobility model where the nodes could move both horizontally and vertically, and their velocities could change in time. The authors derived the time-frequency correlation function and the Doppler power spectrum. The results highlighted the importance of considering vertical movement. Yet the model about the scatterers needs to be carefully addressed for HAPS scenarios.

B. Free-Space Optical Channels

In FSO communications, light signals that carry information are transmitted in free-space environments, such as LOS links on the ground or in the vacuum of space. Due to their cost-effective, license-free, and high-bandwidth nature, FSO communications are a leading technology solution, especially for the HAPS-to-HAPS connectivity and backhaul transmission links. Hence, the usage of FSO for HAPS-based communication systems have been thoroughly investigated. [139] numerically demonstrate**d** the possibility of 9,000 km of inter-HAPS distances with a high reliability. The main impairments encountered in the FSO channel links included fluctuations in the received signal due to turbulence, wind, and pressure fluctuations along with irregularities in temperature [140]. Various statistical models have been proposed to model the channel characteristics. Gamma-gamma distribution was proposed in [141]. [142] proposed a lognormal model to model weak fluctuations. FSO channels have also been used as backhaul links in HAPS nodes. An excellent overview was provided in [40].

C. System Performance Analysis

The channel models discussed above feature prominently in studies of HAPS system performance. The Shannon capacity and coverage probability are considered as the main performance metrics. Furthermore, to tackle the pitfalls of FSO communications, including beam wandering and pointing errors and a sensitivity to atmospheric conditions, the use of multi-hop HAPS communications and relaying was suggested. In [143], the use of WiMAX HAPS-based for delivering data to fixed terrestrial users on the ground was investigated. The authors introduced a channel model comprised of geometrical and statistical components to derive the BER performance. The channel model took into account the LOS occurrence prediction along with statistical shadowing. The authors used satellite communication system records to corroborate their analysis and introduced channel models. This model, however, had limitations for correctly measuring the transition state of the channel. By contrast, [144] used HAPS to provide capacity for a high-speed train using MIMO communication in Ka band. It was shown that despite the strong LOS, the channel was ill-conditioned due to high speed of the train, and that the multiplexing gain of the MIMO system reduced substantially. Suitable antenna distancing, up to couple of centimeters, at the receiver appeared to be effective in curbing the degradation of the ill-conditioned MIMO channel, which, compared to typical handsets, was affordable. The authors of [129] adopted a 3D geometric channel model along with a Rician fading channel to study the impact of antenna placement for achieving an uncorrelated response in HAPS-MIMO communications. It was shown that Doppler spread, array configuration, and the distribution of scatteres had a fundamental impact on the statistics of the channel. The theoretical results could be used to evaluate the performance of HAPS-MIMO channels. In [145], the authors studied the capacity of a HAPS-MIMO interference channel comprised of two HAPS systems and two ground users. It was observed that to achieve the best performance, which corresponded to independent channel power gains, the users had to be sufficiently separated spatially. The high spatial correlation appeared to be due to the angle-of-departure and angle-of-arrival at the transmitters and receivers, respectively. In [71], the authors used mmWave communication to increase the capacity of a single HAPS system and a constellation of eight HAPS systems. Their analysis included the evaluation of Shannon capacity as well as the impact of modulation and coding by incorporating the angular separation between ground users and a HAPS, the link length ratio, and the side-lobe of the antenna. Their analysis indicated that 4 km circular spacing is optimal. In [146], the authors investigated the coverage performance of HAPS systems operating in 28 GHz and 48 GHz via approximating curve-fitting of the antenna pattern radiation. The analysis allowed the authors to shed some light on important issues, such as antenna beam type and frequency re-use, which affect cell planning in HAPS systems.

The use of relays to extend the range of the communication systems due to beam pointing errors and turbulence has been investigated in the literature in the presence of gamma-gamma atmospheric turbulence channels [147]. The impact of different types of relaying, such as amplify-and-forward, channel-state-information-assisted or fixed-gain relays, on the statistical properties of the SINR was investigated to derive the coverage probability via a moment-generating function. Adopting the composite channel gamma-gamma distribution, the closed-form expressions for the channel capacity and BER were derived in [148] by adopting free-space optical links for multi-hop HAPS communication. It was shown that the side effect of beam wandering and random pointing errors can be mitigated via multi-hop communications. The considered system was shown to be robust against fog, rain, snow, and other atmospheric turbulence. The conducted analysis conducted by [149] suggested that the worst relay channel had a profound impact on the reduction of performance, such as capacity, outage probability, and BER, of multi-hop HAPS systems. The authors then proposed the use of power allocation in order to minimize negative effects. [150] investigated a triple-hop triple-hop RF-FSO-RF communication system supported with an FSO link between two HAPS nodes, which were connected to a terrestrial network via RF links. The performance of the system in term of outage probability was derived, which showed that the NLOS occurrence and vulnerability of the FSO link to atmospheric turbulence, pointing errors, and beam wandering rendered the growth of the outage probability.

VI. Radio Resource Management, Interference Management, and Waveform Design in HAPS Systems

As in all wireless communication networks, radio resource management, interference management, and waveform design are crucial aspects for ensuring the performance of a HAPS system. From a service provider point of view, network performance can be measured by the spectral efficiency, i.e., throughput (in bits/sec) per unit Hertz, which needs to be maximized. In addition, energy efficiency is one of the system design objectives that needs to be addressed, since the platform's energy source mostly consists of rechargeable batteries and solar panels, i.e., a HAPS does not have the permanent directly connected power supply that the terrestrial BSs enjoy. By contrast, from a user point of view, the performance of a HAPS network can be assessed on the basis of certain Quality of Service (QoS) metrics, which largely depend on the type of application. For example, in URLLC the end-to-end latency and packet error rate is crucial. The way the HAPS on-board radio power and frequencies, antenna beams, and time scheduling are managed all play an important role in interference management determining the SINR levels. This has a direct impact on the outage probability, BER, transmission delay, throughput and/or spectral efficiency at the system level. In an integrated aerial/terrestrial/satellite system that is comprised of a HAPS constellation, LEO-satellites, and terrestrial BSs, the placement strategies of the HAPS nodes play a vital role as well. Therefore, we highlight some of the key radio resource and interference management schemes developed for HAPS systems in the literature, focusing on power control, channel allocation, user association, beamforming, and the placement algorithms for HAPS systems for which a related taxonomy diagram is provided in Fig. 7.

In connection with the use cases discussed in Section II-B, a HAPS-SMBS can provide coverage for unplanned events, where terrestrial wireless capacity and/or coverage are insufficient for the users attending the event. For this use case, a number of issues need to be taken into consideration:

- The largest number of users need to be admitted, which is equivalent to the minimization of the user blocking probability.
- Minimization of the service dropping probability. This is the probability a certain service QoS requirement (e.g. minimum rate requirement) is not satisfied.
- The uses have heterogeneous service types because of different subscription plans. This means their uplink and downlink target rates are not all the same. The HAPS-SMBS's resources need to be managed such that the target rates are satisfied and fairness is achieved among users in the same service type.

Some HAPS RRM and admission control techniques that consider some of the aforementioned requirements are discussed in this section. Additionally, we believe that the HAPS-SMBS should also be 'event' aware, i.e., have the ability to distinguish between unplanned event types and their requirements. For an emergency event or disaster, the HAPS-SMBS needs to provide only voice call services. On the other hand, in an event like outdoor musical festivals, it may be of little importance to spare much resources for audio calls due to the high musical noise in the surroundings which discourage users from making calls. It would rather need to prioritize hologram and augmented reality services, that could be part of the festival needs. If the unplanned event is a protest, perhaps video upstreaming could be of more significance than video downstreaming.

The use of HAPS-SMBS for backhauling of small-cell or isolated BSs, as discussed in Section II-B, requires joint backhaul link power allocation and associations as in [151] (discussed in Section VI-C). More research is needed, however, especially for HAPS-SMBS mega-constellations with possibly no cooperation from LEO satellites (as in [151]) for this particular use case. The design problem is expected to involve the association of small-cell (or isolated BS) to the HAPS-SMBSs as well as the power allocation jointly. Moreover, using-point-to-multi-point narrow beams between the HAPS and the terrestrial BSs by exploiting the mMIMO beamforming technology, rather than using a wide coverage footprint is expected to come with merits for this use-case. This is expected to considerably improve the resulting SINR of the backhaul connections. That being said, the use of very high-order modulation techniques will be possible in order to increase the spectral efficiency of the backhaul links without any degradation in BER. This is especially crucial since the required data rates over backhaul links are expected to be tremendously large (Tbps). Although the positions of terrestrial BSs are fixed, beam pointing compensation schemes will need to be employed, especially in aerodynamic HAPS platforms that need to move in circles. A more complex scenario that needs to be studied is when the backhaul traffic of a terrestrial BS is relayed over more than one HAPS, which also involves relay selection.

In addition to system level design considerations, link level design aspects are paramount in specifying how the communication will take place at the bit and waveform level through the channel. The link level (or PHY) design is concerned with a single wireless link between a transmitter and a receiver and plays a vital role in determining the achievable transmission reliability (measured in BER or outage probability) as well as the achievable spectral efficiency. In a multi-user system, the adopted waveform technology would be a main factor in determining/developing the multiple access scheme. Unfortunately, neither waveform technology nor the related multiple access scheme(s) have yet received much attention in the literature on HAPS systems. In this section, we also discuss some promising waveforms for HAPS systems.

A. Power Control/Allocation and Interference Management in HAPS systems

Power is the fundamental radio resource in any wireless system including HAPS systems. In order to serve a large number of users/devices with different QoS requirements, the SINR level at the receiver is critical and requires sophisticated power management schemes. A significant portion of the proposed power control schemes in the literature on HAPS systems dates back

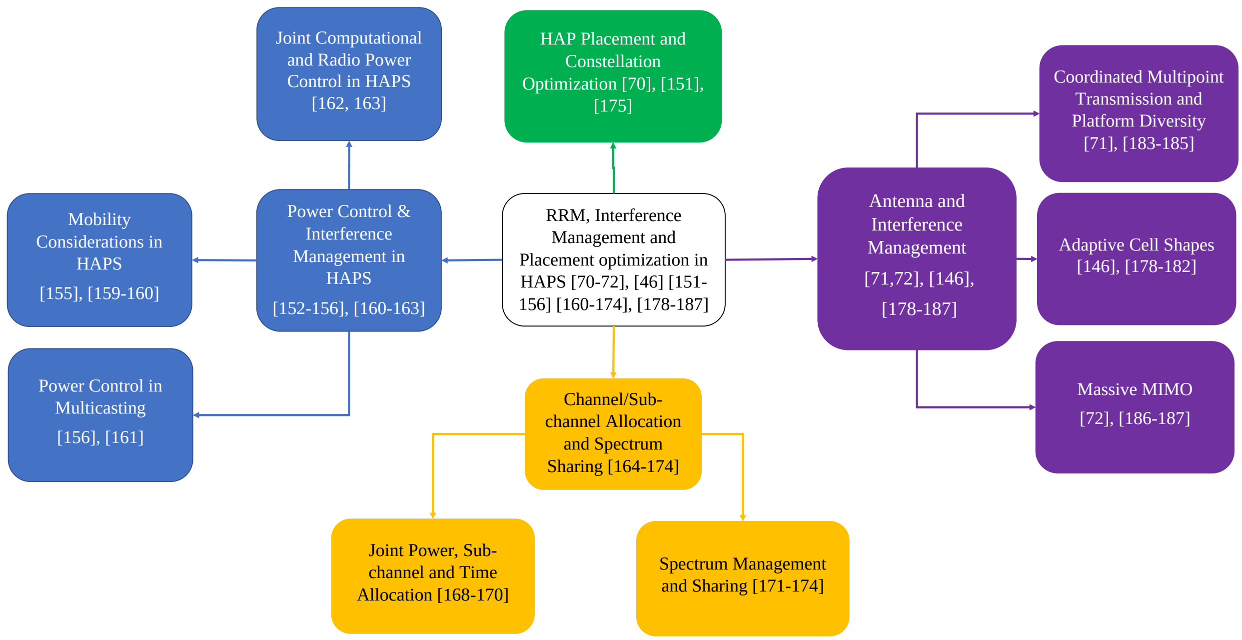


Fig. 7: Taxonomy diagram for the key radio resource management, antenna and interference management, and HAPS placement strategies in the literature.

to early 2000s, when most wireless communications research employed wide-band CDMA (WCDMA) for their air interface technology [152]–[156]. The frameworks of these power allocation schemes are more general and could be suitable (with minor modifications) for other potential radio access technologies, like multicarrier-CDMA [157] or power domain NOMA [158]. While CDMA is primarily built on the idea that users are separated by exploiting the differences among their spreading codes, NOMA allows multiple users to employ exactly the same code and allocates more power to UEs with lower channel gain. The interference is removed at the UE using the *successive interference cancellation* (SIC) scheme, where the UE first decodes the interferer's message and then removes this message from its observation before decoding its own message. By contrast, since we expect that HAPS will play a major role in providing a worldwide network connectivity, the CDMA technology may emerge as a possible solution for a particular region. A summary of the power control schemes reported in the HAPS literature is provided in Table V.

The works [152]–[156] studied power control for the purpose of call admission control (CAC)[7], where users were admitted into the system such that the Grade of Service (GoS) was maximized by minimizing a weighted sum of the dropping and blocking probabilities, while satisfying the SINR and power constraints. In [153], the unique characteristic of HAPS systems that all base stations are collocated on the same platform was exploited for uplink connections. Unlike terrestrial cellular networks, this feature allows the exchange of information on the interference conditions within the cells between base stations with no signaling overhead. If the total power at any BS is less than or equal to a power outage threshold, the call gets accepted; otherwise it gets blocked. The central admission controller in [153] updates the BS total received power levels on a call-by-call basis so that the admission decision for new calls can be made more accurately. The work in [154] extended the schemes in [153] and explored a downlink CAC scheme. It studied a HAPS that centrally managed the radio power at the platform level and allocated it to the cells based on their demands. The basic idea for the BS-based downlink CAC in [154] is to manage incoming calls according to the increase in the interference levels of the target cell as well as adjacent cells. Hence, with the admission of the new call, the downlink powers for all UEs must be increased to satisfy all UEs' SINR requirements. A call is blocked if admitting the call would cause the UE's target base station as well as other neighboring base stations to exceed the maximum allowable output powers and is admitted if the total platform power is not exceeded and the SIR thresholds are satisfied.

1) Mobility and Power Control: The mobility of UEs in a HAPS service area has an impact on how power should be controlled such that UE admission is optimized. Only a few publications have considered the mobility of UEs in power control of HAPS systems. [155] considered a hierarchical system in which a single HAPS and a terrestrial cellular network were jointly deployed, as illustrated in Fig. 8. In that system, the HAPS would be used to provide SMBS coverage and the terrestrial cellular towers would be used for macro-cell coverage at a different frequency band, therefore cross-layer interference is avoided. The

[7]It should be noted that the term 'call' here is equivalent to user admission request and is not limited to voice calls.

CAC scheme that the authors' developed uses a combination of overflow and speed sensitive strategies to direct calls arriving within overlapping service areas served by both HAPS macro-cell and terrestrial micro-cell layers to the appropriate layer.

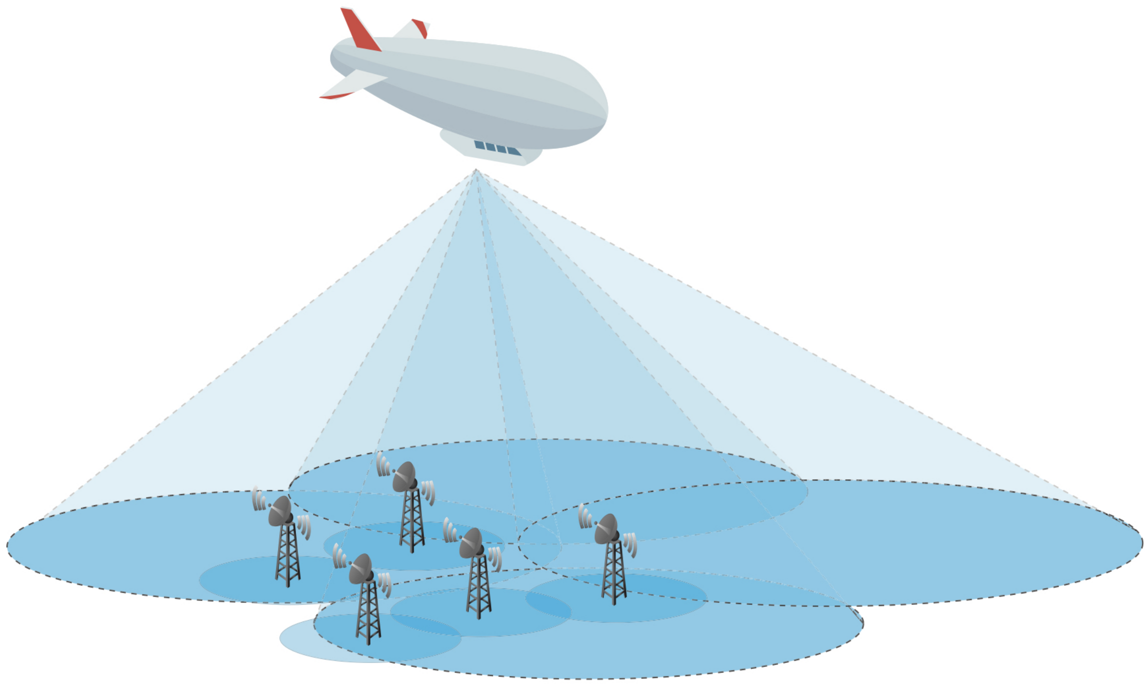


Fig. 8: A hierarchical HAPS-SMBS and terrestrial cellular system.

In [159], a speed and direction-based CAC scheme was developed for a standalone HAPS system with the objective of reducing the handoff call dropping probability as much as possible, as forced termination is less desirable than the blocking of a new call. For this scheme, the system continuously tracked the SIR received from the UE's serving BS's pilot channel and the next strongest SIR received from the UE's neighboring base stations' pilot signals. It was used to derive the speed and direction of the mobile UE relative to the rest of the UEs. In [160], the authors studied high altitude on-the-move flying wireless access points powered by renewable energy. The access point allocates its available energy to maximize the total utility (reward) provided to a sequentially observed set of users demanding service.

2) Power Control for Multicast Services: Only a few papers have considered power control for multicasting. In [156], an integrated terrestrial cellular and HAPS system was considered for Multicast Broadcast Multimedia Services (MBMS) applications with the aim of efficiently allocating transmission resources to multicast traffic streams by suitably selecting terrestrial and/or HAPS channels while still preserving the desired QoS for unicast traffic. In [161], a technique was proposed to improve the overall system capacity by selecting the most efficient multicast transport channel in terms of power consumption by defining the switching thresholds between point-to-point and point-to-multipoint connections while taking into account the radio channel conditions, the cell coverage radius, and two sample MBMS application bit rates. It was observed that for MBMS services, the choice of the most efficient transport channel was a key aspect that impacted the overall system capacity.

3) Joint Radio and Computational Power Management: HAPS-SMBSs are also envisioned for aerial edge computing, as discussed in Section II-B. In such cases, power and time consumed in onboard computation should be managed jointly with radio resources. Two recent works that have explored this use case are [162], [163]. In [162] the authors explored task offloading problem in a two-tier aerial network consisting of a low-altitude UAV tier and a HAPS tier. The HAPS nodes were equipped with MEC servers to perform the computations of the tasks offloaded from the low-altitude UAVs. The design choices that were optimized to minimize the offloading delay were the offloading ratios of the tasks, which determined the number of tasks to be processed locally and the number of tasks the low-altitude UAVs were to offload based on the available computational power of the servers onboard. The second optimization design choice was the uplink transmission power of the low-altitude UAVs. The authors in [162] tackled this problem by modeling it as a multi-leader multi-follower Stackelberg game and solving it using the lower complexity equilibrium problem with an equilibrium constraints (EPEC) model. The work in [163] explored the multi-objective problem of minimizing energy and time consumption for task computation and transmission in a MEC-enabled balloon network. Since the data size of each user's computational task varies over time, the HAPS-BSs must dynamically adjust the user association, service sequence, and task partition scheme, which are the design choices that [163] considered, to meet the needs of users. A support vector machine (SVM)-based federated learning (FL) algorithm determined the user association proactively, before the service sequence and task allocation of each user were optimized so as to minimize the weighted sum of the energy and time consumption.

B. Channel/Sub-Channel Allocation and Spectrum Sharing

Channel allocation is one of the principal functions in any multi-user wireless system. When it comes to multi-user/multi-HAPS systems, channel allocation schemes can exploit the inherent diversity of such systems through a dynamic allocation scheme. Basically, the spectrum gets divided into sub-channels, where one or more of these sub-channels can be allocated to one or more UE. The channel attenuation—due to path-loss, shadowing, and fast fading—seen by each user is different, as discussed in Section V. Therefore, each user is expected to experience different and independent attenuation on a given channel, which could be exploited for achieving multi-user diversity gain. Moreover, in integrated HAPS systems, i.e., HAPS/terrestrial/satellite systems, more than one of these layers may be operational within the same band. Hence spectrum sharing schemes as well as inter-layer interference management will be crucial to guarantee the performance of the system. In the rest of this sub-section, we outline some of the key channel/sub-channel approaches reported in the literature and summarize them in Table V.

One of the specific challenges of a HAPS is its horizontal back and forth movement caused by crosswinds in the stratosphere. [164]. This movement poses a problem for ground users near cell edges who then need to handoff between cells, even when they are stationary. To solve the problem, a channel assignment algorithm combining channel reservation and handoff queuing with priorities based on the platform's horizontal movement was proposed. In [165], an AI-based wireless channel allocation algorithm based on a reinforcement learning algorithm for a 5G HAPS massive MIMO communication system was proposed. A Q-learning algorithm combined with a back-propagation neural network enabled the system to learn independently according to the environment and intelligently according to the channel load and blocking conditions.

In [166], a heterogeneous network with two HAPS nodes (illustrated in Fig. 9) was considered where UEs with a limited HAPS choice (labeled Group L) and UEs with a full HAPS choice (labeled Group F) coexisted in the same system. Group F UEs had access to both HAPS1 and HAPS2 by smart or steerable antennas, while Group L UEs only had access to one of the HAPS nodes due to some physical constraints such as fixed antennas. In order to improve the potentially inferior QoS of Group L, a restriction was imposed to Group F to deliberately restrict its channel availability. Using this compensation effect, a balanced blocking probability was achieved. The study in [167] proposed a measure for deciding the minimum distance in mobile user access systems. Based on this measure, the channel allocation problem for HAPS communications hot spot areas was dealt with on the basis of the prediction of user number change and call volume change that could effectively solve the problem of insufficient or wasted channels caused by the lack of proactive cooperation in conventional channel allocation methods.

1) Joint Power, Sub-Channel and Time-Slot Allocation: In [168], the authors studied radio resource allocation for multicasting in OFDMA-based HAPS systems. An optimization problem was formulated and solved to provide the best allocation of HAPS resources, such as radio power, sub-channels, and time slots. The problem also determined the best possible frequency re-use across the cells that constituted the service area of the HAPS. [169] investigated multicast group users receiving multicast session transmissions from more than one antenna simultaneously. This also allowed the users to receive multicast sessions transmitted from neighboring cells, not just those in the cell in which users resided. The users then could have different priority levels from the system's perspective, and the objective was to maximize the admission of highest priority users to the system rather than maximizing the number of admitted users as in [168]. The solution was based on branch and cut framework (see also [170] for more details), in which linear outer approximation using McCormick underestimators was applied for the relaxation of the mixed binary and quadratically constrained problem.

2) Spectrum Management and Sharing: The authors in [171] highlighted the impact of the minimum operational elevation angle, antenna radiation patterns, and the potential of dynamic channel assignment for the purpose of sharing and compatibility between a fixed service using a HAPS and other services in the 31/28 GHz bands. Moreover, [172] investigated the potential of cognitive radio-based dynamic spectrum management in integrated HAPS terrestrial networks. The impact of the antenna beamwidths and adaptive modulation were considered. The authors in [173] investigated the co-existence of HAPS and fixed terrestrial networks in the 5,850-7,075 MHz band by considering both physical distance and frequency separation in terms of the co-channel and adjacent channel frequency through the use of spectrum emission masks as guided by the ITU recommendations. In [174], the authors considered a spectrum sharing problem in a LEO-HAPS cognitive system in a non-ideal spectrum sensing situation, in which a cognitive network model from a multi-beam LEO satellite and HAPS access scenario was introduced. Aiming at dynamic spectrum and power allocation strategy for the non-ideal spectrum sensing case, a correction coefficient was accordingly included. The reported simulation results validated the capacity of HAPS-to-ground downlink connections are improved with their proposed strategy in imperfect estimation scenario compared with the case in which estimation errors were ignored. An overview of the potential of cognitive radio techniques was also given in [16].

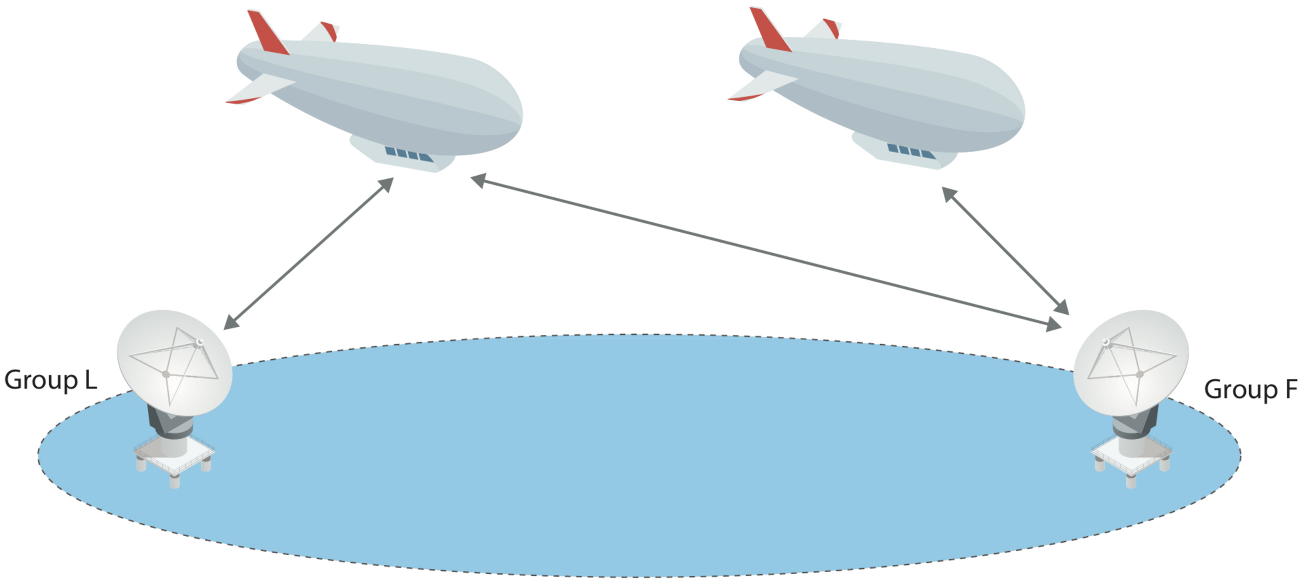


Fig. 9: A system of two HAPS nodes and two groups of users with different access choices (adapted from [166]).

C. HAPS Placement and Constellation Optimization

One of the main challenges of HAPS systems is the design and management of self-organizing networks. In conventional self-organizing networks, self-configuration and optimization as well as self-healing capabilities are among the basic functionalities. This is particularly essential in an aerial network due to its more dynamic nature compared to a fixed cellular network, because the position of the elements in the former may change over time. This may be due to changes in user requirements, atmospheric conditions, coverage necessities, battery status, or abrupt traffic changes in the network.

In [175], the authors explored a layered architecture with aerial flying platforms (AFPs) of various types, flying in low/ medium/ high layers. In their work, the positions of LAPS nodes in the low layer were defined centrally, and the AFP had the ability to reorganise the layer to achieve its target, which could be maximizing the number of UEs served, maximizing the achievable rate and/or fairness among UEs. The optimum placement problem was formulated as a linear binary program. The results showed show that an aerial self-organizing network outperformed a fixed placement. A cost-efficient HAPS constellation design with a QoS and user demand guarantee was investigated in [70]. The QoS metrics were established by considering the SINR, BER, throughput, and availability. For HAPS broadband networks, availability is the percentage of coverage that the system can provide with a BER no worse than the desired target. Based on the network coverage model, the design vector of HAPS system layout optimization, i.e., the number of HAPS nodes, downlink antenna area, power of payload, longitude of HAPS, and latitude of HAPS, was devised. It was found that by applying the proposed constellation design methodology, the optimal cost-efficient broadband network can be realized. In [151], power allocation with fronthauling and backhauling associations in order to improve the global connectivity using satellite, airborne, and terrestrial networks integration was investigated jointly with determining the HAPS nodes placement. It was shown that the satellite stations and HAPS nodes could play a significant role in global connectivity when terrestrial BSs are overloaded or to support users with high throughput located outside terrestrial BS coverage areas (e.g., suburban and remote areas).

D. Antenna and Interference Management

Communication between a HAPSs and UEs requires highly directive antennas to overcome the high attenuation caused by path loss and to prevent interference between UEs receiving transmission from antennas of different HAPS (especially those at the HAPS coverage edge). Additionally, given that the ITU-R allocates terrestrial cellular spectrum to HAPS systems, the expected interference to terrestrial wireless systems requires that the antennas onboard be equipped with dynamic beam pointing to facilitate interference management. This is crucial given that a HAPS is may have hundreds of antennas onboard. Electronically steerable multi-beam antennas were used in early HAPS projects like CAPANINA and HELINET. Overlapping antenna main-lobes and side-lobes of the same frequencies introduces interference, which necessitates interference management

TABLE V: A summary of channel, power allocation, and spectrum sharing schemes reported in the literature about the HAPS systems

Design Aspect(s)/Parameters	Objective	Technique	Network Type	Reference
Power, sub-channels, user-selection, time scheduling	Maximize the number of multicast admissions	Lagrangian relaxation	Stand-alone HAPS	[168]
Associate users with multiple antennas + design parameters in [168]	Admit the highest priority users to the system	McCormick outer approximation relaxations, branch and cut techniques, cloud branching etc.	Stand-alone HAPS	[169]
Complexity reduction for the problem in [168] by reformulations	Admit the highest priority users to the system	Different types of cuts, acceleration heuristics, and variable domain propagation techniques	Stand-alone HAPSs	[170]
Channel allocation	System capacity maximization	Q-learning reinforcement learning and combines back-propagation neural network	System of Multiple HAPS	[165]
Energy allocation	Serving users with the highest priority	Genetic algorithm, rule-based learning neural networks and dynamic programming	Single access point HAPS moving on a trajectory	[160]
Channel allocation	Fair call blocking probability	Continuous time Markov chain and restriction functions	Two HAPSs system	[166]
Radio and computing powers	Minimizing energy and time consumption	SVM-based FL algorithm	Mutliple HAPS-BSs	[163]
Offloading fraction and low-altitude UAV uplink powers	Minimize the offloading delay	Multi-leader multi-follower Stackelberg game and EPEC	Two tier low-altitude and high-altitude UAVs	[162]
Uplink transmit powers	Maximize system's uplink throughput while achieving local fairness	SRA-LF algorithm	Standalone HAPS	[152]
Downlink transmit powers	CAC: Maximize System's Capacity	Centralized Transmit Power Based, Platform Power Limited (CTP-PF) CAC heuristic	Standalone HAPS	[154]
Downlink transmit powers	Minimize dropping and blocking probabilities	Overflow and speed sensitive strategies + centralized resource reservation- random model and traffic selection	Two layer Terrestrial/HAPS network	[155]
Spectrum sharing with conventional fixed service system	Interference mitigation	Dynamic Channel Allocation (DCA) + increasing minimum elevation angle	Two layer terrestrial/HAPS network	[159]
Power driven switching between terrestrial and HAPS FACHs and DCHs for MBMS	Maximize GoS, i.e., minimize call blocking and dropping probabilities	number of multicast users policy + distribution of multicast users policy	Two layer terrestrial/HAPS network	[156]
Power driven switching between HAPS FACHs and DCHs for MPMS	Maximize power utilization: system capacity at a given power level	Defines power switching thresholds to switch between dedicated and common channels	Standalone HAPS	[161]
Spectrum sharing for downlink coexistance of HAPS and terrestrial fixed broadband systems	Improve coexistence performance by reducing outage probability at the user	Interference-to-noise-based scheme + CINR-based scheme	Two layer terrestrial/HAPS network	[172]
Spectrum sharing of 5,850-7,075 MHz band with fixed services and effect of channel bandwidth	Prevention of harmful interference	Co-channel, zero-guard-band and adjacent channel criteria and methods. Separation distance and frequency separation used	terrestrial/HAPS system	[173]
Spectrum and power allocation	Maximize sum rate of HAPS-ground downlinks in imperfect channel estimation	Decomposition, then simplex algorithm and convex optimization	LEO-HAPS cognitive system	[174]

in an intra-HAPS system to mitigate interference from the serving and adjacent beams on HAPS users. A summary of the key HAPS antenna and interference management schemes reported in the literature is given in Table VI. In the rest of this subsection we discuss antenna and interference management schemes in terms of adaptive cell shaping, multipoint transmission and platform diversity, and massive MIMO for HAPS systems.

1) Adaptive Cell Shaping: The design of HAPS antenna beams was first discussed in [176]. Ideally an antenna beam illuminates its corresponding cell with equal power across the cell and with zero power outside the cell, and in doing so acts like a spatial filter. However, for practical antennas, the spot beams do not have this ideal pattern, particularly at millimeter-wave frequencies, where array beam synthesis techniques are challenging. Aperture type antennas may be suitable for this purpose due to their well-studied radiation characteristics. It is highly desirable to be able to construct beams with very low side-lobes and a steep roll-off in the main-lobe. Side-lobe levels can be minimized with corrugated horn designs [177]; however the roll-off rate is mainly affected by the main-lobe width and directivity. There is a trade-off in that if a highly directive main-lobe is used, the cell will experience excessive power roll-off at its edges leading to a low received power there. By contrast, if the directivity chosen is too low, excessive power will fall outside the cell leading to high level of inter-cell interference.

The authors proposed a general formulation in [146] for optimum directivity in order to maximize the received power at the cell edge. This was in contrast to earlier works where the HAPS cell was defined as being within the footprint of the corresponding antenna's half-power beamwidth. The impact of the beam patterns and the frequency re-use technique were further investigated for circular and elliptical beam patterns. Elliptical beams have been demonstrated to be superior in terms of optimized power at cell edges, which is crucial when RF link budgets are marginal. [178] investigated the use of a vertical antenna array with windowing to change the cell shapes, specifically to obtain flat-top ring-shaped cells. The beam shape of the ring cells was improved by making use of a composite weighting functions for flattening the power pattern over the cell stripe as well as reducing the in-cell ripples and side-lobe levels. The analysis of this technique showed that a uniform power pattern with an in-cell ripple of less than 0.25 dB was attainable and this reduced the power control needed for the roll of conventional beam shapes towards the cell boundaries. As a result of the improved power pattern, the signal's CIR was improved both in value and distribution within the serving ring cells.

Beam steering was considered in [179]. The authors presented two steering scenarios: one where all antennas were steered, and one involving a four actuator solution. It was concluded that from a complexity perspective, the four actuator solution was much simpler than having each aperture antenna on its own gimbals arrangement, especially when there might be more than 100 cells. The main disadvantage of this solution was the high number of handoffs required. In [180], the authors investigated the impact of frequency re-use patterns and different antenna models in a multi-beam/multi-cell HAPS-based communication system. In so doing, they compared different models for the antenna side-lobe region and quantified the CIR for a three-channel re-use plan for networks of 121 and 313 cells. The results showed that the ITU recommended pattern for the 47/48 GHz band can lead to poor results compared to an adapted pattern based on fitting the measured data for an elliptical beam lens antenna. The authors in [181] considered irregular cell shapes to obtain the target cell characteristics by grouping pixel spots, which aimed to limit co-channel interference. This cell design technique optimized the cell shape according to the user distribution and behavior in the coverage area, and thus it was expected that this would reduce the frequent handoff and signaling traffic of location updating from moving users. The simulation results showed that a cell with any irregular shape can be formed with a side-lobe level as low as 40 dB using a Gaussian concentric ring array. [182] introduced a cell-pointing approach that made use of HAPS-induced beams to provide contiguous coverage delivery by providing an overlap between beams using a planar antenna array over an extended coverage area.

2) Exploiting Multipoint Transmission and Platform Diversity: User-centric joint transmission coordinated multipoint (JT-CoMP) has proved to boost the capacity of terrestrial cellular systems by overcoming cell-edge interference. In [183], the authors investigated how JT-CoMP could be extended to a HAPS system architecture by exploiting a phased array antenna, which generated multiple beams that formed cells, each of which could be mapped on to pooled virtual BS equipment, thereby replacing multiple terrestrial cell sites. CoMP was designed to enhance the user experience at the edge of the HAPS cells. Methods to overcome the known trade-off for JT-CoMP between carrier-to-interference plus noise ratio (CINR) gain and loss of capacity accessible to the users were explored. In [184], the performance of using multiple HAPS nodes by using antennas was investigated. The impact of the distance between HAPS nodes on the CINR distribution was considered. The use of multiple HAPS as HAPS constellations was considered in [71], where the authors considered the millimeter-wave band transmission. The potential gains in capacity that various HAPS constellations can deliver, both theoretically using the Shannon equation and also while operating a number of practical modulation and coding schemes were quantified. An evaluation methodology consisting of minimum angular separation of HAPs as seen by the user, link length ratio, and sidelobe floor beamwidth was developed. For a $5°$ beamwidth user antenna, the optimum HAP spacing radius was shown to be approximately 4 km. The authors in [185] determined the diversity order improvement that could be obtained by using multiple HAPS nodes via virtual MIMO transmission. The ergodic capacity improvement was also quantified.

3) Massive MIMO for HAPS Systems: As in terrestrial wireless systems, massive MIMO takes advantage of a large number (hundreds) of antenna elements in an array, which can be used for the following

1) To improve the diversity gain in wireless fading channels, where the independence of the paths of each signal is exploited to ensure that an outage probability is minimized, or the receiver signal power is always above an acceptable level;
2) To improve the SINR in an interference limited system by controlling the direction and width of a beam's main lobe as well as the spatial nulls (i.e., beamforming);
3) spatial multiplexing to boost the system's throughput by feeding each antenna element with a different data stream.

It was shown in [186] that a distributed sub-array architecture yielded a significantly better diversity performance than the co-located antenna architectures. This means that the diversity gain in HAPS systems is achievable by the HAPS mega-constellations, which adds another benefit to its envisioned advantages. The problem of system interference caused by beam-forming technology in a HAPS communication system using massive MIMO was explored in [188]. An intelligent beamforming algorithm based on game theory was proposed, and a mathematical model of a beamforming game algorithm was constructed.
A robust beamforming scheme was proposed in [72] for an integrated satellite and HAPS network, where a multi-beam satellite system shared the millimeter wave spectrum with a HAPS system. A multi-objective optimization problem was formulated to obtain the Pareto optimal trade-off between two conflicting yet desirable objectives of the sum rate maximization and total transmit power minimization, while satisfying the QoS constraints of both earth stations and mobile terminals and per-antenna

TABLE VI: A summary of antenna and interference management related aspects and approaches in HAPS systems

HAPS Antenna Related Aspect	Investigated Parameters, Objectives and Approach	Important Findings	HAPS System Type	Reference
Adaptive cell shaping	○ Optimized directivity to maximize the received power at the cell edge. ○ Impact of the beam patterns and the frequency re-use technique was investigated for circular and elliptical beam patterns.	Elliptical beams have been demonstrated to be superior in terms of optimized power at cell edges.	Mutli-cellular (>100 cells) stand-alone single HAPS.	[146]
	Improved beam shape of ring cells using composite weighting functions for flattening the power pattern over the cell stripe as well as reducing the in-cell ripples and side-lobe levels.	Uniform power pattern with a lower in-cell ripple of less than 0.25 dB is attainable reducing the power control needed for the roll of conventional beam shapes at cell boundaries.	System of multiple concentric antenna beam HAPS.	[178]
	○ Platform antenna adjustment mechanisms for horizontal and vertical position variation. ○ Two steering scenarios: all antennas steered; and a four actuator scenario.	The actuator solution was better in terms of complexity, weight, power and CIR.	Single standalone HAPS.	[179].
	Impact of different antenna models.	○ The “mask" (ITU) approach over-estimated mean side-lobe level. ○ The flat side-lobe approximation remained very effective and computationally straightforward. ○ Regular hexagonal cell layouts outperformed the equivalent equiangular hexagonal cell layout in terms of CIR.	Multi-beam/multi-cell HAPS-based system.	[180]
	Optimized the cell shapes according to the user distribution and behavior in the coverage area.	A cell with any irregular shape could be formed with a side-lobe level as low as 40 dB using a Gaussian concentric ring array.	Single HAPS with pixel spot beams.	[181]
	Cell-pointing algorithm that accounted for the broadening of cells at low elevation angles.	Scheme significantly improved user CNR and CINR, achieving a CINR improvement of 5-15dB compared with the other schemes.	Mutli-cellular stand-alone single HAPS.	[182]
Coordinated multipoint transmission	○ Improved user experience at the edge of HAPS cells. ○ Two different methods of identifying non-CoMP and CoMP users are based on the centralized CINR threshold and flexible CINR threshold. ○ Two bandwidth allocation approaches: full bandwidth (FBW) and half bandwidth (HBW).	The schemes based on the flexible CINR threshold approach provided the best balance between loss and gain of the user capacity, while the centralized CINR threshold-based schemes performed well and benefitted up to 57% of users.	HAPS system architecture with phased array antenna and pooled virtual eNodeBs mapped onto directional beams generated by the phased array controller.	[183]
	Impact of the distance between HAPS nodes on the CINR distribution was considered.	Locating HAPS nodes at a specific spacing radius outside the coverage area was shown to improve performance.	Multiple HAPS nodes system.	[184]
	Maximized CINR and spectral efficiency by determining the optimal HAPS nodes spacing for given antenna beamwidths.	○ For a 5° beamwidth user antenna, the optimum HAP spacing radius was approximately 4 km. ○ Capacity increases were commensurate with the increase in the number of platforms, up to 10 HAPs	Multiple HAPS nodes system.	[71]
	○ Determined the diversity order improvement that could be obtained by using multiple HAPS nodes via virtual MIMO transmission in wireless sensor networks. ○ PDF and CDF of received SNR derived.	Virtual MIMO with multiple HAPSs was shown to be a promising solution for future high-data-rate and frequency-efficient smart wireless sensor networks.	Multiple HAPS network.	[185]

Table VI: (Continued) A summary of antenna and interference management related aspects and approaches in HAPS systems.

HAPS Antenna Related Aspect	Investigated Parameters, Objectives and Approach	Important Findings	HAPS System Type	Reference
Massive MIMO for HAPS systems	○ Investigated the interference caused by beamforming technology using massive MIMO. ○ Intelligent beamforming algorithm based on game theory is proposed.	The AI-based algorithm had better array gain than the traditional beamforming algorithm which could focus on the desired user and place spatial nulls in the direction of undesired users.	Single multi-antenna standalone HAPS.	[186]
	A robust multi-objective Pareto-optimal beamforming for sum rate maximization and total transmit power minimization.	A better performance could be achieved in comparison to the commonly used SCA-based scheme.	Integrated multibeam satellite and HAPS system sharing mmWave band.	[72]
	User grouping and beamforming based on statistical-eigenmode.	The solution was shown to outperform existing schemes based on channel correlation matrix.	A single HAPS mMIMO system with a uniform planar array.	[187]

transmit power budget. Finally, motivated by the fact that signal power is mainly concentrated on the statistical eigen-mode, user grouping and beamforming is applied for HAPS nodes in [187]. Numerically it was shown that significant performance gains could be achieved through the use of massive MIMO and that the technique proposed by the authors outperformed the existing schemes based on the channel correlation matrix. These works all contribute towards enabling the use of HAPS-SMBS to fill coverage gaps, as discussed in Section II-B.

E. The Waveform: Signaling and Multiple Access

Signaling and multiple access formats, also referred to as the waveform design, have witnessed a long and radical evolution in wireless communications where they serve as its foundation. For example, WCDMA is the technological pillar of 3G, while OFDM/OFDMA and SC-FDMA are the main approaches of 4G. OFDM is also the main waveform technology in 5G New Radio (NR) technology, which allows dynamic sub-carrier spacings in multiples of 15 kHz to support applications with different latency requirements. OFDMA is still the main multiple access scheme besides the optional Non-Orthogonal Multiple Access (NOMA) technology [189]. However, it is worth considering the issue of candidate waveform structures for HAPS systems. There is no standard yet that defines a specific waveform structure for HAPS and, to the best of our knowledge, no active research on this has been reported in the literature so far. However, wireless waveform solutions that are under investigation for 6G wireless communications technologies can be exploited for use in HAPS access link's radio interface or for inter-platform/backhaul links.

Despite the prominence of OFDM, it presents a number of drawbacks, discussed in [190], which need to be tackled:

1) High peak-to-average-power ratio due to the summation of uncorrelated inputs in the *inverse-fast-Fourier transform*. This drawback can be mitigated by precoding the OFDM signals at the cost of a slightly higher equalization complexity at the receiver. To reduce the complexity at the receiver, the novel solutions based on advanced deep learning architectures seem promising.
2) The need for higher spectral efficiency, which can potentially be improved by relaxing the orthogonality provided that the cyclic prefixes—included to circumvent inter-symbol interference—are reduced or discarded outright. Technologies based on filter bank multi-carrier modulation (FBMC) could be adopted.
3) Issues related to the applicability of OFDM to the mmWave spectrum given the enormous bandwidths therein and the difficulty of developing efficient power amplifiers at those frequencies. A single carrier with faster-than-Nyquist (FTN) signaling technology [191], which can achieve higher spectral efficiencies for the same target BER compared to Nyquist signalling over a single carrier, could be a promising solution for HAPS transmissions in the mmWave band.

In the rest of this section, we overview alternative approaches that are actively being investigated in the PHY research community and that could be suitable waveform candidates for HAPSs. These approaches, which are also summarized in Table VII, could be considered as slight departures from OFDM/OFDMA-based designs rather than eruptive changes.

1) Filter Bank MultiCarrier (FBMC) Scheme: FBMC is one of the best well known multi-carrier modulation formats in the wireless communications literature. It offers a great advantage in being able to shape each sub-carrier and enables a flexible utilization of the spectrum while satisfying different system requirements, such as low latency and multiple access. It also offers advantages by making the transmitted signal immune to many channel impairments, such as dispersion in time and frequency domains. For example, rectangular filters are desirable for time dispersive channels, while raised cosine filters are more robust against frequency dispersion. Many other pulse shaping filters have also been investigated to cope with the various effects of the channel, and they provide a reliable system design based on different scenarios, such as the isotropic weighted Hermite pulse [192]. By contrast, FBMC has drawbacks that include long filter lengths resulting in enormously large symbol duration, which might not be suitable for low latency applications or short bursts of machine type communications. Moreover, when used with MIMO technologies, the signal detection computational complexity is expected to be quite large as the channel coherence bandwidth would fall below the sub-carrier bandwidth [193].

2) Faster-than-Nyquist Signaling: One of the promising ideas to increase spectral efficiency at the physical layer that has been under research for many years is faster-than-Nyquist (FTN) signalling [194]. In this technique, rather than making the duration of pulses shorter, we increase their degree of overlap in time by transmitting them at a rate higher than the Nyquist's signalling rate. In this way, we avoid occupying larger bandwidths but introduce intentional yet controllable inter-symbolic interference (ISI) at the receiver sampling instants, which Nyquist signalling avoids under perfect synchronization, as Figure 10 demonstrates. Despite the presence of ISI, in 1975 James Mazo showed that for a binary sinc-pulse, the minimum Euclidean distance of the signals at the receiver experienced no reduction for an acceleration parameter $\tau \geq 0.802$ [195]. This means that if an optimal maximum likelihood sequence estimation (MLSE) detector is used, then the performance measured in BER is not compromised. The gain is an increase of around 25% in the data rate within the same bandwidth and energy, but at the expense of a more complex receiver. It was shown that the same phenomenon occurred with root raised cosine pulses [196], the ones most commonly used in different applications. An example is the binary 30% excess bandwidth root raised cosine pulse, which ceases to have distance 2 at $\tau = 0.703$ yielding a 42% increase in the bit density.

The spectral and energy efficiency of FTN comes with the cost of high complexity of the optimal detection. This has made low complexity detection a critical issue of investigation over the past few years. The first symbol-by-symbol FTN sequence estimation was proposed for binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) in [197]. Under these modulation schemes, an 11% increase in throughput is guaranteed without any penalties in terms of additional bandwidth, energy, or BER. In [198], the authors proved the feasibility of high order quadrature amplitude modulation (QAM) FTN signaling detection using a polynomial time complexity semi-definite relaxation-based detector. Their simulation results showed that a data rate increase of up to 25% could be achieved at root raised cosine roll off factor of 0.3 without increasing the BER, the bandwidth, or the data symbols energy, when compared to Nyquist signaling; or up to 42.86% increase in the data rate can be achieved at a roll off factor 0.5 with 0.7 dB penalty in the SNR.

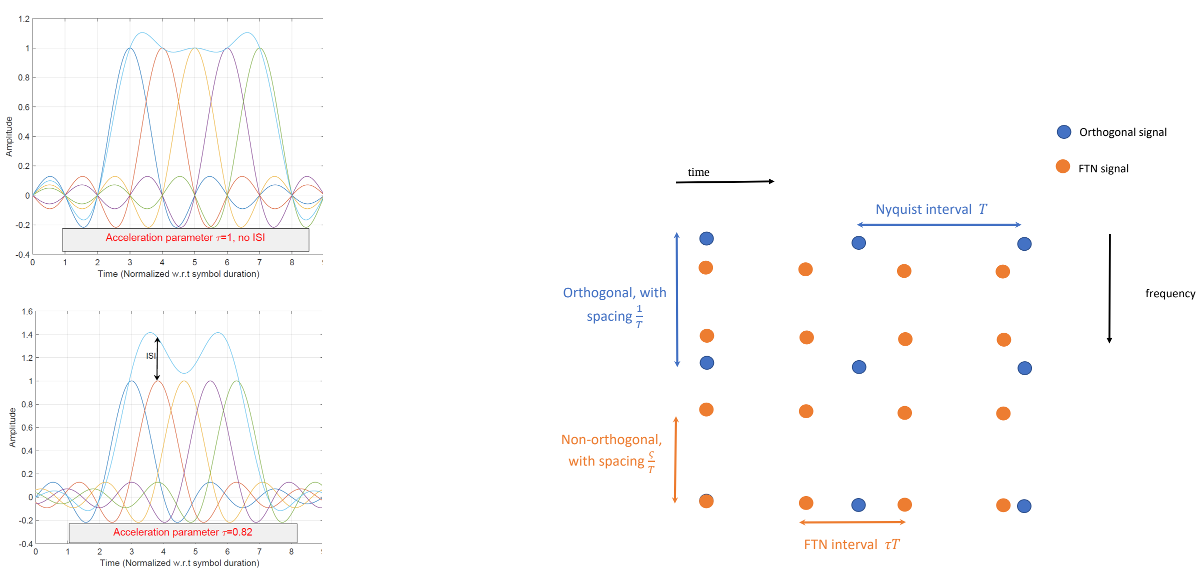
In narrow-band (NB) IoT services that HAPS-SMBS is envisioned to support, uplink connections of IoT devices have limited transmission power of up to 23dBm and small transmission bandwidths of up to 180 kHz [199]. In order to achieve higher transmission rates within the given bandwidth restrictions, higher SNR will be needed in order to transmit with higher modulation orders than the NB-IoT's QPSK without increasing the BER. A higher SNR cannot be achieved by simply increasing the power due to the low power and long battery life requirements. This is even more challenging in HAPS given the much longer distance between IoT devices and the HAPS-SMBS. FTN signaling could instead be used in the uplink connections to enable the sensors pack more bits/sec/Hertz, without any additional SNR requirements and without increasing the transmission errors. The cost paid would be additional complexity, which HAPS receivers would easily endure because of the huge on-board computational power they are expected to have. This is especially important since the bit rate requirements for many IoT applications could increase in the future for new applications. For example, if the IoT devices are artificial skin, nose or tasting devices [200], the bit rate requirements would be higher than existing NB-IoT could support. It is worth noting that further spectral efficiency improvements could be obtained by combining FTN transmission at the IoT device and mMIMO beamforming at the HAPS-SMBS to achieve the target data rate and BER. In such a system, two types of interference would need to be eliminated, the ISI, and the IoT inter-device interference in the uplink at the HAPS receiver. We believe this is a very important area that needs more research.

3) Spectrally Efficient Frequency Division Multiplexing (SEFDM): The idea of FTN signaling has been also studied in frequency domain, which is known as spectrally efficient frequency division multiplexing (SEFDM), extending it to both time and frequency domains, as shown in Figure 10. A squeezing factor ς allows the sub-carriers to be packed closer than in the orthogonal case, hence improving the spectrum utilization at the expense of a controlled inter-carrier interference (ICI). The existence of Mazo limit in both time and frequency domains was proved in [201] and [202]. SEFDM (multicarrier FTN) transceiver design, optimization, and performance were addressed in [203]–[206]. Besides the high spectral efficiency offered, SEFDM can further enhance the energy efficiency of communication systems because it improves the bandwidth efficiency without extra energy consumption. Since SEFDM is a spectrally efficient multicarrier modulation scheme, it is certainly a promising technology to be used for HAPS access links, i.e., between HAPS and UEs in order to achieve the ultra-high broadband data rates anticipated for 6G. The selection of the sub-carriers and their spacing for each user is an open area of HAPS research, depending on the application type and QoS requirements of each UE.

4) Non-Orthogonal Multiple Access: One of the relatively novel multiple access approaches is the non-orthogonal multiple access (NOMA) scheme proposed by the mobile phone operator NTT DOCOMO in Japan [189]. In this scheme, multiple users of different channel conditions are multiplexed in the power domain on the transmitter side, requiring multi-user signal separation on the receiver side. From an information-theoretic point of view, using superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver, non-orthogonal user multiplexing not only outperforms orthogonal multiplexing, but can also achieve the capacity region of the downlink broadcast channel. NOMA can be also applied to the uplink, and despite the fact that under the orthogonal multiple access (OMA) one can achieve the capacity of the channel, NOMA achieves a better trade-off between system capacity and user fairness [207].

TABLE VII: Summary of waveform candidates for HAPS systems: signaling and multiple access

Waveform or Multiple Access Technology	**Key Distinguishing Feature(s)**	**Advantages**	**Disadvantages**
FBMC	Employs high quality pulse shape filtering for each sub-carrier separately.	∘ Addresses the need for large guard bands in OFDM. ∘ Permits a robust estimation of very large propagation delays and of arbitrarily high carrier frequency offsets [190].	∘ Falls short in handling MIMO channels. ∘ The design of wideband and high dynamic range systems with FBMC results in significant RF development challenges.
FTN	Accelerates the pulse rate beyond the Nyquist signaling rate, thereby introducing a controlled ISI.	∘ Packs more bits/second/Hertz by packing more pulses per unit time. This increases the spectral efficiency in a given single-carrier modulation type and order without requiring additional SNR and without degrading the BER, asymptotically. ∘ Substantial acceleration of the transmit pulses increases the *constrained capacity*.	∘ The required additional precoding and/or detection needed to mitigate the artificial ISI effect increases the transceiver complexity. ∘ Results in a higher peak-to-average power ratio. ∘ Complicates the synchronization problem.
SEFDM	∘ Reduces the sub-carrier spacing in a multi-carrier modulation below the minimum orthogonality spacing, hence, introducing controlled ICI. More data streams in a given frequency channel can hence be transmitted. ∘ The demodulator collects statistics of the incoming signal by projecting it onto orthogonal bases while the detector estimates the transmit sequence based on the collected statistics.	Enhances the spectral efficiency of a multi-carrier modulation system requiring no additional SNR and no BER degradation.	∘ The removal of the artificially introduced ICI increases the complexity of the system. ∘ Complicates the synchronization and carrier frequency-offset compensation.
NOMA	∘ Multiple users of different channel conditions are multiplexed in the power domain on the transmitter side. ∘ Superposition coding used at the transmitter, and SIC is employed at the receiver.	∘ Enhances spectral efficiency by assigning multiple users on the same frequency resource. ∘ Outperforms orthogonal multiplexing and can achieve the capacity region of the downlink broadcast channel. ∘ Achieves a better trade-off between system capacity and user fairness in the uplink. ∘ NOMA along with MIMO delivers enhanced performance.	∘ Each user needs to decode information of all the other users even ones with poorest channel gains. This leads to higher complexity and energy consumption at the receiver. ∘ If an SIC decoding error occurs for a single user, decoding of all other user information will be erroneous. This limits the number of users.



(a) (b)

Fig. 10: FTN and SEFDM (multi-carrier FTN), (a) An illustration of Nyquist and FTN transmission. (i)$\tau = 1$ (Nyquist transmission), (ii)$\tau = 0.82$ (FTN transmission), (b) 2D orthogonal versus FTN symbols.

By taking advantage of the spatial dimensions that multi-antenna HAPS systems offer, *spatial division multiple access* (SDMA) is facilitated allowing multiple users to communicate at the same time and frequency but in different spaces/beams.

MIMO-NOMA overloads SDMA by allocating a cluster of UEs to each beam and using SC-SIC within each group [208]. The interference between the clusters is managed by assigning a different beam to each of the clusters. MIMO-NOMA differs from multi-user MIMO in that the former allows a cluster of users, not just one user, to share one beam. Hence, MIMO-NOMA can serve a larger number of users and paves the way for massive connectivity.

VII. Handoff Management in HAPS Networks

Terrestrial cellular networks support the mobility of UEs across different BSs. When a UE moves out of one BS coverage area to another, the communication will be handed over from the first BS to the next without a discernible disruption to the UE's call or data session, which is carried out by a handoff procedure[8]. A properly designed handoff algorithm is essential for reducing the overhead of the handoff process, while maintaining the desired QoS of the UE, and reducing the probability of blocking new calls or sessions. Basically, the handoff process consists of three main phases: (1) handoff information gathering, (2) handoff decision, and (3) handoff execution. However, terrestrial handoff algorithms are designed to manage the mobility of the UEs while assuming that BSs are stationary.

The stratosphere is relatively stable but can be affected by short-term airflow. Therefore, a HAPS needs to maintain a quasi-stationary position. However, some HAPS systems need to move in a certain pattern and area, as discussed in Section IV. According to the recommendations of the ITU, the position of a HAPS should be maintained in a cylinder with a radius of 400 m and a height of approximately 700 m [7]. From this, HAPS movements can be classified into four categories: horizontal, vertical, rotation and swing.

Disturbances to the position of a HAPS cause changes in the size/position of cell coverage on Earth (i.e., HAPS footprint). This can lead to the instability of user communication links, which increases the probability and frequency of handoffs. Unfortunately, the handoff management algorithms of terrestrial networks are inadequate for handoff management in HAPS systems. The main reason is that in HAPS systems not only the UEs are moving but also the HAPS coverage area and position are changing. In addition, the disturbance of HAPS positions is irregular, which means that it is difficult to establish a clear relation between the speed and position information of a UE and the cell coverage area. In HAPS systems, handoffs can be inter-HAPS or intra-HAPS (i.e., inter-cell handoff). There are two types of inter-cell handoff in HAPS communication systems: one is a user mobility initiated handoff, which results from a user moving into a neighboring cell; the other is triggered only by the instability of the platform [209].

In an intra-HAPS handoff, where the handoff occurs between cells served by the same HAPS, the centralized architecture and control can be exploited. The important issue is controlling which cell to switch to at which time. In [210], the handoff algorithm was based on a time-reuse time-division multiple/time-division multiple access frame structure that is similar to that available with IEEE 802.16. A single-frequency variant was suggested, where the HAPS transmits to/receives from different spot beams (i.e., cells) in different portions of the frame. A multiple-frequency variant was also suggested as a way of increasing the system's capacity. In this case, each cell transmits/receives using a sequence of frequencies in different parts of the frame, with each cell in a cluster starting at a different point in the sequence so as to create a hybrid time/frequency re-use plan.

A radial based function neural network was used in [211] to make intelligent handoff decisions, while considering the parameters of Received Signal Strength Indicator (RSSI), direction of user mobility, HAPS position, traffic intensity, steerable antenna, elevation angle of HAPS systems and delay as inputs of the neural networks. By taking into account the curvature of the earth, the author in [212] analyzed the influence of the rotational movement on the user handoff probability in the equal beam-width coverage model. It was pointed out that the outer layer cell was more susceptible to the rotational movement.

In [209], after establishing an antenna beam coverage geometry model for HAPS systems, the author used the Monte Carlo method to calculate the overlap area and analyze the handoff probability during the swing movement in the equal coverage area model. The average and maximum handoff probability of the different tier cellular were deduced. The simulation results showed that the handoff performance of the cells was severely affected by the swing state, especially for outer tier cells, but that the effect could be reduced by increasing the cell coverage radius, to a certain extent.

The traditional handoff algorithms that depends on fixed thresholds usually deal effectively with the handoff issue caused by UE mobility. However, given the quasi-stationary state of HAPS systems, these algorithms show poor handoff management. The quasi-stationary state of a HAPS causes the cell edge users to receive a variable signal strength, resulting in frequent handoffs between cells or the ping pong effect [9]. In addition, representing the unbalanced cell load becomes inaccurate. The effects of the quasi-stationary state on the inner and outer layers are different. Employing a handoff algorithm with a fixed threshold fails to provide efficient handoff in the entire communication system. When the threshold is too low, frequent handoffs are likely to happen; in contrast, if the threshold is too high, the handoff will be triggered too late causing long periods of communication disruption. In [213], by considering the received signal strength, the terminal of mobile speed, and the platform disturbance factors, the author proposed an adaptive handoff algorithm that predicted the received signal strength. In a similar approach, the author in [214] proposed a prediction-based handoff decision algorithm with an adaptive threshold. The algorithm predicted

[8] Handover is used within Europe, whereas handoff is the term used in North America.

[9] The ping-pong effect occurs when a UE keeps performing handoffs between two adjacent cells due to fluctuation in received signal strength.

the values of received signal strength using a time series analysis model and dynamically adjusting the handoff initiation time according to the prediction.

However, in these studies a simple coverage model was used, such as circular or regular hexagonal cell coverage, to analyze the handoff probability. Although these models simplify the analyses of handoff probability, they are difficult to implement in practical engineering, which leads to fewer applications. The equal beam-width coverage model was mainly proposed on the basis of the attenuation characteristics of the antenna directional gain. However, as HAPS systems are located at high altitudes, the difference in path loss at each location in the coverage area should also be considered.

In order to solve the problem of the high outage probability and longtime service interruption during the handoff process between HAPS systems, an adaptive handoff scheme that uses cooperative transmission was proposed [215]. In this scheme, the HAPS with the higher channel gain was selected for cooperative transmission to improve the system reliability, and the handoff was determined by the direction of terminal motion and channel gain reduce service interruptions caused by frequent handoffs.

Under the influence of a stratospheric wind, a HAPS will inevitably move within a certain range. In [216], the author discussed both the vertical and swing movements of HAPS systems and the effect of these movements on path loss. In addition, the author analyzed the coverage on the basis of a derived ground coverage model and calculated the handoff probability of the two movement modes. The simulation results showed that the HAPS swing movement has greater influence on the handoff's probability than the vertical movement. This is because the swing movement of the HAPS generates cell position drift and shape change.

Exploiting effective and seamless integration among heterogeneous aerospace segments (e.g., LEO and HAPS) in order to globally extend broadband wireless connectivity [16] seems promising for improving handoff performance. In such scenarios, LEO satellites can provide the backhual link of a HAPS. Under this assumption, the author in [217] proposed a dynamic handoff strategy to optimize the moment of handoff and resource allocation. The author considered factors of user priority, minimum rate requirement, delay requirement, channel gain, and the traffic of beams.

In [218], a directional traffic-aware intra-HAPS handoff scheme was proposed, where users in overlapping areas of overloaded cells would be forced to handoff earlier than their optimal handoff boundaries in order to partially balance traffic among adjacent cells. A cooperative directional inter-cell handoff scheme for HAPS systems was studied in [219], where the handoff target cell and the two cells adjacent to it worked cooperatively to exploit the traffic fluctuation to improve handoff performance. Basically, users in the overlap area of the overloaded handoff target cell were forced to handoff directionally before their optimal handoff boundary in order to free up resources for the handoff calls which would otherwise be dropped due to the shortage of resources and queue time out.

[220] investigated the inter-HAPS handoff process when a HAPS operates with fixed or steerable directional antennas in the case of a HAPS replacement either for maintenance or periodic replacement of short-endurance HAPS systems. Handoff performance was evaluated for both types of antennas based on a number of criteria, such as the antenna beamwidth, platform height, and the HAPS position cylinder. Results showed that for users employing fixed antennas pointing towards the center of the position cylinder, the handoff can start as soon as the new platform enters the cylinder. Users from the center of the service area are required to employ the widest beam width antenna (29°), whereas users at the edge of the service area could employ a narrower beam width. Users employing steerable antennas could also use a narrower beam width. However, it was shown that connections would be dropped for any beam width of less than 5°, unless users employed two antennas or unless the new platform followed a close flight path to the current serving platform (±305 m vertical separation).

[221] proposed a connection admission control scheme, referred to as the Rate Transition Area assisted Guaranteed Handoff Scheme, which utilized geographical information, rate transition areas, and overlap areas to help eliminate both the inter-cell and the intra-cell handoff failures through adaptive modulation and coding in the physical layer.

Using the RSSI values as the decision criterion will make the HAPS with large RSSI overloaded, causing data congestion in these nodes. By contrast, HAPS systems with small RSSI values might remain idle, which can lead to insufficient utilization of network resources. Meanwhile, due to the limited energy of high altitude platforms, the energy of HAPS systems with large RSSI quickly run out, and the energy of a HAPS with small RSSI values remains excessive, resulting in an imbalance of energy consumption among HAPS systems. To address this issue, the author of [222] proposed a load balancing handoff algorithm based on RSSI values and energy-awareness in HAPS networks. Table VIII provides a comparison between available handoff schemes in terms of their proposed solutions, (inter-/intra-HAPS), parameters considered in making handoff decisions, and type of movement causing a handoff.

Overall, it needs to be mentioned that an efficient handoff management is extremely important to support the HAPS-SMBS role in the previously mentioned use cases of delivering IoT services, covering unplanned user events, and supporting intelligent transportation systems. Three main handoff related points should be considered to fulfil the HAPS use cases requirements. First, the mobility patterns are random in IoT and unplanned events use cases, whereas in intelligent transportation use case mobility patterns are more predictable. Second, mobility speed should be considered in order to perform fast handoff or normal handoff. Obviously, intelligent transportation and aerial network support requires fast handoff as users tend to move at high speeds e.g., cars, trains, and aerial vehicles (see use cases 6 and 7 in Section II-B), while IoT devices (sensors) or users in unplanned events may tolerate normal handoff delays. Thus, future handoff management solutions need to consider

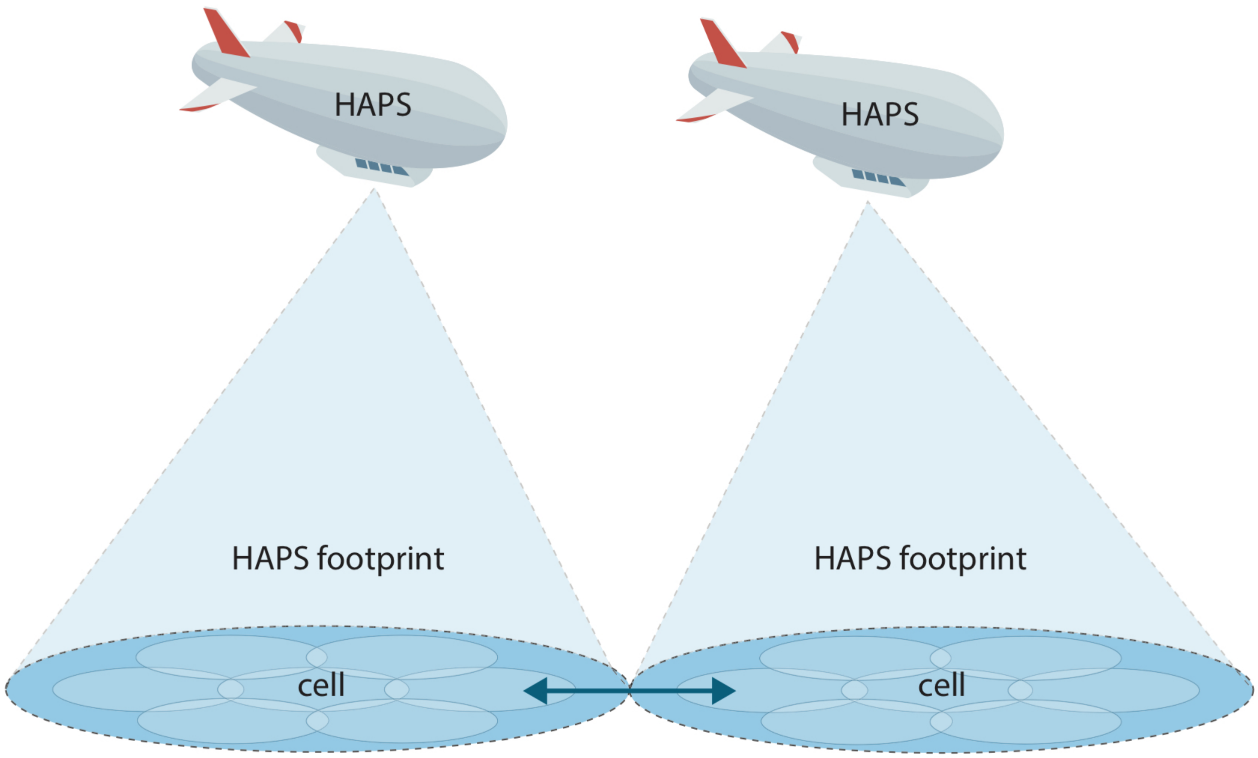


Fig. 11: Inter-HAPS handoff.

time sensitive applications for rapidly moving network entities. Third, user applications requirements of each use case should be considered in handoff algorithms as some applications are time-sensitive (e.g., use case 6 and 7) and require fast handoff algorithms with low packet loss rates. Note that under 5G specifications, handoff protocols rely on uplink synchronization which may require the random access procedure. However, the 3/4-way handshaking for initial access could result in unacceptable propagation delays, especially in use case 6 and 7 (i.e., HAPS-SMBS to support and manage aerial network and HAPS-SMBS to support intelligent transportation systems). It is not entirely clear yet whether it will be possible with conventional solutions to adhere to the latency requirements of 5G and beyond.

VIII. HAPS Network Management and Computational role

To operate a HAPS, two to four ground-based crew members are required to oversee various aspects of mission planning, flight control, sensor operation, and data assessment [223]. Operational complexity and cost will likely scale up in scenarios where multiple HAPS systems are deployed and need to coordinate and work together as a swarm. To overcome the technical and economical problems of deploying a network of HAPS systems, HAPS systems control and coordination will require some level of autonomy. Autonomy will eliminate the need for direct human intervention on many operational levels and allow HAPS systems to make intelligent decisions in a collaborative manner. In effect, HAPSs can play important roles in aerial network management and network slicing, as described in the sixth use case in Section II-B. This is due to the HAPS higher position which enables it to collect data and network status information from a large part of the aerial network. Another advantage is that a HAPS can be equipped with computational devices, which enables full or partial computations to be accomplished in the air without congesting the communication links towards the terrestrial data centers. However, this approach requires strong and reliable collaboration between HAPS systems to fully utilize their distributed computational resources. We should also mention that as privacy is one of the main concerns in data collection and analysis, federated learning may offer learning without moving data from devices to a centralized server, thus preserving user privacy. One recommended solution might be the utilization of federated learning in future HAPS networks.

The implementation of a semi-autonomous high-altitude platform swarm with self-organizing capabilities was investigated to maximize communications area coverage in [224]. The author compared the application of Reinforcement Learning (RL) and Swarm Intelligence (SI) based methods for resolving the problem of coordinating multiple HAPS to maximize communications

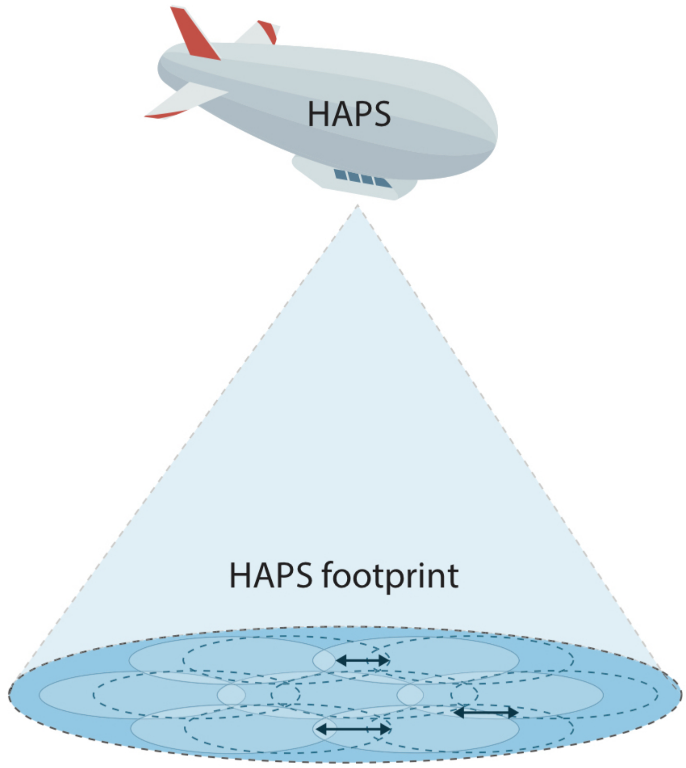


Fig. 12: Intra-HAPS handoff.

area coverage. It was observed that the SI algorithm showed faster convergence and a more stable user coverage profile due to the simple rule-based logic. However, the RL algorithm achieved higher overall peak user coverage rates but with some coverage dips due to individual HAPS exploration strategy. RL-based techniques demonstrated inherent coordination resilience due to independence from feedback loops and cross-agent communications. Therefore in HAPS systems coordination, swarm intelligence-based approaches may be more efficient and reliable but with less optimal coverage results. By contrast, RL algorithms may achieve better coverage peaks but at the risk of occasional dips. This conclusion should be considered in the design of the fifth use case, HAPS-SMBS to fill coverage gaps, which was described in Section II-B. As it is very difficult to predict/detect coverage gaps using conventional mathematical models, RL based solutions have high values as they circumvent the need for a tractable mathematical models, to some extents. Nevertheless, one should note that the RL approaches are generally sensitive to the design of a proper reward function, otherwise there is no guarantee that the algorithm could converge to a suitable solution.

The author of [225] investigated the coordination among a swarm of four autonomous HAPS systems in a volcanic ash cloud emergency scenario for aerial communications coverage, where terrestrial or satellite infrastructure was degraded or non-existent. Due to the extreme nature of the environment, it was shown that a HAPS platform may fail and require replacement. The swarm of HAPS were autonomously coordinated and used their self-organizational capabilities to react to the failure of one or more HAPS and to autonomously adapt to the addition of a spare HAPS. Autonomy in this regard refers to the ability of a HAPS to make local decisions with limited or no global knowledge and still achieve network-wide objectives cooperatively. In a HAPS swarm, self-organization and coordination is crucial to provide communications coverage in volcanic cloud emergency conditions, and the author in [225] developed a swarm intelligence algorithm for this scenario. The participating HAPS systems in the swarm exchanged essential data as they explored the environment. The algorithm developed had four phases: scouting mode, exploitation mode, decision making loop, and exploration mode. The simulation results showed that through self-organization and swarm coordination, within one hour the spare HAPS provided the needed boost in the global coverage performance.

Promising solutions have also been introduced in the literature in the matter of network control and management softwarization. For example, in [226], SDN decoupled data and control planes from each other in order to reduce network control complexity. In [227], NFV decoupled network functions from physical devices, which demonstrated the potential of facilitating the deployment of new services with increased agility and a faster time-to-value. Also in [228], network slicing enabled connectivity for devices with diverse requirements via multiple logical networks built on top of the shared physical infrastructure.

TABLE VIII: A comparison of handoff management techniques in HAPS networks

Reference	Proposed solution	Inter-/Intra-HAPS	Parameters considered	Movement type
[210]	Low-latency MAC layer handoff	Intra-HAPS	RSSI, CIR, traffic load, and user position	Pitch movement
[211]	Proposed a radial-based neural network to make intelligent handoff decisions	Intra-HAPS	RSSI, direction of user mobility, HAPS position, traffic intensity, steerable antenna, elevation angle of HAPS systems, and delay	Vertical and horizontal movement
[213]	Proposed an adaptive handoff algorithm that predicts the received signal strength	Intra-HAPS	RSSI, the mobile terminal speed, and the platform disturbance factors	Swing movement
[214]	Proposed a prediction-based handoff decision algorithm with an adaptive threshold to dynamically adjust the handoff initiation time	Intra-HAPS	RSSI values set	Horizontal movement
[215]	Proposed an adaptive handoff scheme that used cooperative transmission to improve system reliability	Inter-HAPS	The direction of terminal motion and channel gain	Mobile terminal movement
[217]	Proposed a dynamic handoff strategy to optimize the moment of handoff and resource allocation	HAPS with LEO satellites	User priority, minimum rate requirement, delay requirement, channel gain, and the traffic of beams	Mobile terminal movement
[220]	Studied the effect of antennas type and beamwidth on handoff during HAPS replacement	Inter-HAPS	Antenna beamwidth, platform height, and user antenna direction	Replacement movement
[221]	Proposed using adaptive modulation and coding in the physical layer to ensure that ongoing calls are not disrupted by the platform movement	Intra-HAPS	the geographical information, rate transition areas and overlapping areas	Replacement movement
[219]	Proposed neighbouring cells cooperatively force users in the overlapping area of the overloaded handoff target cell to handoff before their optimal handoff boundary in order to free up resources for the handoff calls	Intra-HAPS	Position of users, HAPS movement direction, and HAPS capacity load	Rotational movement
[222]	Proposed a load balancing handoff algorithm based on RSSI and energy-awareness in HAPS networks	Inter-HAPS	RSSI, HAPS residual energy, and mobile terminal movement direction	Mobile terminal movement
[218]	Proposed forcing UEs in overlapping areas to handoff in order to balance load among cells	Intra-HAPS	HAPS traffic load and UE position	Horizontal displacement and rotation

To enable the availability of the networks-as-a-service according to user demands, network slicing employed NFV, SDN, cloud computing, and edge computing. Enabling network slicing requires the successful interaction among these technologies which is a challenging task [228]. Softwarization combined with intelligent algorithms is expected to make network control and management automated and self-organized. For example, software defined aerial networks components can be reprogrammed automatically and dynamically on the basis of intelligent decisions to adapt to changes in the communications environment. To address the challenges of dynamic network traffic, multiple service providers, and mobility, dynamic network slicing needs to be considered [228]. To enable dynamic network slicing, it is necessary to accurately estimate the user demands and dynamically allocate resources accordingly. Several learning theory schemes, such as deep learning and reinforcement learning, can be used for the prediction of user traffic. After an accurate prediction, effective resource allocation schemes can be used for enabling dynamic network slicing.

In [229], HAPS systems were used as the control plane of a software defined aerial network. The controllers were deployed in HAPS systems to take advantage of their wide coverage and relative stability, which was shown to potentially reduce the configuration updating time in the data plane of the aerial network caused by the length and connectivity variation of links among aerial network components due to their high mobility. This study can be quite useful in realizing and developing the sixth use case “HAPS-SMBS to support and manage aerial network," discussed in Section II-B. In [230], a Software Defined Airborne Backbone Network Architecture (SD-ABN) was proposed to maintain coverage and provide reach-back to military units and to ensure network flexibility, openness, interoperability, and evolvability. To meet the challenges of traffic management in SD-ABN, segment routing was applied. Moreover, a network traffic scheduling algorithm was designed on the basis of SD-ABN to improve the transmission reliability and bandwidth utilization by balancing network traffic among multiple reliable transmission paths.

In future HAPS networks, network management functions will be distributed and automated to best meet multi-dimensional (cost, latency, availability, throughput, massive connectivity, etc.) service requirements. This process will be self-organizing and self-optimizing across administrative boundaries, either within a single operator or between operators with autonomous re-arrangement of network partitions. When multiple providers/operators are involved, managing the whole network using a single management unit (orchestrator) increases complexity and delay. Such an increase in delay will be more prominent for massive machine-type communication in 5G and massive ultra-reliable low-latency communication in the upcoming 6G wireless systems. To cope with these issues, multiple distributed orchestrators can be used to reduce complexity. In such a scheme, every orchestrator is designed to control particular network segments. These multiple orchestrators are then controlled by another entity, called a hyperstrator, whose job is to control the overall network resource allocation [228]. Although this management model was not originally proposed for HAPS systems, it it is worth investigating more deeply. This high level of control and orchestration is a necessary requirement for realizing many of the envisioned HAPS-SMBS use cases, such as creating an aerial data center, filling coverage gaps, and supporting and managing aerial networks. As HAPS systems can form an MEC cluster or an aerial data centre for processing offloaded data from aerial or satellite networks (refer to the fourth use case, Section II-B), intelligent task scheduling schemes are required, which take into consideration HAPS energy consumption, computational capabilities, and processing loads. Intelligent decision-making algorithms are required to decide on when it is more efficient to process data in HAPS MEC clusters than to send the raw data to terrestrial data centers.

Ultra-reliable low latency applications that have emerged from the confluence of 5G, SDN/NFV, and AI/ML (e.g., autonomous driving, emergency response systems, remote medical, etc.) require control and processing functions to be distributed toward the point of data collection and consumption. In this regard, HAPS systems can provide the services of a huge network edge above aerial networks and below satellite networks. HAPS systems are expected to play the role of floating aerial data centre, as described in the fourth use case, mentioned in Section II-B. This is due to their wide coverage above low-altitude aerial network components (e.g., UAVs), which makes them ideal for collecting large amounts of data about aerial network statuses and for using such data in network management. However, the critical issue is managing and scheduling the computational and communication resources in HAPS systems to serve the speedy and dynamic environment of UAVs and satellites.

Recently, several studies have proposed using multi-UAVs to form a Mobile Edge Computing (MEC) cluster. In [231], a multi-UAV aided MEC system was proposed, where ground IoT nodes could offload the computational tasks that could not be processed with their limited capabilities. The author introduced a load balancing algorithm to balance computational loads among UAVs and used deep reinforcement learning for computational task scheduling. In an MEC network formed by multiple UAVs, the sum power minimization problem was considered in [232]. The author minimized the power by jointly optimizing user association, power control, computation capacity allocation, and UAV location planning. In [233], the author introduced two architectures where a UAV could work as either a node in a distributed MEC cluster or or as a relay node that assisted in computational offloading from IoT devices to a far terrestrial edge computing node. A game-theoretic and reinforcement learning framework was introduced in [234] for computational offloading in an MEC network operated by multiple service providers. The network was formed by MEC servers installed at stationary BSs and UAVs which were quasi-stationary. Although these studies proposed using multiple UAVs to form an MEC cluster and process the offloaded computational tasks, the same ideas can be implemented in HAPS networks. In fact, a network of HAPS systems can provide a more stable MEC cluster with stronger computational capabilities in comparison to a UAV-base MEC. This is because of the quasi-stationary status of HAPS systems with their ability to carry more advanced computational servers and their longer flight durations. A HAPS-based MEC can not only serve terrestrial UEs but also aerial UEs and satellites. However, to achieve the vision of creating a HAPS-based MEC, reliable communications among HAPS systems, intelligent task scheduling, and advanced resource allocation techniques are necessary.

Regarding support for the use cases mentioned in Section II-B, HAPS network management should be automated to enable a network of HAPS systems to be a self-evolving network [235]. As HAPS systems are envisioned to provide aerial data centers (the fourth use case), several requirements should be considered, including reliable collaboration among HAPS systems and efficient computational and storage resource management among distributed HAPS systems. In addition, intelligent task scheduling, which considers the capabilities, energy consumption, and processing loads of each HAPS. Moreover, it is very important to have intelligent decision-making algorithms for data offloading to decide on where to process the data (e.g., in a HAPS or terrestrial network), which is necessary to support the second, third, fourth, sixth, and seventh use cases mentioned in Section II-B. Another crucial requirement for all use cases is that HAPS networks will need to support the SDN and NFV paradigms. In fact, HAPS systems are a potential candidate for SDN controller palcement in an SDN-based VHetNet architecture.

IX. The Role of AI in HAPS Systems

Active research is currently being carried out to enable ML in highly resource-scarce Micro Controller Unit (MCU)s and Field-Programmable Gate Arrays [236]. In 2017, Microchip manufactured the first MCU with a high-performance 2D GPU, the PIC32MZ DA, to handle parallel calculations [237]. Implementing low-power tiny MCUs with embedded GPU capabilities is a step toward implementing advanced ML algorithms in HAPS systems. In 2019, ARM launched its Helium technology, which will be present in the next generation of ARMv8.1 MCUs (Cortex-M). This technology is intended to provide high digital signal processing and machine learning capabilities [238]. STM Microelectronics sells sensors with incorporated machine learning cores that have embedded classifiers [239]. As companies race to provide high digital signal processing and ML capabilities to their MCUs, we will witness a tight combination between electronic devices and novel ML algorithms designed to be executed with limited resources.

Advances in ML have produced a number of emerging powerful ML algorithms, such as deep neural networks consisting of two stages (i.e., offline training and online execution). In the on-line execution stage, deep neural networks make decisions using the environment states as input, even when some of the environment states have not been experienced in the offline training phase [240]. Another powerful ML approach is reinforcement learning, which resembles the trial and error process of the human brain. The decision-making entity of the reinforcement learning framework interacts with the environment continuously through iterative observations of the environment state. The reinforcement learning framework then selects the actions that affect the environment and obtain immediate rewards, before observing new environment states. Basically, the decision-making entity tends to select the best action with the greatest long-term reward for each environmental state [165]. In recent publications, reinforcement learning has been adopted to address decision-making problems in communications environments, such as access radio technology handoffs [241], spectrum sharing [242], and user scheduling [243]. However, in a large state-action space, reinforcement learning performance drops since many state-action pairs may not be explored. More recently, a new version of reinforcement learning, "deep reinforcement learning," has emerged, which applies the intelligent data representation of the deep neural network in the reinforcement learning [244]. Although merging deep neural networks and reinforcement learning shows promise capabilities in adapting to complicated and dynamic communications environments with extensive state-action spaces, the scalability of such solutions needs to be considered. For resource-limited equipment, some simplified novel ML algorithms (e.g., compressed deep neural network learning) have been proposed. FastGRNN and FastRNN are algorithms to implement Recurrent Neural Networks (RNNs), and gated RNNs in tiny devices [245].

In future networks, AI will play an essential role in the orchestration and management of HAPS systems. On the other hand, HAPS systems will be a great enabler for AI and computing in aerial and space networks, as HAPS systems can carry an aerial data centre and perform edge computing functionality. In fact, HAPS systems are physically located at high altitudes between satellite and terrestrial networks. Due to their high altitudes and wide coverage, HAPS systems can collect a massive volume of data. In the Internet of Everything (IoE) era, data is the precious fuel of data analytics and ML algorithms. Such data can be used to reveal trends, hidden patterns, unseen correlations, and achieve automated decision making. It can also be used to continuously learn about wireless network environment and user behaviour and enable the network to proactively adapt to changes. This will allow HAPS systems to achieve optimal performance. HAPS systems are a potential candidate for collaborative computing and distributed ML. In big data centers, complex ML tasks are divided into smaller ones that are executed in parallel on multiple virtual or physical machines. This makes the idea of collaborative computing [246] feasible by distributing the tasks of ML among a group of collaborating HAPS systems forming an aerial data center, as described in the fourth use case in Section II-B. As a leading alternative to centralized ML algorithms, federated learning techniques can provide a platform to achieve distributed ML with high prediction accuracy in a privacy-preserving manner. However, to support artificial intelligence in future HAPS systems through collaborative ML execution, reliable communications among HAPS are required.

The current trends demonstrate that AI algorithms started to gain more interest among researchers to optimize the functionality of HAPS systems, reduce the operational cost, and adapt to changes in communication environment. Current studies on HAPS systems consider the deployment of a single or a small number of HAPS. However, in future networks, it is expected that a HAPS network will consist of several HAPS systems of different types and characteristics. Managing, controlling, and operating such systems in conventional ways will not be efficient and might be impossible. Therefore, there is a vital need to introduce automation in HAPS systems by exploiting the power of AI algorithms. For example, when an unexpected change happens in the density distribution of UEs, an intelligent HAPS system can detect such a change by observing the movement of UEs. Afterward, by analyzing the collected data, the HAPS system can make an intelligent decision to redirect or form a beam towards the newly emerging UEs groups. In such a situation, the required characteristic of the formed beam (e.g., capacity and coverage area) can be predicted using a machine learning algorithm.

Recently, some studies have investigated AI to address certain complex optimization problems in HAPS systems. To maximize the network capacity per cost via optimizing a HAPS network constellation, an artificial immune algorithm was used in [70]. The author considered the constraints of QoS (e.g., signal to noise ratio, bit error rate, bits per second coverage) and user demand metrics. In a different scenario, neural networks were used to handle the issue of frequent handoffs that users at cell edge may experience due to HAPS movement. The author in [211] used radial-based function neural network to make intelligent handoff decisions. The RSSI, direction of user mobility, position of HAPS, traffic intensity, steerable antenna, elevation angle of HAPS and delay were the inputs of the neural networks.

In a wireless communication network operated by HAPS systems, the key factor for the improvement of the Carrier-to-Interference Ratio (CIR) is a reduction in the antenna Side-Lobe Level (SLL). In [247], the author optimized the beamforming parameters using a comprehensive learning particle swarm optimizer to reduce the SLL. The antenna array configuration was chosen as a concentric circular antenna array and the HAPS cellular system consisted of 169 cells. The proposed method significantly suppressed the SLL which led to a significant improvement in CIR.

To address the limited power and poor computational capabilities of UAVs, the author in [248] studied mobile edge computing services through HAPS systems, where UAVs could offload their computing tasks. The author proposed a multi-leader multi-follower Stackelberg game to formulate the offloading problem. As the leaders of the game, the HAPS systems optimized their pricing by considering the behavior of their competitors to maximize their revenue. Each UAV selected the best computing tasks offload strategy to minimize latency. From this perspective, the stochastic equilibrium problem of equilibrium program with equilibrium constraints model was proposed to develop the optimal supply strategies for HAPS to maximize their profits

TABLE IX: Section-wise Classification of Challenges

Section of the Paper	Challenge(s)
The Role of AI in HAPS Systems (Section IX)	○ Efficient Network Re-configuration ○ Support for Edge Intelligence ○ Efficient Network Re-configurations
Regulatory Aspects (Section III)	○ Regulatory Aspects ○ Integration with Satellite Network
The HAPS Subsystems (Section IV)	○ System Issues
Channel Models for HAPS Systems (Section V)	○ Channel Model and Performance Evaluation
Radio Resource Management, Interference Management and Waveform Design in HAPS (Section VI)	○ PHY and Related Cross Layer Design ○ Radio Resource Management ○ Massive MIMO Communications ○ Beam Tracking
Handoff Management in HAPS Networks (Section VII)	○ Handoff Management in HAPS Networks
HAPS Network Management and Computational Role (Section VIII)	○ Networks Management of HAPS Systems ○ Computational Roles ○ Privacy and Security Concerns ○ HAPS Mega-Constellation

and minimize UAVs' cost. Computational task planning in HAPS systems is essential to optimize HAPS computational services and resource utilization.

A hierarchical task planning structure is favorable for its capability to accommodate constraints at different abstraction levels. This structure is adopted for task planning among multiple HAPS systems. As the combinatorial search problem grows with the presence of multiple agents, the author in [249] proposed a genetic algorithm-based method that guided the decomposition of the tasks in order to find quality plans within limited time.

To prove the feasibility of executing AI algorithms using HAPS resources, [250] described a successful test of a commercial off-the-shelf neural network accelerator on a HAPS. Various advances in hardware acceleration for specific algorithms and approaches (e.g. neuromorphic processors) can offer advantages when compared to general-purpose CPUs that would otherwise be necessary to accomplish an equivalent task. These improvements have led to a marked interest in the idea of running nontrivial computing tasks directly on a HAPS before data passes through the link. In so doing, the amount of data transmitted to terrestrial networks can be significantly reduced while simultaneously improving the speed at which a system can analyze and react to a dynamic environment. This raised the motivation of incorporating artificial intelligence with HAPS systems and utilizing HAPS systems to form an aerial data center.

X. Open Issues

The challenges and open issues related to HAPS system can be categorized into two groups, one that mainly covers the next-generation (up to 10 years) challenges and the other the next-next-generation (10-20 years) challenges. The former will require intensive research but in a more incremental fashion with regard to the current technologies for communications systems. For example, the use of massive MIMO and mmWave communications for HAPS systems can be categorized as a next-generation challenge as the required theory and practice has been well investigated for the terrestrial networks. However, the use of these technologies for HAPS systems will require additional investigations. Corresponding research investigations could be related to new communications techniques to compensate for the lack of enough Degree-of-Freedom (DoF) in HAPS system channels, the restricted transmission energy, or the detection without availability of the channel statistics/model.

For next-next-generation wireless networks, there needs to be a disruptive shift about how we design and configure these networks. An example of challenges for the next-next generation might be how HAPS mega-constellations will interact with satellite mega-constellations. As the potential and pitfalls of satellite mega-constellations are not yet known, since participating companies tend to keep certain technologies secret, the design of HAPS mega-constellations will be dramatically more challenging and highly speculative in the initial phases. Should the former be more of a complementary technology compensating for the latter's shortcomings? Or, should satellite and HAPS mega-constellations be considered as competing technologies targeting potentially separate use cases? With this categorization in mind, in this section we enumerate many important challenges and open issues. We do our best to provide suitable solutions and, where possible, road maps to tackle the challenges.

For the list of challenges and where these are discussed in the paper refer to Table IX. Note that although some of the challenges may be discussed in several sections, for simplicity we only provide the relation of the challenge to the section that overwhelmingly influence it. For example, handoff management challenges are mainly discussed in Section VII while network management Section VIII and Section IX have some influence on it.

A. Next 10 Years: On the Use of HAPS in Next-Generation Networks

1) Regulatory Aspects: The spectrum provided by ITU for dedicated HAPS usage is critical. Unlicensed bands are specifically designated bands worldwide that are intended for industrial, scientific and medical (ISM) applications. Although WiFi-based systems highlight the successful usage of communication purposes in ISM bands, this is not their main functionality, as the name ISM also implies. In fact, the use of unlicensed ISM bands may have a significant effect on radio astronomy due to electromagnetic interference. This matter was substantiated in Google's Project Loon tests in Oceania [251]. Hence the use of these bands in HAPS nodes have to be carefully planned in order to protect radio-astronomy research from unintended interference. To this end, dynamic frequency allocation techniques with cognitive radio capabilities seem promising to manage interference.

2) System Issues: Since different types of HAPS have different payload capacities and different energy consumption specifications, understanding the trade-offs between platform type, cost, performance, and flight endurance is necessary. In general, the energy consumption of a HAPS related to its conventional communication functionalities has been discussed in the literature. Nevertheless, the future of HAPS networks is broader than current functionalities. For example, if HAPS are intended to be used for data centers, the payload type and energy consumption requirements need to be discussed. This is also true when HAPS are used as computation or machine learning platforms. In many cases, we expect the station has at least another functionality besides the common BS/relay one. Therefore, more investigations into energy management and continuity of service is needed. This might require supporting a HAPS partially with other sources of energy sources such as remote charging or nuclear energy, to ensure sustainable and continuous operations.

On the other hand, the use of RSS, while beneficial for reducing payload weights and energy consumption, results in a smaller usable surface area for the installation of solar panels, thus reducing the amount of solar energy absorbed in the long run. In effect, as we mentioned, to increase the directionality of the reflected signal, and thus the spectral efficiency, more surface area needs to be dedicated to the RSS. Therefore, a balance between the necessity of solar panels for energy absorption and RSS for reducing energy consumption seems important. One of the potential solutions to this is to utilize the upper surface of the platform for the solar energy, while the bottom surface would be dedicated to the RSS functions. In addition, since different types of HAPS nodes have different surface shapes, (e.g., flat or curved), the effects of different surface shapes on RSS performance need to be studied.

3) PHY and Related Cross Layer Design: As discussed in Section VI, there is not yet a suggested PHY waveform specified for HAPS. Indeed it is desirable to exploit the promising technologies that are currently under active research in the literature for terrestrial wireless systems; however, simulations and careful system performance analysis will be required. The analysis will assess the suitability of candidate waveforms as well as pulse shaping filters for the mm-Wave band taking into account the unique propagation and channel fading nature of a channel propagation of HAPS. After developing or determining the most suitable waveform, a rigorous design for the corresponding detectors that accounts for computational complexity as well as performance could be established. This should take two important goals into account: 1) the integration with massive MIMO, and 2) the lack of model-based detection due to lack of complete/reliable knowledge of the underlying channel model. Using advanced AI/ML techniques offers benefits over traditional model-based approaches [252]. First, ML methods are independent of the underlying stochastic model and thus can operate efficiently in scenarios where a model is unknown or its parameters cannot be accurately estimated. Second, when the underlying model is extremely complex, ML algorithms have demonstrated the ability to extract meaningful features from the observed data, which is difficult to carry out using traditional model-based approaches. Finally, ML techniques often lead to faster convergence compared to iterative model-based approaches, even when the model is known [253].

Another challenge that needs to be considered is the non-linearity of FSO communications, which are used in inter-platform link communications, LEO/HAPS communications, and back-haul link communications. These non-linearities make using high order modulations quite challenging. Hence, there should be ways to increase the spectral efficiency, as the most commonly used modulation scheme is On-Off keying, or binary amplitude shift keying (BASK). One possibility could be to use single carrier FTN for that purpose and design the suitable detectors for a BASK-based FTN signaling while taking into account the FSO pulse shaping filters that are commonly used. This could be very promising to support the use of HAPS-SMBSs in providing Tbps FSO link backhauling for small-cell (or isolated) BSs, which is one of the use cases discussed in Section II-B.

When new waveform technologies are introduced, cross layer design challenges appear. For FTN and SEFDM technologies, power and channel allocation as well as acceleration and/or squeezing parameters can be considered jointly as a single design problem. For instance, if we consider a single carrier FTN system, then as discussed in Section VI, decreasing the acceleration parameter would increase the spectral efficiency of a particular user but would degrade the performance due to larger ISI. A channel allocation and parameter selection scheme can assign the channels and select acceleration parameters for HAPS users depending on the channel fading each user experiences, hence taking advantage of multi-user diversity. This can be done such that the overall spectral efficiency of the system is maximized. This becomes more complex in SEFDM multicarrier HAPS access links, where we expect time and frequency squeezing parameters to be jointly optimized with power and sub-channel allocations for each HAPS user, where each sub-channel could even have a different number of sub-carriers depending on the frequency-squeezing parameter.

4) Radio Resource Management (RRM): Despite the fact that research on the RRM and interference management for HAPS systems dates back to the early 2000s, there are still many open issues and challenges. Developing techniques that yield acceptable performance with low computational overhead is a balance that designers and researchers try to strike. This is partly why we expect that AI and ML techniques for the design and optimization of HAPS systems will prosper. AI/ML schemes, such as reinforcement learning for channel allocation in a 5G massive MIMO HAPS have begun to appear in the HAPS RRM literature. There is a gap actually, when it comes to the desired performance that is possible using model-based mathematical optimization and the real-time implementation requirements in terms of the computational overhead required. In [254], an AI deep neural network (DNN) was proposed to address this, where the input and output of an RRA algorithm was treated as an unknown non-linear mapping problem to approximate the algorithm. It was demonstrated that DNNs can achieve orders of magnitude speedup in computational time when compared to state-of-the-art power allocation algorithms based on optimization. The role of AI/ML for system design aspects (e.g. RRM, interference management, etc.) is even more emphasized for integrated networks of HAPS, LEO satellites, terrestrial networks, and UAVs, where the mathematical models are still not mature and are expected to be quite complex, possibly making model-based optimization techniques unsuitable. Little work has been done on RRM and interference management in integrated HAPS/ LEO systems.

There is a gap in the literature that heterogeneous types of services (data traffic) have not been considered for HAPS. For example, URLLC with massive broadband and/or massive machine type communications (mMTC) have almost completely different QoS requirements which must be satisfied and hence need to be considered in the mathematical formulations. This requires the development of multi-objective schemes that can be executed in real-time, and therefore an ultra-low complexity is needed. For example, the HAPS system might want to maximize throughput for massive broadband UEs while minimizing end-to-end delay and packet loss for URLLCs. Additionally, technology has thus far interacted primarily with only two senses, sight and sound. Interestingly, in [200], Ericsson Research envisioned enabling an Internet of the five senses in around 2025, which would require the establishment of new QoS metrics that reflect the user's convenience or satisfaction for these new types of services. This will need to be considered in HAPS RRM, interference management, and placement schemes as they are being developed. Also, more research needs to be conducted on emerging technologies like hologram streaming, its QoS metrics, and the development of related novel HAPS RRM schemes.

HAPS systems are expected to be powered by rechargeable batteries and solar panels. This was not sufficiently taken into consideration in the vast majority of HAPS RRM, interference management, and placement research papers. We believe that for optimum energy utilization, we need to take this into account while developing suitable model-based or AI-based schemes for power management in the HAPS access downlink, inter-platform links and backhaul links, possibly jointly. In addition, as we anticipate deployments of HAPS mega-constellations, it is important to consider relaying between platforms over multihops to facilitate communication between two devices associated with different HAPS for certain applications (e.g. URLLC), possibly in different cities, rather than pushing the communication through the core network. For such scenarios, inter-platform link power control together with relay selection for inter-platform routing over multiple hops will be necessary. As HAPS systems are expected to be a major part of 6G communication systems, more research is needed into resource allocation and interference management in HAPS systems for new use cases, such as mission-critical robotics, self-driving cars, high-capacity AR/VR applications, and high-stakes cargo drones. Specifically, cargo drones (in huge numbers) are part of the intelligent transportation system that a HAPS-SMBS is envisioned to support. The channel models to capture 3D mobility effects between HAPS-SMBSs and drones have yet to be developed. These will be crucial for analyzing SINR and outage probabilities that drones could experience and whose insights will be of great importance for developing RRM schemes. Moreover, associating cargo drones with terrestrial BSs, a medium altitude platform or a HAPS-SMBS needs to be addressed. Under what conditions should a drone connect to a HAPS or a terrestrial BS? Or should we advocate for double connectivity in HAPS systems? This needs to take distance into account as well as available radio resources, such as power. It is worth noting that the rechargeable nature of power supplies for aerial platforms must be taken into account as well. It is worth keeping in mind that about 80% of the traffic demand is media-driven, which calls for more research into video streaming, caching, and QoE in HAPS systems. Finally, in the context of joint control-communication system design, new performance metrics have emerged, such as age of information (AoI) and information freshness, which have thus far been completely overlooked in the HAPS literature, and therefore new studies need to consider these.

5) Channel Model and Performance Evaluation: Channel models, especially for HAPS-to-LAPS and HAPS-to-satellite links, need further elaboration as this is still an open area in the current literature. Despite its vital importance and many unresolved issues, the performance evaluation of HAPS systems has also been overlooked. One reason might be due to the lack of a universally agreed-upon, easy-to-use, and practically substantiated channel model facilitating the performance evaluation. On the other hand, the analyses found in the literature have typically considered a single HAPS along with a limited number of users on the ground. Moveover, interactions between terrestrial, HAPS, and satellite networks have not been considered. Due to the complex structure of HAPS and its role in VHetNet more sophisticated tools should be adopted for the performance evaluation.

To study the coverage and capacity of a HAPS or cluster of HAPS nodes, we recommend tools from stochastic geometry for modeling the spatial locations of UEs and UAVs. These tools have been widely adopted for investigating various aspects of terrestrial networks as well as UAV systems. In general, these tools are able to exploit some measures regarding the average behavior of the network to anticipate easy-to-use performance bounds of the network, which can be used to better understand the large-scale impact of various system parameters. A powerful aspect of these tools lie in their abilities to incorporate a mathematically amenable formulation of the inter-cell interference in the analysis of the network, which is difficult with other approaches. These tools also seem promising for evaluating the performance of a large-scale HAPS systems by modeling the location of HAPS nodes via sophisticated point processes, such as the Determinantal Point process [255] and Ginibre Point Process [256], as these mathematical models allow for the inclusion of the (deliberate) repulsion that exists between the stations. Accordingly, an accurate account of the inter-cell interference between HAPS cells and terrestrial cells can be included in the analysis. In HAPS systems, the effect of inter-cell interference is far more severe than that of the UAV and terrestrial networks due mainly to highly dominated LOS air-to-ground/ground-to-air channel components [257]. In effect, even stations hundreds of kilometers away can still cause severe interference for ground users, even merely due to side-lobe antenna gain [258]. This means that more advanced resource allocation along with sophisticated antenna techniques should be adopted at the stations, ideally without creating high computational burdens for user terminals or IoT devices. Note, on the other hand, that since each platform may be a collection of several macro BSs, the typical assumptions regarding the independency of large-scale path-loss attenuation (including the LOS occurrence) and shadowing, which are the main assumptions for deriving the coverage and capacity performance of the terrestrial networks, need to be revisited. This makes the performance evaluation of HAPS systems particularly challenging in comparison to its counterparts, which calls for new investigations. Finally, we expect that stochastic geometry will play a key role for understanding the performance of a HAPS system for robotic applications and edge intelligence—via analysis information freshness or the age of information—which deviates from the conventional techniques based on the average analysis of the performance metrics. This matter can be addressed via the meta distribution analysis of Poisson networks [259].

6) Massive MIMO Communications: Massive MIMO communication is among the disruptive technologies that has made the 1,000x capacity growth of 5G possible. Nevertheless, the promise of the technology, as it is developed iin the context of the ground terrestrial networks, may or may not be the right fit for HAPS applications. This is simply because air-to-ground and ground-to-air channels are highly LOS dominant and also suffer from low scattering profile; therefore the exploitable DoF can be limited. In effect, pilot contamination, which is a principal performance-degrading phenomenon in massive MIMO communications, can be even more detrimental in the HAPS systems. The pilots can be contaminated from stations located hundreds of kilometers away, which can lead to a small frequency re-use factor. Furthermore, the possibility of the antenna array to properly disjoint signals in the spatial domain can be less effective, perhaps regardless of the number of antennas or the processing power of the stations, as the received signals from large areas might be highly correlated. One solution to tackle this issue might be to intelligently cluster the users in the spatial domain in order to minimize the effect of the correlated received signals. However, given the size of the coverage area and massive number of users in each coverage zone, attention should be given so as not to deplete computation and energy resources. In general, we expect novel breeds of MIMO techniques that are tuned for highly correlated signals, allowing to exploit the signal correlations for jointly encode/decode signals for the best possible performance.

7) Beam Tracking: In 5G and beyond, mmWave communication is among the key enablers for 5G New Radio (NR) developed by the 3GPP. Due to very high antenna gain and narrow beams, it is possible to substantially increase the data rate and reduce the latency. However, it is more efficient to spatially disjoint multiple users with different radios within the coverage area, and thus serve them simultaneously. This would lead to a much higher capacity per coverage area, which can be useful for serving swarms of UAVs via HAPS systems and also serving a massive number of devices on the ground. Nevertheless, accurate beam steering/alignment and diligent beam tracking, communication should be taken care of. For example, UAVs are able to maneuver very fast or could be blocked by large objects or buildings temporarily. Without accurate, low-cost, and fast beam tracking the communication can be jeopardized—or worse, lost—which is not acceptable for many mission-critical applications. Conventional solutions, which only rely on the radio signals for estimation and adjustment of the beams, may not be suitable any more. Novel solutions utilizing machine learning in order to predict the mobility of devices seems to be crucial. The use of computer vision in order to extract valuable information regarding the existence of blockages could also improve the overall performance of mmWave communication.

8) Networks Management of HAPS Systems: HAPS-enabled wireless systems are relatively fast to deploy and to some extent re-configurable, which is important for ever-changing demands. Nevertheless, the need for the 3D systems in accordance with onboard energy limitations and permissible payload weight presents unprecedented challenges for network management. This implies the essential role that the optimal deployment of HAPS has for coverage extension as well as capacity improvement, while energy and computation flows are also crucially important. Furthermore, usually the deployment of HAPS systems could be short-term—compared with terrestrial networks that are long-term—where the functionalities and responsibilities are subject to change, modification, or augmentation. For example, a station might be initially deployed for the purposes of communications as a flying BS or a relay node, but with possible upgrades and sufficient provisions will be promoted to a computation platform. Hence, there is a need to develop intelligent self-organizing control algorithms to optimize the network resources and deployment of HAPS with respect to the functionalities or responsibilities. AI will play a critical role in designing and optimizing HAPS architectures, protocols, and operations accordingly.

In future networks, multiple HAPS networks will be deployed and instead of working in isolation, they will form a network. Coordinating HAPS networks through ground stations will not be efficient due to response delays, and ground stations with their limited footprints cannot have communication coverage to all the HAPS network. Therefore, it is envisioned that HAPS networks will be self-organizing with either centralized or distributed control and management systems. In the centralized approach, one HAPS will be designated as a manager while the others will be designated as followers. In the distributed approach, the available HAPS nodes in a network will need to negotiate and coordinate in distributing the communication tasks in order to avoid interference, wasting resources, overlapping footprints or beamforming, etc. In this regard, intelligent control and management, based on data analysis and predictions, will be super valuable.

9) Handoff Management in HAPS Networks: The existing studies on handoff management in HAPS systems consider simple scenarios that might occur in the early deployment stage. However, such scenarios might not be realistic for future HAPS systems whose networks will span the globe (i.e, HAPS mega constellations). The future HAPS networks are expected to have multiple layers with several hundred HAPS components. Managing handoff in such a complicated network cannot be efficiently achieved using conventional approaches. There are a number of issues that need to be considered to manage handoffs in an efficient way in future HAPS networks.

It is expected that HAPS systems will be part of the all-IP network. Thus, handoff management solutions should consider both Layer 2 (i.e., scanning and selecting a new radio channel then associating to a new cell) and Layer 3 (i.e., configuring a new IPv6 address, registering the new IPv6 address using the mobility management protocol, rerouting packets) handoff management.

HAPS systems will provide coverage for not only smartphone holders but also for network entities moving at high speeds (e.g., cars, trains, and aerial vehicles). Thus, future handoff management solutions need to consider time sensitive applications for rapidly moving network entities.

As handoff management in future networks need to consider many parameters that change in a very dynamic way, intelligent and self-adaptive handoff management solutions are required for both inter- and intra-HAPS handoff management. Dynamic beamforming techniques should be utilized to reduce the handoff frequency for the largest number of users. To minimize the transmitted power or to maximize the capacity, needs to be revised accordingly. This is because such solutions may render ping-pong effect, which is very undesirable form handoff perspective. Consequently, a more holistic solution for beamforming that addresses the requirements of handoffs seems necessary.

In the 5G handoff protocol, the random access procedure plays an important role in uplink synchronization. However, the three-way handshake will result in unacceptable propagation delays. In particular, it is not yet clear if under the conventional solutions it is possible to adhere to the latency requirements of 5G and beyond. Furthermore, in 5G networks, HAPS systems will use the mmWave communication frequencies, which can be absorbed by the atmosphere and affected by weather conditions (e.g., rain, fog, moisture in the air). Thus, mmWave signals might have high attenuation resulting in reduced signal strength. As most of the handoff algorithms depend on signal strength as a main indication to establish handoff, the characteristics of mmWave signals might result in unnecessary handoffs. As a remedy, a double connectivity solution that would allow connectivity via microwave for handoff and beam management and payload communication via mmWave links should be investigated for HAPS systems.

10) Computational Roles: A HAPS can play a role in the aerial network management and network slicing. This is due to the higher position of a HAPS that enables it to collect data and network status information from a large part of the aerial network. Another advantage is that it can be equipped with computational devices, which enables full or partial computations to be accomplished in the air without congesting the communication links with terrestrial data centers. In fact, due to their quasi-stationary positions and large footprints (no frequent handoffs required), HAPS systems are ideal for computational offloading either form satellite networks or from aerial networks (e.g. UAVs). In comparison to offloading computations from satellites and aerial networks to terrestrial networks, offloading to HAPS systems can reduce the response delays, reduce the interruptions during offloading due to the mobility of satellites or UAVs, and free the terrestrial networks links for terrestrial-aerial or terrestrial-satellite communications.

However, this approach requires strong and reliable collaboration between HAPS systems to fully utilize the distributed computational resources . As privacy is one of the main concerns in data collection and analysis tasks, the federated learning may offer learning without moving data from devices to a centralized server, thus preserving user privacy. Therefore, it is recommended to utilize federated learning in future HAPS networks. However, in the near future, it is envisioned that there will be groups of HAPS systems surrounding the Earth. Thus, collaboration and coordination between HAPS systems is essential to achieving optimized HAPS resource management, load balancing, and UE mobility management.

Note also that as HAPS systems can form an MEC cluster for processing offloaded data from aerial or satellites, intelligent task scheduling schemes are required, which take into consideration the HAPS energy consumption, computational capabilities, and processing loads. Intelligent decision-making algorithms are required to decide on when it is more efficient to process data in HAPS MEC clusters rather than sending the raw data to terrestrial data centers.

11) Privacy and Security Concerns: The security of HAPS systems can be challenging due to their unique characteristics and also the integrated ground-HAPS-satellite communication paradigm. On the one hand, if by any means a HAPS node is compromised, the integrity of any communication passing through the node will be questionable. This could be catastrophic given the enormous footprint of a HAPS, which could include numerous devices and users with different levels of security and privacy vulnerabilities. Cautions must be practiced regarding the applicability of the current techniques that merely rely upon detection and localization of malicious devices by exploiting conventional signal sensing and ranging techniques, as these can fall short of effectively combating passive eavesdropping. Large scale radar surveillance and computer vision techniques can be helpful; however, this can increase the payload and energy consumption of the HAPS.

From a physical layer communication perspective, one can guarantee highly directional signals with great resolutions via mmWave link or, if possible, FSO communications. Apart from the immediate benefits of lowering interference and increasing the data rate, mmWave communications can enhance the security of the communication channel as well as protect the ground users against passive eavesdropping and active jamming [260], [261]. However, due to imperfect beam alignment and also leaky antenna patterns due to side lobes, the communication links may be vulnerable. This calls for more effective techniques rely on information theoretic security [262], [263] and also covert communications [264] for HAPS communications. In addition, the feasibility of HAPS systems for quantum key distribution is also under investigation to help improve the security and promising results are obtained according to the presented link budget analysis [265].

Given the diverse roles of a station (e.g., as a communication platform, a data center platform, and a computation platform) the magnitude of security and privacy issues is even greater. This means that simply protecting the communication link may not be sufficient. Furthermore, analogous the vulnerability of autonomous vehicles to hijacking and the dangers this poses, the hijacking of a HAPS also poses great dangers. For example, this could put airplanes traveling in the vicinity at risk of colliding with a HAPS. One shall designate dedicated HAPS nodes with the only responsibility of security monitoring and also preservation. These dedicated stations must be equipped with advanced radar, computer vision, and jamming functionalities in order to detect any possible threats. Also, we ought to allow such a station to practice preemptive rights for freezing (with respect to functionalities) and towing (or take over the responsibilities and functionalities) compromised stations if deemed necessary.

B. Next 20 Years: On the Use of HAPS in Next-Next-Generation Networks

1) Integration with Satellite Network: Vertical integration of HAPS systems with the satellite networks, known also as multilevel satellite/HAPS architecture [266], [267], seems attractive and is deemed imperative to attain super connectivity. Such a reliance on the satellite communications will be effective, noting that many projects, e.g., SpaceX's Starlink, OneWeb, Amazon's Project Kuiper, Telesat, are geared toward providing worldwide 5G/6G coverage via satellite mega-constellations. For instance, Starlink is considering launching up to 42,000 satellites for occupying different orbital shells. Meanwhile, SpaceX is targeting deployment of up to 12,000 satellites through low Earth and very low Earth orbit (500 km to 2000 km, roughly speaking). Smaller players, such as the satellite startup OneWeb is planing to launch 900 small satellites into orbit in order to provide broadband internet connections to remote areas. Despite many indispensable advantages, such integrations present vulnerability issues for HAPS systems. In effect, any partial collapse of satellite communications, such as a collision between satellites, could degrade a HAPS network's performance. Accordingly, such challenges make the design of a robust HAPS network even more complex. Should the HAPS network compensate for the resulted coverage holes? If yes, what regulations should be put in place and what extra functionalities should be provisioned for HAPS nodes? Equally important, one should also discuss how transparent the satellite networks should be to HAPS networks and vice versa.

2) HAPS Mega-Constellation: The emergence of satellite mega-constellations to provide broadband Internet access across the globe could present a major shift in the future of telecommunication systems. For a satellite mega-constellation to be economically feasible, it must provide Internet access faster than what is already available through fiber-optics. Provided that satellites are equipped with laser-link communication capabilities, this goal is indeed reachable [268]. However, this technology is only in its infancy, and recently launched satellites are not equipped with it. Accordingly, a stand-alone satellite mega-constellation may not guarantee fast, long-distance Internet access as long as fast and cost-effective technologies for inter-satellite communications are missing. Current practices advocate reducing the altitude of the satellites and installing millions of ground-based relay nodes. It is speculated that with these adjustments fast communications across satellites will still be possible without the existence of laser-link communication [10]. However, such a solution will be costly and may not be attainable for whole world. A better solution might be the use of a mega-constellation that allows multi-hop FSO communications, hence the traverse of the data up to thousands of kilometers becomes feasible, eliminating the requirement of frequent satellite-relay zigzag data exchanges. In this way, the number of hops that would be needed from one satellite to another would be substantially decreased. Note also that the installation/monitoring/protection of ground-based nodes in remote/coastal areas could be costly, which is less problematic in the case of HAPS systems.

In addition, by using HAPS systems, the coverage zone of each satellite can be considerably extended due to much higher computation/communication capabilities of HAPS systems. For example, as satellite signals might get too weak on the boundary cells and due to excessive interference form neighboring satellites, a HAPS can boost, combine, and transmit satellite signals via joint transmission techniques. We should further point out that although we mention HAPS mega-constellations as a solution for enhancing the coverage performance of satellite mega-constellation, we also advocate for the stand-alone HAPS mega-constellations as a robust solution for fast internet access across borders. In effect, a large cluster of HAPS systems for communications, relaying, routing, data centers, servers, computation platforms, and security/cyber-policing, can provide the backbone infrastructure of a mobile Internet.

3) Efficient Network Reconfigurations: HAPS networks are highly dynamic and heterogeneous. For example, some stations may disappear intermittently for a while to recharge their energy resources. If a network is primarily configured to provide maximum capacity, a new configuration may require adjustments for preserving the coverage requirements. Given the vast geographic area that each station is capable of serving, such a consequential alternation in functionality would be unprecedented. The complexity of network reconfiguration can augment as each station may have distinctive functionalities and given that different types of HAPS, such as aerostatic and aerodynamic platforms, have distinctive traits—some stations are quasi-stationary while the others must be keep moving. In effect, the continuous coordination among a diverse array of stations and simultaneously with the ground stations or satellite mega-constellation to preserve coverage would be daunting. Coordinated action across heterogeneous stations would require a tremendous amount of data and extensive optimization routines. From a computational perspective, caution is advised to avoid exhausting HAPS energy and computational resources. It appears that common approaches of coordination, resource allocation, and networking, which rely on the selection of actions based on a given network structure and specified task, are impractical.

One way to smoothly cope with this issue is by using meta learning[10]; Instead of having to constantly solving the optimization problems (for routing, coverage, backhauling, resource allocation, computation offloading, and the like) to derive action parameters on the basis of new network configurations, the network could learn the underlying optimization structures. For example, one can train the network for several prominent tasks, such as coverage preservation, capacity enhancement, energy consumption minimization, computation offloading, and latency reduction, and then with meta learning an emerging task/environment can be quickly recognized and dealt with.

4) Support for Edge Intelligence: Under 6G, we are expected to achieve

1) very high data rates, up to 1 Tbps, in order to facilitate the broad uses of Virtual Reality (VR) and large-scale machine learning applications,
2) secure connected globe,
3) extreme reliability and relatively low latency communication[11], for control and monitoring of massive number of intelligent, mission-critical high-stake robots, UAVs, and devices,
4) over-the-air connected intelligence allowing widespread use of machine learning and data analytics tools on the edge.

In effect, the concept of edge computing is already under investigation and is part of 5G wireless communications networking. In addition, a coherent integration of edge computing and machine learning is under development, known as edge ML. This is expected to be a crucial element of 6G as an enabling computation-communication paradigm for omnipresent machine intelligence. The evolution of telecommunication infrastructures towards 6G will call for dispersing artificial intelligence utilizing edge computing resources. Edge devices such as AI-enabled UAVs, self-driving cars, robots, and the like are expected to locally train sub-models and share the trained models instead of sharing data, which has important consequences form a privacy perspective as well. For this large-scale, distributed edge ML, HAPS networks can provide a universal intelligence blanket. In effect, for a given application, e.g., self-driving cars, flying taxis, or cargo deliveries, a station can collect hundreds of thousands of sub-models from AI-enabled devices in a synchronous or asynchronous manner. The station can then apply training routines by including its own collected data/intelligence.

Nevertheless, to stand as an effective universal edge intelligence provider, one must ensure the timely, secure, and efficient communication links to the diverse array of devices including, robots, drones, street lights, servers, driving cars, and the like. In effect, one should optimize the shared communication resources for two disjoint purposes: communication for data communication and communication for intelligence. The former is well understood, being the main focus telecommunication system design. Nevertheless, new applications such as mission-critical robotics requires a joint communication-control resource allocation, which is largely unprecedented in the design of communication networks. A joint communication-control resource allocation framework could be used to facilitate large-scale distributed machine learning tasks. Therefore, common approaches in resource allocation, scheduling, and computational offloading should be geared toward the required communication and computation media that such algorithms require. However, resource sharing between these two communications paradigms is inevitable. Such resource sharing in large-scale HAPS network should be discussed.

XI. Conclusions

This article has aimed to highlight the unexplored potential of the High Altitude Platform Station (HAPS) systems. With the potential to address the ubiquitous connectivity target of 6G networks, HAPS systems seem indispensable in future deployments. Several prospective use-cases for the near future and beyond have been described above, along with the technological synergies that will enable the dense use of HAPS systems in terms of mega-constellations.

Along with the diverse set of applications addressed in these use-cases, a HAPS-mounted Super Macro Base Station (SMBS) paradigm was introduced as a promising and cost-effective solution for addressing the traffic demands of future networks. As

[10]In machine learning, the meta-learning is also known as "learning to learn" [269]. In a nutshell, meta-learning attempts to design models that can learn new skills or adapt to new environments rapidly with a few training examples. By contrast, meta-reinforcement learning (meta-RL) is meta-learning on reinforcement learning tasks. Here, after training the agents over a distribution of tasks, the agent is able to solve a new task by developing a new reinforcement learning algorithm with its internal activity dynamics. For example, instead of solving a particular graph problem, e.g., minimum cut problem, meta-RL intends to learn a whole set of algorithms on the graph such as shortest path, graph coloring, minimum spanning tree, and the like.

[11]Under 5G, URLLC requires the 5-nine (99.999%) reliability and 1 ms latency targets. With the emerge of new mission-critical applications such as self-driving cars and high-precision robots, 6G needs to address extreme URLLC with 9-nine (99.9999999%) reliability and at least 0.1 ms latency targets.

we showed, this platform is also capable of supporting computing, caching, and processing in a plethora of application domains including sensing, machine type communications, UAV communications, and various IoT applications.

A wide spectrum of topics were discussed with a forward looking perspective. The evolution of HAPS network architecture was highlighted with a focus on HAPS energy subsystems and the latest technologies introduced for communications payloads. The promising technology of passive payloads offered by the Reconfigurable Smart Surface (RSS) was introduced. A detailed review and discussion of the Radio Resource Management (RRM) and interference management schemes were reported. Suitable waveform designs and multiple access techniques were elaborated. The mobility management was also studied by discussing both inter-HAPS and intra-HAPS handoff algorithms. The interaction between existing softwarized techniques, such as network slicing, software defined networks, and network function virtualization techniques, and HAPS networks were detailed. The necessary Artificial Intelligence (AI) enablers in future HAPS systems were also introduced.

The current literature is expected to evolve, targeting the realization of the proposed visionary framework by addressing the open issues discussed. The challenges and open issues related to VHetNets and HAPS systems can be categorized into two groups: one that mainly covers next-generation (up to 10 years) challenges; and the other next-next-generation (10-20 years) challenges. The former will require intensive research but in a more incremental fashion with regards to the current technologies of the communications systems. As an example, the use of massive MIMO and mmWave communications for HAPS systems can be categorized as a next-generation challenge, as the required theory and practice are jointly investigated for terrestrial networks. However, the use of these technologies for HAPS systems will require further investigation. Future research activities should target the lack of enough HAPS system channels, the restricted transmission energy, or the detection without availability of the channel statistics/model.

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