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 altitude around 20 km and is instrumental for providing communication services. Triggered by the technological innovations in the areas of autonomous avionics, array antennas, solar panel efficiency levels, and the battery energy density, and fueled by the flourishing industry ecosystems, the HAPS exerts itself as an indispensable component of the 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 survey. We highlight the undiscovered 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 delineated. The notable contribution of Artificial Intelligence (AI) in HAPS, including machine learning in the design, topology management, handoff, and resource allocation aspects are emphasized. The provided extensive overview of the literature is crucial for substantiating our vision that 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).

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I. Introduction

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

A. Survey and Overview Articles on HAPS

Several overview articles have been published on the use of HAPS as a communication platform. [11] provides a summary of the essential technical aspects of HAPS deployments including possible architectures, cell formations and architectural details.

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]. Even almost all HAPS projects have much smaller coverage areas around (100 km), a network of few multiple HAPS can extend the coverage to serve a whole country. For example, while a 18 HAPS system is estimated to be sufficient to cover Greece including all islands [8], a constellation of 16 HAPS is considered to cover Japan [9].
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Fig. 1: An overview the transition from 5G to 6G. A fully integrated Vertical Heterogeneous Network (VHetNet) is envisioned in 6G.

as of 2005. The literature on the use of optical communications in HAPS platforms is presented in [12]. The commercial and research project deployments of HAPS systems as of 2009 is provided in [13]. The authors of [14] provide an overview of the HAPS related activities at past World Radiocommunication Conference (WRC) of the International Telecommunications Union (ITU), until 2010. Furthermore, [15] provides a survey of the technological changes as of 2016. A summary of the existing and potential applications as well as the past field trials along with open technical issues are enumerated in [16]. The books [17], [18] demonstrate the use of HAPS nodes either as a stand-alone or as a complementary part of the terrestrial networks. [19] describes the integration of the satellite systems and the HAPS, paving the way for hybrid terrestrial-satellite communication system. Findings from experimental studies from the HeliNet project are presented in [20]. The work in [21] demonstrates that HAPS accommodates a suitable system for wide-area synthetic aperture radar (SAR) imaging in a microwave remote sensing. Furthermore, An overview on the channel models for HAPS along with the satellite systems for both Single-Input Single-Output (SISO) and Multiple-Input Multiple-Output (MIMO) antenna systems has been detailed in [22]. The book [23] provides an in depth overview of the channel models in HAPS and satellites. Note that, although these numerous work provide an overview of the past and suggest use-cases, the main focus is on the use of HAPS 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 are extensively over-viewing the related literature. Among them [24] provides a comprehensive tutorial of the subject, reviews the recent developments, and highlights important open issues. The authors extensively discuss the problem of joint rate allocation and trajectory design in UAV systems. Furthermore, a very comprehensive overview of channel modeling in the UAV systems covering UAV to ground, and BS to UAV is presented. A review of recent development of UAV communications from a 5G perspective is given in [24]. Therein, the authors also discuss several exemplary problems in UAV trajectory design with accordance to communication requirements and the limited energy battery of the UAV for IoT applications.

3It is worth highlighting that while 3GPP technical reports, e.g., TR 22,829, consider the term “UAV” for low-altitude vehicles with altitudes roughly up to 150 m, the general literature sometimes uses this term for broader applications expanding from low to medium and occasionally to high altitude platforms [25], [26]. In this paper, we stick to the ITU definition; unless otherwise stated.
Also, [25] comprehensively overviews the use of mmWave communications in low-altitude platforms. [27] surveys the literature of UAVs from a cyber physical 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 temporarily, small-scale, and on-demand service provider or computational platform for the 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 with doing so for a coverage area of size 60 km to 400 km. Instead of managing the movement to preserve the service for couple of hours, we now face the problem of preserving the functionality 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 [28]. Therein, the authors discuss how the coverage of a HAPS can be extended a several order of magnitude compared to the 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 are listed as main enabling factors and many relevant papers are reviewed accordingly. We should note that [28] mainly considers the 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, [28] often does not explicitly distinguish between UAV and HAPS to the extend that many developed ideas/analyses for the former are implicitly assumed to be (automatically) transferable to the latter, which, as we also discussed above, may not be valid or precise. From a technological viewpoint, the use of HAPS in [28] is mainly restricted for the single-station applications for remote areas and disastrous situations. In the contrary, in this work, our main goal is to shed light on undiscovered potentials of the HAPS where, in particular, dense-urban areas can greatly benefit from. As the existing overview papers do not address the use of HAPS systems in densely populated metropolitan areas, hence they do not fully reflect the potential of stratospheric platforms.

B. Contributions and Outline

The aim of this article is to provide prominent research directions while providing a comprehensive overview of the current literature. Although the use of HAPS extends beyond an essential networking component, such as component wide-area synthetic aperture radar (SAR) imaging in microwave remote sensing [21], here we mainly discuss communication, computation, and networking aspects towards the HAPS mega constellations, as depicted in Fig. 2. We differentiate the next-generation and the next-next-generation deployment scenarios, respectively looking in to the future for the 10 and 20 years. Our main contributions are given below:

- Enlisting the use-cases of HAPS systems, and introducing the HAPS mounted Super Macro Base Station (SMBS) as a promising and cost-effective solution for addressing the traffic demands of 5G and 6G era. Unlike the conventional macro BS, the envisioned HAPS mounted SMBS not only enhances the coverage and capacity, but this platform can also support data acquisition, computing, caching, and processing in a plethora of application domains.

- Providing the recent advancements in the HAPS energy subsystem and the latest technologies introduced for communications payload, while sorting out historically the prominent past HAPS projects up to the most recent ones, and highlighting the evolution of the HAPS network architecture according to the development in the components of the HAPS system.

- Introducing the use of Reconfigurable Smart Surface (RSS) in the communications payload in HAPS systems and the potential use-cases, as well as the associated benefits brought by such 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. Power control schemes including techniques that take into account mobility, multicasting, and computational power for edge computing over HAPS are included. 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 motivating discussion for virtual massive MIMO over a HAPS mega constellation.

- Proposing suitable waveform designs and multiple access techniques for HAPS communication links, where the 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 the mobility management by discussing both inter-HAPS and intra-HAPS handoff algorithms that are 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 the softwarized techniques such as network slicing, software defined networks and network function virtualization.

- Depicting the unique role of Artificial Intelligence (AI) including machine learning in the design, topology management, handoff and resource allocation in HAPS communication systems.
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Fig. 2: The next-20-year vision of \textit{HAPS} mega-constellations, bridging the space network with the terrestrial network over densely populated urban centers, providing connectivity and computation even in terrains that are not suitable for ground network architectures.

- Elaborating on various challenges that the wide-spread implementation of \textit{HAPS} may encounter in coming years. We categorize the challenges and open issues into two groups of next 10 and next 20 years, and provide numerous examples of each group along with tentative solutions and the possible road-maps accordingly.

This article is organized as follows. Next-generation use-cases of \textit{HAPS} are described in the following section. The aviation and the spectrum regulations that aim to harmonize the worldwide usage of \textit{HAPS} are over-viewed in Section IV. In Section IV, we describe the main components of the \textit{HAPS} communication system, along with its onboard subsystems, while highlighting the prominent past and recent projects. The channel models that characterize the performance limits of the \textit{HAPS} nodes are presented in Section V. Section VI provides a comprehensive perspective on the radio resource management and interference management of \textit{HAPS} nodes from the overall network performance perspective. The handoff management of \textit{HAPS} nodes, in accordance with the existing terrestrial networks is detailed in Section VII. In Section VIII, the network management perspective is depicted. 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, conclusions are drawn in Section XI.

II. PROMISING USE-CASES FOR HAPS SYSTEMS IN THE NEXT-GENERATION NETWORKS

\textit{HAPS} systems have promising advantages over satellite communications, as summarized in Table II. These advantages make them an indispensable component of the next generation wireless networks. The conventional wireless communication
TABLE I: Complementary features of HAPS systems when compared to Low Earth Orbit (LEO) satellite networks.

| 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 400 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 [UE] 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 [LEO] satellites communication capacity is wasted while they are moving over oceans and underpopulated areas. On the other hand, the relatively stationary position of [HAPS] systems prevents a waste of capacity. |
| Smaller footprint with a large platform | - The smaller footprint due to low altitudes provides a higher area throughput. Due to its large volume, a [HAPS] is suitable for [MIMO] and massive [MIMO] deployments. Composed by multi-antenna arrays, [HAPS] systems can generate highly directional 3D beams with narrow beamwidths that improve the [SNR] for all users. |
| Reduced round-trip delay | - The relatively low altitude of [HAPS] systems corresponds to a round trip delay of 0.13 to 0.33 ms which makes them a good option for low latency such as URLLC applications. Hence, the [HAPS] constellation-based communication system can overcome the inherent high-latency problem of the satellite networks. |
| Deployment and maintenance advantages | - The costs and risks of launching are less in the case of [HAPS] compared to [LEO] Moreover, [HAPS] systems are easier to bring back to earth once they finish their mission while satellites may turn to debris. |

TABLE II: Features of the envisioned HAPS systems over conventional HAPS systems.

| Comparison Aspect | Conventional HAPS | Envisioned HAPS |
|-------------------|-------------------|-----------------|
| Application scenarios | Rural and remote areas, emergency cases | Urban and suburban areas in addition to the remote areas |
| Population density | Applicable only to low user density regions | Suitable for areas with high user density |
| Goals | Extending the coverage of the terrestrial network | Maximizing the achievable capacity to cover a lot of users |
| Functions | Providing connectivity for the ground users | In addition to connectivity, supporting computation, control, and caching |
| 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 defeating coverage holes |
| Coexistence | As an alternative to terrestrial network | As a complementary element to terrestrial and satellite networks |
| Network type | Related to [4G] and [5G] technologies | Related to [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 provisioning using HAPS systems are limited to rural and remote areas to provide broadband access as an alternative to terrestrial systems and for disaster recovery [28], mainly targeting low user densities. However, communication services in urban and suburban areas are heavily concentrated with an ever-increasing demand. The envisioned HAPS-based wireless access architecture is a compelling alternative to terrestrial network densification due to the possibility of the use of one platform for multiple applications, as detailed below. Table II summarizes the features of 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 [29]. However, the communication needs of metropolitan areas are very high and constantly increasing. Hence, small cell deployments will become insufficient to address the ever-increasing demand, as they may fail to solve the supply and demand matching problem [30]. Although network coverage and capacity can be improved through the injection of UAV-mounted BSs, their Size, Weight, and Power (SWAP) constraints limit the UAV BS lifetime and coverage area. Also, the mobility of UAV BS introduces a fast on/off restriction, where the BS needs to be activated/deactivated very rapidly.

On the other hand, HAPS systems have the inherent characteristics of quasi-stationarity, larger footprint with more computational power when compared to UAVs, and better LOS communication links. Hence, a HAPS-mounted SMBS termed as HAPS-SMBS, can be regarded as a powerful platform to enhance the connectivity. It is important to note that the introduction of HAPS-SMBS is not an alternative to terrestrial BSs, rather a complementary solution for network management and control. The use of HAPS-SMBS systems to support the terrestrial communication network introduces agility to the network and enables rapid capacity improvement solutions in an intelligent manner to address the high and variable traffic demands. With this agility (flexibility) in network architecture design, while the average user-demand can be simply addressed through the terrestrial network, a complementary HAPS-SMBS can be designed to satisfy the rapid-changing and often unpredictable user demands. Due to its larger volume, the application of massive MIMO techniques can be exploited at HAPS-SMBS to...
provide improved channel capacity. Even, the use of multiple coordinated HAPS-SMBS systems, which are equipped with multi-antenna arrays, can also enable further flexibility of the extremely precise beams through a distributed MIMO set-up. Furthermore, connectivity of multiple HAPS-SMBS systems that cover multiple metropolitan areas is also envisioned. It is noteworthy to mention that, unlike conventional macro BS the HAPS-SMBS not only enhances the coverage and capacity, but it also serves as a computational platform. It encompasses an intelligent framework 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 more than a conventional macro BS. The future HAPS-SMBS architecture can support data acquisition, computing, caching, and processing in diverse application domains, as exemplified in in Fig. [3] and detailed below.

B. Use-Cases for HAPS-SMBS

1) HAPS-SMBS to deliver IoT services: It is expected that HAPS will play a key role to support diverse Internet of Things (IoT) applications [31]–[33]. The ever-increasing applications of the IoT technologies in the context of the smart city vision together with their stipulations present substantial challenges to the research community in order to address the distinct connectivity, reliability, and latency requirements of the massive number of connected devices. In this context, it is evident that the current infrastructure and so far considered 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 larger 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., forest, mountains, and oceans). HAPS-SMBS is therefore an attractive solution to complement terrestrial networks to collect data from IoT devices and provide reliable uplink connections with them in a seamless, efficient, and cost-effective manner, as shown in Fig. [3]a).

2) HAPS-SMBS for backhauling small and isolated BSs: Although, fiber optic communications remain as a superior option for backhaul connectivity, installing fiber for backhauling small cell BS may not be an efficient solution for many environments due to its high-cost [34]. A cost-effective backhauling solution is the use of in wireless through microwave links and is already a well-accepted approach. Also, the combination of mmWave bands’ wider channel bandwidths and MIMO digital beamforming with high gain advanced antennas makes the mmWave as a viable solution for in-band backhauling [35]. Furthermore, inspired by the recent advances in HAPS systems and FSO [36], [37], backhauling outdoor small cell BS can be realized through HAPS-SMBS. Furthermore, the availability of HAPS-SMBS backhaul links can be enhanced by considering hybrid mmWave Radio Frequency (RF)–FSO links [36]–[39], as depicted in Fig. [3]b.

3) HAPS-SMBS 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 [40], [41]. Such events normally happen in crowded cities possibly leading to network congestion. UAV mounted BS have recently gained great attention to boost the wireless capacity and offload traffic from a congested terrestrial BS during such events [42]. Compared to the UAV mounted aerial BS, which have SWAP constraints, HAPS-SMBS possesses improved capacity to the ground users due to their large platform with the massive MIMO capability and higher transmission power. Hence, the envisioned HAPS-SMBS architecture can address this need by increasing relevance between the distributions of supply and demand, as shown in Fig. [3]c).

4) HAPS-SMBS as an aerial data center: HAPS-SMBS will also have the possibility to work as an aerial data center 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 [43], [44]. As HAPS-SMBS systems can have more computational power than the user terminals (e.g., UAV nodes or ground users), which might be useful to provide 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. Besides, this flying data center can provide a back-up computational facility.

5) HAPS-SMBS to defeat coverage holes: The HAPS-SMBS system can supplement the existing terrestrial network by defeating coverage holes in a cost-effective manner. Coverage holes are encountered when the terrestrial UE in an area experience insufficient Signal-to-Interference-plus-Noise Ratio (SINR) from a terrestrial BS to run a high data rate application due to the blockage of physical obstructions [45]. 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 needs to steer a beam to the targeted direction. When compared to UAV BS, the advantage of using HAPS-SMBS systems is their large platform and the ability to perform 3D beamforming [46] with massive MIMO that enables the creation of separate beams in the three-dimensional space at the same time for different users. 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).

6) HAPS-SMBS to support and manage aerial networks: Enhancing the computational capabilities of UAVs is becoming more important in order to maintain the critical tasks at UAV. However, due to their SWAP constraints, UAVs have limited onboard computational resources [47], [48]. The HAPS-SMBS system can be equipped with powerful processors that can provide computational support for limited-resources UAV network elements, to enhance the computation power of UAV. In addition, using Machine Learning (ML) algorithms, they can control and manage the UAV network intelligently with minimum dependence on terrestrial-based control, as exemplified in Fig. [3]d).
Fig. 3: (a) HAPS-SMBS to deliver IoT services. (b) HAPS-SMBS for backhauling small and isolated BSs. (c) HAPS-SMBS to cover unplanned events and defeat coverage holes. (d) HAPS-SMBS to support and manage aerial networks. (e) HAPS-SMBS to support intelligent transportation systems. (f) HAPS-SMBS as an interface to LEO satellites and aerial data center.
7) HAPS-SMBS to support intelligent transportation systems: The full-scale introduction of the Connected Autonomous Vehicle (CAV) paradigm will be the most powerful automobile revolution in history [49]. Recent advances in sensors, high-end computational units, and the introduction of in-car wireless communication capabilities have paved the way for CAV that enables unprecedented scenarios for road transportation [50]. Nowadays, the automaker companies are spending billions of dollars to prompt the idea of CAV can greatly reduce the accidental rate and to create a safer society. However, such breakthroughs will certainly create new challenges for the design and implementation of CAV infrastructure. For example, CAV should support services such as, interact with their driver, cooperation among the vehicles, decision support, traffic control and management strategies. Also, CAV will be able to recognize the scene, plan the path, and control the motion without any human input. Nevertheless, wide-scale data fusion and processing are necessary for such CAV applications [51]. Interestingly, a HAPS-SMBS can play a key role in providing the ubiquitous coverage for ITS/CAV paradigm. As vehicles may be limited to computing processing capabilities, they might require offloading the data [52], [53]. Due to its large coverage area and greater computational capabilities, a HAPS-SMBS can be used for data offloading in low communication delays. Moreover, HAPS-SMBS systems can provide coverage in rural and remote areas, which is essential for travelling on highways and using trains, flights, or ships (Fig. 3(e)).

HAPS-SMBS can also provide coverage for cargo drones that will likely disrupt the retail industry in the near future. Usually, the cargo drones are supported through terrestrial networks [54]. The use of cargo drones is currently being promoted by the mega-retailers, that can use the drones to carry courier packages. For instance, the cargo drones can be used for Amazon’s prime air drone delivery service, and autonomous delivery of emergency drugs [55]. In this scenario, a large number of cargo drones will fly for all times, will make our skies crammed, and hence 3D highways can be expected that will serve the cargo package distributions of platooning autonomous drones. A single HAPS-SMBS can be used to provide reliable coverage for such a high number of cargo drones in major cities.

8) HAPS-SMBS to handle LEO satellites handoffs and provide seamless connectivity: The high speed and the predictable motion of LEO satellites result in frequent handoffs at the terrestrial gateways [56]. This is considered a serious barrier facing the integration of LEO satellites in global wireless connectivity. Fortunately, HAPS-SMBS systems have a wide upper footprint that can cover many satellites simultaneously. Therefore, to provide seamless LEO satellite connectivity to the aerial and terrestrial networks, the HAPS-SMBS system can act as an interface to manage the handoff in the LEO satellite network, as shown in Fig. 3(f). Under this scenario, the frequent handoff of LEO satellites will be handled by HAPS-SMBS. Also, if the ground users are able to communicate with HAPS-SMBS interface directly, then there is no need for the users to have to use special devices or ground stations to communicate with LEO satellites. In this regard, HAPS-SMBS systems can learn the mobility patterns of the LEO satellites by utilizing a machine learning approach in order to predict their handoff then establish a connection to a coming satellite before losing the current connection.

III. REGULATORY ASPECTS

The regulation in aerospace industry is crucial for a 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 [4]. ITU Radiocommunication Sector (ITU-R) F.1569 indicates that there is a local minimum in the wind speed around 20 to 25 km, targeting to minimize the required propulsion power for keeping the HAPS nodes stationary [57]. In the recent deployments, HAPS have been frequently deployed at 17 or 18 km above the ground [15]. Countries determine the maximum altitude of controlled airspaces, and a typical value is 20 km [16]. 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 the HAPS safety [58]. The recently founded industry consortium HAPS Alliance [1] also works on the aviation and commercialization aspects along with the commercialization opportunities 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 the relations with civil aviation activities. The licensing and the control of the airspace lie within the responsibility of the national civil aviation authorities, and the 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 the unmanned aircraft is an aircraft which is intended to operate with no pilot on board [59]. Although the regulatory guidance is still in progress, regulations associated with these two classes have significant differences. As the main difference, balloons are excluded from real-time management. The regulations are applied according to the specifics of each development. For example, Google Loon Project is 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 [58].
The current aviation regulations are monitored according to the specific rules of the national civil aviation authorities of the corresponding country. All the licensing and operational control is monitored by the responsibilities of the national civil aviation authorities. Yet, the large-scale HAPS deployments are envisioned to be conducted by an international consortium. To catalyze the successful large-scale HAPS deployments, an international set of rules and regulations are necessary to control the licensing and the operation control. Addressing this concern, Liu and Tronchetti [60] propose the categorization of the near space, from 18 km to 100 km as exclusive utilization space along with the corresponding set of rules. This solution may avoid the uncertainty associated with the international legal status of the near space.

B. Spectrum Regulations

ITU has been working on the support and the integration of HAPS nodes in the communication networks since 1997. Based on technical investigations, as reported in recently published reports, including F.2471 [61], F.2472 [62] and F.2475 [63], it is concluded that a bandwidth of 396 MHz to 2969 MHz is needed for the ground-to-HAPS links. A bandwidth of 324 MHz to 1505 MHz is determined as necessary for the HAPS-to-ground links. At World Radiocommunication Conference 2019 (WRC-19), which aimed to revise the regulatory framework for HAPS and non-geostationary satellite systems, it is agreed to append the 31 - 31.3 GHz, 38 - 39.5 GHz bands for the 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 the 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 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 band also introduces the inherent advantages associated with the small antenna sizes and the small array sizes, that 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 can be seen, 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 the 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 demand from the end-users by providing commercial broadband services. The ITU regulations also limit the interference of the communication services on the earth observation sensors in radio astronomy stations. WRC-19 also provides the recommendations in the requirements for the maximum transmit equivalent isotropic radiated power (EIRP), antenna radiation pattern, power flux density (PFD) limits, the separation distance between radio astronomy station to limit the interference and the nadir of a HAPS platform [65].

C. Recommendations and Challenges

The spectrum provided by ITU for dedicated HAPS usage is quite critical. As another extension unlicensed bands are considered in the trails. Unlicensed bands are specifically designated bands worldwide that are intended for industrial, scientific and medical (ISM) applications. Although WiFi-based systems prove 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 imposed electromagnetic interference. This matter is substantiated in Googles Project Loon tests in Oceania [66]. Hence the use of these bands in HAPS nodes have to be carefully planned in order to protect the radio-astronomy research from unintended interference. To this end, dynamic frequency allocation techniques with cognitive radio capabilities seem promising to manage interference.

IV. THE HAPS SYSTEM

In this section, we present the 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 the energy and the communications payload subsystems. Moreover, the characteristics of different types of HAPS along with the classification and the key features of the most popular HAPS projects are highlighted.
Fig. 5: A general view of the HAPS system and its main components.
A. System Components

A HAPS is located in the stratosphere, a layer in the Earth’s atmosphere. This layer has unique properties, which makes it suitable for HAPS deployment. This layer is almost free from any weather disturbance such as lightning or a thunderstorm. Because of the absence of clouds in this layer, solar energy can be effectively utilized without atmospheric pollution. Moreover, this layer is safe for deployment as it is above commercial air-traffic heights. Due to these intrinsic features of the stratosphere layer, two different types of stratospheric platforms, (aerostatic and aerodynamic), can be deployed to stay in a quasi-stationary position above the earth for a long duration, as will be explained in details in the following subsections. In general, a HAPS communications system can be considered as two disjoint parts: Aerial and Ground, as detailed below.

1) Aerial Part: This part includes all the main relative network components in the air as well as the essential onboard subsystems for 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 the station 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 [17]. The energy management subsystem handles the energy generation and storage process, as well as 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 aerial nodes that are potentially involved in the HAPS communication systems, as depicted in Fig. 5. A HAPS might be connected with other types of HAPS forming a constellation with multiple HAPS [67], [68], or it could be a part of a network with different layers of satellites [19], [69]. Moreover, the HAPS layer might be connected with different types of Low Altitude Platform Station (LAPS)s, such as UAVs base stations or relays (UxNBs), or serving a swarm with diverse kinds of UAV users (UAV-UEs) [36].

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

- **Control station:** It 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 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 wired backhaul infrastructure. Depending on the HAPS payload and the type of a terrestrial network, a HAPS may either communicate directly with terrestrial users, or the data information is exchanged through the communications gateway. Control station and communications gateway could be either co-located within the same building facilities or have separate locations. They basically consist of processing units and antennas. Typical used antennas have parabolic dish reflectors to guarantee high directivity gain.

- **Terrestrial networks:** This segment includes all the terrestrial nodes or users that are involved in the HAPS communication systems. This include 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 B-57 Canberra and Lockheed F-104 [70]. Most of these manned HAPS were considered for meteorology, scientific purposes or military applications. The Proteus is an example of manned HAPS designed for telecommunication usage. However, typical communications applications require prolonged support, and it is difficult for human pilots to fly for a very long duration in the harsh stratospheric environment. Therefore, unmanned HAPS nodes are more popular and preferable for communications.

Based 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 are making use of buoyancy to float in the air, aerodynamic platforms use dynamic forces created by the movement through the air [28], [71]. Aerostatic platforms appear in two shapes balloons or airships, and they make use of a lifting gas in an envelope for providing buoyancy to float in the air [71].

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.
Balloons are usually unpowered platforms and 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 is an example of balloons intended for communication purposes. It is made from large size sheets of polyethylene, equipped with antennas and solar panels, and can stay over 100 days in the stratosphere. Loon’s early experiments were conducted in 2011, and successful WiFi and LTE connections were realized through Loon since 2013 [72].

Airships are typically powered platforms with propulsion systems, and can stay in the stratosphere for several months or years [11]. Although the huge size of airships rises the dynamic drag during the flight and imposes significant challenges for takeoff and landing, it offers great flexibility in terms of payloads and the generated power using solar cells [71]. Aerodynamic [HAPS] uses electric motors and propellers as a propulsion system. In contrast to aerostatic platforms, aerodynamic aircraft have limited payload capacity with higher resistance to strong winds and turbulent conditions [17]. Moreover, an aerodynamic [HAPS] has to move forward and circle around the intended area for coverage to maintain in a quasi-stationary position. Also, they require large size wings (35 to 80 m) for lifting due to the reduced air density in the 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 types of aerostatic and aerodynamic [HAPS] types have their own advantages and disadvantages. The differences are in the 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 dictating the best [HAPS] option [11], [71]. For instance, an aerodynamic [HAPS] might be more preferable for disaster or emergency situations due to their reduced deployment costs [17], flexibility in take-off/landing and mobility control, while an aerostatic [HAPS] seems to be more appropriate for longer-term scenarios due to their large payload capacity and high energy generation capability using solar cells. However, station-keeping is more difficult and challenging for aerostatic platforms when strong winds and severe turbulent conditions exist.

Table [11] enlist the past and recent projects. As seen, in most cases, each [HAPS] project adopts a certain type for the platform, but perhaps a hybrid type of [HAPS] that combines the advantages of both current types is needed for near-future applications of [HAPS] nodes. In this regards, both projects Loon and HAPSMobile signed a long-term strategic relationship in 2019 for advancing both types of aerostatic and aerodynamic [HAPS] systems [72].

C. Energy Management Subsystem

Managing the [HAPS] supplied or consumed energy is an essential task and impacts the flight duration and the deployment costs of a [HAPS]. Since using a [HAPS] system for communications requires generally prolong operations, careful energy management is required in order to make [HAPS] based solutions feasible and cost-effective.

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 [18]. The use of conventional energy sources is suitable for a temporary solution or an emergency situation. Alternatively, energy beams from the ground can be used to supply the [HAPS] energy system. This idea was early proposed in the 1980s using microwave beams [84], [85]. An example of such telecommunication [HAPS] is the SHARP project [73] consisting of a large ground antenna system for transmitting a large diameter of microwave beams. Such [HAPS] energy systems use collectors consisting of a large number of 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 USA using laser-beam powered [HAPS]. However, due to the high power irradiation risks by both microwave-powered and laser-powered platforms, they are not regarded as safe solutions [18].

Solar energy, on the other hand, is a renewable energy source and a safe option for powering the [HAPS] and is the main energy source considered by most [HAPS] projects. Solar energy is appropriate for [HAPS] due to two basic reasons. First, [HAPS] are operated above the clouds, where the natural solar energy is abundant there. Second, [HAPS] are typically huge platforms that can have large solar panels to generate large amounts of energy. Solar-powered [HAPS] are typically accompanied by secondary energy sources to power the [HAPS] functions during nights or in winter. These secondary sources, 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 the operations between primary and secondary energy sources. Effective [HAPS] solar system designs, harvested solar energy analysis, efficient energy storage systems, and cooperation strategy between solar energy systems and secondary energy sources [86]–[89] are widely investigated in the literature.

Several studies have recently introduced methods for improving the solar energy conversion efficiency [90]–[92]. MicroLink Devices, a leader 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 the world’s record in comparison to any other solar cell technology [93]. 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 [94]. Fuel cells, which are the other alternative energy storage system, have superior advancements. In 2009, the state-of-the-art fuel cells were around 400 Wh/kg [95]. Current fuel cells have a high energy density of 1600 Wh/kg [96].
| Project / Product | Type       | Company/Organization | Country | Project period | Description / Features                                                                                                                                 |
|-------------------|------------|----------------------|---------|----------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| SHARP [73]        | Aerodynamic| Communications Research Centre (CRC) | Canada  | 1980-1987      | ◦ It is powered by microwave beams from the ground.  
◦ It demonstrates successful communication for one hour flight duration.                                                                              |
| Pathfinder, Centurion & Helios [74] | 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 demonstrates the communications of high-definition TV (HDTV) signals, 3G mobile voice, video and data, and high-speed internet connectivity. |
| (SkyNet) [11], [15], [17] | 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 airship has about 200 m length and can operate for up to 3 years.                                                                     |
| CAPANINA [75]     | Aerostatic-(Balloon) | Communications Research Group at the University of York | United Kingdom | 2003-2006 | ◦ The goal of the project was to improve broadband access for both urban and rural communities in Europe.  
◦ A successful demonstration of data transmission with rate 1.25 Gbps form a HAPS.                                                   |
| X-station [76]    | Aerostatic-(Airship) | StratXX | Switzerland | 2005-Now | ◦ It supports different communication technologies such as TV and radio, broadcast, mobile telephony, VoIP, remote sensing, and local GPS.  
◦ It uses solar energy and batteries, supports 100 kg payload for up to one-year flight duration.                                                 |
| Elevate [77]      | 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 technologies.  
◦ Its STRATOS vehicle can carry up to 100 kg for about 24 flight endurance.                                                                 |
| Loon [72]         | Aerostatic-(Balloon) | Subsidiary of: (Alphabet Inc.) Previously: (Google X) | United States | 2011-Now | ◦ Its mission is to connect people everywhere using a network of HAPS.  
◦ Current design can fly up to 223 days, with 40 km coverage radius.  
◦ In 2019, it accomplishes one million flights flying 40 million kilometers.                                                             |
| Zephyr S [78]     | Aerodynamic | Airbus Defense and space | United Kingdom | 2013-Now | ◦ One of its goals is to connect isolated people in the globe.  
◦ It can achieve 100 Mbps broadcast with up to 12 kg payload for 100 days continuous flight.                                                   |
| Aquila [79]       | Aerodynamic | Facebook | United Kingdom | 2014-2018 | ◦ The aim of the project was to provide broadband coverage for remote areas with 80 km radius and 90 days flight duration.                                           |
| Stratobus [80]    | Aerostatic-(Airship) | Thales Alenia Space | France | 2014-Now | ◦ One of its goals is to provide 4G/5G telecommunication.  
◦ Its length is 115 m and can carry up to 450 kg payload for 5-year mission with annual maintenance.                                               |
| HAWK30 [81]       | Aerodynamic | HAPSMobile | Japan | 2017-Now | ◦ Its objective is to connect mobiles, UAVs, IoT around the world.  
◦ Each HAPS provides 100 km coverage radius for several months.                                                                           |
| PHASA-35 [82], [83] | Aerodynamic | BAE Systems and Prismatic | United Kingdom | 2018-Now | ◦ Its designed for variety of services including 5G communications.  
◦ It has 15 kg payload capability with up to one year of continuous flight.                                                                 |
2) **HAPS Energy Consumption:** Generally, the energy 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 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 continuous circular movement, they have generally higher energy consumption. 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, their generated solar energy is less than airships. Consequently, their capacity for payload power is relatively small. The remaining of the generated energy is consumed by the payload for the communications operations that chiefly depends on the type of the communications payload as well as the communication techniques. In general, as more active components and computation processes are included in the payload, heavier payloads are required and more energy consumption is expected.

### D. Communications Payload Subsystem

1) **Active Payload:** The active payload generally includes antennas, transponder, low-noise power amplifiers, and frequency converters, IF processors, and filters. The payload type is dependent on the intended application and use-cases. Typically, HAPS payload can be either as a relay station (HAPS-RS) or as a full base station (HAPS-BS). More active components and higher processing capabilities are associated with a HAPS-BS, which accordingly requires more energy consumption, which leads to larger and heavier communications components. While HAPS-BS can fully process signals and serve users directly, HAPS-RS requires an intermediate station to process the users signals. Thus, HAPS-RS involves an increase in the round-trip delay. On the other hand, as already discussed in Section IV-C, HAPS can be equipped with a BS with superior caching, computing and communication capabilities, termed as HAPS-SMBS, for serving dense urban environments. However, this advanced and powerful capabilities of the HAPS-SMBS comes with the costs of the payload weight and its consumed energy. In this case, the choice of the platform needs to be carefully considered. Airships, with their intrinsic features including huge size and large payload capacity, have the potential to accommodate such heavyweight and high energy consumption payload. For instance, the Strtobus 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.

2) **Passive payload- HAPS-RSS:** The HAPS deployment for wireless applications is profit-driven. The platforms weight, energy efficiency, and flight duration play an important role in determining the HAPS deployment costs. Although it is possible to equip HAPS with advanced communication, caching and computing functions, it might not be profitable in some scenarios, where the role of a HAPS is limited to relay signals, or it is only targeting limited number of users in remote areas. In such situations, a cost-effective HAPS-RSS deployment requires having 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 seems plausible. RSS has recently gained a lot of interest in the research community and emerged as a new technology— as one of the driving technologies in 6G networks—to support wireless communications. It is shown in [100] that using RSS one can increase the received SNR and by doubling the number of RSS units, the SNR quadratically increases. Also, as studied in [101], adopting RSS the data rate can be substantially improved. RSS consists of a thin layer of meta-surfaces, which can be used to deliberately manipulate the phases and the directions of incident waves in a controlled approach, 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 coating different surfaces [102]. Moreover, using digital meta-materials [103], the manipulation of the electromagnetic waves can be digitally controlled. To manipulate high-frequency signals, e.g., Gigahertz (GHz) and Terahertz (THz) bands, tune-able materials such as liquid crystal and graphene, are used. Experiments conducted in [107] confirm that dynamic control of high-frequency signals is feasible. Also, [108] shows 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 potentials of RSS and its special features, industry efforts have started to utilize this technology for different wireless applications. For instance, NTT DOCOMO in collaboration with Metawave demonstrated an increase in data rate by approximately ten times using RSS at 28 GHz [109]. Greenerwave company currently manufactures RSS applicable for a wide frequency ranges up to 100GHz.

More recently, researchers started investigating the integration of RSS in different aerial platforms. Two possible scenarios for utilizing HAPS-RSS are illustrated in Fig. 6. Backhauling signals from rural areas to the gateway and inter-HAPS communications. In such scenarios, the ground control station is responsible to send the required configurations allowing the onboard RSS controller to configure and manipulate and direct the signals to the targeted direction.

HAPS-RSS resembles the function of HAPS-RS but with extra advantages. For instance, several recent studies indicate that the capacity achieved through RSS is comparable to the one achieved through radio relays. As the performance of supporting wireless communications is strongly dependent on the number of reflectors and given that the HAPS is typically a large platform, it is possible to accommodate a large number of reflectors, which will enhance the spectral efficiency. Also, RSS supports full-duplex communications without suffering from high noise or residual loop-back. The dimensions of each reflector unit are typically between \([\lambda/10, \lambda/5]\), where \(\lambda\) is the wavelength.
self-interference, which are the typical limitations of relays [100], [113]. 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 [114]. As a result of the reduction in the platforms weight and consumed energy, the flight duration of the HAPS could be prolonged, which leads to lower maintenance and deployment costs. Studies show that an RSS-assisted communication system could have 40% more energy efficient than a relay-assisted system [112]. 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.](image)

**E. Recommendations and Challenges**

Since different types of HAPS have varied payload capabilities and energy consumption, understanding the trade-off between the type of the platform and its cost, performance, and flight endurance is necessary. Commonly, the energy consumption of HAPS related to its conventional communication functionalities is focused in the literature. Nevertheless, the future of HAPS is broader than current functionalities. For example, if HAPS is intended to be used for data centers, the payload type and energy consumption needs to be discussed. This is also true when it is used as a computation platform or a machine learning platform. In many cases, we expect the station has at least another functionality, as mentioned, besides the common BS/relay one. Therefore, more sophisticated investigations on the energy management and continuity of the service should be considered. On the other hand, the use of RSS while it is beneficial for reducing the payload weights and energy consumption, renders a smaller usable surface area for the installation of solar panels, thus reducing the absorbed solar energy in long run. In effect, as we mentioned, to increase the directionality of the reflected signal, and thus the spectral efficiency, more surface shall be dedicated to the RSS. Therefore, a balance between the necessity of solar panels for energy absorption and RSS to reduce energy consumption seems important. In addition, since different types of HAPS nodes have different surface shapes, (e.g., flat or curved), the effects of the surface shape to the RSS performance need to be studied.

**V. Channel Models for HAPS Systems**

To understand the full potentials that HAPS networks can offer a deep understanding of the channel model is necessary. This need has been addressed by several studies in the literature. An extensive overview of the channel models, including extending
from [116] to satellite channel models is given in [122]. Although a recent survey on HAPS channel is not available, there are numerous studies for modeling the channels of lower altitude platforms, such as [115]. However, as the scatterers are mostly present on the ground but not on the stratosphere, the channel characteristics show significant deviations, hence extra caution is necessary 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 the land-mobile satellite channels. A high-resolution time series provided by the data from German Aerospace Centre (DLR) have been first presented in 1991 in [116], where the authors use the land mobile satellite channel to model the link via a digital two-state Gilbert-Elliott structure. This model is then used to assess the performance of the proposed [HAPS] channel models. An overview of the satellite channel models that can be used for [HAPS] are first noted in [117]. The channel modeling studies in the stratospheric telecommunication systems started with the consideration of modeling the atmospheric effects in the system performance [118].

2) Non-Geometric Stochastic Models: The first study that considered the impact of multi-path (i.e. small scale) fading to the presence of terrestrial scatterers in [HAPS] channels is [119], where the authors derive the channel model for 2GHz band. As the rain attenuation is negligible in this band, it is not considered in the analyses. The authors have considered an ellipsoid channel model by placing the transmitter and the receiver as foci. The scatterers are assumed to be uniformly scattered along the formed ellipsoid.

Statistical model for mixed propagation conditions for land mobile-satellite systems are presented in the ITU-R Recommendation P.681-11 [120], 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 is proposed in [121] and extended to tapped-delay lines in [122]. The impact of these state switches on the error performance is noted. [123] presents a statistical model for jointly estimating the statistical time-series and power spatial delay profile for HAPS-MIMO channels. A model comparison is also provided with the data provided by DLR [116], using the corresponding first order statistics.

3) Geometry-based Stochastic Models: The first study that proposes a geometry-based stochastic model (GBSB), specifically a geometry-based single-bounce (GBSB) model, is introduced in [124], where the authors introduce a 3-D scattering model for stratospheric multi-path fading channel for isotropic and nonisotropic scattering environments. The spiral and temporal correlation functions are provided and the required antenna separation distance is derived. The authors study the impact of the channel model on the capacity expressions that can be obtained in [HAPS] communication channels in [125]. The work is then extended in [126], where the elevation angle of the platform, the array orientation and configuration, the Doppler spread, and the distribution of the scatterers are considered for non-isotropic scattering environments using a 3-D geometry-based single-bounce reference model for Ricean fading channels. It is observed that the considered model parameters have a significant effect on the space-time correlation, and the corresponding impact needs to be taken into account in the array designs. [127] defines a 3-D GBSB the sum-of-sinusoids (SoS) principle-based statistical simulation model for HAPS-MIMO channels, under the framework of the reference model in [126]. Its wideband extension is presented in [127].

Considering the relay channel use-case of [HAPS] nodes between two terrestrial nodes, a geometry-based modeling of M-to-M relay-based channels is presented in [129]. An extension of the [126] model for the low altitude air-to-ground communication channels is introduced in [130]. 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 is presented in [131], where the authors detailed the derivation of the multiuser spatial correlation function, extending the use-cases to multi-user [HAPS] environments. A non-stationary 3D [MIMO] GBSM is investigated in [132], where the authors model the appearance and the disappearance of the multipath components using a two-state continuous-time Markov process. Closed form expressions of survival probabilities are derived. Long distance and small-scale time-variant parameters are also considered to model the non-stationary aspects of the [MIMO] channel. The Space-Time Correlation Function and the Doppler Power Spectral Density expressions are presented. Dual polarized [MIMO] channel model for [HAPS] is studied in [133], where spatial correlation and polarization correlation expressions are also provided.

The dynamic evolution of the [LOS] component in 3-D models is investigated in [134] by a two-state continuous-time Markov chain. Closed for 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: Extension to air-to-air [HAPS] scenarios is also considered in the literature. The authors in [135] introduce a 3-D non-stationary geometry-based scholastic model for air-to-air channels by using a 3-D Markov mobility model where the nodes can move both in the horizontal and vertical directions, and their velocities can change in time. The amount of mobility randomness is adjustable. The authors derive the time-frequency correlation function and the Doppler power spectrum. The results highlight the importance of considering the vertical movement. Yet the model about the scatterers need 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 vacuum in space. Due to the cost-effective license-free high-bandwidth nature, FSO emerges as a leading technology solution, especially for the HAPS to HAPS connectivity and the backhaul transmission links. Hence, the usage of FSO for HAPS-based communication systems have been thoroughly investigated. Numerically demonstrates the possibility of 9000 km of inter-HAPS distances with a high reliability. The main impairments encountered in the FSO channel links include fluctuations in the received signal due to turbulence, wind and pressure fluctuations and inhomogeneities in the temperature. Varous statistical models have been proposed to model the channel characteristics. Gamma-gamma distribution is proposed in [138], proposed a lognormal model to model weak fluctuations. FSO channels have also been used as backhaul links in HAPS nodes. An excellent overview is provided in [37].

C. System Performance Analysis

The discussed channel models are vastly adopted to study the performance of HAPS systems. Usually, 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 as well as its sensitivity to atmospheric conditions, the use of multi-hop HAPS communications and relaying is suggested. In [140], the use of WiMAX HAPS-based for delivering data to fixed terrestrial users on the ground is investigated. The authors introduce a channel model comprising of geometrical and statistical components to derive the BER performance. The channel model takes into account the LOS occurrence prediction along with statistical shadowing. The authors use satellite communication system records to corroborate their analysis and introduced channel models. The introduced model however has limitations for correctly measuring the transition state of the channel. On the other hand, [141] uses HAPS to provide capacity for high-speed train using MIMO communication in Ka band. It is shown that despite the strong LOS the channel is ill-conditioned due to high speed of the train, thus the multiplexing gain of the MIMO system reduces substantially. Suitable antenna distancing, up to couple of centimeters, at the receiver seems effective to curb the mentioned degradation effect of ill-conditioned MIMO channel, which, compared to typical handsets, is affordable. The authors of [126] adopt a 3-D geometric channel model along with Rician fading channel to study the impact of antenna placing for achieving uncorrelated response in HAPS-MIMO communications. It is shown that Doppler spread, array configuration, and the distribution of scatteres have fundamental impact on the statistic of the channel. The theoretical results can be used to evaluate the performance of HAPS-MIMO channels. In [142], the authors study the capacity of a HAPS-MIMO interference channel comprising of two HAPS systems and 2 ground users. It is observed that to achieve the best performance, which corresponds to the independent channel power gains, the users must be sufficiently separated spatially. The high spatial correlation seems to be due to angle-of-departure and angle-of-arrival at the transmitters and receivers, respectively. In [68], the authors use mmWave communication to increase the capacity of a single HAPS system and a cluster of 3 HAPS systems. Their analysis includes the evaluation of Shannon capacity as well as the impact of modulation and coding by incorporating the angular separation that the user on the ground experiences from the serving HAPS, the link length ratio, and the side-lobe of the antenna. Their analysis indicates that 4 km circular spacing is optimal. In [143], the authors investigate the coverage performance of HAPS operating in 28 GHz and 48 GHz via approximating curve-fitting of the antenna pattern radiation. The analysis allows the authors to shed some lights on the importance issues, such as the type of the antenna beam and the frequency reuse, affecting the 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 presence of gamma-gamma atmospheric turbulence channels. The impact of different type of relaying such as amplify-and-forward channel-state-information-assisted or fixed-gain relays on the statistical properties of the SINR is investigated in order to derive the coverage probability via moment-generating function. Adopting the composite channel gamma-gamma distribution the closed-form expressions for the channel capacity and BER are derived in [135], by adopting free-space optical links for multi-hop HAPS communication. It is shown that the side effect of beam wandering and random pointing error can be mitigated via multi-hop communications. The considered system is shown to be robust against fog, rain, snow, and other atmospheric turbulence. The conducted analysis of [146] suggests that the worst relay channel has profound impact on the reduction of the performance, such as capacity, outage probability, and BER of multi-hop HAPS systems. The authors then propose the use of power allocation in order to minimize the mentioned negative effect. [147] investigates the triple-hop RF-FSO-RF communication system supported with an FSO link between two HAPS nodes, which are connected to the terrestrial network via RF links. The performance of the system in term of outage probability is derived, which shows that the NLOS occurrence and the vulnerability of the FSO link to atmospheric turbulence, pointing errors, and beam wandering renders the growth of the outage probability.

D. Recommendations and Challenges

The channel models especially considering the HAPS-LAPS, and HAPS-to-satellite needs further elaboration as this is yet an open area in the current literature. Despite its vital importance and many unresolved issues, the performance evaluation
of HAPS systems is also 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 conducted analysis in the literature usually consider a single HAPS along with a limited number of users on the ground. More, the interaction between terrestrial, HAPS and satellite networks are not considered. Due to complex structure of HAPS and its role in VHetNet more sophisticated tools should be adopted for the performance evaluation.

As a powerful candidate we recommend tools from stochastic geometry for modeling the spatial location of UE and UAV in order to study the coverage/capacity performance of a HAPS or a cluster of HAPS nodes. This tool is widely adopted for investigating various aspects of the terrestrial systems as well as UAV systems. In general, the tool is 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 large-scale impact of various system parameters. A powerful aspect of the theory lies in its ability to incorporate a mathematically amenable formulation of the inter-cell interference in the analysis of the network, which is very hard under other approaches. On the other hand, this tool seems promising for understanding the performance of a large-scale HAPS systems, by modeling the location of HAPS nodes via sophisticated point processes such as Determinantal Point process and Ginibre Point Process, as these mathematical models allow the inclusion of the (deliberate) repulsion that exists between the stations. Accordingly, accurate account of the inter-cell interference between HAPS cells as well as terrestrial cells can be included in the analysis. In HAPS systems, the effect of inter-cell interference is far more sever than that of the UAV and terrestrial networks, due, mainly, to highly dominated LOS air-to-ground/gound-air channel component. In effect, even stations hundreds of kilometers away still can impose severe interference on the ground users, even merely due to side-lobe antenna gain. This implies that more advanced resource allocation along with sophisticated antenna techniques should be adopted at the stations, desirably without posing high computational burdens on the user terminals and 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/capacity performance of the terrestrial networks, need to be revisited. This makes the performance evaluation of HAPS systems very challenging in comparison to its counterparts, which calls for new investigations. Finally, we expect that this tool plays 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 can be addressed via the meta distribution analysis of Poisson networks.

VI. RADIO RESOURCE MANAGEMENT, INTERFERENCE MANAGEMENT AND WAVEFORM DESIGN IN HAPS

As in all wireless communication networks, radio resource management, interference management, as well as the waveform design are crucial aspects for ensuring the performance of a HAPS system. From the service provider’s point of view, the network’s performance can be measured the spectral efficiency, i.e. throughput (in bits/sec) per unit Hertz. In addition, energy efficiency is one of the system design objectives that needs to be addressed, since the platform’s energy source is mostly either rechargeable batteries and/or solar panels, i.e. no direct connection to the mains power grid. From the user’s point of view, the performance of the HAPS network is assessed based on certain Quality of Service (QoS) measures that largely depend on the type of application. For example, in URLLC the end-to-end latency and packet error rate is crucial. Limited onboard HAPS resources are allocated plays an important role on interference management, along with the platform placement in a constellation, determining the SINR. This directly has an impact on the outage outage probability, BER transmission delay, throughput and/or spectral efficiency at the system level. In this section, we highlight some of the key radio resources 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 addition to the system level design considerations, link level design aspects is paramount in specifying how the communication will take place at the bit and wave level. The link level (or PHY) design is concerned with a single wireless link between a transmitter and a receiver, playing a vital role in determining the achievable transmission reliability (measured in BER or outage probability) as well as the achievable spectral efficiency. In a multiuser system, the waveform technology adopted would play a main factor in determining/developing the multiple access scheme. Unfortunately, both the waveform technology and related multiple access have not yet received much attention in the HAPS systems’ literature. In this section, we also discuss some of the possible 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 devices with different QoS requirements, the SINR level seen at the receiver becomes extremely important. This necessitates power control/allocation, which we thoroughly discuss in this subsection. A summary of the power control schemes reported in the HAPS literature is provided in Table IV.
A significant portion of the proposed power control schemes in the [HAPS] systems literature dates back to early 2000’s, where at that time, the air interface technology that was adopted in most wireless communications research works was the wide-band CDMA (WCDMA) [153–157]. 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 [158] or power domain NOMA [159]. While CDMA is primarily built upon 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 the UEs with the lower channel gains. The interference is removed at the UEs 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. On the other hand, as we expect that HAPS will play a major role in providing a worldwide network connectivity, the CDMA technology may emerge as a plausible solution for a particular region.

The works [153–157] study power control for the purpose of call admission control (CAC) where users are admitted into the system such that the Grade of Service (GoS), measured by a weighted sum of the dropping and blocking probabilities, is maximized while satisfying the [SINR] and power constraints. In [154], the unique characteristic of [HAPS] systems, that all base stations are collocated on the same platform is 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. [155] extends the schemes in [154] and explores a downlink CAC scheme. It studies a [HAPS] that centrally manages the radio power at the platform level and allocates it to the cells based on their demands.

1) Mobility and Power Control: The mobility of the UEs in the [HAPS] service area has an impact on how power should be controlled such that UE admission is optimized. Only a few articles considered this mobility of UEs for the power control operation of [HAPS] systems. [156] considers an hierarchical system in which a single [HAPS] and a terrestrial cellular network are jointly deployed as illustrated in Fig. 8. The [HAPS] is used to provide a macro-cell coverage and the terrestrial cellular towers are used for micro-cell coverage at a different frequency band, therefore cross-layer interference is avoided.

In [160], a speed and direction-based CAC scheme is developed for a standalone [HAPS] system with the objective of reducing the handoff call dropping probability as much as possible, as forced termination is more undesired than new call blocking. For this scheme, the system continuously tracks SIR received from the UE’s serving base station’s pilot channel and the next strongest SIR received from the UE’s neighboring base stations’ pilot signals. It is used to derive the speed and direction of the mobile UE relative to the rest of the UEs. In [161], high altitude on-the-move flying wireless access points powered by renewable energy is studied. The access point allocates its available energy to maximize the total utility (reward) provided to a sequentially observed set of users demanding service. The problem is addressed through deterministic

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7 It is worth noting that the term ‘call’ here is equivalent to user admission request and is not limited to voice calls.
and stochastic formulations followed by a model where the statistics of the underlying processes are not known and learned through rule-based and neural network approaches.

2) Power Control for Multicast Services: Only a few papers in the literature consider power control for multicasting. In [157], an integrated system of HAPS and terrestrial cellular is 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 of unicast traffic. In [162], a technique is 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. It was observed that for MBMS services, the choice of the most efficient transport channel is a key aspect.

3) Joint Radio and Computational Power Management: HAPS systems are expected to be used also for aerial edge computing. Thus the power and time consumed in onboard computation should be managed jointly with radio resources. In [163], the authors consider the problem of minimizing energy and time consumption for task computation and transmission in a mobile edge computing (MEC)-enabled balloon network. Since the data size of each users computational task varies over time, the HAPS-BSs must dynamically adjust the user association, service sequence, and task partition scheme to meet the users needs. This problem is formulated as an optimization problem whose multi-objective is to minimize the energy and time consumption for task computing and transmission by adjusting the user association, service sequence, and task allocation scheme. A support vector machine (SVM)-based federated learning (FL) algorithm determines the user association proactively and solves the problem.

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 through a dynamic allocation scheme. Basically, the spectrum gets divided into sub-channels, where one or more of these can be allocated to more than one UE. The channel attenuation—due to path-loss, shadowing, and fast fading—seen by each user is different as discussed in Section V due to the following reasons: Moreover, in integrated HAPS systems, i.e., 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 becomes 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. Table IV provides a summery.
One of the specific challenges of HAPS is its horizontal back and forth movement due to the crosswinds in the stratosphere \[164\]. This perturbation results in the problem that ground users near cell edges 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 platform’s horizontal movement is proposed. In \[165\], an AI-based wireless channel allocation algorithm based on the reinforcement learning algorithm for a 5G HAPS massive MIMO communication system is proposed. A Q-learning algorithm combined with a back-propagation neural network enables the system to learn independently according to the environment and intelligently according to the channel, load, and blocking.

In \[166\], a heterogeneous network with two HAPS nodes, illustrated in Fig. 9, is considered where UEs with a limited HAPS choice (labeled Group L) and users with a full HAPS choice (labeled Group F) coexist in the same system. Group F users have access to both HAPS1 and HAPS2 by smart or steerable antennas, while Group L users only have 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 due to relatively poorer HAPS availability, a restriction is imposed to Group F to deliberately restrict its channels availability. Using this compensation effect, a balanced blocking probability is achieved. The study in \[167\] proposes a measure for deciding the minimum distance in mobile user access systems. Based on this measure, the channel allocation problem is dealt with based on 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.

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

1) Joint Power, Sub-channel and Time-Slot Allocation: In \[168\], the authors study radio resource allocation for multicasting in OFDMA-based HAPS systems. An optimization problem is formulated and solved to provide the best allocation of HAPS resources such as radio power, sub-channels, and time slots. The problem also finds the best possible frequency reuse across the cells that constitute the service area of the HAPS. In \[169\], multicast group users to receive a session’s transmission from more than one antenna simultaneously at different frequencies is considered. This also allows the user to receive multicast sessions transmitted in neighboring cells too, not just those transmitted in the cell which the user resides in. The users now could be with different priority levels from the system’s perspective and the objective is to maximize the admission of highest priority users to the system rather than maximizing the number of admitted users in \[168\]. The solution method is based on branch and cut framework, see also \[170\] for more details, in which linear outer approximation using McCormick underestimators is applied for the relaxation of the mixed binary quadratically constrained problem.

2) Spectrum Management and Sharing: The authors in \[171\] highlight the impact of the minimum operational elevation angle, antenna radiation patterns and the potential of dynamic channel assignment. Moreover, \[172\] investigate the potential of cognitive radio-based dynamic spectrum management in integrated HAPS terrestrial networks. The impact of the antenna beamwidths and adaptive modulation are considered. The authors in \[173\] investigates the co-existence of HAPS and fixed terrestrial networks in the 5850-7075 MHz band. In \[174\], the authors consider a spectrum sharing problem in a LEO-HAPS...
TABLE IV: A summary of channel, power allocation and spectrum sharing schemes reported in the literature about the HAPS systems.

| Design Aspect/Parameters                       | Objective                                                                 | Technique                                                                 | Network Type     | Reference |
|-----------------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|------------------|-----------|
| Power, subchannels, user-selection,           | Maximize the number of multicast admissions                               | Lagrangian relaxation                                                    | Stand-alone HAPS | [168]     |
| time scheduling                               |                                                                           |                                                                           |                  |           |
| Associate users with multiple antennas +     | Admit the highest priority users to the system                            | McCormick outer approximation relaxations, branch and cut techniques,    | Standalone HAPS  | [169]     |
| design parameters in [168]                    |                                                                           | cloud branching etc.                                                     |                  |           |
| Complexity reduction for the problem in      | Admit the highest priority users to the system                            | Different types of cuts, acceleration heuristics, and variable domain    | Standalone HAPS  | [170]     |
| [168] by reformulations                      |                                                                           | propagation techniques                                                   |                  |           |
| Channel allocation                            | System capacity maximization                                              | Q-learning reinforcement learning and combines back-propagation neural   | System of Multiple HAPS | [165] |
|                                              |                                                                           | network                                                                   |                  |           |
| Energy allocation                             | Serving users with highest priority                                       | Genetic algorithm, rule-based learning neural networks and dynamic       | Single access point HAPS | [161] |
| Energy allocation                             |                                                                           | programming                                                               |                  |           |
| Channel allocation                            | Fair call blocking probability                                            | Continuous time Markov chain and restriction functions                    | Two HAPS system  | [166] |
| Radio and Computing Powers                    | Minimizing energy and time consumption                                    | SVM-based FL algorithm                                                    | Multiple HAPS-Bs | [163] |
| Uplink Transmit Powers                        | Maximize system’s uplink throughput while achieving local fairness       | SRA-LF algorithm                                                          | Standalone HAPS  | [153] |
| Downlink Transmit Powers                      | CAC: Maximize System’s Capacity                                           | Centralized Transmit Power Based, Platform Power Limited (CTP-PF)        | Standalone HAPS  | [155] |
| Downlink Transmit Powers                      | Minimize dropping and blocking probabilities                              | Overflow and speed sensitive strategies + Centralized Resource            | Two layer Terrestrial HAPS | [156] |
|                                              |                                                                          | Reservation- Random Model and Traffic Selection                            |                  |           |
| Spectrum sharing with conventional fixed      | Interference Mitigation                                                   | Dynamic Channel Allocation (DCA) + increasing minimum elevation angle    | Two layer Terrestrial HAPS | [160] |
| service system                                |                                                                          |                                                                           |                  |           |
| Power driven switching between                | Maximize GoS, i.e. Minimize call blocking and dropping probabilities     | Number of Multicast Users Policy + Distribution of Multicast Users Policy | Two layer Terrestrial HAPS | [157] |
| terrestrial and HAPS FACHs and DCHs for       |                                                                          |                                                                           |                  |           |
| MBMS                                         |                                                                          |                                                                           |                  |           |
| Power driven switching between HAPS FACHs     | Maximize power utilization: system capacity at a given power level        | Defines power switching thresholds from dedicated to Common Channels      | Standalone HAPS  | [162] |
| and DCHs for MPMS                            |                                                                          |                                                                           |                  |           |
| Spectrum sharing for downlink co-existence    | Improve coexistence performance by reducing outage probability at the    | Interference-to-noise-based scheme + CINR-based scheme                    | Two layer Terrestrial HAPS | [172] |
| of HAPS and terrestrial fixed broadband       | user                                                                      |                                                                           |                  |           |
| systems                                       |                                                                          |                                                                           |                  |           |
| Spectrum sharing of 5850-7075 MHz band with   | Prevention of harmful interference                                       | Co-channel, zero-guard-band and adjacent channel criteria and methods.   | Terrestrial HAPS system | [173] |
| Fixed Services and effect of channel          |                                                                          | Separation distance and frequency separation used                        |                  |           |
| bandwidth                                     |                                                                          |                                                                           |                  |           |
| Spectrum and power allocation                 | Maximize sum rate of HAPS-ground downlinks in imperfect channel          | Decomposition, then Simplex Algorithm and convex optimization            | LEO-HAPS cognitive system | [174] |

A VISION AND FRAMEWORK FOR THE HAPS NETWORKS

cognitive system in the non-ideal spectrum sensing situation, in which a cognitive network model from multi-beam LEO satellite and HAPS access scenario is introduced. Aiming at dynamic spectrum and power allocation strategy for the non-ideal spectrum sensing case, a correction coefficient is accordingly included. An overview of the potential of cognitive radio techniques are also summarized in [71].

C. HAPS Placement and Constellation Optimization

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

In [175], the authors explore a layered architecture with aerial flying platforms (AFPs) of various types, flying in low/medium/high layers. In that architecture, the position of LAPS nodes in the low layer is defined centrally and the AFP has the ability to re-organise the layer to achieve its target, which can be maximizing the number of UEs served, maximizing the achievable
rate, and/or fairness among UEs. The optimum placement problem is formulated as a linear binary program. The reported results show that an aerial self-organizing network outperforms a fixed placement. Cost-efficient HAPS constellation design with QoS and user demand guarantee is investigated in [67]. The QoS metrics are established by considering the SINR, BER, throughputs, 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, is devised. It is concluded that by applying the proposed constellation design methodology, the optimal cost-efficient broadband network can be realized. In [175], power allocation with fronthauling and backhauling associations in order to improve the global connectivity using satellite, airborne, and terrestrial networks integration is investigated jointly with determining the HAPS locations. It is shown that the satellite stations and HAPS nodes can play significant role in global connectivity when the terrestrial BSs are overloaded or to support users with high throughput located outside the terrestrial BSs coverage areas (e.g., suburban and remote areas).

D. Antenna and Interference Management

Communication from a HAPS to UEs requires highly directive antennas to overcome the high attenuation caused by path loss and to prevent interference between UEs receiving transmission from different antennas. Moreover, 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 becomes crucial, given that HAPS are expected to have hundreds of antennas onboard. Electronically steerable multi-beam antennas have been 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 in an intra-HAPS system to mitigate interference from the serving and adjacent beams on HAPS users.

1) Adaptive Cell Shaping: Ideally an antenna beam illuminates its corresponding cell with equal power across the cell and with zero power outside the cell, acting like a spatial filter. However for practical antennas the spot beams fail to have this ideal desirable pattern, specifically at millimeter-wave frequencies, where array beam synthesis techniques are challenging. Among the practically suitable antennas for this purpose are likely to be aperture types known for the 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 level can be minimized with corrugated horn designs [177], however the roll-off rate is mainly affected by the main-lobe width and directivity. The trade-off is as follows, 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. On the other hand, if the directivity chosen is too low, excessive power will fall outside the cell leading to high level of inter-cell interference.

The design of HAPS antenna beams has been investigated in [178]. The authors propose a general formulation in [143] for optimum directivity in order to maximize the received power at the cell edge. The impact of the beam patterns and the frequency reuse technique are further investigated for circular and elliptical beam patterns. Elliptic beams have been demonstrated to be superior in terms of optimized power at cell edges, which is crucial where RF link budgets are marginal. [179] investigates 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 is 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 shows that a uniform power pattern with a lower in-cell ripple of less than 0.25 dB is attainable and this reduces the needed power control over the cell stripe as well as reducing the in-cell ripples and side-lobe levels. The analysis of this technique shows that a uniform power pattern with a lower in-cell ripple of less than 0.25 dB is attainable and this reduces the needed power control for the roll of conventional beam shapes towards the cell boundaries. As a result of the improved power pattern, the signal’s CIR has been improved both in value and distribution within the serving ring cells.

Beam steering is considered in [180]. The authors present two steering scenarios and a four actuator scenario. It is concluded that from a complexity perspective, the four actuator solution is 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 the considered solution is in the number of handoffs required. In [181], the authors investigate the impact of frequency re-use patterns and different antenna models in a multi-beam/multi-cell HAPS-based communication system. In their paper, they compare different models for the antenna side-lobe region and quantifies the CIR for a 3 channel re-use plan for networks of 121 and 313 cells that are compared. The reported results show the ITU recommended pattern for the 47/48 GHz band can leads to poor results compared to a adapted pattern based on fitting the measured data for an elliptic beam lens antenna. [182] considers irregular cell shapes in [182], aiming to obtain the target cell characteristics by grouping pixel spots, aiming to limit the co-channel interference. The proposed cell design technique optimizes the cell shape according to the user distribution and behavior in the covered area and consequently is expected to reduce the frequent handoff and signaling traffic of location updating from moving users. The reported simulation results show that a cell with any irregular shape can be formed with as low as 40 dB side-lobe level using Gaussian concentric ring array. [183] introduces a cell-pointing approach making used of the HAPS induced beams to provide contiguous coverage delivery, by providing overlaps between the beams using a planar antenna array over an extended coverage area.
2) Exploiting Coordinated 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 [184], the authors investigate how JT-CoMP can be extended to a HAPS system architecture by exploiting a phased array antenna, which generates multiple beams that form cells, each of which can map on to pooled virtual base-station equipment, thereby replacing multiple terrestrial cell sites. CoMP is 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 are considered. The use of multiple HAPS have also been considered to improve coverage and capacity by using the nodes as a virtual MIMO system through the use of platform diversity. In [185] the performance of using multiple HAPS nodes by using antennas is investigated. The impact on the distance between HAPS nodes on the CINR distribution is considered. The use of multiple HAPS in forms of HAPS constellations is considered in [68], where the authors consider the millimeter-wave band transmission. A significant performance improvement is shown through numerical analysis. The authors in [186] determine the diversity order improvement that can be obtained by using multiple HAPS nodes. The erodic capacity improvement is 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 so that it can be used for:

1) Improving 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) Beamforming 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,
3) Spatial multiplexing to boost the system’s throughput by feeding each antenna element with a different data stream.

It is shown in [187] that a distributed sub-array architecture yields a significantly better diversity performance than the co-located antenna architectures. This implies that the diversity gain in HAPS systems is achievable by the HAPS mega-constellations, which adds another merit to its envisioned advantages. The problem of system interference caused by beamforming technology in a HAPS communication system using massive MIMO is explored in [188]. An intelligent beamforming algorithm based on game theory is proposed, and a mathematical model of the beamforming game algorithm is constructed. A robust beamforming scheme is proposed in [69] for an integrated satellite and high altitude platform network, where a multi-beam satellite system shares the millimeter wave spectrum with a HAPS system. A multi-objective optimization problem is 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 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 [189]. Numerically it is shown that significant performance gains can be achieved through the use of massive MIMO.

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 for wireless communications where they serve as the foundation. For example, WCDMA is the technology 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 allowing a dynamic sub-carrier spacings that are 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 [190]. This being said, it is quite valid to bring up the issue of the 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, there is not active research reported in the literature so far. However, the wireless waveform solutions that are under investigation for the 6G wireless communications technologies can be exploited for use in HAPS access link’s radio interface or for inter-platform/back-haul links.

Despite OFDM’s being a prevailing technology so far, a number of drawbacks, discussed also in [191], should be tackled:

1) High peak-to-average-power ratio due to the summation of uncorrelated inputs in the inverse-fast-Fourier transform. This is 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 seems 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—become smaller or are discarded overall. Technologies based on filter bank multi-carrier modulation (FBMC) could be adopted.
3) Issues related to the applicability of OFDM to 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 [192], 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 mm-Wave band.
Below, we overview alternative approaches being actively investigated in the PHY research community, that could be suitable waveform candidates for the HAPS. Mostly, these could be considered as gradual departures from OFDM/OFDMA-based design rather than eruptive changes.

1) Filter Bank MultiCarrier (FBMC) Scheme: FBMC is one of the most well known multi-carrier modulation formats in wireless communications literature. It offers a great advantage of shaping each subcarrier and enables a flexible utilization of the spectrum while satisfying different system requirements, e.g., low latency, multiple access, etc. It also offers advantages of 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 are also investigated to cope with various effects of the channel and provide a reliable system design based on different scenarios, such as the isotropic weighted Hermite pulse [193]. On the other hand, FBMC has come with cons as well 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 subcarrier bandwidth [194].

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 [195]. In this technique, rather than making the pulse duration smaller, we increase their degree of overlap in time by transmitting them at a rate higher than the Nyquists signalling rate. In this way, we avoid occupying larger bandwidth, but introduce intentional, yet controllable, 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 sampling instants, which Nyquist signalling avoids under perfect synchronization, as Figure 10 demonstrates. The gain is around 25% increase in data rate within the same bandwidth and the same energy, but at the expense of a more complex receiver. It was shown that the same phenomenon occurred with root raised cosine pulses [197], 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 $\tau = 0.703$, a 42% increase in the bit density.

The cost that we have to pay for the spectral and energy efficiency of FTN, is the high complexity of the optimal detection. This makes low complexity detection a critical issue under investigation for 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 [198]. Under these modulation schemes, one is able to guarantee up to 11% increase in throughput without paying any additional bandwidth, energy or BER penalties. In [199], 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. Reported simulation results showed that up to 25% increase in the data rate can 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 dB with 0.7 dB penalty in the SNR.

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) and extended to both time and frequency domains as illustrated in Figure 10. A squeezing factor $\varsigma$ allows a the subcarriers to be backed close than in the orthogonal case, hence improving the the spectrum utilization at the expense of a controlled inter-carrier-interference. The existence of Mazo in both time and frequency domains has been proved in [200] and [201]. Multicarrier FTN transceiver design, optimization, and performance have been addressed in [202]–[205]. With the proposed transceiver architectures, FTN signaling can be combined with the current communication technologies, such as OFDM [206]. Besides the high spectral efficiency offered, FTN signaling 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 the HAPS access links, i.e. between the HAPS and the 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 would then become an open area of research for HAPS depending upon 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 [190]. 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 also can achieve the capacity region of the downlink broadcast channel. NOMA can be also applied to the uplink, which 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].

By taking advantage of the spatial dimensions that multi-antenna HAPS systems offer, spatial division multiple access (SDMA) is facilitated allowing multiple users can communicate at the same time and frequency but in different spaces/beams.
A VISION AND FRAMEWORK FOR THE HAPS NETWORKS

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 multiuser MIMO whereby a cluster of users, rather than just one user, share one beam. Hence, it can serve a larger number of users and paves the way for massive connectivity.

F. Challenges and Recommendations

Despite the fact that research on the RRM and interference management for HAPS systems dates back to early 2000s, there are still quite many open issues and challenges. Developing techniques that yield acceptable performance at a low computational overhead is generally one of the main trade-offs that designers and researchers try to strike a balance between. This is one of the main reasons why we expect that AI and ML techniques for HAPS systems’ design and optimization will prosper. AI/ML schemes such as reinforcement learning for channel allocation in a 5G massive MIMO HAPS started 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 require computational overhead. In [209], an AI deep neural network (DNN) was proposed to fill this gap, where the input and output of an RRA algorithm is treated as an unknown non-linear mapping, to approximate the algorithm. It was demonstrated that DNNs can achieve orders of magnitude speedup in computational time compared to state-of-the-art power allocation algorithms based on optimization. The role of AI/ML for system deign 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 expected to be quite complex, possibly making model based optimization techniques not a suitable option. There is very little work done on RRM and interference management on integrated HAPS/LEO systems.

Among the holes in the literature, is that heterogeneous types of services (data traffic) are not considered. 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 development of multi-objective schemes that can be executed in real-time, hence and 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 UMTS. So far, technology has been interacting primarily with only two senses, which are sight and sound. Interestingly, in [210], Ericsson Research envisions enabling internet of all five senses at around 2025, requiring the establishment of new QoS metrics that reflect the user’s convenience or satisfaction for these new types of traffic. This will need to be considered in HAPS systems’ 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 the related novel HAPS RRM schemes.

HAPS systems are expected to be powered by re-chargeable batteries and solar panels, this aspect was not taken intro consideration in the vast majority of HAPS RRM, interference management and placement research papers. We believe that optimum power utilization need to take this into account, and hence suitable model-based or AI-based schemes should be

Fig. 10: FTN and SEFD M (multicarrier 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.
developed for power control in the HAPS access downlink, inter-platform links and backhaul links, possibly jointly. In addition to the aforementioned, as deployments of mega-constellations of HAPS systems are anticipated, it is important to consider relaying between platforms over multihops to facilitate communication between two devices associated to 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.

On the other hand, the cell association has not yet been studied in HAPS systems. Under what condition a terrestrial user/UAV should connect to a HAPS or a terrestrial BS? Or should we advocate for double connectivity in HAPS systems? As the HAPS nodes are expected to be a major part of 6G communication systems, we require more investigations of resource allocation and interference management in the HAPS systems in accordance to new use-cases, such as mission-critical robotics, self-driving cars, high-capacity AR/VR applications, and high-stake cargo drones. Last but not least, related to joined control-communication system design umbrella new performance metrics such as age of information (AoI) and information freshness is emerging, which is entirely overlooked in the current literature of HAPS system. Finally, given that about 80% of the traffic demand is media-driven, more investigations regarding video streaming, caching, and QoE in HAPS system need to be included.

VII. Handoff Management in HAPS Networks

Terrestrial cellular networks support UE’s mobility among BSs. When a UE moves out of one BS coverage to the next, the communication will be handed over from the first BS to the next without discernible disruption to the UE’s call or data session, which is carried out via handoff procedure. A properly designed handoff algorithm is essential to reduce the overhead of the handoff process, while maintaining the desired QoS of the UE in progress session 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 UE while assuming that BSs are stationary.

The stratospheric atmosphere is relatively stable but sometimes affected by short-term airflow. Therefore, the HAPS needs to maintain a quasi-stationary state. On the other hand, the mechanical design of some HAPS systems requires the movement of the HAPS in a certain pattern and area, as earlier discussed in Section IV. According to the recommendations of the ITU, the HAPS position is maintained in a cylinder with the radius of 400 m and height of plus or minus 700 m [7]. This implies that the movement of a HAPS can be classified into four categories: horizontal, vertical, rotation and swing.

The HAPS position disturbances cause changes in the size/position of cells coverage on Earth (i.e., HAPS footprint). This can lead to the instability of users’ 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’s size and position are changing. In addition, the HAPS disturbance 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, handoff 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 user mobility initiated handoff, which results from user motion toward another neighboring cell; the other is triggered only by the platform position instability [211].

Intra-HAPS handoff, i.e., moving to new cells served by the same HAPS can exploit the centralized architecture and control. The important issue is to control to which cell to switch and at what time. In [212], the handoff algorithm is 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 has been suggested, where the HAPS transmits/receives from different spot beams (i.e., cells) in different portions of the frame. A multiple-frequency variant has also been 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 reuse plan.

A radial based function neural network is used in [213] 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 [214] 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 is more susceptible to the rotational movement.

In [211], 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 have been deduced. The simulation results show that the handoff performance of the cells is severely affected by the swing state, especially for outer tier cells, and the effect can be reduced by increase of cell coverage radius to a certain extent.

*Handover is used within Europe, whereas handoff is the term used in North America.*
The traditional handoff algorithms that depend on fixed thresholds usually deal effectively with the handoff issue caused by UEs’ mobility. However, given the HAPS quasi-stationary state, 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 the frequent handoff between cells or the ping pong effect. 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 predicts the received signal strength. In a similar approach, the author in [216] propose a prediction-based handoff decision algorithm with an adaptive threshold. The algorithm predicts the values of received signal strength using time series analysis model and dynamically adjust 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 is mainly proposed based on the attenuation characteristics of the antenna directional gain. However, as the HAPS is far from the ground, 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, the adaptive handoff scheme that uses cooperative transmission was proposed [217]. The HAPS which has higher channel gain, was selected for cooperative transmission to improve the system reliability, and the handoff decision result was decided by the direction of terminal motion and channel gain to reduce the service interruption time caused by frequent handoffs.

Under the influence of a stratospheric wind, HAPS will inevitably move within a certain range. In [218], the author discussed both HAPS vertical and swing movement and the movement effect on path loss. In addition, based on the derived ground coverage model, the author analyzed the coverage and calculated the handoff probability of the two movement modes. The simulations results show 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 the broadband wireless connectivity [71], seems promising for improving the handoff performance. In this scenario LEO satellites can provide the backhaul link of a HAPS. Under this assumption, the authors in [219] propose a dynamic handoff strategy to optimize the handoff moment and resource allocation. The authors considered the factors of user priority, minimum rate requirement, delay requirement, channel gain and the traffic of beams.

In [220], a directional traffic-aware intra-HAPS handoff scheme is proposed, where users in overlapping areas of overloaded cells may be forced to handoff earlier than their optimal handoff boundaries, in order to partially balance the traffic among the adjacent cells. A cooperative directional inter-cell handoff scheme for HAPS systems is studied in [221], where the handoff target cell and the two cells adjacent to it work cooperatively to exploit the traffic fluctuation to improve handoff performance. Basically, users in the overlap area of the overloaded handoff target cell will be 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.

[222] investigates the inter-HAPS handoff process when the 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’s beamwidth, the platforms’ height, and the position cylinder. Results showed that for users employing fixed antennas pointing towards the center of the position cylinder, 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 can employ a narrower beam width. Users employing steerable antennas can use a narrower beamwidth. However, connections will be dropped for any beam width less than 5, unless users employ two antennas, or the new platform follows a close flight path to the current serving platform (305 m vertical separation).

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

Depending on RSSI values as the decision criterion will make the HAPS with large RSSI overloaded, causing data congestion in these nodes. On the contrary, HAPS systems with small RSSI might remain idle, which leads to insufficient utilization of network resources. Meanwhile, due to the limited energy of high altitude platform, the energy of HAPS with large RSSI exhausts quickly and the energy of HAPS with small RSSI remains excessive, resulting in the imbalance of energy consumption among HAPS systems. To address this issue, the author of [224] proposes a load balancing handoff algorithm based on RSSI and...
energy-awareness in HAPS networks. Table V provides a comparison between available handoff schemes in terms of their proposed solution, scope (inter/intra-HAPS), the considered parameters in making handoff decision, and the type of movement that causes handoff.

A. Recommendations and Challenges

The existing studies on HAPS systems handoff management are considering simple scenarios that might occur in the early deployment stage. However, such scenarios might not be realistic for future HAPS systems that will create a network of HAPS wrapped around Earth (i.e., mega constellations of HAPS). The future network of HAPS systems is expected to be in multi-layer with several hundred of 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 systems 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 smart phones holders, but it will be necessary to provide coverage for network entities moving in 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. In fact, apart from conventional ways in which beamforming system are designed, for example, 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 to beamforming regarding the requirements of handoff 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 delay. 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 mmWaves communication frequencies, which can be absorbed by the atmosphere and affected by weather conditions (e.g., rain, fog, and any moisture in the air). Thus, mmWave signals might have very 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, double connectivity solution allowing connectivity via microwave for handoff/beam management and payload communication via mmWave link should be investigated for HAPS systems.

VIII. HAPS NETWORK MANAGEMENT AND COMPUTATIONAL ROLE

To operate a two to four ground-based crew members are required to oversee various aspects of mission planning, flight control, sensor operation and data assessment. Operational complexity and cost will likely scale up in scenarios where multiple 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 need to involve 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.

The implementation of semi autonomous high altitude platform swarm with self-organising capabilities was investigated to maximize communications area coverage. The author compared the application of Reinforcement Learning and Swarm Intelligence-based methods for resolving the problem of coordinating multiple HAPS to maximize communications area coverage. It was observed that the SI algorithm showed faster convergence and 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 exploration strategy. RL-based techniques demonstrate 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; while RL algorithms will achieve better coverage peaks but at the risk of occasional dips.

investigates the coordination among a swarm of four autonomous HAPS in a volcanic ash cloud emergency scenario for aerial communications coverage, where terrestrial or satellite infrastructure is degraded or non existent. Due to the extreme
Proposed solution | Inter/Intra | Considered parameters | Movement type |
---|---|---|---|
[212] | Low latency MAC layer handoff | Intra-HAPS | RSSI, CIR, traffic load, and user position | Pitch movement |
[213] | A radial-based function neural network is used 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 |
[215] | 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 |
[216] | 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 |
[217] | Proposed an adaptive handoff scheme that uses cooperative transmission to improve system reliability | Inter-HAPS | The direction of terminal motion and channel gain | Mobile terminal movement |
[219] | Proposed a dynamic handoff strategy to optimize the handoff moment and resource allocation | Inter-HAPS | User priority, minimum rate requirement, delay requirement, channel gain, and the traffic of beams | Mobile terminal movement |
[222] | Studied the effect of antennas type and beamwidth on handoff during HAPS replacement | Inter-HAPS | Antenna’s beamwidth, the platforms’ height, and user’s antenna direction | Replacement movement |
[223] | Proposed to use adaptive modulation and coding in the physical layer to ensure that the ongoing calls are not disrupted during the platform movement | Intra-HAPS | The geographical information, rate transition areas and overlap areas | Replacement movement |
[224] | Proposed that the neighboring cells cooperatively force users in the overlap 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 | Users position, HAPS movement direction, and HAPS capacity load | Rotational movement |
[224] | 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 |
[220] | Forcing UEs in overlapping areas to handoff to balance load among cells | Intra-HAPS | HAPS traffic load and UE position | Horizontal displacement and rotation |

| Reference | Proposed solution | Inter/Intra | Considered parameters | Movement type |
|---|---|---|---|---|
[212] | Low latency MAC layer handoff | Intra-HAPS | RSSI, CIR, traffic load, and user position | Pitch movement |
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[224] | 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 |
[220] | Forcing UEs in overlapping areas to handoff to balance load among cells | Intra-HAPS | HAPS traffic load and UE position | Horizontal displacement and rotation |

TABLE V: A comparison of handoff management techniques in HAPS networks.

environment nature, a HAPS platform may fail and require replacement. The swarm of HAPS are autonomously coordinated and will use its self-organisational 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 the HAPS to make local decisions with limited or no global knowledge and still achieve network-wide objectives cooperatively. As a swarm, self-organisation and coordination is very crucial to provide communications coverage in volcanic cloud emergency conditions, the author developed a swarm intelligence algorithm for this problem scenario. The participating HAPS in the swarm exchange essential data as they explore the environment. The developed algorithm has four phases: scouting mode, exploitation mode, decision making loop, and exploration mode. The simulation results showed that through self-organization and swarm coordination, within 1 hour the spare HAPS provided the needed boost in the global coverage performance.

Towards network control and management softwarization, promising solutions have been introduced in the literature. For example, SDN decouples the data and control planes from each other in order to reduce network control complexity. NFV decouples network functions from the physical devices and has the potential to facilitate the deployment of new services with increased agility and faster time-to-value. Network slicing enables connectivity for devices with diverse requirements via multiple logical networks built on the top of the shared physical infrastructure. To enable the availability of the networks-as-a-service according to user demands, network slicing employs NFV, SDN, cloud computing, and edge computing. Enabling network slicing requires successful interaction among these players which is a challenging task. Softwarization combined with intelligent algorithms is expected to move network control and management to be 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 face the challenges of dynamic nature of network traffic, multiple service providers, and mobility, dynamic network slicing needs to be considered. Several learning theory schemes such as deep learning and reinforcement learning can be used for the prediction of user traffic. After accurate prediction, effective resource allocation schemes can be used for enabling dynamic network slicing.

In HAPS systems are used as the control plane of software defined aerial network. The controllers are deployed in HAPS systems to take advantage of their wide coverage and relative stability, which can 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 component due to their high mobility. In a relevant work, a Software Defined Airborne Backbone Network Architecture (SD-ABN) architecture is proposed to maintain coverage and provide reach-back to military units, and ensure network flexibility, openness,
interoperability, and evolvability. To meet the challenges of traffic management in HAPS networks, the network management functions are going to be distributed and automated to best meet the 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 type of 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 the complexity. 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 [230]. Although this management model was not originally proposed for HAPS systems, it is worths a more deep investigation.

Ultra-reliable low latency applications emerging from the confluence of 5G, SDN/NFV and AI/ML (e.g., autonomous driving, emergency response systems, remote medical, etc.) necessitate that control and processing functions are distributed toward the point of data collection and consumption. In this regard, HAPS systems can provide the services of a huge network edge located on top of aerial networks and underneath satellite networks. HAPS systems are expected to play the role of a floating aerial data centre. This is due to their wide coverage above the low altitude aerial network components (e.g., UAVs), which makes them ideal to collect large amount of data about aerial networks status and use such data in the network management aspects. However, the critical issue is managing and scheduling the computational and communication resources in HAPS systems to serve the the speedy and dynamic environment of UAVs and satellites.

Recently, several studies proposed to use multi-UAVs to form a Mobile Edge Computing (MEC) cluster. In [233], a multi-UAV aided MEC system is proposed, where ground IoT nodes can offload the computational tasks that cannot be processed using their limited capabilities. The author introduced a load balancing algorithm to balance computational loads among UAVs and used deep reinforcement learning for computational tasks scheduling. In a MEC network formed by multiple UAVs, the sum power minimization problem was considered in [234]. The author minimized the power through jointly optimizing user association, power control, computation capacity allocation and UAV location planning. In [235], the author introduced two architectures where a UAV can work as either a node in a distributed MEC cluster or a relay node that assists in the computational offloading from IoT devices to a far terrestrial edge computing node. A game-theoretic and reinforcement learning framework is introduced in [236] for computational offloading in a MEC network operated by multiple service providers. The network is formed by MEC servers installed at stationary BSs and UAVs which are quasi-stationary. Although these studies propose to use multiple UAVs to form a MEC cluster and process the offloaded computational tasks, the same ideas can be implemented in HAPS networks. In fact, a network of HAPSs can provide a more stable MEC cluster with stronger computational capabilities in comparison to UAV-based MEC. This is because of the quasi-stationary status of HAPS systems, their ability to carry more advanced computational servers, and their longer flight duration. HAPS system MECs can not only serve terrestrial UEs but also aerial UEs and satellites. However, to achieve this vision, reliable communications among HAPS systems, intelligent tasks scheduling, and advanced resource allocation techniques are necessary.

A. Recommendations and Challenges

A HAPS can play a role in the aerial network management and network slicing. This is due to its higher position which enables a HAPS 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 air without congesting the communication links towards the terrestrial data centres. However, this approach requires strong and reliable collaboration between HAPS systems to fully utilize the distributed computational resources in HAPS systems. 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.

Due to its low altitude when compared to satellites, HAPSs can support reliable and low latency computational offloading for some delay sensitive applications that are running in areas that do not have terrestrial coverage. However, this issue still needs further investigation and a feasibility analysis through simulations. 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 very essential to achieve optimized resource management, load balancing, and UE mobility management.

As future networks are expected to be an integration of satellite, aerial, and terrestrial networks, HAPS systems need to be involved in the overall integrated network orchestration. With the use of dynamic beamforming and steering capabilities, it is very important to have continuous coordination between HAPS systems to prevent coverage areas overlapping and interference.

In many types of terrestrial networks (e.g., wireless sensor networks), network clustering is implemented to enhance energy consumption efficiency, routing performance, and distributed computational resources management. As HAPS networks will
consist of clusters of HAPS systems that form a sphere around the earth, clustering techniques should be explored to optimize HAPS computation resource management, routing among HAPS systems, and efficient use of energy. HAPS network slicing should consider dynamic spectrum slicing to avoid underutilization or overutilization.

As HAPS systems can form a MEC cluster for processing offloaded data from aerial or satellites, intelligent tasks 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.

IX. THE ROLE OF AI IN HAPS SYSTEMS

Active research is currently being carried out to enable ML in highly resource-scarce MCUs and Field-Programmable Gate Arrays [237]. In 2017, Microchip manufactured the first MCU that has a high-performance 2D GPU, the PIC32MZ DA family [238]. Microchip manufactured the PIC32MZ MCU with a high-performance GPU that can handle parallel calculations. Implementing low-power tiny MCUs with embedded GPU capabilities, is a step forward toward implementing advanced ML algorithms in HAPS systems. In 2019, ARM has 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 to their MCUs [239]. STM Microelectronics has offered in the market sensors with incorporated machine learning cores that have an embedded classifier [240]. As companies race to provide high digital signal processing and ML capabilities to their MCUs, in the coming years, we will witness a tight combination between electronic devices and novel ML algorithms designed to be executed using limited resources.

Advances in ML produced a number of emerging powerful ML algorithms. For example, deep neural network which consists of two stages, i.e., offline training and online execution. In the on-line execution stage, the deep neural network makes adequate decisions based on the input environment state, even when the environment state has not been experienced in the offline training phase [241]. Another powerful ML approach is reinforcement learning, which resemble the brain learning process of trial and error. The decision-making entity of the reinforcement learning framework interacts with the environment continuously through iterative observation of the environment state. Next, the reinforcement learning framework 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 some recent publications, the reinforcement learning is widely adopted to address decision-making problems in communications environment, such as access radio technology handoffs [242], spectrum sharing [243], and user scheduling [244]. However, in a large state-action space, reinforcement learning performance drops since many state-action pairs may not be explored. Recently, the 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 [245]. Although merging deep neural networks and reinforcement learning shows promising capabilities in adapting to complicated and dynamic communications environments with extensive state-action spaces, the scalability of such solutions need to be considered. For resource-limited equipment, some simplified novel ML algorithms (e.g., compressed deep neural networks learning) have been proposed. FastGRNN and FastRNN are algorithms to implement Recurrent Neural Network (RNN) s, and gated RNN into tiny devices [246].

In future networks, AI will play an essential role in HAPS systems orchestration and management. On the other hand, HAPS systems will be a great enabler for AI and computing in aerial and space networks as than can carry an aerial data centre and perform edge computing functionality. In effect:

- HAPS systems are physically located in high position between satellite network and the terrestrial network. Due to their high position and wide coverage, massive volume of data can be collected through HAPS systems. 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 user behaviour and enable the network to proactively adapt to changes in the communications environment. Basically, feeding such data to machine-learning algorithms will allow the continuous learning of the environment, the automated adaptation to changes, and the achievement of optimal performance. HAPS systems can be more proactive instead of reactive by predicting and adapting to the variable communications environment.

- HAPS systems are potential candidate for collaborative computing and distributed ML. In big data centers, complex ML jobs are divided into small tasks that are executed in parallel on multiple virtual or physical machines. This makes the idea of collaborative computing feasible by distributing the tasks of ML among a group of collaborating HAPS systems. 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 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 HAPS systems will consist of several HAPS 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 high need to introduce automation in HAPS systems through exploiting the power of AI algorithms to learn about variable environments and adapting to changes in the best way with minimum human interventions. For example, when an unexpected change happens in the density distribution of UE, an intelligent HAPS system can learn and detect such change through observing UE movement. Afterward, through analysing the collected data, the HAPS system can make an intelligent decision to redirect or form a beam towards the newly emerging UE groups. In this 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 adopted the AI approach in addressing some of the 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 [67]. The author considered the constraints of QoS (e.g., signal to noise ratio, bit error rate, bits per second coverage) and user demands metrics. In a different scenario, neural networks are used to handle the frequent handoff issue that users at cell edge might experience due to HAPS movement. The author in [213] 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 are the inputs of the neural networks.

In a wireless communication network operated by HAPS systems, the key factor for the Carrier-to-Interference Ratio (CIR) improvement is the antenna Side-Lobe Level (SLL) reduction. In [248], the author optimizes the beamforming parameters using a comprehensive learning particle swarm optimizer to reduce the SLL. The antenna array configuration is chosen as concentric circular antenna array and the HAPS cellular system is consisting 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 UAV, the author in [249] studies providing mobile edge computing services through HAPS systems, where UAVs can 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 optimize their pricing by considering the behavior of their competitors to maximize their revenue. Each UAV selects 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 and minimize UAVs cost. Computational tasks 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 the task planning among multiple HAPS systems. As the combinatorial search problem grows with the presence of multiple agents, the author in [250] proposes a genetic algorithm-based method that guide the decomposition of the tasks down the hierarchy in order to find quality plans within limited time.

To prove the feasibility of executing AI algorithms using a HAPS resources, [251] describes 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 compute tasks directly on HAPS before data passes through the link. Thereby, data transmission towards terrestrial networks can be significantly reduced while simultaneously improving the speed at which a system can analyze and react to a dynamic environment. This experiment raises the motivation of incorporating intelligence with HAPS systems and utilizing HAPS systems for edge computing in space.

X. Open Issues

The challenges and open issues related to HAPS system can be categorized into two groups one mainly covers the next-generation (up to 10 years) challenges and the other the next-next-generation (10-20 years) challenges. The former requires 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 the HAPS system can be categorized as the next-generation challenge as the required theory and practice is well investigated for the terrestrial networks. However, the use of it for the HAPS systems is an unknown territory which requires extra 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.

On the other hand, the latter needs disruptive shifts about how we design and configure wireless networks. For instance, what will be the HAPS mega-constellation and how it will interact with the satellite mega-constellation can be categorized in this group. As it is not yet known the actual potentials/pitfalls of the satellite mega-constellation, as participating companies tend to keep the technological issues as secret currently, the design of the HAPS mega-constellation becomes dramatically more challenging and highly speculative in the initial phases. Likewise, the HAPS mega-constellation’s interaction with the satellite mega-constellation becomes challenging: Should the former be more of a complementary technology compensating for the latter’s shortcomings? Or, should they be considered as competing technologies targeting probably separate use-cases? Having this categorization in mind, in this section we enumerate many important challenges and open issues. We do out best to provide suitable solutions and if possible road maps to tackle the challenges.
A. Next 10 Years: On the Use of HAPS in the Next-Generation Networks

1) PHY and Related Cross Layer Design: As highlighted 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 is required. The analysis will assess the suitability of candidate waveforms as well as pulse shaping filters for mm-Wave band taking into account the channel propagation of HAPS. After developing or finding out the most suitable waveform, a rigorous design for the corresponding detectors that take into account the computational complexity as well as the performance could be established. This should take into account two important goals: 1) the integration with massive MIMO and 2) lack of model-based detection due to lack of complete/reliable knowledge of the underlying channel model. Using advanced AI/ML techniques offer 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 this 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 and meaningful features from the observed data, which is very 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 in FSO communications, that are used for inter-platform link communications, LEO/HAPS communications and back-haul link communications. These non-linearities make the use of high order modulation quite challenging and hence, there should be ways to increase the spectral efficiency as the most commonly used modulation scheme is the On-Off keying, or binary amplitude shift keying (BASK). One possibility could be to resort single carrier FTN for that purpose, and design the suitable detectors for this a BASK-based FTN signaling while taking into account the FSO pulse shaping filters that are commonly used.

When new waveform technologies are introduced, cross layer design challenges appear. Considering the FTN and SEFDM technologies, channel allocation as well as acceleration and/or squeezing parameters can be considered jointly in 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 the HAPS users depending on the channel fading each user experiences, hence taking advantage of multiuser diversity. This can be done such that the overall spectral efficiency of the system is maximized. This becomes more complex in SEFDM multicarrier system, where we can have a time and frequency squeezing parameters to be jointly optimized with sub-channel for each HAPS user, where each sub-channel could even have a different number of sub-carriers depending on the frequency-squeezing parameter.

2) Massive MIMO Communications: Massive MIMO communication is among the disruptive technologies for making the 1000x capacity growth of 5G feasible. Nevertheless, the promise of the technology, as it is investigated/developed under the characteristics of the ground terrestrial networks, could be over-fitting or under-fitting for the HAPS applications. This is simply because the 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, as one of the main performance-degrading phenomenon in massive MIMO communications, can become even more devastating in the HAPS systems. The pilots can be contaminated from stations hundreds of kilometers away, leading to very small frequency reuse factor. Furthermore, the possibility of the antenna array to properly disjoint signals in the spacial domain can become less effective, perhaps regardless of the number of antennas and the processing power of the stations, as the received signals from large areas become highly correlated. One solution to tackle this issue might be via intelligent clustering of the users in the spacial domain in order to minimize effect of the correlated received signals. However, given the sheer size of the coverage area and massive number of users in each coverage zone, one should pay more attention to not deplete the large portion of the computation and energy resources mainly for such issue. 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.

3) Beam Tracking: In 5G and beyond, mmWave communication in 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. On the other hand, it is more efficient to spatially disjoint multiple users with different radios within the coverage area, and thus serve them simultaneously. This leads to much higher capacity per coverage area, which can be useful for serving swarm of UAVs via HAPS system and also serving massive number of devices on the ground. Nevertheless, accurate beam steering/alignment and diligent beam tracking should be taken care of. For example, UAVs are able to maneuver very fast or could be blocked by large objects/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 the machine learning in order to predict the mobility of the device seems to be crucial. On the other hand, the use of computer vision in order to extract valuable information regarding the existence of blockages could improve the overall performance of the mmWave communication.

4) HAPS for Computational Offloading of Aerial and Satellite Networks: A HAPS has a large surface area which enables the installation of many solar panels. In addition, it can be equipped with powerful computing equipment. With the advent
of its quasi-stationary position and large footprint (no frequent handoff 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 interruption during offloading due to mobility of satellites or UAVs, and free the terrestrial networks links for terrestrial-aerial or terrestrial-satellite communications.

5) Networks Management of HAPS Systems: HAPS-enabled wireless systems are relatively fast to deploy and opens to reconfiguration, which is important for ever-changing demand. Nevertheless, the need for the 3D mobility/deployment with accordance with the onboard energy limitation and permissible payload weight brings unprecedented challenges into the network managements. This implies the essential role that the optimal deployment of HAPS has for coverage extension as well as capacity improvement under the definite desire for prolonged energy and computation flows. Furthermore, usually the deployment of HAPS systems could be short-term—compared with the terrestrial networks that are long-term—where the functionalities/responsibilities are subject to change/modification/augmentation. For example, a station might be initially deployed for the sheer 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/responsibilities. AI will play a critical role in designing and optimizing HAPS architectures, protocols, and operations accordingly.

On the other hand, in future networks, multiple HAPS system are going to be deployed and instead of working in isolation, they will form a network. Coordinating the HAPS network through ground stations is not going to be efficient due to response delays and a ground station with its limited footprint cannot have communication coverage to all the HAPS network. Therefore, it is envisioned that HAPS networks are going to be self-organised with either centralised or distributed control and management system. In the centralised approach, a HAPS is elected to be the manager while the others are followers. In the distributed approach, the available HAPS in a network 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, is going to be super valuable.

6) Privacy and Security Concerns: The security of HAPS systems can be challenging due to its unique characteristic and also the integrated ground/HAPS satellite communication paradigm. On the one hand, if, by any mean, a HAPS node is compromised, the integrity of any communication passing through the station is questionable. This can lead to catastrophic events given the enormous coverage footprint of HAPS that include the dissimilar number of devices/users with different level of security/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 such techniques come short effectively combating the passive eavesdropping. Large scale radar surveillance and computer vision techniques can be helpful, which, on the other hand, increases 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 immediate benefits for lowering the interference and higher 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. However, due to imperfect beam alignment and also leaky antenna patterns due to side lobes, the communication links may stay vulnerable. This implies the necessity of stronger techniques relying on information theoretic security and also covert communications for HAPS communications.

On the other hand, given the diverse roles of a station, e.g., a communication platform, a data center platform, and a computation platform, the magnitude of the security and privacy becomes even greater. This implies that simply protecting the communication link may not be sufficient anymore. Furthermore, analogous to the driver-less cars’ vulnerability issues to hijacking and the possible physical dangers that such autonomous vehicles can bring to pedestrians and other vehicles, a hijacked HAPS can cause various dangerous situations. For example, a direct victim can be the safety of airplanes traveling in a region or the collisions with other HAPS systems. We expect the inclusion of dedicated HAPS with the only responsibility of security monitoring/preservation. Such a station 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/pass over the responsibilities/responsibilities) the compromised stations if deemed necessary.

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

1) Integration with Satellite Network: Vertical integration of HAPS system with the satellite networks, known also as multilevel satellite HAPS architecture, seems attractive and is deemed imperative to attain super connectivity. Such a reliance on the satellite communications is actually well-coming observing 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 considers launching up to 42,000 satellites for occupying different orbital shells. Meanwhile, SpaceX is targeting scattering 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 aims at launching 900 small satellites into orbit in order to provide broadband internet connections to remote areas. Nevertheless, despite many indispensable advantages, such an integration poses vulnerability issues for HAPS system. In effect, whatever causes the partial collapse of the satellite communications, for example due to chained collisions between satellites, could cascade to the degradation of HAPS network’s performance. Accordingly, such pressing challenges convolute the design of a robust HAPS network. For instance, how we should account for the consequences of satellite collisions or worse the bankruptcy of the company providing the satellite mega-constellation. For instance, should the HAPS network compensates for the imposed coverage holes? If yes, what regulations should be thought of and what extra functionalities must be provisioned for HAPS? Equally important, given that different sectors are focused in each domain and the tendencies that some companies exercise to keep the developing technologies secret, how transparent the satellite network should be to HAPS or vice versa?

2) HAPS Mega-Constellation: The emergence of satellite mega-constellations to provide broadband Internet access across the globe could postulate a cosmic shift in the future of telecommunication systems. For the satellite mega-constellation to be worthy it must provide Internet access faster than the already available fiber-optics. Provided that the satellites are equipped with laser-link communication capabilities this goal is indeed reachable [261]. However, this technology is already in infancy stage and the currently launched satellites are not equipped with it. Accordingly, the standalone satellite mega-constellation could not guarantee a fast, long-distance Internet access as long as fast and cost-effective technology for inter-satellite communications is missing. Current practices advocate reducing the altitude of the satellites along with installing millions of ground-based relay nodes. It is speculated that with these adjustments the fast communications across satellites is still possible without the existence of the laser-link communication [10]. However, such a solution is costly and may not be world-wide attainable. A better solution might be the use of a mega-constellation, which via multi-hop FSO communications 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 should be taken to reach from one satellite to the other one is drastically 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.

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

3) Efficient Network Re-configurations: HAPS network is highly dynamic and heterogeneous. For example, some stations may disappear intermittently for a while to recharge their energy resources. If the network is primarily configured for providing the maximum capacity, the new configuration may call for switching to preserving the coverage in order to compensate for the coverage hole. Given the vast geographic size that each station is capable of serving, such a consequential alternation in functionality is 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 of the stations are quasi-stationary while the others must be keep moving. In effect, the continuous coordination among diverse array of stations and simultaneously with the ground stations or the satellite mega-constellation to preserve the service becomes very daunting. The coordinated actions across heterogeneous stations call for a colossal amount of data and extensive optimization routines. From the computational perspective, one should practice caution in order to circumvent the exhaustion of the stations’ energy and computation resources. It appears that the common approach of coordination, resource allocation, and networking relying upon the selection of actions based on a given structure of the network and the specified task is impractical.

One way to smoothly cope with this issue is via meta learning. Instead of constantly solving the optimization problems (for routing, coverage, backhauling, resource allocation, computation offloading, and the like) to derive the action parameters based on the new emerging configuration of the network, the network should 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 via the meta learning an emerging task/environment can be quickly recognized and dealt with.

4) Support for Edge Intelligence: HAPS network is provisioned to be a crucial part of the next generation of communication networks. Under 6G, we desire to achieve 1) very high data rate, up to 1 Tbps, in order to facilitate the broad uses of virtual systems for communications, relaying, routing, data-center and servers, computation platforms, and security/cyber-policing, and due to excessive interference from neighboring satellites, HAPS can boost, combine, and transmit the satellite signals via joint transmission techniques. We should further point out that although we mention HAPS mega-constellation as a solution for enhancing the coverage/access performance of the satellite mega-constellation, we also advocate the standalone HAPS mega-constellation as a robust solution for the fast internet access across the states and countries. In effect, a large cluster of HAPS systems for communications, relaying, routing, data-center and servers, computation platforms, and security/cyber-policing, can provide the backbone infrastructure of a mobile Internet.

[10] In machine learning the meta-learning is also known as learning to learn [262]. 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. On the other hand, 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.
targeting the realization of the proposed visionary framework by addressing the listed open issues. Synergies that will enable the dense use of HAPS in terms of mega-constellations. The current literature is expected to evolve, deployments. Several prospective use-cases for the near future and beyond are depicted above, along with the technological potential to address the ubiquitous connectivity target of the 6G networks, the role of a HAPS seems indispensable in future telecommunication systems. Nevertheless, new applications such as mission-critic robotics requires a join communication-control resource allocation, which is largely unprecedented in the design of communication networks. By the latter the communication platform can be exploited to facilitate large-scale distributed machine learning tasks. Therefore, the common control resource allocation, which is largely unprecedented in the design of communication networks. In effect, the concept of edge computing is already under investigation and is part of 5G wireless communications networking. On the other hand, a pleasant marriage between edge computing and machine learning is under development, known as edge ML, is expected to be a crucial segment of 6G as an enabling computation-communication paradigm for the omnipresent machine intelligence. The goal of edge ML is to circumvent the reliance on dedicated servers for training ML models and solving ML tasks. In effect, the evolution of telecommunication infrastructures towards 6G will call for dispersing the intelligence from the central clouds to the entirely distributed AI utilizing edge computing resources. Edge devices such as AI-enabled HAPS, 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 privacy perspective too. For this large-scale, distributed edge ML, network can provide a universal intelligence blanket. In effect, for a given application, e.g., self-driving cars, flying taxi, or cargo delivery, a station can collect hundreds of thousands of sub-models from the AI-enabled devices in synchronous or asynchronous manner. The station then can apply training routine by including its own collected data/intelligence. Usually, the trained model can be used as a “critic” adjusting the sub-models’ training routines, orchestrating the intelligence across the devices.

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 resource for two disjoint purposes: communication for data communication and communication for intelligence. The former is well understood and is the main focus of the design of the telecommunication systems. Nevertheless, new applications such as mission-critic robotics requires a join communication-control resource allocation, which is largely unprecedented in the design of communication networks. By the latter the communication platform can be exploited to facilitate large-scale distributed machine learning tasks. Therefore, the common approaches in resource allocation, scheduling, and computational offloading should be geared for the required environment that such algorithms pose. On the other hand, the resource sharing between these two paradigms of communications is inevitable. Such a resource sharing in large-scale HAPS network should be discussed.

XI. Conclusions

This article aims to highlight the unexplored potential of the High Altitude Platform Station (HAPS) systems. Harboring the potential to address the ubiquitous connectivity target of the 6G networks, the role of a HAPS seems indispensable in future deployments. Several prospective use-cases for the near future and beyond are depicted above, along with the technological synergies that will enable the dense use of HAPS in terms of mega-constellations. The current literature is expected to evolve, targeting the realization of the proposed visionary framework by addressing the listed open issues.

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