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

Gunes Kurt, *Senior Member, IEEE,* Mohammad G. Khoshkholgh, *Member, IEEE,* Safwan Alfattani, *Student Member, IEEE,* Ahmed Ibrahim, *Member, IEEE,* Tasneem S. J. Darwish, *Member, IEEE,* Md Sahabul Alam, *Member, IEEE,* Halim Yanikomeroglu, *Fellow, IEEE,* and Abbas Yongacoglu, *Life Member, IEEE*

arXiv:2007.15088v2 [cs.IT] 24 Dec 2020

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 contributions 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).

Gunes Kurt, Mohammad G. Khoshkholgh, Ahmed Ibrahim, Tasneem S. J. Darwish, Md Sahabul Alam, and H. Yanikomeroglu are with the Department of Systems and Computer Engineering, Carleton University, Ottawa, Canada; e-mails: guneskurt@sce.carleton.ca, m.g.khoshkholgh@gmail.com, ahmedibrahim@sce.carleton.ca, tasneemdarwish@sce.carleton.ca, sahabulalam@sce.carleton.ca, halim@sce.carleton.ca. Gunes Kurt is also with the Department of Electronics and Communications Engineering, Istanbul Technical University, Istanbul, Turkey.

Safwan Alfattani and Abbas Yongacoglu are with the School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON, Canada, emails: yongac@uottawa.ca, salfa043@uottawa.ca.

Manuscript received July 23, 2020.

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][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 VHetNets.

A HAPS is a network node that operates in the stratosphere at an altitude around 20 km. Due to the unique properties of the stratosphere, a HAPS can stay at quasi-stationary position, providing significant benefits to the ubiquitous connectivity goal. Onset of HAPS related research activities can be traced back to 1990s with numerous research perspectives [4]. In a nutshell, the prior art, including the deployments such as the Google Loon project, has targeted rural areas and disaster relief applications. However, the use of HAPS as a new promising platform can catalyze advanced mobile wireless communication services with ultra-wide coverage and high capacity.

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

On the other hand, with the disruptive shifts that are happening in wireless communication design, for instance, data-driven design, as well as emerging use-cases, such as on-demand distributed machine learning platforms and data centers, HAPS becomes even a more appealing technology due to the potential benefits. Accordingly, the stand-alone balloon over a remote area for providing Internet access or remote sensing demonstrates the potentials in a rather restrictive manner. The era of portable data-centers, intelligent signal boosters, distributed, flying macro base stations, and machine-learning platforms, making intelligent decisions for massive number of cargo drones and flying cabs, are gradually transpiring. In effect, we envision the future with a massive constellation of HAPSs, which is termed as *HAPS mega-constellation*[2] (analogous to satellite mega-constellation), enabling high capacity network access, computation offloading, and data analytics tools, to millions of users/devices not only in suburban areas but also in dense urban areas, as shown in Fig. 1. As depicted in this figure, our proposed framework can be summarized as follows:

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

Based on these observations, we envision that the use of HAPS systems can be a remedy to the architectural problems that will be encountered as the use of aerial components will increase in the wireless networks. The utilization of HAPS systems as new wireless access platforms for the future wireless communication system embodies a high potential, and the associated promises are detailed in this paper.

A. Survey and Overview Articles on HAPS

Several overview articles have been published on the use of HAPS 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].

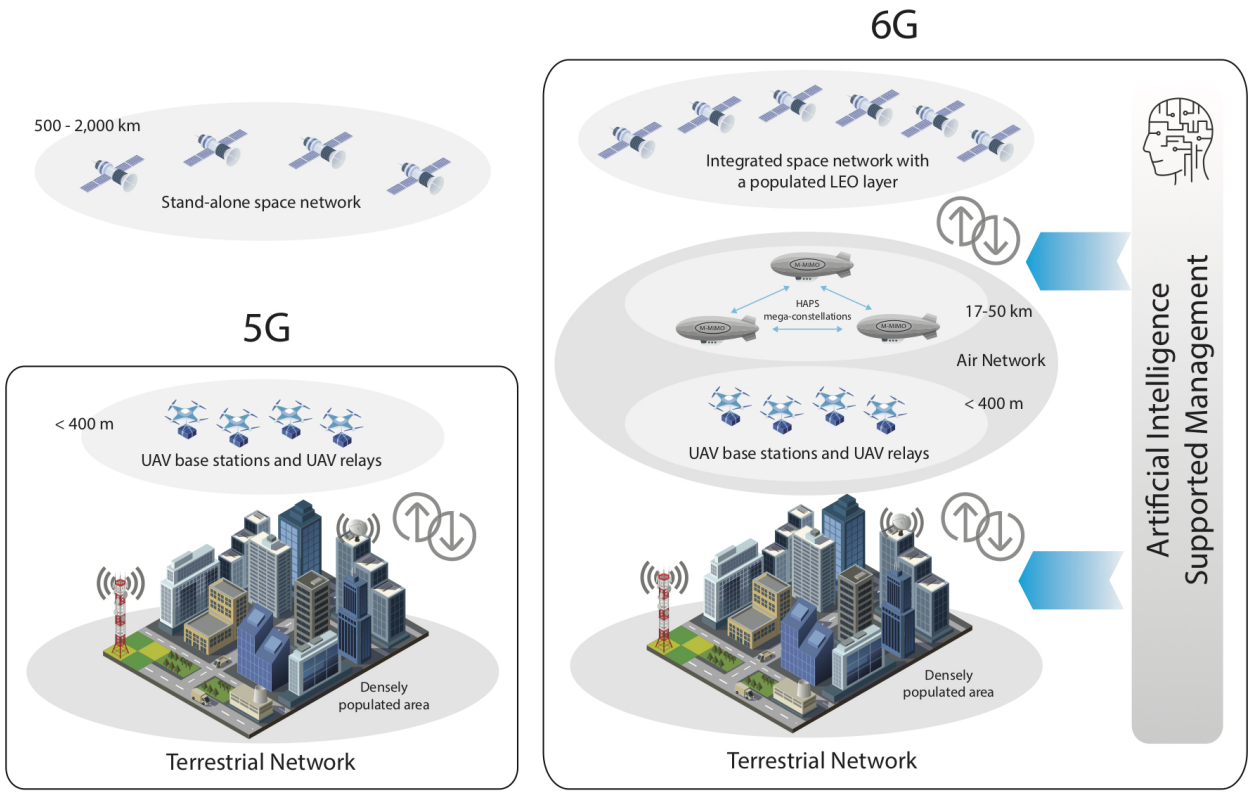


Fig. 1: An overview the transition from 5G to 6G. A fully integrated Vertical Heterogeneous Network (VHetNet) is envisioned in 6G.

as of 2005. A summary of the existing and potential applications as well as the past field trials along with open technical issues are enumerated in [12]. The commercial and research project deployments of HAPS systems as of 2009 is provided in [13]. The literature on the use of optical communications in HAPS platforms is presented in [14]. The authors of [15] provide an overview of the HAPS related activities at past World Radiocommunication Conference (WRC) of the International Telecommunications Union (ITU), until 2010. [16], published in 2011, presents an overview of possible architectures for using HAPS to provide global connectivity. Furthermore, [17] provides a survey of the technological changes as of 2016. The books [18], [19] demonstrate the use of HAPS nodes either as a stand-alone or as a complementary part of the terrestrial networks. [20] 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 [21]. The work in [22] 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 [23]. The book [24] 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[3]. Among them [27] 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 [25]. Therein, the authors also discuss several exemplary problems in UAV

[3]It 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.

trajectory design with accordance to communication requirements and the limited energy battery of the UAV for IoT applications. Also, [26] comprehensively overviews the use of mmWave communications in low-altitude platforms. [28] surveys the literature of UAV 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 [29]. 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 [29] 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, [29] 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 [29] 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. For an overview of the surveys and books on HAPS systems refer to Table I.

B. Contributions and Outline

The aim of this article is to 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 [22], 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 BSs, 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.

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

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

- Depicting the unique role of Artificial Intelligence (AI) including machine learning in the design, topology management, handoff and resource allocation in HAPS communication systems.
- Elaborating on various challenges that the wide-spread implementation of 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 HAPS are described in the following section. The aviation and the spectrum regulations that aim to harmonize the worldwide usage of HAPS are over-viewed in Section III. In Section IV, we describe the main components of the 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 HAPS nodes are presented in Section V. Section VI provides a comprehensive perspective on the radio resource management and interference

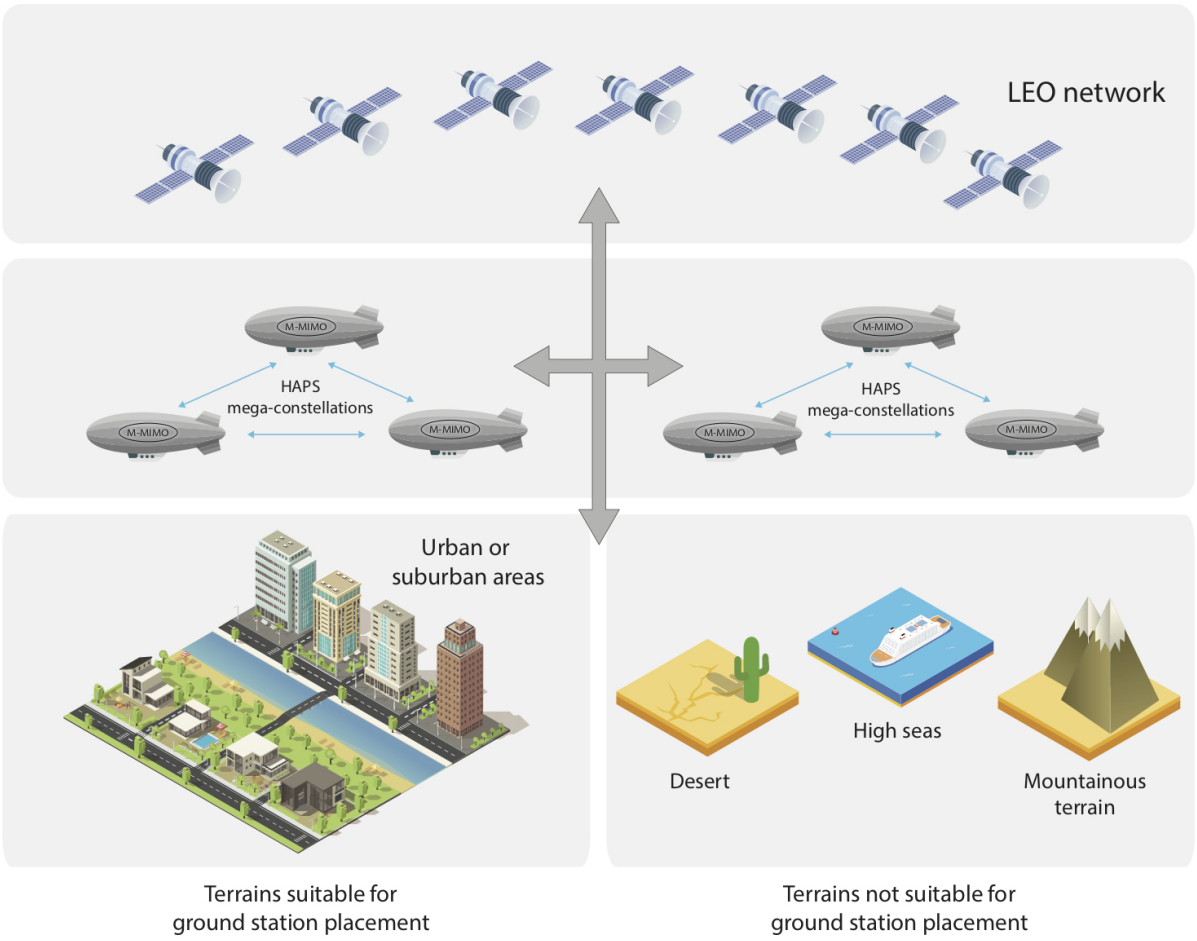


Fig. 2: The next-20-year vision of HAPS mega-constellations, bridging the space network with the terrestrial network over densely populated urban centers, providing connectivity and computation even in terrains that are not suitable for ground network architectures.

management of HAPS nodes from the overall network performance perspective. The handoff management of HAPS nodes, in accordance with the existing terrestrial networks is detailed in Section VII. In Section VIII, 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

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 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 [29], 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 III summarizes the features of envisioned HAPS systems over

TABLE II: 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 UEs as the terminals which have limited transmit power levels, without the need for specialized ground stations.
Almost Stationary positions	○ LEO satellites can cross over continents within several minutes due to their high speeds. As a result, some of the 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. ○ Due to the stationary of the links, the effect of significant Doppler shift can be avoided.
Smaller footprint with a large surface volume	○ A HAPS system has a smaller footprint compared to LEO that provisions a higher area throughput. Due to its large volume, a HAPS is suitable for MIMO and massive-MIMO deployments. Compounded by multi-antenna arrays, HAPS systems can generate highly directional 3D beams with narrow beamwidths that improve the SINR for all users. ○ The larger volume of HAPS systems can be equipped with huge solar panels and energy storage systems. Due to advancements in solar panel efficiency and energy-storage, HAPS systems can have a long endurance with the required energy consumption.
Reduced round-trip delay	○ Due to its lower altitude, HAPS system 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 III: 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 Guaranteeing low latency for mission-critical applications
Functions	Providing connectivity for the ground users	In addition to connectivity, supporting computation, control, and caching Connecting the UAV and satellite mega-constellation nodes
Target use-cases	Broadband coverage, internet access, natural disaster recovery, and environment monitoring	Internet of Things (IoT) applications, intelligent transportation systems, high-stake cargo drones, high-capacity Augmented Reality (AR)/Virtual Reality (VR) applications, temporary unpredictable events, computation offloading, and defeating coverage holes
Coexistence	As an alternative to terrestrial network	As a complementary element to terrestrial and satellite networks
Network type	Related to 3G/4G 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

conventional HAPS systems.

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

A macro BS is a crucial component in wireless access architectures to provide coverage and support capacity. Currently, the concept of network densification through small cell deployments has been widely acknowledged in 4G, Long-Term Evolution (LTE), and 5G standards to address the requirements of coverage and capacity in terrestrial networks [30]. However, the communication needs of metropolitan areas are 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 [31]. 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 BSs lifetime and coverage area. Also, the mobility of UAV BSs 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 [32], 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 formation of future HAPS-SMBS can assist data acquisition, computing, caching, and processing in diverse application domains, as exemplified in Fig. 3, and detailed below. These potential use cases have been recently presented in [32], however their overall general requirements to access the feasibility of deployments have not yet been discussed. In this article, we discuss highlight requirements in terms of design and technical analysis to attain these use cases with the goal of revealing their full potential.

B. Use-Cases for HAPS-SMBS

1) Support IoT services: It is expected that HAPS will play a key role to support diverse Internet of Things (IoT) applications [33]–[35]. 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).

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

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

2) Backhauling small and isolated BSs: Although, fiber optic communications remain as a superior option for backhaul connectivity, installing fiber for backhauling small cell BSs may not be an efficient solution for many environments due to its high-cost [36]. A cost-effective backhauling solution is the use of 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 [37].

Although the distance between HAPS and the ground femto-BS can be in order of 20 km to 200 km (depending on the coverage footprint of the HAPS), the communication link is almost LOS dominant (with path-loss exponential factor around 2) with moderate shadowing/fading fluctuations due to lack of scattering. Hence, a rule of thumb calculation implies that a small-BS with 3D distance 200 km from the HAPS could gather almost the same average power gain that it could receive from a macro-BS but with a distance of 1000 meters. As the vision depicted in this paper advocates the use of HAPS for metropolitan areas, industrial areas, and even mega-cities, hence the coverage footprints of HAPS could be as small as 20-50 km. Therefore, these figures become more promising for a femto-cell with 50 km distance to the HAPS, which receives average signal power similar to the case that it is served by a macro-BS at the distance of about 100 meters. Furthermore, we should note that as femto-BSs are stationary and HAPS is also quasi-stationary the establishment of such links and preserving them become less demanding, as beam tracking and beam adjustment becomes less necessary. As a result, the extra communication delay imposed due to long distance between HAPS and femto-BS can be compensated with occasional events of beam adjustment/establishment (compared to the counterpart terrestrial networks).

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

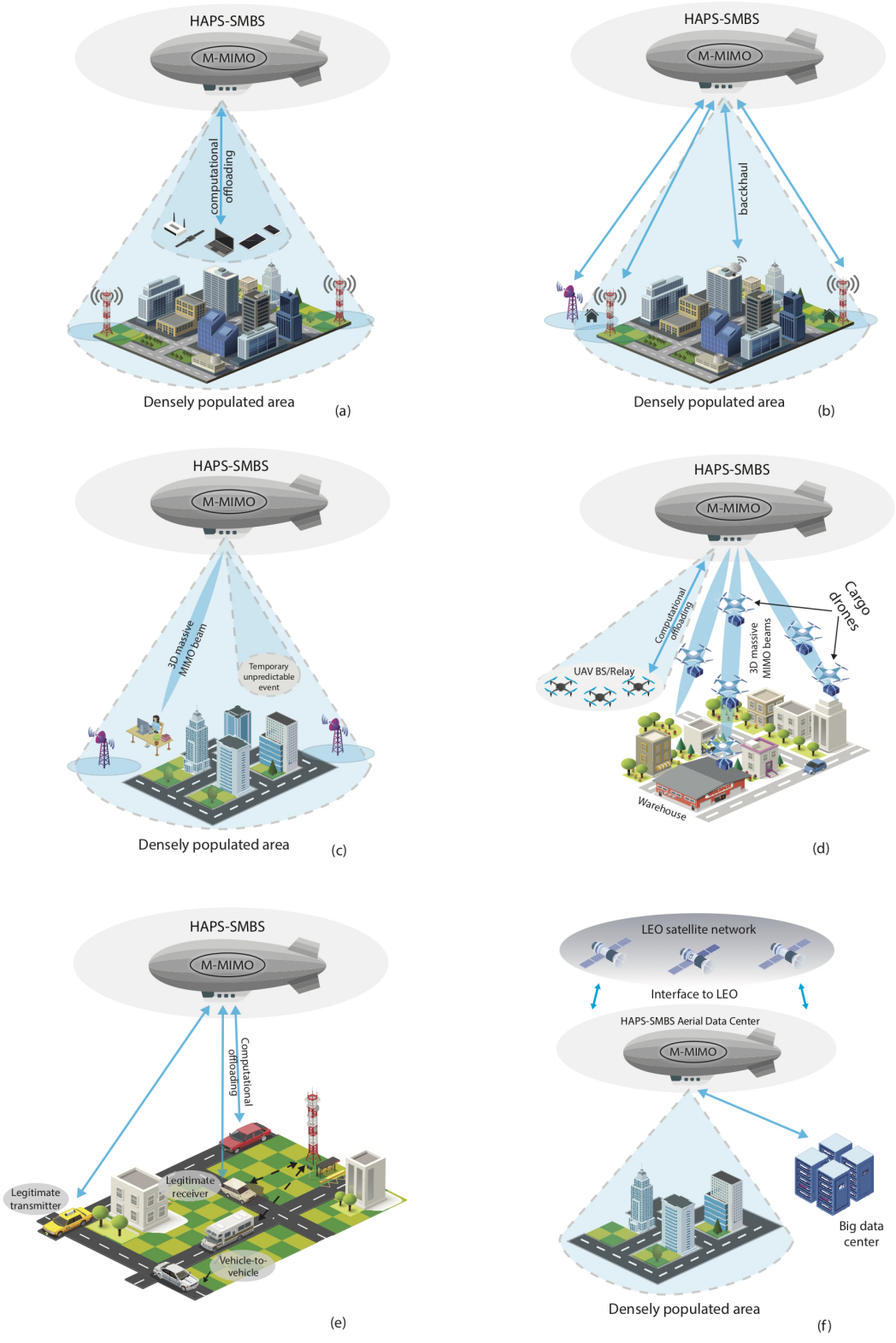


Fig. 3: (a) HAPS-SMBS to deliver IoT services. (b) HAPS-SMBS for backhauling small and isolated BSs. (c) HAPS-SMBS to cover unplanned events and defeat coverage holes. (d) HAPS-SMBS to support and manage aerial networks. (e) HAPS-SMBS to support intelligent transportation systems. (f) HAPS-SMBS as an interface to LEO satellites and aerial data center.

Furthermore, inspired by the HAPS systems and FSO advances [39], [40], outdoor small cell BSs can be backhauled through HAPS-SMBS. Note that FSO links are vulnerable to weather conditions. Under the case of cloudy, rainy, and foggy conditions, the quality of FSO links could substantially deteriorate. Hence, as FSO link is generally more robust under clear weather conditions, robust solutions in order to effectively deal with various weather conditions should be investigated. One straightforward solution might be to boost the robustness of the FSO backhaul links by considering hybrid mmWave Radio Frequency (RF)/FSO technologies [39]–[42], as depicted in Fig. 3(b). While this solution is feasible and has immediate merits, one should note that as mmWave communication may have smaller spectral efficiency compare to FSO, the backhaul data rate between the HAPS-SMBS and ground station could be affected. As a result, apart from early detection for automatic switching between technologies, sophisticated resource allocations and 3D beam-forming seem necessary.

3) Cover unplanned user events: In case of unexpected and temporary events which are difficult to predict, such as flash crowds, wireless networks might require additional support to maintain ubiquitous connectivity [43], [44]. Such events normally happen in crowded cities possibly leading to network congestion. UAV mounted BSs have recently gained great attention to boost the wireless capacity and offload traffic from a congested terrestrial BS during such events [45]. Compared to the UAV mounted aerial BSs, 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).

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

4) As an aerial data center: A HAPS-SMBS can also be regarded 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 [46], [47]. 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.

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

5) Defeat coverage holes: The HAPS-SMBS system can supplement the existing terrestrial network by defeating coverage holes in an efficient way. Coverage holes are encountered when the terrestrial UEs 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 [49]. Such blockage effects become more severe for mmWave cellular networks and may have a higher negative impact on user associations.

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

6) Support and manage aerial networks: Enhancing the computational capabilities of UAVs is becoming more important in order to maintain the critical tasks at UAVs. However, due to their SWAP constraints, UAVs have limited onboard computational resources [51], [52]. The HAPS-SMBS system will be suited with powerful processors that can enhance the computation power

of limited-resources UAVs as a complementary of terrestrial network. The larger coverage area of a single HAPS-SMBS enables to collect data from large portions of the aerial network which reduces the dependency on terrestrial stations that are already overcrowded in general for urban areas. Moreover, the effect of interference would be much higher in ground base stations compared to HAPS-SMBS for such computational offload for UAVs. In addition, using Machine Learning (ML) algorithms, HAPS-SMBS can control and manage the UAV network intelligently with minimum dependence on terrestrial-based control, as exemplified in Fig. 3(d).

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

7) Support intelligent transportation systems: The full-scale introduction of the Intelligent Transportation System (ITS)/Connected Autonomous Vehicle (CAV) paradigm will be the most powerful automobile revolution in history [53]. Recent advances in sensors, high-end computational units, and the introduction of in-car wireless communication capabilities have paved the way for CAV that enables unprecedented scenarios for road transportation [54]. Nowadays, the automaker companies are spending billions of dollars to prompt the idea that CAVs 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, CAVs should support services such as, interact with their driver, cooperation among the vehicles, decision support, traffic control and management strategies. Also, CAVs 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 [55]. 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 [56], [57]. 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 travailing on highways and using trains, flights, or ships (Fig. 3(e)).

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

HAPS-SMBS can also provide coverage for cargo drones. Usually, the cargo drones are supported through terrestrial networks [58]. 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 [59]. 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 using these drones. A single HAPS-SMBS can be used to provide coverage for such a high number of cargo drones in major cities.

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

8) 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 [60]. This is considered a serious barrier facing the integration of LEO satellites in global wireless connectivity. Fortunately, HAPS-SMBS systems can cover many satellites simultaneously due to its wide upper footprint. Therefore, the HAPS-SMBS system can serve as an interface to manage the handoff in the LEO satellite network, as shown in Fig. 3(f). Also, if the ground users are able to communicate with HAPS-SMBS interface directly, then there is no need for the users to accommodate special devices for communication with LEO satellites.

There are two types of link in this system: user to HAPS and HAPS to LEO satellite. The link between a user and a HAPS-SMBS can be realized through RF whereas FSO should be a better choice for HAPS to LEO connection. The achievable performance improvement of the aforementioned architecture can be realized through link budget analysis. An improvement in the link budget can be translated reducing the transmit power as well as the cost and size of the user terminal. However, to establish reliable and uninterrupted connections from ground/aerial users to LEO through HAPS-SMBS, HAPS-SMBS systems need to learn the mobility patterns of the LEO satellites in order to predict their handoff, then establish a connection to a coming satellite before losing the current connection. In this regard, machine learning approaches will play a significant role to learn the mobility patterns. One should also note that as new satellite constellations will be added into the current satellite communication systems, the ML solutions should be flexible enough to handle continual environmental changes. On the other

hand, one may also require to incorporate the satellite tracking system/data—gathered and processed in order to predict any possible collisions among the satellites—into the model in order to compensate for the relatively sudden change in the orbital movements of some satellites.

III. Regulatory Aspects

The regulation in 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 [2]. 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 [61]. In the recent deployments, HAPS have been frequently deployed at 17 or 18 km above the ground [17]. Countries determine the maximum altitude of controlled airspaces, and a typical value is 20 km [12]. Although at the borderline between the controlled and the uncontrolled airspace, regulations of HAPS need to be carefully designed for safe and secure operations, and currently there are limited studies addressing the HAPS safety [62]. The recently founded industry consortium HAPS Alliance[4], 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 [63]. 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 [62].

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 of the licensing and the operation control. Addressing this concern, Liu and Tronchetti [64] 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 [65], F.2472 [66] and F.2475 [67], 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 [68] 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

[4]https://hapsalliance.org/

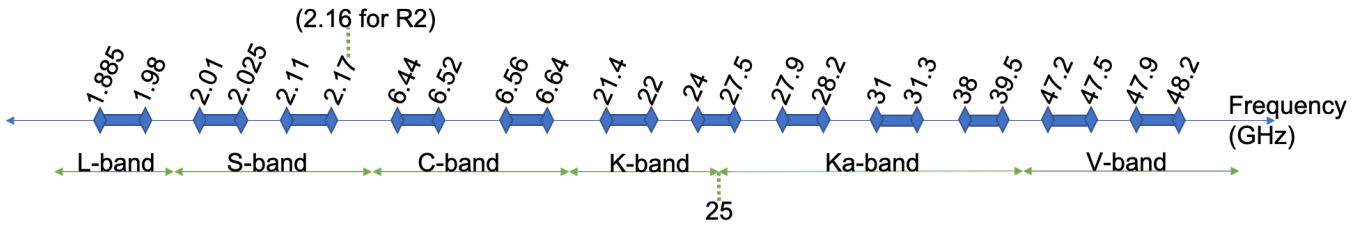


Fig. 4: An overview of the spectrum bands dedicated for HAPS.

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 [69].

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.

A. System Components

A HAPS is located in the stratosphere[5], 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 subsection. 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 [18]. 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 [70], [71], or it could be a part of a network with different layers of satellites [20], [72]. Moreover, the HAPS layer might be connected with 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) [39].

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.

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

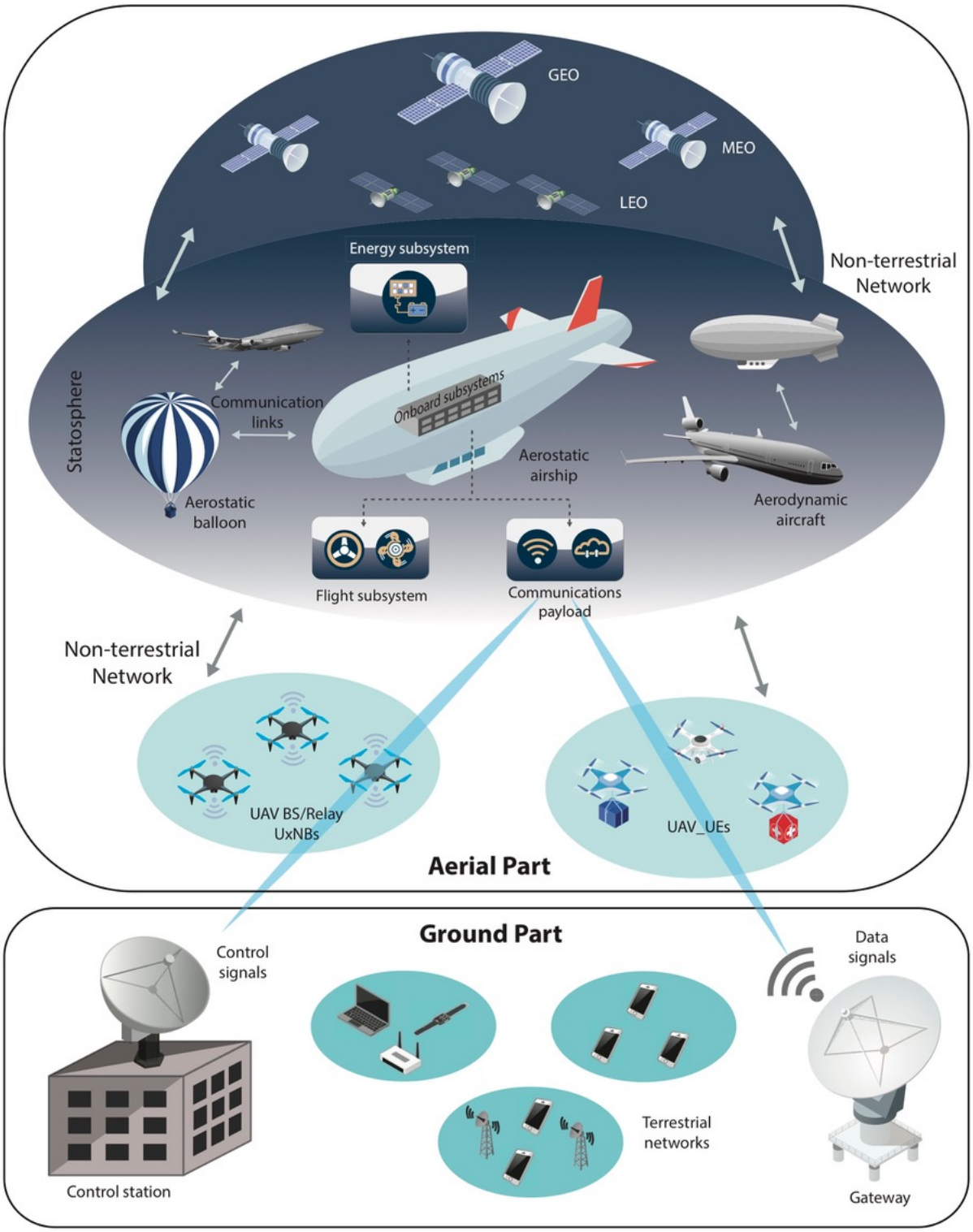


Fig. 5: A general view of the HAPS system and its main components.

- *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 amplifiers, 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 [73]. 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 [16], [29]. 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 [16].

Balloons are usually unpowered platforms and they can be tethered to easily control their flights. However, tethered balloons in the stratosphere have been abandoned due to air-safety constraints, and currently tethered HAPS are mostly restricted to a maximum altitude of 2 km. Google Loon is an example of balloons intended for communication proposes. 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 [74].

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 [16]. 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 [18]. 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], [16]. For instance, an aerodynamic HAPS might be more preferable for unplanned events or emergency situations due to their reduced deployment costs [18], flexibility in take-off/landing and mobility control, while an aerostatic HAPS seems to be more appropriate for longer-term use-cases such as supporting cargo drones, autonomous vehicles and computation offloading 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 IV enlists some of the popular past and recent projects along with their classification and key features. 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 [74].

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.

TABLE IV: Classification and description of popular HAPS examples

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

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

Project /Product	Type	Company/ Organization	Country	Project period	Description / Important features
Aquila [81]	Aerodynamic	Facebook	United Kingdom	2014-2018	○ The aim of the project was to provide broadband coverage for remote areas with 80 km radius and 90 days flight duration. ○ It was intended to fly at altitudes of 27 km during the day, dropping to 18 km at nights. ○ After several successful tests, the project was ended to work with partners like Airbus.
Stratobus [82]	Aerostatic-(Airship)	Thales Alenia Space	France	2014-Now	○ One of its goals is to provide 5G telecommunications. ○ Its length and width are about (115 m x 34 m), and can carry up to 450 kg payload for 5-year mission with annual maintenance. ○ It is positioned at 20 km height and could cover up to 500 km in diameter. ○ It is expected to be in the market in 2021.
HAWK30 [83]	Aerodynamic	HAPSMobile	Japan	2017-Now	○ Its objective is to connect mobiles, UAVs and IoT nodes around the world. ○ It has 78 m wingspan, positioned around 20 km height, and would give 100 km coverage radius for several months.
PHASA-35 [84], [85]	Aerodynamic	BAE Systems and Prismatic	United Kingdom	2018-Now	○ It is designed for variety of services including 5G communications. ○ It has 15 kg payload capability with up to one year of continuous flight. ○ The altitude is between 17-21 km, and its payload power capability is between 300-1000 w, and it would offer coverage radius up to 200 km.

1) HAPS Energy Sources: There are three types of energy sources that have been used for HAPS operations: conventional energy sources, e.g., fuel tanks and electrical batteries, energy beams, and solar energy. HAPS supplied by conventional energy sources have a very short flight duration of about 48 hours and require frequent landing for refueling [19]. The use of conventional energy sources is suitable 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 [86], [87]. An example of such telecommunication HAPS is the SHARP project [75] 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 [19].

Solar energy, on the other hand, is a renewable energy source and a safe option for powering the HAPS, and it 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 deigns, harvested solar energy analysis, efficient energy storage systems, and cooperation strategy between solar energy systems and secondary energy sources [88]–[91] are widely investigated in the literature.

Several studies have recently introduced methods for improving the solar energy conversion efficiency [92]–[94]. 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 [95]. On the other hand, for the secondary sources, the values of the energy density of Lithium-ion batteries in early HAPS studies were around 100 Wh/kg [11]. However, the current commercial state-of-the-art Lithium-ion batteries have 250 Wh/kg [96]. Fuel cells, which are the other alternative energy storage system, have superior advancements. In 2009, the state-of-the-art fuel cells were around 400 Wh/kg [97]. Current fuel cells have a high energy density of 1600 Wh/kg [98].

2) HAPS Energy Consumption: Generally, the HAPS energy is consumed by the two subsystems: the flight control and the communications payload subsystem. The energy consumed by the flight subsystem includes the consumption for the stability

and propulsion power, and the consumption caused by controlling the HAPS altitude and direction. Also, the platform's type and its features, such as weight and size, impacts the flight system energy consumption. Since aerodynamic platforms require continuous circular movement, they have generally higher energy consumption [11], [16], [19]. In addition, as the size and the weight of the platform increases, more energy is required for the flight system. Since aerodynamic HAPS also have a relatively smaller size than airships, 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) [4]. 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 I-B, 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. Therefore, careful analysis of the intended use-case with the platform's choice and its payload size and weight capabilities as well as its energy consumption are of paramount importance for successful and cost-effective HAPS deployment. Sub-optimal mechanisms that trade the computational costs, and therefor consumed energy, for the performance in a controlled manner should be developed. Note also that as the HAPS systems are expected to supplement the terrestrial networks for improving the coverage, enhancing capacity and also offering portable computational platforms, one can also properly share required computational loads of optimal resource allocation, handoff, and computational offloading properly across HAPS systems and terrestrial networks.

2) Passive payload- HAPS-RSS: The HAPS deployment for wireless applications is profit-driven. The platform's 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 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 [99]–[101]—to support wireless communications. It is shown in [102] 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 [103], 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 [104]. Moreover, using digital meta-materials [105], the manipulation of the electromagnetic waves can be digitally controlled. To manipulate high-frequency signals, e.g., Gigahertz (GHz) and Terahertz (THz) bands, tunable materials such as liquid crystal [106] and graphene [107], [108] are used. Experiments conducted in [109] confirm that dynamic control of high-frequency signals is feasible. Also, [110] 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 [111]. Greenerwave company currently manufactures RSS applicable for a wide frequency ranges up to 100 GHz [112].

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

HAPS-RSS resembles the function of HAPS-RS but with extra advantages, as detailed in [114]. For instance, several recent studies indicate that the capacity achieved through RSS is comparable to the one achieved through radio relays [102], [115], [116]. As the performance of RSS supporting wireless communications is strongly dependent on the number of reflectors[6] and

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

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 self-interference, which are the typical limitations of relays [102], [116]. On the other hand, using RSS, the communication payload energy consumption of HAPS declines to the required power for the RSS controller. A recent experiment demonstrated that the configuration of each reflector unit consumed 0.33 mW [117]. As a result of the reduction in the platform's weight and consumed energy, the flight duration of the HAPS could be prolonged, which 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 [115]. Thus, HAPS-RSS can be regarded as an energy-efficient and cost-effective solution.

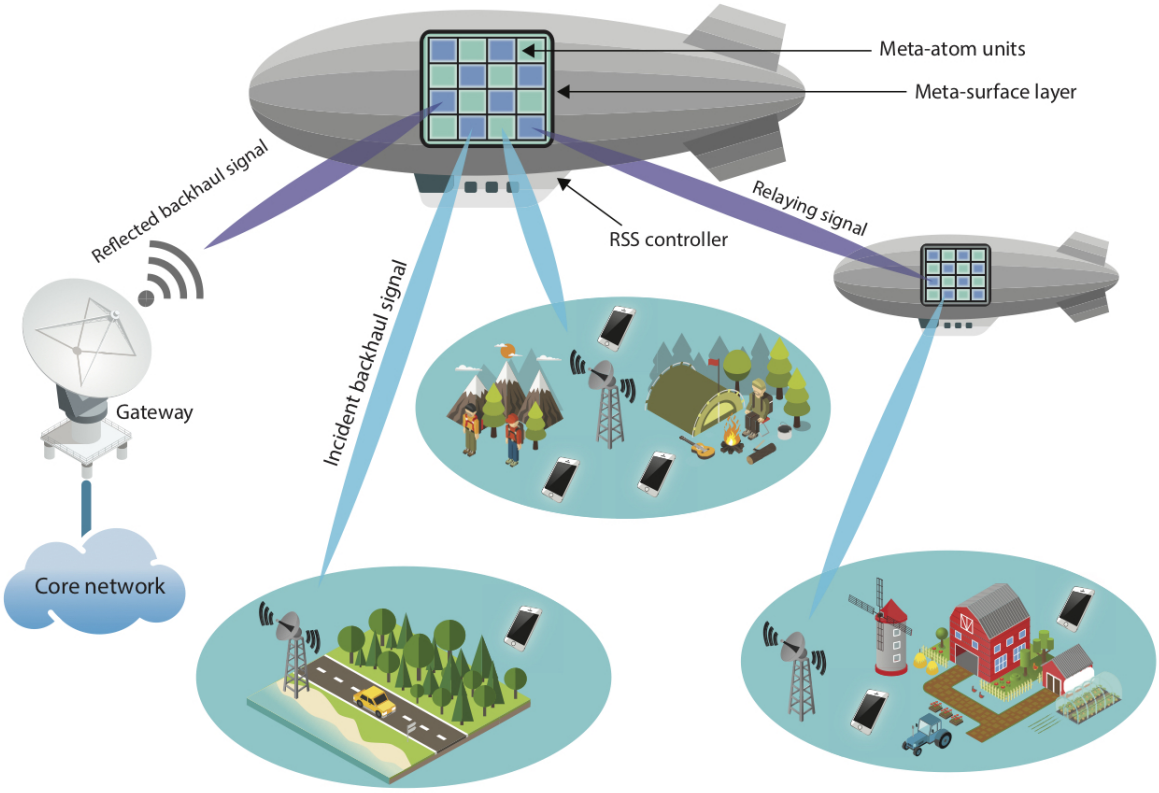


Fig. 6: HAPS-RSS for relaying signals and supporting backhaul from remote BSs.

Despite the discussed advancements in HAPS systems in terms of various platforms types and features, onboard energy system and communications payload; embracing the novel vision of the HAPS to support the presented future use-cases necessitate satisfying several requirements. These requirements are dependent on the intended use-cases. In situations where the HAPS is used to tackle the connectivity demands of temporary large events or flash crowd, fast deployment is necessary in these cases. Therefore, aerodynamic HAPS are more suitable in such use-cases. However, considering the huge data demands in such scenarios, this require aerodynamic HAPS with relatively high payload capabilities. Fortunately, this is feasible with recent progress in HAPS projects. As an example, the recent aerodynamic HAPS "PHASA-35" has payload power capability up to 1000 W [84], [85], which indicate the great potential for supporting huge number of users with high data rate requirements. On the other hand, utilizing HAPS for IoT services, supporting ITS/CAV or as data centers require HAPS with prolonged flight duration as well as considerably higher power, communication, caching and computation capabilities. In these cases, 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 Stratobus airship, expected to be deployed late in 2021, can accommodate a payload of 450 kg with a power rating of 8 kW for a 5-year mission [82]. In addition, unlike the stand-alone HAPS, the envisioned use-cases demand typically for a constellation of HAPS. Building such constellation require cost-effective and energy-efficient inter-HAPS communication links. The HAPS-RSS with its passive nature can be utilized to support the required multi-hop links in a cost-effective manner.

V. Channel Models for HAPS Systems

To understand the full 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 HAPS to satellite channel models is given in [23]. Although a recent survey on HAPS channel is not available, there are numerous studies for modeling the channels of lower altitude platforms, such as [118]. 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 form German Aerospace Centre (DLR) have been first presented in 1991 in [119], 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 [120]. The channel modeling studies in the stratospheric telecommunication systems started with the consideration of modeling the atmospheric effects in the system performance [121].

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 [122], 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 [123], along with the duration, state distributions and the transition probabilities. The combination of the line-of-sight, slight shadowing and the total obstruction conditions for the HAPS channel models using a semi-Markov studied is proposed in [124] and extended to tapped-delay lines in [125]. The impact of these state switches on the error performance is noted. [126] 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 [119], using the corresponding first order statistics.

3) Geometry-based Stochastic Models: The first study that proposes a geometry-based stochastic model (GBSM), specifically a geometry-based single-bounce (GBSB) model, is introduced in [127], 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 [128]. The work is then extended in [129], where the elevation angle of the platform, the array orientation and configuration, the Doppler spread, and the distribution of the scatterers 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. [130] 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 [129]. Its wideband extension is presented in [131].

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

4) Non-Stationary Models: A birth-death process-based non-stationary LOS component appearance and disappearance is presented in [134], 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 [135], 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 [136], where spatial correlation and polarization correlation expressions are also provided.

The dynamic evolution of the LOS component in 3-D models is investigated in [137] 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 [138] 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. [139] 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 [140]. Varıous statistical models have been proposed to model the channel characteristics. Gamma-gamma distribution is proposed in [141]. [142] proposed a lognormal model to model weak fluctuations. FSO channels have also been used as backhaul links in HAPS nodes. An excellent overview is provided in [40].

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 [143], 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, [144] 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 [129] 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 [145], 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 [71], the authors use mmWave communication to increase the capacity of a single HAPS system and a cluster of 8 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 [146], 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 [147]. 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 [148], 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 [149] 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. [150] 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.

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 by the spectral efficiency, i.e. throughput (in bits/sec) per unit Hertz, which needs to be maximized. In addition, energy efficiency is one of the system design objectives that needs to be addressed, since the platform's energy source is mostly rechargeable batteries as well as solar panels, i.e. a HAPS does not have the permanent directly connected power supply that the terrestrial BSs enjoy. On the other hand, 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. The way the HAPS on-board radio power and frequencies, antenna beams and time scheduling are managed all play an important role in interference management determining the SINR levels. This directly has an impact on the outage probability, BER, transmission delay, throughput and/or spectral efficiency at the system level. In an integrated aerial/terrestrial/satellite system that is comprised of a HAPS constellation, LEO-satellites and terrestrial BSs, the placement strategies of the HAPS nodes play a vital role as well. We hence highlight some of the key radio resource and interference management schemes developed for HAPS systems in the literature, focusing on power control, channel allocation, user association, beamforming, and the placement algorithms for HAPS systems for which a related taxonomy diagram is provided in Fig. 7.

In connection to the use-cases discussed in Section II-B, a HAPS-SMBS would provide coverage for unplanned events, where there is not enough terrestrial wireless capacity and/or coverage for the users attending the events. For this use-case a number of issues need to be taken into consideration

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

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

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

In addition to the system level design considerations, link level design aspects are paramount in specifying how the communication will take place at the bit and waveform level through the channel. The link level (or PHY) design is concerned with a single wireless link between a transmitter and a receiver 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 adopted waveform technology would play a main factor in determining/developing the multiple access scheme. Unfortunately, both the waveform technology and the related multiple access scheme(s) 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 users/devices with different QoS requirements, the SINR level seen at the receiver becomes critical, requiring sophisticated

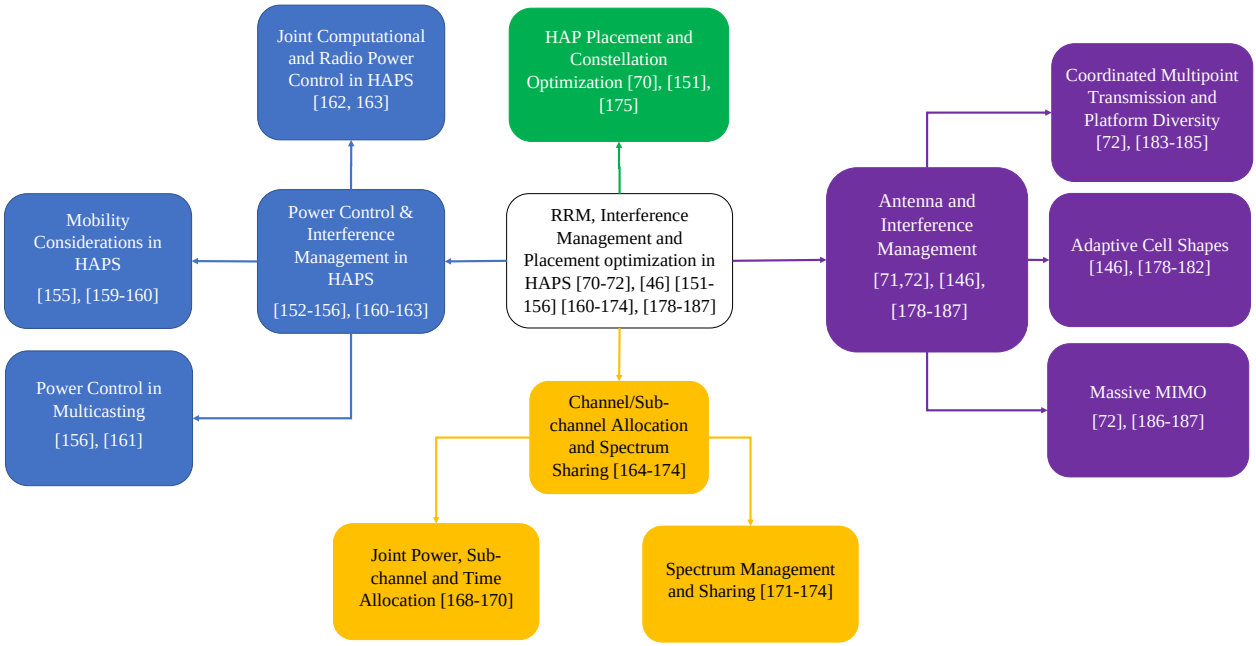


Fig. 7: Taxonomy diagram for the key radio resource, antenna and interference management, and HAPS placement strategies in the literature.

power management schemes. 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) [152]–[156]. The frameworks of these power allocation schemes are more general and could be suitable (with minor modifications) for other potential radio access technologies like multicarrier-CDMA [157] or power domain NOMA [158]. While CDMA is primarily built 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. A summary of the power control schemes reported in the HAPS literature is provided in Table V.

The works [152]–[156] study power control for the purpose of call admission control (CAC)[7] where users are admitted into the system such that the Grade of Service (GoS) is maximized by minimizing a weighted sum of the dropping and blocking probabilities, while satisfying the SINR and power constraints. In [153], the unique characteristic of HAPS systems that all base stations are collocated on the same platform 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. If the total power at any BS is less than or equal a power outage threshold, the call gets accepted otherwise it gets blocked. The central admission controller updates the BS total received power levels on a call-by-call basis so that the admission decision for new calls can be made more accurately. The work in [154] extends the schemes in [153] 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. The basic idea for the BS-based downlink CAC is to manage incoming calls according to the increase in the interference levels of the target cell as well as adjacent cells. Hence, with the admission of the new call, the downlink powers for all UEs must be increased to satisfy all UEs' SINR requirements. A call is blocked if admitting the call would cause the UE's target base station as well as other neighboring base stations to exceed the maximum allowable output powers and is admitted if the total platform power is not exceeded and the SIR thresholds are satisfied.

1) Mobility and Power Control: The mobility of 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 the mobility of UEs in power control of HAPS systems. [155] considers a hierarchical system in which a single HAPS and a terrestrial cellular network are jointly deployed as illustrated in Fig. 8. The HAPS can be used to provide SMBS coverage and the terrestrial cellular towers can be used for macro-cell coverage at a different frequency band, therefore cross-layer interference is avoided. The developed CAC

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

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

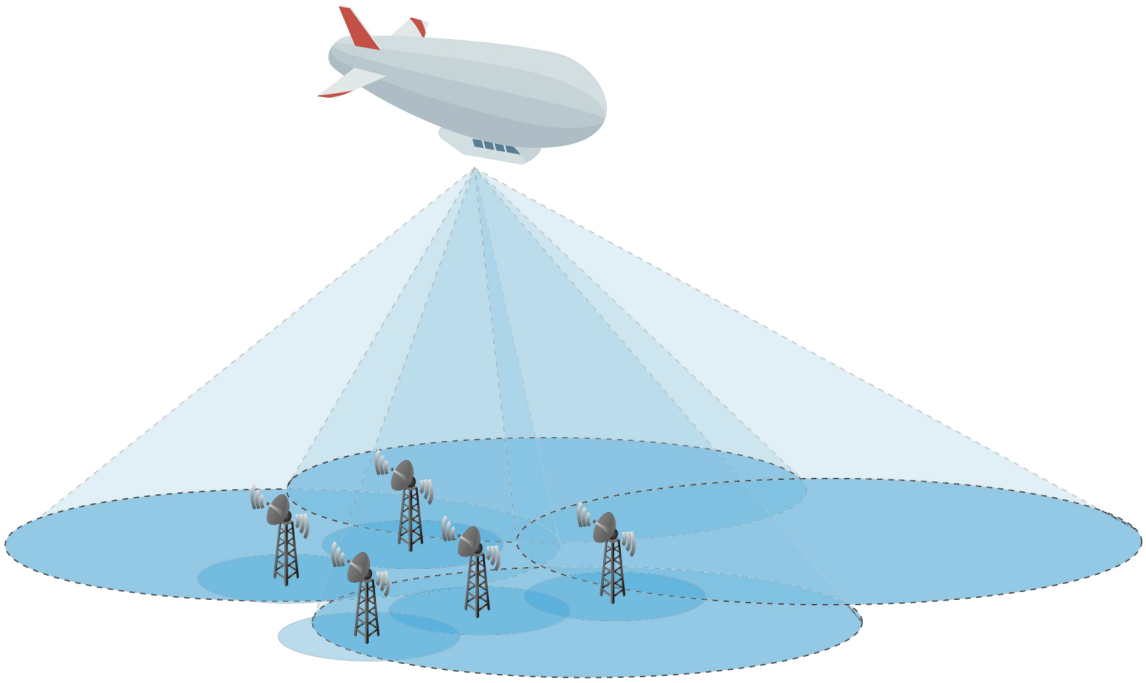


Fig. 8: A hierarchical HAPS-SMBS and terrestrial cellular system.

In [159], a speed and direction-based CAC scheme 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 the SIR received from the UE's serving BS's pilot channel and the next strongest SIR received from the UE's neighboring base stations' pilot signals. It is used to derive the speed and direction of the mobile UE relative to the rest of the UEs. In [160], 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.

2) Power Control for Multicast Services: Only a few papers in the literature consider power control for multicasting. In [156], 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 [161], 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 while taking into account the radio channel conditions, the cell coverage radius, and two sample MBMS application bit rates. It was observed that for MBMS services, the choice of the most efficient transport channel is a key aspect that impacts the overall system capacity.

3) Joint Radio and Computational Power Management: A HAPS-SMBS is envisioned also for aerial edge computing as discussed in Section II-B. Thus the power and time consumed in onboard computation should be manged jointly with radio resources. Recently, some research works that explore this use-case started appearing in the literature [162], [163]. In [162] the task offloading problem in a two-tier aerial network, consisting of a low-altitude UAV tier and a HAPS tier, is explored. The HAPS nodes are equipped with MEC servers to perform the computations of the tasks offloaded from the low-altitude UAVs. The design choices that were optimized to minimize the the offloading delay are the offloading ratios of the tasks, which determines the number of tasks to be processed locally and the number of tasks the low-altitude UAVs are to offload based on the available computational power of the servers onboard. The second optimization design choice is the uplink transmission power of the low-altitude UAVs. The authors in [162] tackle this problem by modeling it as a multi-leader multi-follower Stackelberg game which is solved using the lower complexity equilibrium problem with equilibrium constraints (EPEC) model. The work in [163] explores the multi-objective problem of minimizing energy and time consumption for task

computation and transmission in a MEC-enabled balloon network. Since the data size of each user's computational task varies over time, the HAPS-BSs must dynamically adjust the user association, service sequence, and task partition scheme, which are the design choices that [163] considered, to meet the users' needs. A support vector machine (SVM)-based federated learning (FL) algorithm determines the user association proactively, before the service sequence and task allocation of each user are optimized so as to minimize the weighted sum of the energy and time consumption.

B. Channel/Sub-channel Allocation and Spectrum Sharing

Channel allocation is one of the principal functions in any multi-user wireless system. When it comes to multi-user/multi-HAPS systems, channel allocation schemes can exploit the inherent diversity 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. Therefore, each user is expected to experience different and independent attenuation on a given channel, which could be exploited for achieving multi-user diversity gain. Moreover, in integrated HAPS systems, i.e., HAPS/terrestrial/satellite systems, more than one of these layers may be operational within the same band. Hence spectrum sharing schemes as well as inter-layer interference management 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 and summarize those in Table V as well.

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 conditions.

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 for HAPS communications hot spot areas 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.

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 multicast 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 For the purpose of sharing and compatibility between fixed service using HAPS and other services in the 31/28 GHz bands. Moreover, [172] investigates 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 by considering both the physical distance and the frequency separation in terms of the cochannel and adjacent channel frequency through the use of spectrum emission masks as guided by the ITU recommendations. In [174], the authors consider a spectrum sharing problem in a LEO-HAPS 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. The reported simulation results validate that the capacity of HAP-ground downlinks connections are improved with their proposed strategy in imperfect estimation scenario compared with the case in which estimation errors are ignored. An overview of the potential of cognitive radio techniques are also summarized in [16].

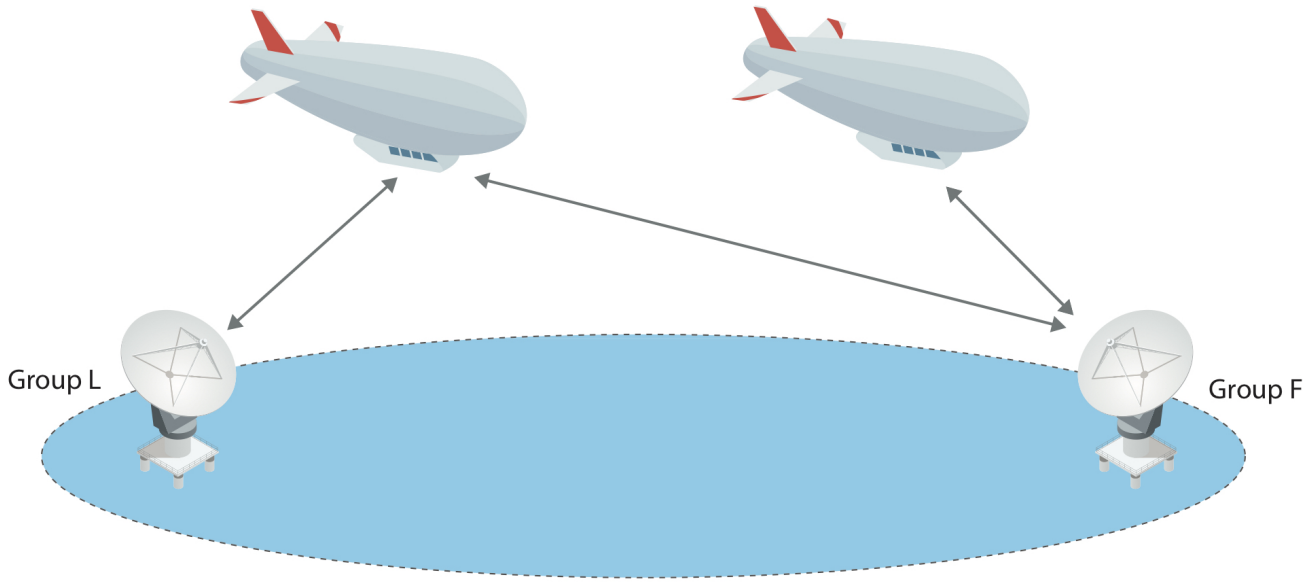


Fig. 9: A system of two HAPS nodes and two groups of users with different access choices (adapted from [166]).

C. HAPS Placement and Constellation Optimization

One of the main challenges of HAPS systems is the design and management of self-organized networks. In conventional self-organizing networks, self-configuration and optimization as well as self-healing capabilities are among the basic functionalities. This is particularly essential in an aerial network due to its more dynamic nature compared to a fixed cellular network because the position of 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 [70]. The QoS metrics are established by considering the SINR, BER, throughput, and availability. For HAPS broadband networks, availability is the percentage of coverage that the system can provide with a BER no worse than the desired target. Based on the network coverage model, the design vector of HAPS system layout optimization, i.e., the number of HAPS nodes, downlink antenna area, power of payload, longitude of HAPS, and latitude of HAPS, is devised. It was found that by applying the proposed constellation design methodology, the optimal cost-efficient broadband network can be realized. In [151], power allocation with fronthauling and backhauling associations in order to improve the global connectivity using satellite, airborne, and terrestrial networks integration is investigated jointly with determining the HAPS locations. It is shown that the satellite stations and HAPS nodes can play a 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 between a HAPS and UEs requires highly directive antennas to overcome the high attenuation caused by path loss and to prevent interference between UEs receiving transmission from antennas of different HAPS (especially those at the HAPS coverage edge). Additionally, given that the ITU-R allocates terrestrial cellular spectrum to HAPS systems, the expected interference to terrestrial wireless systems requires that the antennas onboard be equipped with dynamic beam pointing to facilitate interference management. This becomes crucial given that a HAPS is 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

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

Design Aspect(s)/Parameters	Objective	Technique	Network Type	Reference
Power, subchannels, user-selection, time scheduling	Maximize the number of multicast admissions	Lagrangian relaxation	Stand-alone HAPS	[168]
Associate users with multiple antennas + design parameters in [168]	Admit the highest priority users to the system	McCormick outer approximation relaxations, branch and cut techniques, cloud branching etc.	Standalone HAPS	[169]
Complexity reduction for the problem in [168] by reformulations	Admit the highest priority users to the system	Different types of cuts, acceleration heuristics, and variable domain propagation techniques	Standalone HAPS	[170]
Channel allocation	System capacity maximization	Q-learning reinforcement learning and combines back-propagation neural network	System of Multiple HAPS	[165]
Energy allocation	Serving users with highest priority	Genetic algorithm, rule-based learning neural networks and dynamic programming	Single access point HAPS moving on a trajectory	[160]
Channel allocation	Fair call blocking probability	Continuous time Markov chain and restriction functions	Two HAPS system	[166]
Radio and computing powers	Minimizing energy and time consumption	SVM-based FL algorithm	Mutliple HAPS-BSs	[163]
Offloading fraction and low-altitude UAV uplink powers	Minimize the offloading delay	Multi-leader multi-follower Stackelberg game and EPEC	Two tier- low-altitude and high-altitude UAVs	[162]
Uplink transmit powers	Maximize system's uplink throughput while achieving local fairness	SRA-LF algorithm	Standalone HAPS	[152]
Downlink transmit powers	CAC: Maximize System's Capacity	Centralized Transmit Power Based, Platform Power Limited (CTP-PF) CAC Heuristic	Standalone HAPS	[154]
Downlink transmit powers	Minimize dropping and blocking probabilities	Overflow and speed sensitive strategies + Centralized Resource Reservation- Random Model and Traffic Selection	Two layer Terrestrial/HAPS network	[155]
Spectrum sharing with conventional fixed service system	Interference Mitigation	Dynamic Channel Allocation (DCA) + increasing minimum elevation angle	Two layer terrestrial/HAPS network	[159]
Power driven switching between terrestrial and HAPS FACHs and DCHs for MBMS	Maximize GoS, i.e. Minimize call blocking and dropping probabilities	Number of Multicast Users Policy + Distribution of Multicast Users Policy	Two layer terrestrial/HAPS network	[156]
Power driven switching between HAPS FACHs and DCHs for MPMS	Maximize power utilization: system capacity at a given power level	Defines power switching thresholds to switch between Dedicated and Common Channels	Standalone HAPS	[161]
Spectrum sharing for downlink coexistance of HAPS and terrestrial fixed broadband systems	Improve coexistence performance by reducing outage probability at the user	Interference-to-noise-based scheme + CINR-based scheme	Two layer terrestrial/HAPS network	[172]
Spectrum sharing of 5850-7075 MHz band with Fixed Services and effect of channel bandwidth	Prevention of harmful interference	Co-channel, zero-guard-band and adjacent channel criteria and methods. Separation distance and frequency separation used	terrestrial/HAPS system	[173]
Spectrum and power allocation	Maximize sum rate of HAPS-ground downlinks in imperfect channel estimation	Decomposition, then Simplex Algorithm and convex optimization	LEO-HAPS cognitive system	[174]

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

1) Adaptive Cell Shaping: 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 practicably 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 [176], 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 [177]. The authors propose a general formulation in [146] for optimum directivity in order to maximize the received power at the cell edge. This is in contrast to earlier works where the HAP cell is defined as being within the footprint of the corresponding antenna's half-power beam-width. 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. [178] 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 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 [179]. The authors present two steering scenarios, all antennas steered 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 this solution is the high number of handoffs required. In [180], 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 quantify the CIR for a 3 channel re-use plan for networks of 121 and 313 cells. The reported results show the ITU recommended pattern for the 47/48 GHz band can lead to poor results compared to an adapted pattern based on fitting the measured data for an elliptic beam lens antenna. The authors in [181] consider irregular cell shapes to obtain the target cell characteristics by grouping pixel spots, aiming to limit the co-channel interference. This 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. [182] introduces a cell-pointing approach making use 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 Multipoint Transmission and Platform Diversity: User-centric joint transmission coordinated multipoint (JT-CoMP) has proved to boost the capacity of terrestrial cellular systems by overcoming cell-edge interference. In [183], the authors 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 BS 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 were explored. In [184] the performance of using multiple HAPS nodes by using antennas is investigated. The impact of the distance between HAPS nodes on the CINR distribution is considered. The use of multiple HAPS in forms of HAPS constellations is considered in [71], where the authors consider the millimeter-wave band transmission. The potential gains in capacity that various HAP constellations can deliver, both theoretically using the Shannon equation and also while operating a number of practical modulation and coding schemes are quantified. An evaluation methodology consisting of minimum angular separation of HAPs as seen by the user, link length ratio, and sidelobe floor beamwidth was developed. For a 5° beamwidth user antenna, the optimum HAP spacing radius is approximately 4 km. The authors in [185] determine the diversity order improvement that can be obtained by using multiple HAPS nodes via virtual MIMO transmission. The ergodic 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 [186] 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 beam-forming 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 [72] for an integrated satellite and HAPS 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

TABLE VI: A Summary of Antenna and Interference Management related Aspects and Approaches in HAPS Systems.

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

Table VI: (Continued) A Summary of Antenna and Interference Management related Aspects and Approaches in HAPS Systems
.

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

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

E. The Waveform: Signaling and Multiple Access

Signaling and multiple access formats, also referred to as the waveform design, have witnessed a long and radical evolution in wireless communications where they serve as its foundation. For example, WCDMA is the 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 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 [189]. 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 no 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 being a prevailing technology so far, a number of drawbacks, discussed also in [190], 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 seem promising.
2) The need for higher spectral efficiency which can potentially be improved by relaxing the orthogonality provided that the cyclic prefixes—included to circumvent inter-symbol interference—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 [191], which can achieve higher spectral efficiencies for the same target BER compared to Nyquist signalling over a single carrier, could be a promising solution for HAPS transmissions in the mm-Wave band.

In the rest of this section, we overview alternative approaches being actively investigated in the PHY research community that could be suitable waveform candidates for HAPS. These approaches, which are also summarized in Table VII, 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 such as low latency and multiple access. 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 [192]. On the other hand, FBMC has come with drawbacks that include long filter lengths resulting in enormously large symbol duration, which might not be suitable for low latency applications or short bursts of machine type communications. Moreover, when used with

MIMO technologies, the signal detection computational complexity is expected to be quite large as the channel coherence bandwidth would fall below the subcarrier bandwidth [193].

2) Faster-than-Nyquist Signaling: One of the promising ideas to increase spectral efficiency at the physical layer that has been under research for many years is Faster-than-Nyquist (FTN) signalling [194]. In this technique, rather than making the pulse duration smaller, we increase their degree of overlap in time by transmitting them at a rate higher than the Nyquist's signalling rate. In this way, we avoid occupying larger 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 receiver experience no reduction for an acceleration parameter $\tau \geq 0.802$ [195]. This means that if an optimal maximum likelihood sequence estimation (MLSE) detector is used, then the performance, measured in BER is not compromised. The gain is 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 [196], the ones most commonly used in different applications. An example is the binary 30% excess bandwidth root raised cosine pulse, which ceases to have distance 2 at $\tau = 0.703$ yielding a 42% increase in the bit density.

The 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 [197]. 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 [198], the authors proved the feasibility of high order quadrature amplitude modulation (QAM) FTN signaling detection using a polynomial time complexity semi-definite relaxation-based detector. 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 with 0.7 dB penalty in the SNR.

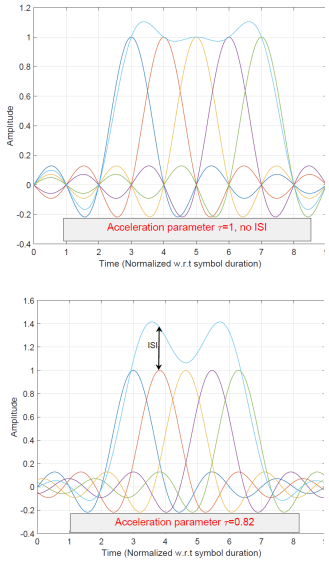
In narrow-band (NB) IoT services that HAPS-SMBS is envisioned to support, uplink connections of IoT devices have limited transmission power of up to 23dBm and small transmission bandwidths of up to 180 kHz. In order to achieve higher transmission rates within the given bandwidth restrictions, higher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

3) Spectrally Efficient Frequency Division Multiplexing (SEFDM): The idea of FTN signaling has been also studied in frequency domain, which is known as spectrally efficient frequency division multiplexing (SEFDM), extending it to both, time and frequency domains, as clarified in Figure 10. A squeezing factor ς allows the subcarriers to be packed closer than in the orthogonal case, hence improving the spectrum utilization at the expense of a controlled inter-carrier-interference. The existence of Mazo limit in both time and frequency domains has been proved in [200] and [201]. SEFDM (multicarrier FTN) transceiver design, optimization, and performance have been addressed in [202]–[205]. Besides the high spectral efficiency offered, SEFDM can further enhance the energy efficiency of communication systems because it improves the bandwidth efficiency without extra energy consumption. Since SEFDM is a spectrally efficient multicarrier modulation scheme, it is certainly a promising technology to be used for 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 is an open area of research for HAPS, depending upon the application type and QoS requirements of each UE.

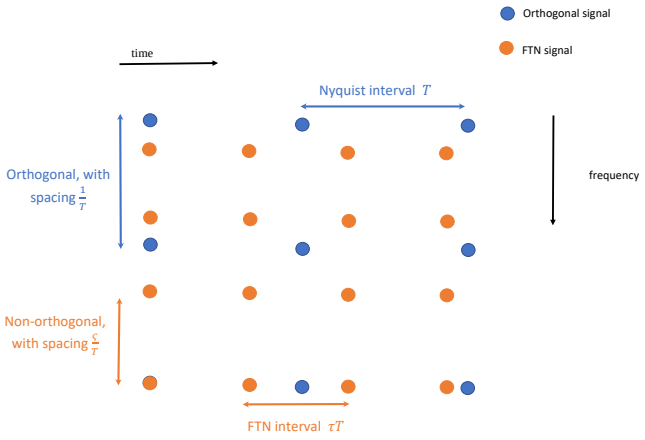
4) Non-Orthogonal Multiple Access: One of the relatively novel multiple access approaches is the non-orthogonal multiple access (NOMA) scheme proposed by the mobile phone operator NTT DOCOMO in Japan [189]. In this scheme, multiple users of different channel conditions are multiplexed in the power domain on the transmitter side, requiring multi-user signal separation on the receiver side. From an information-theoretic point of view, using superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver, non-orthogonal user multiplexing not only outperforms orthogonal multiplexing, but can also achieve the capacity region of the downlink broadcast channel. NOMA can be also applied to the uplink, 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 [206].

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

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



(a)



(b)

Fig. 10: FTN and SEFDM (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.

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

MIMO-NOMA overloads SDMA by allocating a cluster of UEs to each beam and using SC-SIC within each group [207]. 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.

VII. Handoff Management in HAPS Networks

Terrestrial cellular networks support UEs 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[8]. 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 UEs 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 [208].

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 [209], 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 to/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 [210] 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 [211] 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 [208], 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.

The traditional handoff algorithms that depends 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 [9]. In addition, representing the unbalanced cell load becomes inaccurate. The effects of the quasi-stationary state on the inner and outer layers are different. Employing a handoff algorithm with a fixed threshold fails to provide efficient handoff in the entire communication system. When the threshold is too low, frequent handoffs are likely to happen; in contrast, if the threshold is too high, the handoff will be triggered too late causing long periods of communication disruption. In [212], 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 [213] proposed a prediction-based handoff decision algorithm with an adaptive threshold. The algorithm predicts the

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

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

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 [214]. 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 [215], 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 [16], seems promising for improving the handoff performance. In this scenario LEO satellites can provide the backhual link of a HAPS. Under this assumption, the author in [216] propose a dynamic handoff strategy to optimize the handoff moment and resource allocation. The author considered the factors of user priority, minimum rate requirement, delay requirement, channel gain and the traffic of beams.

In [217], 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 [218], 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.

[219] 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).

[220] 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 [221] proposes a load balancing handoff algorithm based on RSSI and energy-awareness in HAPS networks. Table VIII 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.

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

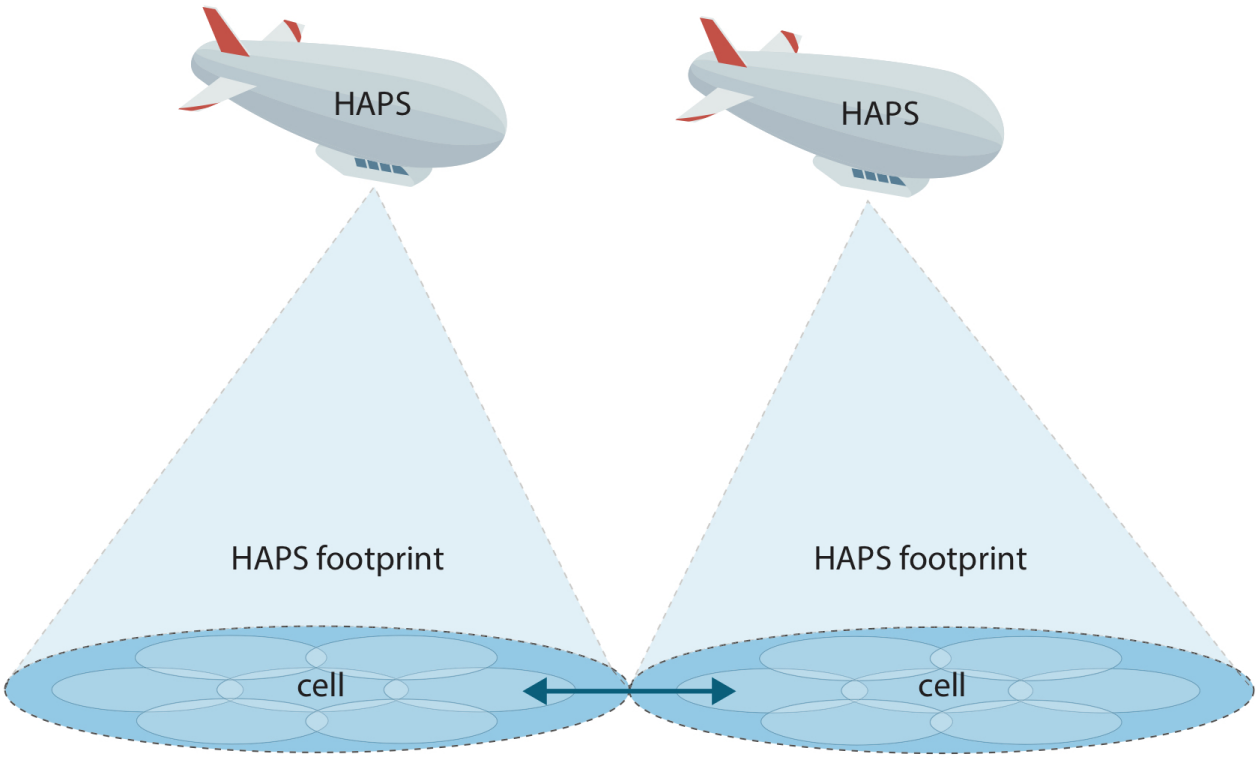


Fig. 11: Inter-HAPS handoff.

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

VIII. HAPS Network Management and Computational role

To operate a HAPS, two to four ground-based crew members are required to oversee various aspects of mission planning, flight control, sensor operation and data assessment [222]. Operational complexity and cost will likely scale up in scenarios where multiple HAPS systems are deployed and need to coordinate and work together as a swarm. To overcome the technical and economical problems of deploying a network of HAPS systems, HAPS systems control and coordination 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. In effect, HAPSs can play important roles in the aerial network management and network slicing, as described in the sixth use case in Section II-B. 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. We should also mention that 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. One recommended solution might be the utilization of federated learning in future HAPS networks.

The implementation of semi autonomous high altitude platform swarm with self-organising capabilities was investigated to maximize communications area coverage [223]. The author compared the application of Reinforcement Learning (RL) and Swarm Intelligence (SI)-based methods for resolving the problem of coordinating multiple HAPS to maximize communications area coverage. It was observed that the SI algorithm showed faster convergence and more stable user coverage profile due

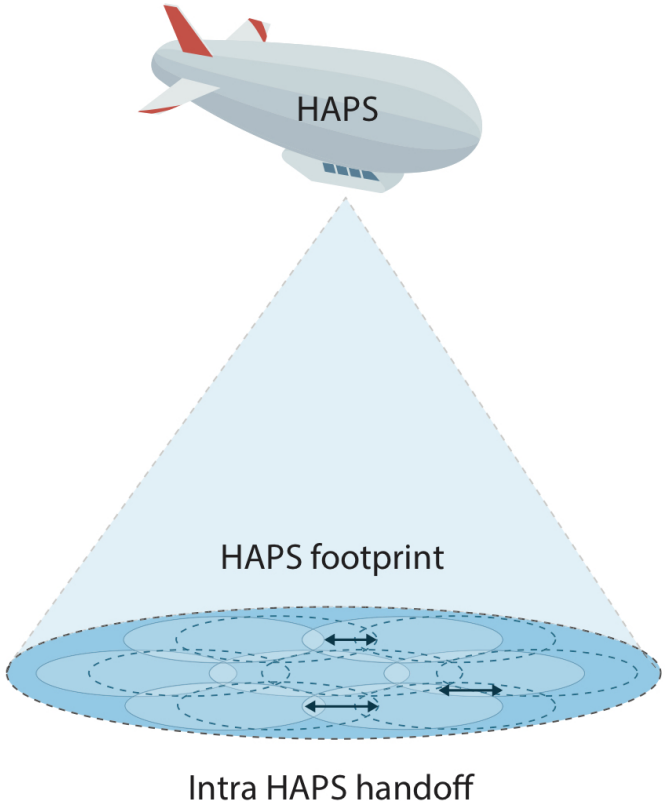


Fig. 12: Intra-HAPS handoff.

to the simple rule-based logic. However, the RL algorithm achieved higher overall peak user coverage rates but with some coverage dips due to individual HAPS exploration strategy. RL-based techniques 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. This conclusion should be considered in the design of the fifth use case, HAPS-SMBS to defeat coverage holes, which was described in Section II-B. Importantly, as the dynamic of appearance of coverage holes could be very intricate to mathematically reason about, RL based solutions are high values as they circumvent the need for a tractable mathematical models, to some extents though. Nevertheless, one should note that the RL approaches are generally sensitive to the design of a proper reward function, otherwise there is no guarantee that the algorithm could converge to a suitable solution.

The author of [224] investigated 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 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. In HAPS 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 [225]. 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 [226]. 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-

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

Reference	Proposed solution	Inter/Intra	Considered parameters	Movement type
[209]	Low latency MAC layer handoff	Intra-HAPS	RSSI, CIR, traffic load, and user position	Pitch movement
[210]	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
[212]	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
[213]	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
[214]	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
[216]	Proposed a dynamic handoff strategy to optimize the handoff moment and resource allocation	Inter HAPS-LEO	User priority, minimum rate requirement, delay requirement, channel gain, and the traffic of beams	Mobile terminal movement
[219]	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
[220]	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
[218]	Proposed that the neighbouring 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
[221]	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
[217]	Forcing UEs in overlapping areas to handoff to balance load among cells	Intra-HAPS	HAPS traffic load and UE position	horizontal displacement and rotation

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 [227]. 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 [227]. To enable dynamic network slicing, it is necessary to accurately estimate the user demands and dynamically allocate resources accordingly. Several learning theory schemes such as deep learning and reinforcement learning can be used for the prediction of user traffic. After accurate prediction, effective resource allocation schemes can be used for enabling dynamic network slicing.

In [228], 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. This study can be quite useful in realizing and developing the sixth use case "HAPS-SMBS to support and manage aerial network", which was mentioned in Section II-B. In a relevant work [229], 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 SD-ABN, segment routing is applied. Moreover, a network traffic scheduling algorithm is designed based on SD-ABN to improve the transmission reliability and bandwidth utilization by balancing network traffic to multiple reliable transmission paths.

In future 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 [227]. Although

this management model was not originally proposed for HAPS systems, it worths a more deep investigation. This high level of control and orchestration is a very necessary requirements to realize many of the envisioned HAPS-SMBS use cases such as creating an aerial data center, defeating coverage holes, and supporting and managing aerial networks. As HAPS systems can form a MEC cluster or an aerial data centre for processing offloaded data from aerial or satellites (refer to the fourth use case, Section II-B), 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.

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, as described in fourth use case mentioned in Section II-B. 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 UAV and satellites.

Recently, several studies proposed to use multi-UAVs to form a Mobile Edge Computing (MEC) cluster. In [230], 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 [231]. The author minimized the power through jointly optimizing user association, power control, computation capacity allocation and UAV location planning. In [232], 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 [233] 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 HAPS can provide a more stable MEC cluster with stronger computational capabilities in comparison to UAV-base 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-based MEC can not only serve terrestrial UEs but also aerial UEs and satellites. However, to achieve the vision of creating HAPS based MEC, reliable communications among HAPS systems, intelligent tasks scheduling, and advanced resource allocation techniques are necessary.

Regarding the support for the use cases mentioned in Section II-B, HAPS network management should be automated to enable HAPS networks to be a self-evolving network [234]. As HAPS systems are envisioned to provide an aerial data center (the fourth use case), several requirements should be considered including reliable collaboration among HAPS, and efficient computational and storage resources management among the distributed HAPS systems. In addition, intelligent tasks scheduling which considers the each HAPS capabilities, energy consumption and processing loads. Moreover, it is very important to have intelligent decision-making algorithms for data offloading to decide on where to process the data (e.g., in HAPS or terrestrial network), which is necessary to support the second, third, fourth, sixth, and seventh use cases mentioned in Section II-B. Another crucial requirement for all use cases is that HAPS networks should support the SDN and NFV paradigms. In fact, HAPS systems are a potential candidate for SDN controller palcement in an SDN-based VHetNet architecture.

IX. The role of AI in HAPS systems

Active research is currently being carried out to enable ML in highly resource-scarce Micro Controller Unit (MCU)s and Field-Programmable Gate Arrays [235]. In 2017, Microchip manufacture the first MCU that has a high-performance 2D GPU, the PIC32MZ DA family [236]. 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 [237]. STM Microelectronics has offered in the market sensors with incorporated machine learning cores that have an embedded classifier [238]. 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 [239]. 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 [240], spectrum sharing [241], and user scheduling [242]. 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 [243]. 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 Networks (RNNs), and gated RNNs into tiny devices [244].

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 they 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 [245] feasible by distributing the tasks of ML among a group of collaborating HAPS systems forming an aerial data centre, as described in the fourth use case in Section II-B. As a leading alternative to centralized ML algorithms, federated learning techniques can provide a platform to achieve distributed ML with high prediction accuracy in a privacy-preserving manner. However, to support 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 UEs, an intelligent HAPS system can learn and detect such change through observing UEs 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 UEs 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 [70]. 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 [210] 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 [246], 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 UAVs, the author in [247] 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

TABLE IX: Section-wise Classification of Challenges.

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

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 [248] 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, [249] 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 to form an aerial data centre.

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.

For the list of discussed challenges and their relations with the sections of the paper refer to Table IX. Note that although some of the challenges may relate two several sections, we clarity we only consider the section that overwhelmingly influence the relationship. As an example, Handoff management challenges mainly considered to be associated with Section VII while it also belongs to network mangement Section VIII as well as Section IX.

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

1) Regulatory Aspects: 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 Google's Project Loon tests in Oceania [250]. 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.

2) System Issues: 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 the 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. This might require supporting the HAPS partially with other types of energy sources such as remote charging or nuclear energy to insure sustainable and continuous operations.

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. One of the potential solutions to this is to utilize the upper surface of the platform for the solar energy, while the bottom surface is dedicated for the RSS functions. 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.

3) 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 unique propagation and channel fading nature of a 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 [251]. 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 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 [252].

Another challenge that needs to be considered is the non-linearity in FSO communications, that are used in inter-platform link communications, LEO/HAPS communications and back-hual 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. This could be very promising to support the use of HAPS-SMBS in providing Tbps FSO link backhauling of small-cell (or isolated) BSs, which is one of the use-cases discussed in Section II-B.

When new waveform technologies are introduced, cross layer design challenges appear. Considering the FTN and SEFDM technologies, power and 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 HAPS access links, where we expect to have time and frequency squeezing parameters to be jointly optimized with power and sub-channel allocation for each HAPS user, where each sub-channel could even have a different number of sub-carriers depending on the frequency-squeezing parameter.

4) Radio Resource Management: 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 among 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 [253], 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 HAPS. For example, URLLC with massive broadband and/or massive machine type communications (mMTC) have almost completely different QoS requirements which must be satisfied and hence need to be considered in the mathematical formulations. This requires development of multi-objective schemes that can be executed in real-time, hence an ultra-low complexity is needed. For example, the HAPS system might want to maximize throughput for massive Broadband UEs while minimizing end to end delay and packet loss for URLLCs. Additionally, so far, technology has been interacting primarily with only two senses, which are sight and sound. Interestingly, in [199], 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 services. 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 sufficiently taken into consideration in the vast majority of HAPS RRM, interference management and placement research papers. We believe that for optimum energy utilization, we need to take this into account while developing suitable model-based or AI-based schemes for power management in the HAPS access downlink, inter-platform links and backhaul links, possibly jointly. In addition 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. As HAPS systems are expected to be a major part of 6G communication systems, we require more investigation into 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. Specifically, cargo drones (in huge numbers) are part of the intelligent transportation system that a HAPS-SMBS is envisioned to support. The channel models that capture the 3D mobility effects between the HAPS-SMBS and the drones are yet to be developed. These are crucial in analyzing the SINR and outage probability that the drones would experience, whose insights are of great importance for developing RRM schemes. Moreover, associating the cargo drone to a terrestrial BS, a medium altitude platform or a HAPS-SMBS, needs to be addressed. Under what condition a drone should connect to a HAPS or a terrestrial BS? Or should we advocate for double connectivity in HAPS systems? This needs to take into account the distance as well as the available radio resources, such as power. It is worth noting that in designing this, the aerial platforms' rechargeable power supply nature must be taken into account as well. It is worth keeping in mind that about 80% of the traffic demand is media-driven, which necessitates more investigations regarding video streaming, caching, and QoE in HAPS systems. Last but not least, related to the joint control-communication system design umbrella, new performance metrics such as age of information (AoI) and information freshness are emerging, which are entirely overlooked so far in the HAPS literature and therefore new studies need to consider those.

5) Channel Model and Performance Evaluation: 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 UEs and UAVs 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 sophisticate point processes such as Determinantal Point process [254] and Ginibre Point Process [255], 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 server than that of the UAV and terrestrial networks, due, mainly, to highly dominated LOS air-to-ground/ground-to-air channel component [256]. 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 [257]. 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 [258].

6) 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.

7) 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.

8) 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.

9) Handoff Management in HAPS Networks: 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. Furthermoe, 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.

10) Computational Roles: 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. In fact, 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.

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. On the other hand, 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 HAPS resource management, load balancing, and UE mobility management.

Note also that 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.

11) 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 [259], [260]. 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 [261], [262] and also covert communications [263] 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/functionalities) 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 [264], [265], 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 network and vise 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 [266]. 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 word-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 extended, 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 form 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.

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 cautions 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[10]; 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 Reality (VR) and large-scale machine learning applications, 2) secure connected globe, 3) extreme reliability and relatively low latency communication [11], for control and monitoring of massive number of intelligent, mission-critical high-stake robots, UAVs, and devices, and 4) over-the-air connected intelligence allowing widespread use of machine learning and data analytics tools on the edge. In effect, the concept of edge computing is already under investigation and is part of 5G wireless communications networking. 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 UAVs, self-driving cars, robots, and the like, are expected to locally train sub-models and share the trained models instead of sharing data, which has important consequences form privacy perspective too. For this large-scale, distributed edge ML, HAPS 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

[10]In machine learning the meta-learning is also known as "learning to learn" [267]. 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.

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

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. Along with the diverse set of applications addressed with the presented use-cases, the HAPS-mounted Super Macro Base Station (SMBS) paradigm is introduced as a promising and cost-effective solution for addressing the traffic demands of future networks. This platform is also capable of supporting computing, caching, and processing in a plethora of application domains including sensing, machine type communications, UAV communications, and various IoT applications.

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

The current literature is expected to evolve, targeting the realization of the proposed visionary framework by addressing the listed open issues. The challenges and open issues related to VHetNets and HAPS systems 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 are joitly 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 HAPS system channels, the restricted transmission energy, or the detection without availability of the channel statistics/model.

Acknowledgment

This work was supported by Huawei Canada Co., Ltd.

References

[1] 3GPP, "Study on New Radio (NR) to support non-terrestrial networks V15.2.0 (Rel. 15)," Tech. Rep., 2019.
[2] ITU, "Radio regulations articles," 2016.
[3] X. Cao, P. Yang, M. Alzenad, X. Xi, D. Wu, and H. Yanikomeroglu, "Airborne communication networks: A survey," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 9, pp. 1907–1926, Sep. 2018.
[4] T. Tozer and D. Grace, "High-altitude platforms for wireless communications," *Electronics & Communication Engineering Journal*, vol. 13, no. 3, pp. 127–137, Jun. 2001.
[5] J. Qiu, D. Grace, G. Ding, M. D. Zakaria, and Q. Wu, "Air-ground heterogeneous networks for 5G and beyond via integrating high and low altitude platforms," *IEEE Wireless Communications*, vol. 26, no. 6, pp. 140–148, Dec. 2019.
[6] K. Hoshino, S. Sudo, and Y. Ohta, "A study on antenna beamforming method considering movement of solar plane in HAPS system," in *IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, 2019, pp. 1–5.
[7] ITU-R, "Preferred characteristics of systems in the fixed service using high altitude platforms operating in the bands 47.2-47.5 GHz and 47.9-48.2 GHz." International Telecommunication Union, Geneva, Recommendation F.1500, Jan. 2000.
[8] V. Milas, M. Koletta, and P. Constantinou, "Interference and compatibility studies between satellite service systems and systems using high altitude platform stations," in *ESA Special Publication*, vol. 541, Jul. 2003.
[9] R. Miura and M. Oodo, "Wireless communications system using stratospheric platforms: R and D program on telecom and broadcasting system using high altitude platform stations," *JCRL*, vol. 48, no. 4, pp. 33–48, Nov. 2001.
[10] M. Handley, "Using ground relays for low-latency wide-area routing in mega constellations," in *18th ACM Workshop on Hot Topics in Networks (HotNets)*, 2019, pp. 125–132.
[11] S. Karapantazis and F. Pavlidou, "Broadband communications via high-altitude platforms: A survey," *IEEE Communications Surveys & Tutorials*, vol. 7, no. 1, pp. 2–31, firstquarter 2005.
[12] A. K. Widiawan and R. Tafazolli, "High altitude platform station (HAPS): A review of new infrastructure development for future wireless communications," *Wireless Personal Communications*, vol. 42, no. 3, pp. 387–404, Aug. 2007.
[13] J. Gavan, S. Tapuchi, and D. Grace, "Concepts and main applications of high-altitude-platform radio relays," *URSI Radio Science Bulletin*, vol. 2009, no. 330, pp. 20–31, Sep. 2009.
[14] F. Fidler, M. Knapek, J. Horwath, and W. R. Leeb, "Optical communications for high-altitude platforms," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 16, no. 5, pp. 1058–1070, Aug. 2010.
[15] P. Aubineau, S. Buonomo, W. Frank, and K. Hughes, "ITU's regulatory framework, technical studies in ITU-R, and future activities in relation to high-altitude-platform stations (HAPS)," *URSI Radio Science Bulletin*, vol. 2010, no. 333, pp. 67–74, Mar. 2010.
[16] A. Mohammed, A. Mehmood, F.-N. Pavlidou, and M. Mohorcic, "The role of high-altitude platforms (HAPs) in the global wireless connectivity," *Proceedings of the IEEE*, vol. 99, no. 11, pp. 1939–1953, Nov. 2011.

[17] F. A. d'Oliveira, F. C. L. d. Melo, and T. C. Devezas, "High-altitude platforms—present situation and technology trends," *Journal of Aerospace Technology and Management*, vol. 8, no. 3, pp. 249–262, Jul./Sep. 2016.

[18] A. Aragon-Zavala, J. L. Cuevas-Ruíz, and J. A. Delgado-Penín, *High-altitude platforms for wireless communications*. Wiley Online Library, 2008, vol. 5.

[19] D. Grace and M. Mohorcic, *Broadband communications via high altitude platforms*. John Wiley & Sons, 2011.

[20] E. Cianca, R. Prasad, M. De Sanctis, A. De Luise, M. Antonini, D. Teotino, and M. Ruggieri, "Integrated satellite-HAP systems," *IEEE Communications Magazine*, vol. 43, no. 12, pp. 33–39, Dec. 2005.

[21] J. Thornton, D. Grace, C. Spillard, T. Konefal, and T. Tozer, "Broadband communications from a high-altitude platform: The european HeliNet programme," *Electronics & Communication Engineering Journal*, vol. 13, no. 3, pp. 138–144, Jun. 2001.

[22] W.-Q. Wang and H. Shao, "High altitude platform multichannel SAR for wide-area and staring imaging," *IEEE Aerospace and Electronic Systems Magazine*, vol. 29, no. 5, pp. 12–17, May 2014.

[23] P.-D. Arapoglou, E. T. Michailidis, A. D. Panagopoulos, A. G. Kanatas, and R. Prieto-Cerdeira, "The land mobile earth-space channel," *IEEE Vehicular Technology Magazine*, vol. 6, no. 2, pp. 44–53, Jun. 2011.

[24] A. G. Kanatas and A. D. Panagopoulos, *Radio Wave Propagation and Channel Modeling for Earth–Space Systems*. CRC Press, 2016.

[25] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, "A tutorial on UAVs for wireless networks: Applications, challenges, and open problems," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2334–2360, thirdquarter 2019.

[26] L. Zhang, H. Zhao, S. Hou, Z. Zhao, H. Xu, X. Wu, Q. Wu, and R. Zhang, "A survey on 5G millimeter wave communications for UAV-assisted wireless networks," *IEEE Access*, vol. 7, pp. 117 460–117 504, 2019.

[27] Y. Zeng, Q. Wu, and R. Zhang, "Accessing from the sky: A tutorial on UAV communications for 5G and beyond," *Proceedings of the IEEE*, vol. 107, no. 12, pp. 2327–2375, Dec. 2019.

[28] H. Wang, H. Zhao, J. Zhang, D. Ma, J. Li, and J. Wei, "Survey on unmanned aerial vehicle networks: A cyber physical system perspective," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 2, pp. 1027–1070, thirdquarter 2019.

[29] S. C. Arum, D. Grace, and P. D. Mitchell, "A review of wireless communication using high-altitude platforms for extended coverage and capacity," *Computer Communications*, vol. 157, no. 1, pp. 232–256, May 2020.

[30] N. Bhushan, J. Li, D. Malladi, R. Gilmore, D. Brenner, A. Damnjanovic, R. T. Sukhavasi, C. Patel, and S. Geirhofer, "Network densification: the dominant theme for wireless evolution into 5G," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 82–89, Feb. 2014.

[31] J. G. Andrews, X. Zhang, G. D. Durgin, and A. K. Gupta, "Are we approaching the fundamental limits of wireless network densification?" *IEEE Communications Magazine*, vol. 54, no. 10, pp. 184–190, Oct. 2016.

[32] M. S. Alam, G. K. Kurt, H. Yanikomeroglu, P. Zhu, and N. Dao, "High altitude platform station based super macro base station (HAPS-SMBS) constellations," *arXiv preprint arXiv:2007.08747*, 2020.

[33] S. Sibiya and O. O. Olugbara, "Reliable internet of things network architecture based on high altitude platforms," in *IEEE Conference on Information Communications Technology and Society (ICTAS)*, 2019, pp. 1–4.

[34] M. Gineste, T. Deleu, M. Cohen, N. Chuberre, V. Saravanan, V. Frascolla, M. Mueck, E. C. Strinati, and E. Dutkiewicz, "Narrowband IoT service provision to 5G user equipment via a satellite component," in *IEEE Globecom Workshops (GC Wkshps)*, 2017, pp. 1–4.

[35] A. A. Abu-Arabia, R. Hakimi *et al.*, "Performance of 5G services deployed via HAPS system," in *IEEE 13th International Conference on Telecommunication Systems, Services, and Applications (TSSA)*, 2019, pp. 168–172.

[36] H. Dahrouj, A. Douik, F. Rayal, T. Y. Al-Naffouri, and M.-S. Alouini, "Cost-effective hybrid RF/FSO backhaul solution for next generation wireless systems," *IEEE Wireless Communications*, vol. 22, no. 5, pp. 98–104, Oct. 2015.

[37] R. Taori and A. Sridharan, "Point-to-multipoint in-band mmWave backhaul for 5G networks," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 195–201, Jan. 2015.

[38] F. Yuan, Y. H. Lee, Y. S. Meng, S. Manandhar, and J. T. Ong, "High-resolution ITU-R cloud attenuation model for satellite communications in tropical region," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 9, pp. 6115–6122, Sep. 2019.

[39] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M.-S. Alouini, "FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 218–224, Jan. 2018.

[40] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 57–96, Firstquarter 2016.

[41] A. Alsharoa and M.-S. Alouini, "Facilitating satellite-airborne-terrestrial integration for dynamic and infrastructure-less networks," *arXiv preprint arXiv:1912.03819*, 2019.

[42] A. T. Pham, P. V. Trinh, V. V. Mai, N. T. Dang, and C.-T. Truong, "Hybrid free-space optics/millimeter-wave architecture for 5G cellular backhaul networks," in *IEEE Opto-Electronics and Communications Conference (OECC)*, 2015, pp. 1–3.

[43] I. Bor-Yaliniz and H. Yanikomeroglu, "The new frontier in RAN heterogeneity: Multi-tier drone-cells," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 48–55, Nov. 2016.

[44] M. Mirahsan, "HetHetNets: Heterogeneous wireless cellular networks with heterogeneous traffic," Ph.D. dissertation, Carleton University, 2017.

[45] M. Alzenad and H. Yanikomeroglu, "Coverage and rate analysis for unmanned aerial vehicle base stations with LoS/NLoS propagation," in *IEEE Globecom Workshops (GC Wkshps)*, 2018, pp. 1–7.

[46] K. Kumar, J. Liu, Y.-H. Lu, and B. Bhargava, "A survey of computation offloading for mobile systems," *Mobile networks and Applications*, vol. 18, no. 1, pp. 129–140, Apr. 2013.

[47] C. Wang, C. Liang, F. R. Yu, Q. Chen, and L. Tang, "Computation offloading and resource allocation in wireless cellular networks with mobile edge computing," *IEEE Transactions on Wireless Communications*, vol. 16, no. 8, pp. 4924–4938, Aug. 2017.

[48] "Nws jetstream - layers of the atmosphere." [Online]. Available: www.weather.gov

[49] T. Bai, R. Vaze, and R. W. Heath, "Analysis of blockage effects on urban cellular networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 9, pp. 5070–5083, Sep. 2014.

[50] H. Halbauer, S. Saur, J. Koppenborg, and C. Hoek, "3D beamforming: Performance improvement for cellular networks," *Bell Labs Technical Journal*, vol. 18, no. 2, pp. 37–56, Sep. 2013.

[51] X. Cao, J. Xu, and R. Zhangt, "Mobile edge computing for cellular-connected UAV: Computation offloading and trajectory optimization," in *IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, 2018, pp. 1–5.

[52] M.-A. Messous, H. Sedjelmaci, N. Houari, and S.-M. Senouci, "Computation offloading game for an UAV network in mobile edge computing," in *IEEE International Conference on Communications (ICC)*, 2017, pp. 1–6.

[53] A. Nikitas, E. T. Njoya, and S. Dani, "Examining the myths of connected and autonomous vehicles: analysing the pathway to a driverless mobility paradigm," *International Journal of Automotive Technology and Management*, vol. 19, no. 1-2, pp. 10–30, March 2019.

[54] A. Talebpour and H. S. Mahmassani, "Influence of connected and autonomous vehicles on traffic flow stability and throughput," *Transportation Research Part C: Emerging Technologies*, vol. 71, pp. 143–163, Oct. 2016.

[55] J. Zhang, F.-Y. Wang, K. Wang, W.-H. Lin, X. Xu, and C. Chen, "Data-driven intelligent transportation systems: A survey," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 4, pp. 1624–1639, Dec. 2011.

[56] J. Wang, J. Cho, S. Lee, and T. Ma, "Real time services for future cloud computing enabled vehicle networks," in *IEEE International Conference on Wireless Communications and Signal Processing (WCSP)*, 2011, pp. 1–5.

[57] I. Stojmenovic and S. Wen, "The fog computing paradigm: Scenarios and security issues," in *IEEE Federated Conference on Computer Science and Information Systems*, 2014, pp. 1–4.
[58] J. Stanczak, D. Kozioł, I. Z. Kovács, J. Wigard, M. Wimmer, and R. Amorim, "Enhanced unmanned aerial vehicle communication support in LTE-advanced," in *IEEE Conference on Standards for Communications and Networking (CSCN)*, 2018, pp. 1–6.
[59] D. Bamburry, "Drones: Designed for product delivery," *Design Management Review*, vol. 26, no. 1, pp. 40–48, Jul. 2015.
[60] D. Sarddar, J. Banerjee, S. Chatterjee, P. Ghosh, S. Chakraborty, K. Hui, and M. K. Naskar, "A handover management in LEO satellite network using angular and distance based algorithm," *International Journal of Computer Applications*, vol. 975, p. 8887, Oct. 2011.
[61] ITU, "Recommendation ITU-R F.1569," 2002.
[62] D. Yuniarti, "Regulatory challenges of broadband communication services from high altitude platforms (HAPs)," in *IEEE International Conference on Information and Communications Technology (ICOIACT)*, 2018, pp. 919–922.
[63] ICAO, "Draft regulatory guidance for unmanned aircraft operations – general regulations, APUAS/TF/3 – WP/08," 2019.
[64] H. Liu and F. Tronchetti, "Regulating near-space activities: Using the precedent of the exclusive economic zone as a model?" *Ocean Development & International Law*, vol. 50, no. 2-3, pp. 91–116, Feb. 2019.
[65] ITU, "Report ITU-R F.2471-0," 2019.
[66] ——, "Report ITU-R F.2472-0," 2019.
[67] ——, "Report ITU-R F.2475-0," 2019.
[68] M. Colella, J. N. Martin, and F. Akyildiz, "The HALO network/sup TM," *IEEE Communications Magazine*, vol. 38, no. 6, pp. 142–148, Jun. 2000.
[69] ITU, "World radiocommunication conference 2019 (WRC-19) final acts," 2019.
[70] F. Dong, H. Han, X. Gong, J. Wang, and H. Li, "A constellation design methodology based on QoS and user demand in high-altitude platform broadband networks," *IEEE Transactions on Multimedia*, vol. 18, no. 12, pp. 2384–2397, Dec. 2016.
[71] D. Grace, J. Thornton, G. Chen, G. P. White, and T. C. Tozer, "Improving the system capacity of broadband services using multiple high-altitude platforms," *IEEE Transactions on Wireless Communications*, vol. 4, no. 2, pp. 700–709, Mar. 2005.
[72] Z. Lin, M. Lin, Y. Huang, T. de Cola, and W.-P. Zhu, "Robust multi-objective beamforming for integrated satellite and high altitude platform network with imperfect channel state information," *IEEE Transactions on Signal Processing*, vol. 67, no. 24, pp. 6384–6396, Dec. 2019.
[73] M. Ehrenfried *et al.*, *Stratonauts: Pioneers venturing into the stratosphere*. Springer, 2014.
[74] "Connecting People Everywhere." [Online]. Available: https://www.loon.com/
[75] "SHARP (Stationary High Altitude Relay Platform)." [Online]. Available: http://www.friendsofcrc.ca/Projects/SHARP/sharp.html
[76] "Aerovironment, inc." [Online]. Available: https://www.avinc.com/resources/press-releases/view/solar-high-altitude-long-endurance-uas
[77] "CAPANINA Test Results Summary Report." [Online]. Available: https://www.capanina.org/documents/CAP-D22a-WP44-CGS-PUB-01.pdf
[78] "StratXX." [Online]. Available: http://www.stratxx.com/
[79] "Elevate." [Online]. Available: http://www.zero2infinity.space/elevate/
[80] "Zephyr Pioneering the Stratosphere." [Online]. Available: https://www.airbus.com/defence/uav/zephyr.html
[81] "Flying Aquila: Early lessons from the first full-scale test flight and the path ahead." [Online]. Available: https://engineering.fb.com/connectivity/flying-aquila-early-lessons-from-the-first-full-scale-test-flight-and-the-path-ahead/
[82] "What's up with stratobus?" [Online]. Available: https://www.thalesgroup.com/en/worldwide/space/news/whats-stratobus
[83] "HAPSMobile." [Online]. Available: https://www.hapsmobile.com/
[84] "phasa-35." [Online]. Available: http://prismaticltd.co.uk/products/phasa-35/
[85] "phasa-35 first flight." [Online]. Available: https://www.baesystems.com/en/article/ground-breaking-solar-powered-unmanned-aircraft-makes-first-flight
[86] J. J. Schlesak, A. Alden, and T. Ohno, "A microwave powered high altitude platform," in *IEEE MTT-S International Microwave Symposium Digest*, 1988, pp. 283–286.
[87] W. C. Brown, "A microwaver powered, long duration, high altitude platform," in *IEEE MTT-S International Microwave Symposium Digest*, 1986, pp. 507–510.
[88] X.-Z. Gao, Z.-X. Hou, Z. Guo, J.-X. Liu, and X.-Q. Chen, "Energy management strategy for solar-powered high-altitude long-endurance aircraft," *Energy Conversion and Management*, vol. 70, pp. 20–30, Jun. 2013.
[89] W. Phillips, "Some design considerations for solar-powered aircraft," National Aeronautics and Space Administration (NASA), Hampton, VA (USA), Tech. Rep., 1980.
[90] A. Alsahlani, L. Johnston, P. Atcliffe *et al.*, "Design of a high altitude long endurance flying-wing solar-powered unmanned air vehicle," *Progress in Flight Physics*, vol. 9, pp. 3–24, Oct. 2017.
[91] E. Cestino, "Design of solar high altitude long endurance aircraft for multi payload & operations," *Aerospace Science and Technology*, vol. 10, no. 6, pp. 541–550, Sep. 2006.
[92] K. Yoshikawa, W. Yoshida, T. Irie, H. Kawasaki, K. Konishi, H. Ishibashi, T. Asatani, D. Adachi, M. Kanematsu, H. Uzu *et al.*, "Exceeding conversion efficiency of 26% by heterojunction interdigitated back contact solar cell with thin film Si technology," *Solar Energy Materials and Solar Cells*, vol. 173, pp. 37–42, Dec. 2017.
[93] M. A. Green and S. P. Bremner, "Energy conversion approaches and materials for high-efficiency photovoltaics," *Nature Materials*, vol. 16, no. 1, pp. 23–34, 2017.
[94] X. Zheng and L. Zhang, "Photonic nanostructures for solar energy conversion," *Energy & Environmental Science*, vol. 9, no. 8, pp. 2511–2532, Sep. 2016.
[95] "MicroLink Devices." [Online]. Available: http://www.mldevices.com/index.php/news
[96] G. Zubi, R. Dufo-López, M. Carvalho, and G. Pasaoglu, "The lithium-ion battery: State of the art and future perspectives," *Renewable and Sustainable Energy Reviews*, vol. 89, pp. 292–308, Jun. 2018.
[97] C. Thomas, "Fuel cell and battery electric vehicles compared," *International Journal of Hydrogen Energy*, vol. 34, no. 15, pp. 6005–6020, Aug. 2009.
[98] T. Wilberforce, Z. El-Hassan, F. Khatib, A. Al Makky, A. Baroutaji, J. G. Carton, and A. G. Olabi, "Developments of electric cars and fuel cell hydrogen electric cars," *International Journal of Hydrogen Energy*, vol. 42, no. 40, pp. 25 695–25 734, Oct. 2017.
[99] M. Latva-aho and K. Leppänen, "Key drivers and research challenges for 6G ubiquitous wireless intelligence," in *White Paper*. University of Oulu, Sep. 2019.
[100] M. Di Renzo, M. Debbah, D.-T. Phan-Huy, A. Zappone, M.-S. Alouini, C. Yuen, V. Sciancalepore, G. C. Alexandropoulos, J. Hoydis, H. Gacanin *et al.*, "Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come," *EURASIP Journal on Wireless Communications and Networking*, vol. 2019, no. 1, pp. 1–20, May 2019.
[101] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M.-S. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116 753–116 773, Aug. 2019.
[102] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Transactions on Wireless Communications*, vol. 18, no. 11, pp. 5394–5409, Nov. 2019.
[103] Y. Han, W. Tang, S. Jin, C.-K. Wen, and X. Ma, "Large intelligent surface-assisted wireless communication exploiting statistical CSI," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 8238–8242, Aug. 2019.
[104] C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "A new wireless communication paradigm through software-controlled metasurfaces," *IEEE Communications Magazine*, vol. 56, no. 9, pp. 162–169, Sep. 2018.

[105] T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, and Q. Cheng, "Coding metamaterials, digital metamaterials and programmable metamaterials," *Light: Science & Applications*, vol. 3, no. 10, pp. e218–e218, Oct. 2014.

[106] G. Perez-Palomino, P. Baine, R. Dickie, M. Bain, J. A. Encinar, R. Cahill, M. Barba, and G. Toso, "Design and experimental validation of liquid crystal-based reconfigurable reflectarray elements with improved bandwidth in F-band," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 1704–1713, Apr. 2013.

[107] E. Carrasco, M. Tamagnone, and J. Perruisseau-Carrier, "Tunable graphene reflective cells for THz reflectarrays and generalized law of reflection," *Applied Physics Letters*, vol. 102, no. 10, pp. 1–5, 2013.

[108] E. Carrasco and J. Perruisseau-Carrier, "Reflectarray antenna at terahertz using graphene," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 253–256, Feb. 2013.

[109] R. Kowerdziej, M. Olifierczuk, J. Parka, and J. Wrobel, "Terahertz characterization of tunable metamaterial based on electrically controlled nematic liquid crystal," *Applied Physics Letters*, vol. 105, no. 2, pp. 1–5, 2014.

[110] Z. Liu and B. Bai, "Ultra-thin and high-efficiency graphene metasurface for tunable terahertz wave manipulation," *Optics Express*, vol. 25, no. 8, pp. 8584–8592, Apr. 2017.

[111] "NTT DOCOMO and metawave announce successful demonstration of 28GHz-band 5G using world's first meta-structure technology." [Online]. Available: https://bwnews.pr/2IhH8cc

[112] "Greenerwave." [Online]. Available: http://greenerwave.com/

[113] H. Long, M. Chen, Z. Yang, B. Wang, Z. Li, X. Yun, and M. Shikh-Bahaei, "Reflections in the sky: Joint trajectory and passive beamforming design for secure UAV networks with reconfigurable intelligent surface," *arXiv preprint arXiv:2005.10559*, 2020.

[114] S. Alfattani, W. Jaafar, Y. Hmamouche, H. Yanikomeroglu, A. Yongaçoglu, N. Dao, P. Zhu *et al.*, "Aerial platforms with reconfigurable smart surfaces for 5G and beyond," *arXiv preprint arXiv:2006.09328v3*, 2020.

[115] C. Huang, G. C. Alexandropoulos, A. Zappone, M. Debbah, and C. Yuen, "Energy efficient multi-user MISO communication using low resolution large intelligent surfaces," in *IEEE Globecom Workshops (GC Wkshps)*, 2018, pp. 1–6.

[116] K. Ntontin, M. Di Renzo, J. Song, F. Lazarakis, J. de Rosny, D.-T. Phan-Huy, O. Simeone, R. Zhang, M. Debbah, G. Lerosey *et al.*, "Reconfigurable intelligent surfaces vs. relaying: Differences, similarities, and performance comparison," *arXiv preprint arXiv:1908.08747*, 2019.

[117] W. Tang, M. Z. Chen, X. Chen, J. Y. Dai, Y. Han, M. Di Renzo, Y. Zeng, S. Jin, Q. Cheng, and T. J. Cui, "Wireless communications with reconfigurable intelligent surface: Path loss modeling and experimental measurement," *arXiv preprint arXiv:1911.05326*, 2019. [Online]. Available: http://arxiv.org/abs/1911.05326

[118] W. Khawaja, I. Guvenc, D. W. Matolak, U.-C. Fiebig, and N. Schneckenburger, "A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2361–2391, thirdquarter 2019.

[119] E. Lutz, D. Cygan, M. Dippold, F. Dolainsky, and W. Papke, "The land mobile satellite communication channel-recording, statistics, and channel model," *IEEE Transactions on Vehicular Technology*, vol. 40, no. 2, pp. 375–386, May 1991.

[120] M. Vázquez-Castro, F. Pérez-Fontán, and B. Arbesser-Rastburg, "Channel modeling for satellite and HAPS system design," *Wireless Communications and Mobile Computing*, vol. 2, no. 3, pp. 285–300, May 2002.

[121] C. Oestges and D. Vanhoenacker-Janvier, "Coverage modelling of high-altitude platforms communication systems," *Electronics Letters*, vol. 37, no. 2, pp. 119–121, Jan. 2001.

[122] F. Dovis, R. Fantini, M. Mondin, and P. Savi, "Small-scale fading for high-altitude platform (HAP) propagation channels," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 3, pp. 641–647, Apr. 2002.

[123] ITU, "Recommendation ITU-R P.681-11," 2019.

[124] J. L. Cuevas-Ruíz and J. A. Delgado-Penin, "Channel model based on semi-Markovian processes. an approach for HAPS systems," in *IEEE 14th International Conference on Electronics, Communications and Computers (CONIELECOMP)*, 2004, pp. 52–56.

[125] J. L. Cuevas-Ruiz and J. A. Delgado-Penin, "A statistical switched broadband channel model for HAPS links," in *IEEE Wireless Communications and Networking Conference*, 2004, pp. 290–294.

[126] P. R. King, B. G. Evans, and S. Stavrou, "Physical-statistical model for the land mobile-satellite channel applied to satellite/HAP-MIMO," in *11th VDE European Wireless Conference–Next Generation wireless and Mobile Communications and Services*, 2005, pp. 1–5.

[127] E. T. Michailidis, G. Efthymoglou, and A. G. Kanatas, "Spatially correlated 3-D HAP-MIMO fading channels," in *IEEE Globecom Workshops*, 2008, pp. 1–7.

[128] E. T. Michailidis and A. G. Kanatas, "On the capacity of 3-D space-time correlated HAP-MIMO channels," in *IEEE Second International Conference on Advances in Satellite and Space Communications*, 2010, pp. 87–92.

[129] ——, "Three-dimensional HAP-MIMO channels: Modeling and analysis of space-time correlation," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 5, pp. 2232–2242, Jun. 2010.

[130] ——, "Statistical simulation modeling of 3-D HAP-MIMO channels," *Wireless Personal Communications*, vol. 65, no. 4, pp. 833–841, Apr. 2012.

[131] ——, "Wideband HAP-MIMO channels: A 3-D modeling and simulation approach," *Wireless Personal Communications*, vol. 74, no. 2, pp. 639–664, Jul. 2014.

[132] E. T. Michailidis, P. Theofilakos, and A. G. Kanatas, "Three-dimensional modeling and simulation of MIMO mobile-to-mobile via stratospheric relay fading channels," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 5, pp. 2014–2030, Jun. 2012.

[133] H. A. Mendoza and G. Corral-Briones, "On the application of three dimensional HAP MIMO model in UAV environment," *Vehicular Communications*, vol. 16, pp. 72–84, Apr. 2019.

[134] V. Nikolaidis, N. Moraitis, and A. G. Kanatas, "Dual-polarized narrowband MIMO LMS channel measurements in urban environments," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 2, pp. 763–774, Feb. 2016.

[135] Z. Lian, L. Jiang, C. He, and D. He, "A non-stationary 3-D wideband GBSM for HAP-MIMO communication systems," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 2, pp. 1128–1139, Feb. 2019.

[136] M. Yang, S. Zhang, X. Shao, Q. Guo, and W. Tang, "Statistical modeling of the high altitude platform dual-polarized MIMO propagation channel," *China Communications*, vol. 14, no. 3, pp. 43–54, Mar. 2017.

[137] Z. Lian, L. Jiang, C. He, and D. He, "A 3-D multiuser HAP-MIMO channel model based on dynamic evolution of LOS components," *Chinese Journal of Electronics*, vol. 28, no. 3, pp. 465–450, May 2019.

[138] Z. Ma, B. Ai, R. He, G. Wang, Y. Niu, and Z. Zhong, "A wideband non-stationary air-to-air channel model for UAV communications," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 2, pp. 1214–1226, Feb. 2019.

[139] D. Giggenbach, R. Purvinskis, M. Werner, and M. Holzbock, "Stratospheric optical inter-platform links for high altitude platforms," in *20th AIAA International Communication Satellite Systems Conference and Exhibit*, 2002, p. 1910.

[140] L. C. Andrews and R. L. Phillips, *Laser beam propagation through random media*. SPIE Press, 2005.

[141] A. Al-Habash, L. C. Andrews, and R. L. Phillips, "Mathematical model for the irradiance probability density function of a laser beam propagating through turbulent media," *Optical Engineering*, vol. 40, no. 8, pp. 1554–1563, Aug. 2001.

[142] A. K. Majumdar, "Free-space laser communication performance in the atmospheric channel," *Journal of Optical and Fiber Communications Reports*, vol. 2, no. 4, pp. 345–396, Nov. 2005.

[143] I. R. Palma-Lázgare and J. A. Delgado-Penín, "WiMAX HAPS-based downlink performance employing geometrical and statistical propagation-channel characteristics," *URSI Radio Science Bulletin*, vol. 2010, no. 333, pp. 50–66, Mar. 2010.

[144] I. Zakia, "Capacity of HAP-MIMO channels for high-speed train communications," in *IEEE 3rd International Conference on Wireless and Telematics (ICWT)*, 2017, pp. 26–30.

[145] P. G. Sudheesh, N. Sharma, M. Magarini, and P. Muthuchidambaranathan, "Effect of imperfect CSI on interference alignment in multiple-high altitude platforms based communication," *Physical Communication*, vol. 29, pp. 336–342, Aug. 2017.

[146] J. Thornton, D. Grace, M. H. Capstick, and T. C. Tozer, "Optimizing an array of antennas for cellular coverage from a high altitude platform," *IEEE Transactions on Wireless Communications*, vol. 2, no. 3, pp. 484–492, May 2003.

[147] C. K. Datsikas, K. P. Peppas, N. C. Sagias, and G. S. Tombras, "Serial free-space optical relaying communications over gamma-gamma atmospheric turbulence channels," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 2, no. 8, pp. 576–586, Aug. 2010.

[148] M. Sharma, D. Chadha, and V. Chandra, "High-altitude platform for free-space optical communication: Performance evaluation and reliability analysis," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 8, no. 8, pp. 600–609, Aug. 2016.

[149] A. M. Salhab, "A new scenario of triple-hop mixed RF/FSO/RF relay network with generalized order user scheduling and power allocation," *EURASIP Journal on Wireless Communications and Networking*, vol. 2016, no. 1, pp. 1–20, Oct. 2016.

[150] E. T. Michailidis, N. Nomikos, P. Bithas, D. Vouyioukas, and A. G. Kanatas, "Outage probability of triple-hop mixed RF/FSO/RF stratospheric communication systems," in *IEEE 10th International Conference on Advances in Satellite and Space Communications (SPACOMM)*, 2018, pp. 1–6.

[151] A. Alsharoa and M.-S. Alouini, "Improvement of the global connectivity using integrated satellite-airborne-terrestrial networks with resource optimization," *arXiv preprint arXiv:1912.03828*, 2019.

[152] A. Abrardo and D. SENNATI, "Centralized radio resource management strategies with heterogeneous traffics in HAPS WCMA cellular systems," *IEICE Transactions on Communications*, vol. 86, no. 3, pp. 1040–1049, Mar. 2003.

[153] Y. C. Foo, W. L. Lim, and R. Tafazolli, "Centralized total received power based call admission control for high altitude platform station UMTS," in *13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 2002, pp. 1596–1600.

[154] ——, "Centralized downlink call admission control for high altitude platform station UMTS with onboard power resource sharing," in *IEEE 56th Vehicular Technology Conference*, 2002, pp. 549–553.

[155] ——, "Call admission control schemes for high altitude platform station and terrestrial tower-based hierarchical UMTS," in *IEEE 9th International Conference on Communications Systems (ICCS)*, 2004, pp. 531–536.

[156] G. Araniti, A. Molinaro, and A. Iera, "Multicast in terrestrial-HAP systems: User number vs. user distribution oriented RRM policies," in *IEEE 66th Vehicular Technology Conference*, 2007, pp. 154–158.

[157] F. Adachi, D. Garg, S. Takaoka, and K. Takeda, "Broadband CDMA techniques," *IEEE Wireless communications*, vol. 12, no. 2, pp. 8–18, Apr. 2005.

[158] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. K. Bhargava, "A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 10, pp. 2181–2195, Oct. 2017.

[159] Y. C. Foo and W. L. Lim, "Speed and direction adaptive call admission control for high altitude platform station (HAPS) UMTS," in *IEEE Military Communications Conference (MILCOM)*, 2005, pp. 2182–2188.

[160] E. T. Ceran, T. Erkilic, E. Uysal-Biyikoglu, T. Girici, and K. Leblebicioglu, "Optimal energy allocation policies for a high altitude flying wireless access point," *Transactions on Emerging Telecommunications Technologies*, vol. 28, no. 4, p. e3034, Mar. 2016.

[161] A. Raschellà, G. Araniti, A. Iera, and A. Molinaro, "High altitude platforms: Radio resource management policy for MBMS applications," in *International Conference on Personal Satellite Services*. Springer, 2009, pp. 85–93.

[162] J. Liu, L. Li, F. Yang, X. Liu, X. Li, X. Tang, and Z. Han, "Minimization of offloading delay for two-tier UAV with mobile edge computing," in *Proc. International Wireless Communications Mobile Computing Conference (IWCMC)*, 2019, pp. 1534–1538.

[163] S. Wang, M. Chen, C. Yin, W. Saad, C. S. Hong, S. Cui, and H. V. Poor, "Federated learning for task and resource allocation in wireless high altitude balloon networks," *arXiv preprint arXiv:2003.09375*, 2020.

[164] J. Jiang, B. Zhang, D. Guo, and Z. Ye, "A channel assigning algorithm for platform displacement model in HAPS communication system," *Telecommunication Engineering*, vol. 55, no. 8, pp. 906–912, Aug. 2015.

[165] M. Guan, Z. Wu, Y. Cui, X. Cao, L. Wang, J. Ye, and B. Peng, "An intelligent wireless channel allocation in HAPS 5G communication system based on reinforcement learning," *EURASIP Journal on Wireless Communications and Networking*, vol. 2019, no. 138, pp. 1–10, May 2019.

[166] Y. Liu, D. Grace, and P. D. Mitchell, "Exploiting platform diversity for GoS improvement for users with different high altitude platform availability," *IEEE Transactions on Wireless Communications*, vol. 8, no. 1, pp. 196–203, Feb. 2009.

[167] M. Guan, L. Wang, and L. Chen, "Channel allocation for hot spot areas in HAPS communication based on the prediction of mobile user characteristics," *Intelligent Automation & Soft Computing*, vol. 22, no. 4, pp. 613–620, Apr. 2016.

[168] A. Ibrahim and A. S. Alfa, "Using Lagrangian relaxation for radio resource allocation in high altitude platforms," *IEEE Transactions on Wireless Communications*, vol. 14, no. 10, pp. 5823–5835, Oct. 2015.

[169] ——, "Optimizing radio resources for multicasting on high-altitude platforms," *EURASIP Journal on Wireless Communications and Networking*, vol. 2019, no. 1, p. 213, Aug. 2019.

[170] A. Ibrahim and A. Alfa, *Optimization Methods for User Admissions and Radio Resource Allocation for Multicasting over High Altitude Platforms*. River Publishers, 2019.

[171] M. Oodo, R. Miura, T. Hori, T. Morisaki, K. Kashiki, and M. Suzuki, "Sharing and compatibility study between fixed service using high altitude platform stations (HAPS) and other services in the 31/28 GHz bands," *Wireless Personal Communications*, vol. 23, no. 1, pp. 3–14, Oct. 2002.

[172] P. Likitthanasate, D. Grace, and P. D. Mitchell, "Spectrum etiquettes for terrestrial and high-altitude platform-based cognitive radio systems," *IET communications*, vol. 2, no. 6, pp. 846–855, Jul. 2008.

[173] M. Mokayef, T. A. Rahman, R. Ngah, and M. Y. Ahmed, "Spectrum sharing model for coexistence between high altitude platform system and fixed services at 5.8 GHz," *International Journal of Multimedia and Ubiquitous Engineering*, vol. 8, no. 5, pp. 265–275, 2013.

[174] S. Wang, Y. Li, Q. Wang, M. Su, and W. Zhou, "Dynamic downlink resource allocation based on imperfect estimation in LEO-HAP cognitive system," in *IEEE 11th International Conference on Wireless Communications and Signal Processing (WCSP)*, 2019, pp. 1–6.

[175] H. Ahmadi, K. Katzis, and M. Z. Shakir, "A novel airborne self-organising architecture for 5G+ networks," in *IEEE 86th Vehicular Technology Conference (VTC-Fall)*, 2017, pp. 1–5.

[176] A. D. Olver, P. Clarricoats, L. Shafai, and A. Kishk, *Microwave Horns and Feeds*. IET, 1994, no. 39.

[177] G. M. Djuknic, J. Freidenfelds, and Y. Okunev, "Establishing wireless communications services via high-altitude aeronautical platforms: A concept whose time has come?" *IEEE Communications Magazine*, vol. 35, no. 9, pp. 128–135, Sep. 1997.

[178] Y. Albagory, "Flat-top ring-shaped cell design for high-altitude platform communications," *International Journal of Computer Network and Information Security*, vol. 5, no. 7, p. 51, Jun. 2013.

[179] M. H. Capstick and D. Grace, "High altitude platform mm-Wave aperture antenna steering solutions," *Wireless Personal Communications*, vol. 32, no. 3-4, pp. 215–236, Feb. 2005.

[180] J. Thornton, D. A. Pearce, D. Grace, M. Oodo, K. Katzis, and T. C. Tozer, "Effect of antenna beam pattern and layout on cellular performance in high altitude platform communications," *Wireless Personal Communications*, vol. 35, no. 1-2, pp. 35–51, Oct. 2005.

[181] Y. Albagory and A. E. Abbas, "Smart cell design for high altitude platforms communication," *AEU-International Journal of Electronics and Communications*, vol. 67, no. 9, pp. 780–786, Sep. 2013.

[182] S. C. Arum, D. Grace, P. D. Mitchell, and M. D. Zakaria, "Beam-pointing algorithm for contiguous high-altitude platform cell formation for extended coverage," in *IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, 2019, pp. 1–5.

[183] M. D. Zakaria, D. Grace, P. D. Mitchell, T. M. Shami, and N. Morozs, "Exploiting user-centric joint transmission–coordinated multipoint with a high altitude platform system architecture," *IEEE Access*, vol. 7, pp. 38 957–38 972, Mar. 2019.
[184] G. Chen, D. Grace, and T. C. Tozer, "Performance of multiple high altitude platforms using directive HAP and user antennas," *Wireless Personal Communications*, vol. 32, no. 3-4, pp. 275–299, Feb. 2005.
[185] F. Dong, M. Li, X. Gong, H. Li, and F. Gao, "Diversity performance analysis on multiple HAP networks," *Sensors*, vol. 15, no. 7, pp. 15 398–15 418, Jun. 2015.
[186] D.-W. Yue, S. Xu, and H. H. Nguyen, "Diversity gain of millimeter-wave massive MIMO systems with distributed antenna arrays," *EURASIP Journal on Wireless Communications and Networking*, vol. 2019, no. 1, p. 54, Mar. 2019.
[187] Z. Lian, L. Jiang, C. He, and D. He, "User grouping and beamforming for HAP massive MIMO systems based on statistical-eigenmode," *IEEE Wireless Communications Letters*, vol. 8, no. 3, pp. 961–964, Jun. 2019.
[188] M. Guan, Z. Wu, Y. Cui, X. Cao, L. Wang, J. Ye, and B. Peng, "Efficiency evaluations based on artificial intelligence for 5G massive MIMO communication systems on high-altitude platform stations," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 10, pp. 6632–6640, Oct. 2019.
[189] A. Benjebbour, "An overview of non-orthogonal multiple access," *ZTE Communications*, vol. 15, no. S1, pp. 21–30, June 2017.
[190] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, "What will 5G be?" *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.
[191] F. Rusek and J. B. Anderson, "Constrained capacities for faster-than-Nyquist signaling," *IEEE Transactions on Information Theory*, vol. 55, no. 2, pp. 764–775, Feb. 2009.
[192] J. A. Prakash and G. R. Reddy, "Efficient prototype filter design for filter bank multicarrier (FBMC) system based on ambiguity function analysis of hermite polynomials," in *IEEE International Mutli-Conference on Automation, Computing, Communication, Control and Compressed Sensing (iMac4s)*, 2013, pp. 580–585.
[193] Z. E. Ankaralı, B. Peköz, and H. Arslan, "Enhanced OFDM for 5G RAN," *ZTE Communications*, vol. 15, no. S1, pp. 11–20, Jun. 2020.
[194] J. B. Anderson, F. Rusek, and V. Öwall, "Faster-than-Nyquist signaling," *Proceedings of the IEEE*, vol. 101, no. 8, pp. 1817–1830, Mar. 2013.
[195] J. E. Mazo, "Faster-than-Nyquist signaling," *The Bell System Technical Journal*, vol. 54, no. 8, pp. 1451–1462, Oct. 1975.
[196] A. D. Liveris and C. N. Georghiades, "Exploiting faster-than-Nyquist signaling," *IEEE Transactions on Communications*, vol. 51, no. 9, pp. 1502–1511, Sep. 2003.
[197] E. Bedeer, M. H. Ahmed, and H. Yanikomeroglu, "A very low complexity successive symbol-by-symbol sequence estimator for faster-than-Nyquist signaling," *IEEE Access*, vol. 5, pp. 7414–7422, Mar. 2017.
[198] ——, "Low-complexity detection of high-order QAM faster-than-Nyquist signaling," *IEEE Access*, vol. 5, pp. 14 579–14 588, Jun. 2017.
[199] E. ConsumerLab. 10 hot consumertrends 2030: The internet of senses. [Online]. Available: https://www.ericsson.com/4ae13b/assets/local/reports-papers/consumerlab/reports/2019/10hctreport2030.pdf
[200] F. Rusek and J. B. Anderson, "The two dimensional Mazo limit," in *IEEE International Symposium on Information Theory (ISIT)*, 2005, pp. 970–974.
[201] ——, "Multistream faster than Nyquist signaling," *IEEE Transactions on Communications*, vol. 57, no. 5, pp. 1329–1340, May 2009.
[202] D. Dasalukunte, F. Rusek, and V. Owall, "Multicarrier faster-than-Nyquist transceivers: Hardware architecture and performance analysis," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 58, no. 4, pp. 827–838, May 2010.
[203] S. Peng, A. Liu, L. Song, I. Memon, and H. Wang, "Spectral efficiency maximization for deliberate clipping-based multicarrier faster-than-Nyquist signaling," *IEEE Access*, vol. 6, pp. 13 617–13 623, Mar. 2018.
[204] B. Cai, A. Liu, and X. Liang, "Low-complexity selective mapping methods for multicarrier faster-than-Nyquist signaling," *IEEE Access*, vol. 8, pp. 31 420–31 431, Feb. 2020.
[205] Y. Ma, F. Tian, N. Wu, B. Li, and X. Ma, "A low-complexity receiver for multicarrier faster-than-Nyquist signaling over frequency selective channels," *IEEE Communications Letters*, vol. 24, no. 1, pp. 81–85, Jan. 2019.
[206] K. Higuchi and A. Benjebbour, "Non-orthogonal multiple access (NOMA) with successive interference cancellation for future radio access," *IEICE Transactions on Communications*, vol. 98, no. 3, pp. 403–414, Mar. 2015.
[207] M. Vaezi, R. Schober, Z. Ding, and H. V. Poor, "Non-orthogonal multiple access: Common myths and critical questions," *IEEE Wireless Communications*, vol. 26, no. 5, pp. 174–180, Oct. 2019.
[208] P. He, N. Cheng, and J. Cui, "Handover performance analysis of cellular communication system from high altitude platform in the swing state," in *IEEE International Conference on Signal and Image Processing (ICSIP)*, 2016, pp. 407–411.
[209] D. Grace, K. Katzis, D. Pearce, and P. Mitchell, "Low-latency MAC-layer handoff for a high-altitude platform delivering broadband communications," *URSI Radio Science Bulletin*, vol. 2010, no. 333, pp. 39–49, Mar. 2010.
[210] S. Alsamhi and N. Rajput, "An intelligent hand-off algorithm to enhance quality of service in high altitude platforms using neural network," *Wireless Personal Communications*, vol. 82, no. 4, pp. 2059–2073, Jan. 2015.
[211] Y. Albagory, M. Nofal, and A. Ghoneim, "Handover performance of unstable-yaw stratospheric high-altitude stations," *Wireless Personal Communications*, vol. 84, no. 4, pp. 2651–2663, May 2015.
[212] P. He, N. Cheng, and S. Ni, "Improved LMS predictive link triggering for handover in HAPS communication system," in *IEEE 8th International Conference on Wireless Communications & Signal Processing (WCSP)*, 2016, pp. 1–5.
[213] S.-y. Ni, S. Jin, and H.-l. Hong, "A handover decision algorithm with an adaptive threshold applied in HAPS communication system," in *Theory, Methodology, Tools and Applications for Modeling and Simulation of Complex Systems*. Springer, 2016, pp. 38–47.
[214] P. He, N. Cheng, S. Ni, and C. Li, "An adaptive handover scheme based on cooperative transmission from high altitude platform stations," in *IEEE 2nd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)*, 2017, pp. 1306–1310.
[215] X. Wang, L. Li, and W. Zhou, "The effect of HAPS unstable movement on handover performance," in *IEEE 28th Wireless and Optical Communications Conference (WOCC)*, 2019, pp. 1–5.
[216] K. Li, Y. Li, Z. Qiu, Q. Wang, J. Lu, and W. Zhou, "Handover procedure design and performance optimization strategy in LEO-HAP system," in *IEEE 11th International Conference on Wireless Communications and Signal Processing (WCSP)*, 2019, pp. 1–7.
[217] S. Li, D. Grace, J. Wei, and D. Ma, "Directional traffic-aware intra-HAP handoff scheme for HAP communications systems," *URSI Radio Science Bulletin*, vol. 2010, no. 334, pp. 11–18, Sep. 2010.
[218] S. Li, L. Wang, G. David, and D. Ma, "Cooperative directional inter-cell handover scheme in high altitude platform communications systems," *Journal of Electronics (China)*, vol. 28, no. 2, p. 249, Oct. 2011.
[219] K. Katzis and D. Grace, "Inter-high-altitude-platform handoff for communications systems with directional antennas," *URSI Radio Science Bulletin*, vol. 2010, no. 333, pp. 29–38, Dec. 2010.
[220] S. Li, D. Grace, J. Wei, and D. Ma, "A novel guaranteed handover scheme for HAP communications systems with adaptive modulation and coding," in *IEEE 72nd Vehicular Technology Conference (VTC-Fall)*, 2010, pp. 1–5.
[221] F. An, Y. Wang, and F. Meng, "A load balancing handoff algorithm based on RSSI and energy-aware in HAPs network," in *IEEE International Conference on Signal Processing, Communication and Computing (ICSPCC 2013)*, 2013, pp. 1–6.
[222] V. Hehtke, J. Kiam, and A. Schulte, *An Autonomous Mission Management System to Assist Decision Making of a HALE Operator*. Deutsche Gesellschaft für Luft-und Raumfahrt-Lilienthal-Oberth eV, 2017.
[223] O. Anicho, P. B. Charlesworth, G. S. Baicher, A. Nagar, and N. Buckley, "Comparative study for coordinating multiple unmanned HAPS for communications area coverage," in *International Conference on Unmanned Aircraft Systems (ICUAS)*, 2019, pp. 467–474.

[224] O. Anicho, P. B. Charlesworth, G. S. Baicher, and A. Nagar, "Autonomously coordinated multi-HAPS communications network: Failure mitigation in volcanic incidence area coverage," in *IEEE International Conference on Communication, Networks and Satellite (Comnetsat)*, 2019, pp. 79–84.
[225] K. Kaur, S. Garg, G. S. Aujla, N. Kumar, J. J. Rodrigues, and M. Guizani, "Edge computing in the industrial internet of things environment: Software-defined-networks-based edge-cloud interplay," *IEEE Communications Magazine*, vol. 56, no. 2, pp. 44–51, Feb. 2018.
[226] B. Han, V. Gopalakrishnan, L. Ji, and S. Lee, "Network function virtualization: Challenges and opportunities for innovations," *IEEE Communications Magazine*, vol. 53, no. 2, pp. 90–97, Feb. 2015.
[227] L. U. Khan, I. Yaqoob, N. H. Tran, Z. Han, and C. S. Hong, "Network slicing: Recent advances, taxonomy, requirements, and open research challenges," *IEEE Access*, vol. 8, pp. 36 009–36 028, Feb. 2020.
[228] Y. Shi, Y. Cao, J. Liu, and N. Kato, "A cross-domain SDN architecture for multi-layered space-terrestrial integrated networks," *IEEE Network*, vol. 33, no. 1, pp. 29–35, Jan./Feb. 2019.
[229] K. Chen, S. Zhao, N. Lv, W. Gao, X. Wang, and X. Zou, "Segment routing based traffic scheduling for the software-defined airborne backbone network," *IEEE Access*, vol. 7, pp. 106 162–106 178, 2019.
[230] L. Yang, H. Yao, J. Wang, C. Jiang, A. Benslimane, and Y. Liu, "Multi-UAV enabled load-balance mobile edge computing for IoT networks," *IEEE Internet of Things Journal*, 2020.
[231] Z. Yang, C. Pan, K. Wang, and M. Shikh-Bahaei, "Energy efficient resource allocation in UAV-enabled mobile edge computing networks," *IEEE Transactions on Wireless Communications*, vol. 18, no. 9, pp. 4576–4589, Sep. 2019.
[232] F. Zhou, R. Q. Hu, Z. Li, and Y. Wang, "Mobile edge computing in unmanned aerial vehicle networks," *IEEE Wireless Communications*, vol. 27, no. 1, pp. 140–146, Feb. 2020.
[233] A. Asheralieva and D. Niyato, "Hierarchical game-theoretic and reinforcement learning framework for computational offloading in UAV-enabled mobile edge computing networks with multiple service providers," *IEEE Internet of Things Journal*, vol. 6, no. 5, pp. 8753–8769, Oct. 2019.
[234] T. Darwish, G. K. Kurt, H. Yanikomeroglu, G. Senarath, and P. Zhu, "A Vision of Self-Evolving Network Management for Future Intelligent Vertical HetNet," *arXiv preprint arXiv:2009.02771*, 2020.
[235] S. Branco, A. G. Ferreira, and J. Cabral, "Machine learning in resource-scarce embedded systems, FPGAs, and end-devices: A survey," *Electronics*, vol. 8, no. 11, p. 1289, Nov. 2019.
[236] A. Chandler, "Microchip introduces the industry's first MCU with integrated 2D GPU and integrated DDR2 memory for groundbreaking graphics capabilities," https://cutt.ly/LaieMgt, accessed: 2020-01-20.
[237] R. Dirvin, "Next-generation Armv8.1-M architecture: Delivering enhanced machine learning and signal processing for the smallest embedded devices," https://www.arm.com/company/news/2019/02/next-generation-armv8-1-m-architecture, accessed: 2020-01-20.
[238] STMicroelectronics, "Ism330dhcx: Machine learning core," https://www.st.com/content/ccc/resource/technical/document/application_note/group1/60/c8/a2/6b/35/ab/49/6a/DM00651838/files/DM00651838.pdf/jcr:content/translations/en.DM00651838.pdf, accessed: 2020-01-20.
[239] L. Zhang, Y.-C. Liang, and D. Niyato, "6G visions: Mobile ultra-broadband, super Internet-of-things, and artificial intelligence," *China Communication*, vol. 16, no. 8, pp. 1–14, Aug. 2019.
[240] D. D. Nguyen, H. X. Nguyen, and L. B. White, "Reinforcement learning with network-assisted feedback for heterogeneous RAT selection," *IEEE Transactions on Wireless Communications*, vol. 16, no. 9, pp. 6062–6076, Sep. 2017.
[241] V. Raj, I. Dias, T. Tholeti, and S. Kalyani, "Spectrum access in cognitive radio using a two-stage reinforcement learning approach," *IEEE Journal on Selected Topics in Signal Processing*, vol. 12, no. 1, pp. 20–34, Feb. 2018.
[242] M. Qiao, H. Zhao, L. Zhou, C. Zhu, and S. Huang, "Topology-transparent scheduling based on reinforcement learning in self-organized wireless networks," *IEEE Access*, vol. 6, pp. 20 221–20 230, 2018.
[243] N. C. Luong, D. T. Hoang, S. Gong, D. Niyato, P. Wang, Y.-C. Liang, and D. I. Kim, "Applications of deep reinforcement learning in communications and networking: A survey," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 4, pp. 3133–3174, fourthquarter 2019.
[244] A. Kusupati, M. Singh, K. Bhatia, A. Kumar, P. Jain, and M. Varma, "FastGRNN: A fast, accurate, stable and tiny kilobyte sized gated recurrent neural network," in *Advances in Neural Information Processing Systems (NIPS)*, 2018, pp. 9017–9028.
[245] L. Hochul, L. Jaehun, C. L. Young, H. Hyuck, and K. Sooyong, "Mobile collaborative computing on the fly," *IEEE Access*, vol. 58, pp. 1574–1192, Aug. 2019.
[246] A. M. Ismaiel, E. Elsaidy, Y. Albagory, H. A. Atallah, A. B. Abdel-Rahman, and T. Sallam, "Performance improvement of high altitude platform using concentric circular antenna array based on particle swarm optimization," *AEU-International Journal of Electronics and Communications*, vol. 91, pp. 85–90, Jul. 2018.
[247] J. Liu, L. Li, F. Yang, X. Liu, X. Li, X. Tang, and Z. Han, "Minimization of offloading delay for two-tier UAV with mobile edge computing," in *IEEE 15th International Wireless Communications & Mobile Computing Conference (IWCMC)*, 2019, pp. 1534–1538.
[248] J. J. Kiam, V. Hehtke, E. Besada-Portas, and A. Schulte, "Hierarchical planning guided by genetic algorithms for multiple HAPS in a time-varying environment," in *International Conference on Intelligent Human Systems Integration*. Springer, 2019, pp. 719–724.
[249] G. Clark, G. Landis, E. Barnes, B. LaFuente, and K. Collins, "Testing a neural network accelerator on a high-altitude balloon," in *IEEE Cognitive Communications for Aerospace Applications Workshop (CCAAW)*, 2019, pp. 1–8.
[250] AMSAT-UK, https://amsat-uk.org/2013/07/04/google-project-loon-interference-concerns/.
[251] N. Farsad and A. Goldsmith, "Neural network detection of data sequences in communication systems," *IEEE Transactions on Signal Processing*, vol. 66, no. 21, pp. 5663–5678, Sep. 2018.
[252] N. Shlezinger, N. Farsad, Y. C. Eldar, and A. J. Goldsmith, "Viterbinet: A deep learning based Viterbi algorithm for symbol detection," *IEEE Transactions on Wireless Communications*, vol. 19, no. 5, pp. 3319–3331, Feb. 2020.
[253] H. Sun, X. Chen, Q. Shi, M. Hong, X. Fu, and N. D. Sidiropoulos, "Learning to optimize: Training deep neural networks for wireless resource management," in *IEEE 18th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, 2017, pp. 1–6.
[254] Y. Li, F. Baccelli, H. S. Dhillon, and J. G. Andrews, "Fitting determinantal point processes to macro base station deployments," in *IEEE Global Communications Conference (GLOBCOM)*, 2014, pp. 1–6.
[255] N. Deng, W. Zhou, and M. Haenggi, "The ginibre point process as a model for wireless networks with repulsion," *IEEE Transactions on Wireless Communications*, vol. 14, no. 1, pp. 107–121, Jan. 2015.
[256] M. G. Khoshkholgh, K. Navaie, H. Yanikomeroglu, V. C. M. Leung, and K. G. Shin, "Coverage performance of aerial-terrestrial HetNets," in *IEEE Vehicular Technology Conference (VTC)*, 2019, pp. 1–5.
[257] ——, "How do non-ideal UAV antennas affect air-to-ground communications?" in *IEEE International Conference on Communications (ICC)*, 2019, pp. 1–7.
[258] S. Kalamkar and M. Haenggi, "Simple approximations of the SIR meta distribution in general cellular networks," *IEEE Transactions on Communications*, vol. 67, no. 6, pp. 4393–4406, Jun. 2019.
[259] J. Bao, D. Sprinz, and H. Li, "Blockage of millimeter wave communications on rotor UAVs: Demonstration and mitigation," in *IEEE Military Communications Conference (MILCOM)*, 2017, pp. 768–774.
[260] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K. Karagiannidis, E. Bjornson, K. Yang, I. Chih-Lin, and A. Ghosh, "Millimeter wave communications for future mobile networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 1909–1935, Sep. 2017.
[261] G. Zhang, Q. Wu, M. Cui, and R. Zhang, "Securing UAV communications via joint trajectory and power control," *IEEE Transactions on Wireless Communications*, vol. 18, no. 2, pp. 1376–1389, Feb. 2019.

[262] C. Liu, T. Q. S. Quek, and J. Lee, "Secure UAV communication in the presence of active eavesdropper," in *IEEE International Conference on Wireless Communications and Signal Processing (WCSP)*, 2017, pp. 1–5.
[263] J. Hu, S. Yan, X. Zhou, F. Shu, and J. Wang, "Secure UAV communication in the presence of active eavesdropper," in *IEEE Global Communications Conference (Globecom)*, 2017, pp. 1–6.
[264] O. Said and A. Tolba, "Performance evaluation of a dual coverage system for internet of things environments," *Mobile Information Systems*, vol. 2016, no. 3464392, pp. 1–20, Dec. 2016.
[265] S. O. Olatinwo and T.-H. Joubert, "Enabling communication networks for water quality monitoring applications: A survey," *IEEE Access*, vol. 7, pp. 100 332–100 362, 2019.
[266] M. Handley, "Delay is not an option: Low latency routing in space," in *17th ACM Workshop on Hot Topics in Networks (HotNets)*, 2018, pp. 85–91.
[267] C. Finn, P. Abbeel, and S. Levine, "Model-agnostic meta-learning for fast adaptation of deep networks," in *34th International Conference on Machine Learning (ICML)*, 2017, pp. 1126–1135.