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A Review of Wireless Communication using High-Altitude Platforms for Extended Coverage and Capacity

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***Abstract*—This paper provides an up-to-date review of wireless communications service provisioning in rural or remote areas from High-Altitude Platforms (HAPs) exploiting cellular radio spectrum. With the recent International Telecommunication Union (ITU) report showing that as much as 74% of the population in Africa, most of which are living in rural areas, do not have access to broadband, this paper focuses on the potential of using HAPs as an alternative to terrestrial systems for wireless communication in rural communities. Considering the typically low user densities in rural areas and the importance of HAP coverage maximization while ensuring harmless coexistence with terrestrial systems in rural areas, this paper explores extending the achievable wireless coverage from a HAP. This takes into consideration the coexistence of a HAP with terrestrial systems using intelligent techniques to dynamically manage radio resources and mitigate interference. Studies have shown that efficient intelligent radio resource and topology management can minimize inter-system interference and ensure coexistence with improved system performance. Potential techniques for coverage extension such as exploiting the spatial characteristics of array antennas, radio environment maps (REMs) and device-to-device (D2D) communications are discussed. Generally, this paper presents a comprehensive review of significant HAP related studies and their outcomes.**

***Index Terms*—Artificial Intelligence, High-Altitude Platform, Coverage Extension, Radio Environment Map, Device-to-Device, Resource Management.**

I. INTRODUCTION

MORE than half of the world's population do not have access to mobile broadband as of 2017 according to the latest International Telecommunication Union (ITU) report [1]. The report suggests that close to 74% and 14% of Africans and Europeans respectively are without broadband access, with the majority living in rural and remote areas. On the one hand, this percentage for Africa represents an absence of coverage over significantly large areas. On the other hand, the European scenario which is dominated by islands of coverage, presents a different coverage problem. Delivering broadband in rural areas will significantly increase broadband connectivity. The lack of broadband access in rural areas does not necessarily mean insufficient data capacity in the region of interest. For instance, despite more than 9 Terabits/s of data capacity being available to Nigeria through submarine cable landings, progressive distribution to rural areas still remains an issue [2]. Wireless telecommunications coverage in Nigeria so far is heavily concentrated in the urban and suburban areas. It was estimated that a minimum of 60,000 base stations were required to cover over 36 million people all living in rural areas who are either grossly underserved or unserved [2]. According to a 2014 estimation, an additional 33,000 base stations are needed by 2018 [3] in Nigeria. Unfortunately, the prohibitive cost of deployment, frequent vandalism and low user densities render terrestrial communication systems commercially unattractive in rural areas. Even in technologically advanced countries like the UK, only 70% of the landmass has broadband coverage. Although unlike in Nigeria, 98% of the UK population have broadband access, some areas and population still lack access to wireless telecommunication services due to reasons including restrictions as a result of planning or local regulations [2]. It is clear that wireless coverage problems persist in rural areas. In these cases, the use of HAPs to deliver telecommunication services presents a commercially viable alternative. In [4], it is highlighted that typical benefits of broadband coverage in developing countries are dominated by improved education and health service delivery, community development and an increase in small businesses, rural-urban migration mitigation etc. Similarly, a UK broadband report [5] highlights increased access to and use of e-government services, a positive change in civic participation, ease of learning for pupils/students, quality of web browsing and time saving from faster browsing as some of the impacts of broadband in advanced societies like the UK. Therefore, increased broadband access presents different propositions in different areas.

The work in this paper is based on wireless telecommunication service provisioning using HAPs. The focus is on coverage extension and coexistence of HAP and terrestrial systems with minimal intra-system and inter-system interference. Since a macrocell can potentially transmit up to a distance of 32km [6], it is highly likely that some terrestrial infrastructure will exist within the service area of a HAP. Hence, it is important to ensure coexistence between these systems. Considering the seemingly commercial unviability of terrestrial communications in rural areas due to the low return on investments (ROI) resulting from low user density, HAPs present a compelling alternative. HAPs are aeronautic platforms which are manned or unmanned, located conventionally between 17-22km altitude and used for wireless applications [7]. The advantages of HAPs over terrestrial wireless and satellite systems in addressing some wireless communication issues are highlighted in [8], [9]. HAPs offer some advantages over terrestrial systems due to their elevated look-angle and better propagation performance. The increasing optimism in HAPs is partly due to the possibility of the use of one platform for multiple applications and also due to their potential for low cost, high availability wireless communications service provision over an extended area.

Due to the characteristically low user density in rural areas, optimal coverage is important for the balance between the cost of deployment and ROI. The majority of the previous and current HAP projects like the Japanese Stratospheric Platform (SPF) project [10], HeliNet [11], CAPANINA [12], Loon [13], [14] and other studies [15], [16] consider a service area radius of approximately 30km. Therefore, this paper focuses on coverage extension from HAPs in a heterogeneous network (HetNet) specifically to deal with wide area coverage beyond the 30km radius, especially in rural areas. The design and deployment of wireless communication systems in rural areas must address the need for large coverage, operation in varying geographic terrain, robustness, and ease of installation [4]. In order to satisfy the large coverage requirement using terrestrial systems, extremely tall base station masts are needed with signals transmitted at significantly high power [17]. Apart from regulatory requirements, the high cost of deployment of the terrestrial solution renders it unattractive. It is also important to consider that some rural areas are very remote from the nearest backhaul infrastructure or do not have grid-based power for the terrestrial system. The cost benefit of HAPs over terrestrial systems is properly captured by the studies in [18], [19]. It is estimated in [18] that the cost of deployment, operation and annual maintenance of a macrocell of 1km radius amounts to approximately 168 thousand Euros. Considering an area of 30km radius, at least 900 such macrocells are required to provide continuous coverage. Therefore, the cost of the network is estimated to be 151 million Euros, which is quite significant. On the other hand, the estimated cost of deployment, operation and annual maintenance of a HAP is approximately 5 million Euros for unmanned solar planes and 34 million for unmanned airships as highlighted in [19]. Obviously, the difference in cost of these two networks considering the same coverage area is significant. It is important to note that these estimates are very simplistic and quite optimistic. This is because the cell size of a macrocell can be adjusted according to user density. In rural areas for example, a macrocell can have a radius of 30km or over, which casts aspersion on the estimation. Nonetheless, it is obvious that delivering extended coverage from HAP is vital for it to be economically viable. In summary, HAPs offer increased coverage at a reduced cost, ease of deployment, and the possibility of incremental deployment [7], [17], [20]–[24]. These characteristics encapsulate the requirements of a rural wireless communication system as captured in [4], thus making HAPs a suitable solution for wireless communication in rural areas. HAPs also allow for contiguous coverage with less frequent handovers over a regional service area, potential capacity improvements and reduced roundtrip time, increased throughput, lower latency and improved link budget compared to satellites.

HAPs for communication service delivery can range from having just remote radio heads (RRHs) elevated to the stratospheric altitude to complete base stations [17]. Whether it is better to have just a RRH or a complete base station is dependent on the trade-off between HAP payload weight, power consumption, and allowable service delay. Having a full base station on a HAP can potentially reduce signal round-trip time (RTT) thereby reducing delay as signals are fully processed in the HAP while in RRHs, data is relayed to a processing station thereby increasing the RTT and hence delay. Additionally, the capability of the platform in terms of available payload allowance and power can influence the choice between a full base station and RRH. The increased coverage advantage of HAPs over terrestrial systems arises from their significantly higher elevation angle. Conclusive qualitative studies have been carried out in some projects notably HeliNet, CAPANINA and ABSOLUTE covering only about 60km diameter service area with a HAP at 20km altitude. This corresponds to approximately a 30° minimum elevation angle. Studies in [8], [22] have suggested that with an elevation angle of about 10°, a HAP located at approximately 21km above the ground can provide coverage to an area of approximately 400km diameter. Therefore, there is potential to significantly extend the coverage of HAPs.

A. *Main Contribution*

In this paper, we provide an up-to-date review of the various studies on wireless communications coverage and capacity delivery using HAPs. Contrary to studies in [21], [25], this paper includes a review of recent HAP studies and significant results obtained, focusing mainly on studies in the past 10 years, which is one of the main contributions of the paper. There is a lack of recent publication highlighting the development in HAPs for wireless communication, hence the need for this review. We present the developments in HAP for wireless communications, comparing two decades (2000-2010 and 2010–2020). This includes summaries of recent projects on HAPs for wireless communications with information on the development of different platforms, advances in wireless communication techniques, regulatory and business frameworks relevant to HAPs. How a HAP system can exploit some existing schemes developed for terrestrial systems and the supporting literature is presented. We review the state-of-the-art HAP resource and interference management techniques, highlighting, for the first time, the possible exploitation of REMs and artificial intelligence (AI) for HAP interference and resource management. For instance, reinforcement learning can be used to learn the spectrum usage patterns of all the cells within the HAP service area, which the HAP can leverage in allocating resources and efficiently mitigating inter-cell interference. The central theme of this work is about achieving extended HAP coverage beyond the current state-of-the-art. Some coverage extension techniques are highlighted, including a novel discussion on the possibility of exploiting device-to-device (D2D) communication for coverage extension in HAP systems. The emphasis on extended coverage is largely because most HAP studies and projects such as [13]–[15] are based on a service area of 30km radius. However, with significantly good propagation performance, it is expected that a HAP can provide coverage to an area greater than this.

In the rest of this paper, the aerial platform concept is introduced in section II covering the numerous classifications of aerial platforms, HAP regulations as well as current and past projects on wireless communication from HAP. Section III highlights different HAP network topologies and techniques to ensure coexistence of these technologies with existing and new terrestrial systems sharing the same spectrum. In section IV, an in-depth discussion on potentials and approaches for HAP coverage extension is presented. Factors affecting HAP coverage extension are also presented. Section V provides detailed discussion on radio resource and interference management state-of-the-art scheme and techniques in wireless communication. A number of the discussed schemes and techniques are not HAP-specific, however, they can either be directly implementable or modifiable for HAPs use. In section VI, the issues and challenges facing wireless communications from HAPs are highlighted with some of the studies aimed at addressing these issues. The issues discussed are cell formation, handover, backhaul and inter-platform links, networking and multi-mode user terminals. Potential future research directions including possible approaches to follow are discussed in section VII while the paper is concluded in section VIII.

II. THE AERIAL PLATFORM CONCEPT

The use of aerial platforms (APs) for different applications dates back to ancient history. The Montgolfier brothers in France in 1783 developed a manned hot air balloon. Developments continued with the main application focusing on passenger transport until the Hindenburg disaster [17]. The disaster negatively affected the airship industry [17], [26] and stalled the development of APs like the Graf Zeppelin, which was elegantly popular for transportation. There has been increased interest with significant improvements in AP development and applications in the past 20–30 years. The time-to-market of the technology for various applications is projected to be within the next 5 years. This is due to the rapid development in the key enabling fields of APs such as advanced material science, which allows for the manufacturing of lighter but durable materials. Additionally, solar cells have evolved so much that there are currently ultra-thin, flexible and lightweight solar panels with improved efficiency [27]–[30]. This is driving the development of solar-powered platforms where weight, flexibility, and efficiency is an issue. Advancement in battery/energy storage and advanced materials for the realization of APs are some factors fast-tracking developments. Although the main focus of this paper is on the application of HAPs for wireless communications, the different classes of AP that can be deployed are introduced in the following subsection, identifying their distinguishing features. Various previous and current AP projects on aeronautics and wireless communications are highlighted.

A. *Classification of Aerial Platforms*

Generally, APs can be manned or unmanned [7], [31]. A typical manned HAP is the Proteus [32] designed for the NASA Environmental Research Aircraft and Sensor Technology (ERAST) project, specifically for long-endurance operation at high altitude. The aircraft requires a crew of two pilots. However, since HAP missions, especially for wireless communications, are of very-long duration at altitudes not suitable for human pilots due the harsh stratospheric environment, unmanned platforms enjoy more attention from HAP stakeholders [7]. Hence, the classification discussed in this paper focuses on different unmanned aerial platforms.

According to [33], unmanned aircraft system (UAS) operations are classified based on their operating altitude under the Instrument Flight Rules (IFR). The authors propose two main classifications based on the operations of UAS – very low level and higher-level operations. Very low-level operations are kept below 120m. They are not allowed to operate in populated areas and the altitude limitation makes this class of UAS unsuitable for high-altitude wide area coverage applications. The second class of the UAS, which are suitable for high-altitude applications and are permitted to fly above the 120m altitude threshold, is divided into radio line-of-sight (RLOS) and beyond radio line-of-sight (BRLOS). Whereas RLOS requires a radio link between the pilot and the platform, in BRLOS operation, communication between the pilot and the platform is typically through satellite services [33], [34].

Further classifications of APs based on size, operating altitude, mission endurance, capabilities, method of take-off and landing, engine type, wing loading, etc. exist in the literature [34]–[38]. Some of the categorization and classifications in these studies are overly detailed and unsuitable when considering a straightforward wireless communications application. A simpler and more tractable classification divides APs into HAPs, which operate at stratospheric altitudes, and low altitude platforms (LAPs), which operate at altitudes significantly lower than HAPs. Each class can be further subdivided considering the configuration of platforms typically operating within the class. In this work, we focus on the HAP classification.

1) HAP Classification: HAPs typically operate in stratospheric altitudes [7] above the maximum altitude for commercial flights. As stated earlier, it is generally desirable to have low-cost platforms with flexible payload support. HAPs potentially offer wider coverage, limited ground infrastructure and fast deployment time. A number of HAPs are still in the development phase such as Stratobus [39] which was launched in 2016 and is projected to be completed by 2021, and the Hawk30 [40] being developed specifically for stratospheric communication and projected to be ready for mass production by 2023. HAPs can be classified based on the physical principle providing the lifting force in which case they can be aerostatic or aerodynamic. They can also be classified based on platform design. Commonly, HAPs are classified as balloons, airships, and airplanes and their main characteristics are shown in Table I. The HAP class ideal for any given communication mission depends on a number of factors such as the available HAP payload and the energy available to the platform.

HAP Category	**Characteristics**
High Altitude Aircraft	• Potentially support high payloads • Can be manned or unmanned (e.g Global Hawk and Zephyr) • Complete autonomous operation • Ability for solar-powered operation
Airships	• Float using buoyancy • Significant payload support and higher power available • Fly up to 30km altitude • Ability for solar-powered operation
Balloons	• Lift due lighter-than-air gases • Can be manned or unmanned • Significant payload support

TABLE I – Classification and features of High-Altitude Platforms [7], [33], [41].

The choice of the appropriate category of HAP depends on, among other factors, the regulations guiding the deployment and operation of AP. These regulations are often country specific.

B. Chronology of HAPs for Wireless Communications

The idea of using HAPs to deliver wireless communications, and a number of other applications, started becoming mainstream between late 1990s and early 2000s when Djuknic et al. [8] alluded to this possibility. Over the past two decades, there has been consistent improvements in the research and development of HAPs for wireless communications. There is also an increased acceptance and appetite for the concept as highlighted by the amount of on-going research and development work in the area. Based on the bibliometric analysis in [7], there were roughly 850 publications per year in HAPs from all countries of the world except China in 2015, increasing from roughly 600 in 2010. In China alone, the publication count in HAPs increase from around 100 in 2010 to 350 in 2015. The forecast is that HAPs market will continue to grow annually at the rate of 8.7%, reaching an estimated value of US$4.77 billion by 2023 [42]. Significant achievements have been recorded in the design and development of the platform, energy subsystem including solar cells, antenna subsystem, wireless communication techniques and approaches, communication payload, applications and even business models. These achievements contributed in overcoming some of the issues and challenges identified when the concept was at its infancy. However, some new issues and challenges have also been identified as presented in this section. In order to entrench a greater appreciation of the developmental process, we highlight the maturity of HAP for wireless communication between 2000-2010, herein referred to as ‘then’ and 2010-2020, herein referred to as ‘now’.

Then (2000–2010), majority of the studies focused on developing the concept of HAPs for wireless communications. The proponents did not understand how a platform can overcome station keeping problems to achieve sustained flight at stratospheric altitude for hours [8], [9]. Some proposals then involved using the already matured piloted aircraft with frequent landings to allow for refuelling and giving the pilots some rest [8]. This was unrealistic due to the cost involved and the enormous risks to pilot. However, due to advancements in aeronautic engineering now (2010–2020), the focus veered from fuel-powered piloted aircraft to unmanned aircraft powered by renewable energy. In fact, there are now established manufacturers developing and producing solar-powered HAPs, which are ready or nearly ready for commercialization. Zephyr S [43] and Phasa-35 [44] are some of such aircraft with Hawk30 by HAPSMobile [40] showing good promise. Even stratospheric balloons are not left out in the rapid development as Project Loon [14] shows.

Similarly, there are significant achievements in the development of the necessary subsystems for HAPs. Firstly, considering the energy subsystem involving energy storage and solar cells, the specific energy of Lithium-ion battery moved from 110Wh/kg then [21] to the current state-of-the-art at 250Wh/kg [45]. While this may not be a quantum leap, it shows steady progress towards in battery technology. On the other hand, the specific energy of fuel cells, which is an alternative to batteries for energy storage, improved from between 300–400Wh/kg then [46] to over 1000Wh/kg now [47]. Solar cell development is another aspect of the energy subsystem witnessing significant improvements with the development of ultra-thin solar cells with conversion efficiency up to 37.75% [27]. Despite these improvements, the current state of the art in energy storage is not sufficient for wireless communications from HAPs, especially in areas higher up the northern hemisphere, due to the relatively low energy storage density and the limited payload capabilities of the currently available platforms [48]. Secondly, one of the key aspects of HAPs as highlighted in [8], [21] is HAP-based antennas capable of producing multiple beams. While HAP-specific antenna design was one of the challenges of HAPs then, a significant improvement have been made in this area. Currently, antennas have been developed specifically for use within the HAP system including light weight multi-beam lens antenna for operation between 1.77GHz–2.44GHz [49] and phased array antenna with digital beamformer for operation in K-band [50].

Wireless communications techniques and approaches are not left behind in the recent developments in HAPs. Between 2000-2010, most of the proposed cell designs were circular and concentric rings, which are static and inflexible with respect to user distribution and beam broadening. Currently, adaptive cells designs that optimize cell shapes based on user distribution and beam broadening have been proposed [16], [51], [52]. In addition, channel allocation strategies have advanced to the state-of-the-art intelligent based channel schemes, which is based on reinforcement learning [53]. Furthermore, HAPs now have the ability to use conventional communication techniques like coordinated multipoint (CoMP) and inter-cell interference coordination (ICIC) [15]. HAP architectures have also undergone modifications to include LAPs as part of a HetNet of satellite, HAP, LAP, and terrestrial systems [54], [55] unlike then when it mainly focused on satellite, HAP, and terrestrial systems [56], [57]. Free-space optical (FSO) communication, the most popular technology for inter-platform links connecting these systems, is also significantly improving. Currently, the ability to achieve 80Gbps FSO using orbital angular momentum and MIMO-based spatial multiplexing has been demonstrated [58]. This is definitely a significant improvement from the FSO state-of-the-art then designed for the CAPANINA HAP project, achieveing a data rate of 1.25Gbps [59].

The advancements in HAPs are not limited to the areas of technical research, design, and development only. There are also developments in aviation and radio regulations, business modelling and applications. More spectrum have been allocated for HAPs in world radio congress 2019 (WRC-19). In WRC-19, 21.4–22GHz and 24.25–27.5GHz were identified for use in Region 2, which is made up of Americas and some Pacific Islands, provided harmful interference is not caused to the fixed satellite service also sharing the spectrum. 38-39.5GHz was also identified for use worldwide to facilitate 5G from HAPs [60]. Additionally, international and national civil aviation authorities are currently deliberating on issues relating to the formulation of HAP specific regulations, granting licenses for real flight tests. Liu and Tronchetti [42] propose a model for regulating near-space activities. It is also worthy of highlighting that there are now studies proposing business models and use cases [61]. HAPs are even being proposed to deliver broadband, 5G and beyond 5G wireless communication services [2]. These show the vast potential of HAPs for wireless communication, which is closer to maturity now than it has ever been.

Despite the recent developments, there are still some challenges facing wireless communications service delivery from HAPs. While the issues raised then on the ability of platform's station keeping have been addressed largely with the commercial production of platforms like Zephyr, there are still issues relating to the limited payload carrying capability of the current platforms. In order to be able to support wireless communication payloads, HAPs must be able to carry significantly more than the current systems can support. Other challenges faced include the miniaturization of payloads for reduced weight, development of stable lightweight energy storage systems, lightweight structures that can sustain the stress of operating in stratospheric altitudes [7], coexistence between HAPs and other terrestrial systems etc. Other challenges include difficulty in securing funding for the development of different platform especially airships and designing non-line-of-sight communication required for remotely piloted autonomous aircraft.

C. *HAP Regulations*

There are different types of regulations governing the use of HAPs for wireless communications. On the one hand, there are aviation regulations, which governs the licensing and operation of the platforms. This is typically within the jurisdiction of international and national civil aviation authorities. On the other hand, there are radio regulations governing the spectrum usage for HAPs, which is within the duties of ITU-R.

1) Aviation Regulation: The deployment of any given class of AP is subject to a set of aviation regulations, which differ in different countries. These regulations more often than not specify how the platforms are allowed to operate and the maximum allowable altitude for each class. Generally, it is typical for unmanned aircraft operators, irrespective of size, to obtain a license from the Civil Aviation Authority (CAA) of the country where they intend to operate. The major aim of CAAs is to enforce safety, security and privacy rules [62]–[64]. Despite the increased discussions worldwide, there is no legal specification particularly regulating the operation of HAPs anywhere currently [42], which is hampering the development and deployment of the system.

Liu and Tronchetti [42] propose a new categorization of near space, spanning from 18–100km, as the exclusive utilization space (EUS). The model suggest differentiating the legal status of near space group from that of national airspace and outer space. The authors suggest abrogating near space, which will be regulated by a set of rules targeted at profit maximization and sustainability, from the national sovereignty of the underlying states. However, it proposes to maintain the sovereign rights of the underlying states by allocating them the right to decide the conditions for use, negotiate the conditions to be complied with by foreign bodies, and regulate/enforce safety and security issues as concerns the states.

2) Radio Regulation: Irrespective of platform characteristics, broadband communications from a High-Altitude Platform Station (HAPS) is based on a set of spectrum globally regulated by the ITU-R [22]. The ITU defines HAPS as a station located on an object at an altitude of 20–50km and at a specified, nominal, fixed point relative to the Earth [65]. This definition of HAPS is restrictive considering the capabilities of current platforms. The more general definition of a high-altitude platform captures operating altitudes typically between 17–22km [9]. It is expected that the HAPS definition by the ITU will be revised in the near future. Over the past 20 years, different spectrum bands in the millimetre wave (mm-Wave) and IMT bands have been assigned for HAPS use in different regions by the ITU-R.

Recently, ITU-R released at WRC-19, more regulations on the requirements for the maximum transmit equivalent isotropically radiated power (EIRP), antenna beam pattern, power flux density (PFD) level per HAP produced at the surface of the earth, separation distance between radio astronomy station and the nadir of a HAP platform for operation in HAP spectrum bands as contained in [60]. In [22], [63] the authors highlight the allocated HAPS spectrum bands in particular regions as follows:

1) **47/48-GHz Band:** Subdivided into 47.2–47.5 GHz and 47.9–48.2 GHz, allowing up to 300 MHz bandwidth in both UL and DL. The bands allocated for HAPS use in WRC-97 is shared with satellites and available for fixed services use globally.
2) **31/28-GHz Band:** Subdivided into 31–31.3 GHz UL and 27.9–28.2 GHz DL which also allows for up to 300MHz bandwidth in specific countries in regions 1 and 3. The band allocated during WRC-00 and WRC-07 for fixed services use is not available for use in the whole of Europe.
3) **2.1-GHz IMT-2000 Band:** This band is subdivided into 1.885-1.980 GHz, 2.110–2.160 GHz and 2.010–2.025 GHz bands and allocated for use in regions 1 and 3 by ITU-R in WRC-00. Only the first two sub-bands are available for use in region 2 [64]. These bands are for the use of IMT-2000 services.
4) **6.5/6.6-GHz Band:** This band was allocated in WRC-12 and is only available in Australia in region 1 and 4 African countries in region 3 for HAPS gateway links. For the DL, 6.440–6520 GHz is assigned while the UL uses 6.560–6.640 GHz [64].
5) **38–39.5-GHz Band:** This band was identified for HAPs use in WRC-19 for use globally. HAPs share this spectrum with fixed service as co-primary systems, with HAPs prohibited from causing harmful interference to fixed service system [60].
6) **21.4–22-GHz Band:** This band, identified for HAPs use in Region 2 in WRC-19, is limited to HAP-to-ground (DL) direction. It is shared with fixed service, which must not be harmfully interfered with by the HAPs [60].
7) **24.25–25.25-GHz and 25.25–27.5-GHz Bands:** These bands, identified for HAPs use in Region 2, are shared with fixed service. While, the 24.25–25.25 GHz band is limited to HAP-to-ground (DL) direction only, 25.25–27.5 GHz band can be used for both ground-to-HAP (UL) and HAP-to-ground (DL) directions [60].

The mm-Wave bands are typically beneficial to services requiring capacity like backhauling, but no so much for coverage. Additionally, antennas with smaller form factor are needed for communication in these bands compared to the IMT-2000 band. Unfortunately, their propagation performance is severely affected by the attenuation due to rain, which makes their use in tropical regions more complex. On the other hand, due to the negligible effect of rain attenuation in sub-6GHz bands, the IMT-2000 propagation performance is not constrained by rain in tropical areas as highlighted in [64], although, compared to the mm-Wave bands. IMT-2000 can allow for wider coverage but not provide as much capacity.

In order to integrate APs into the global communication systems, appropriate regulations governing their design, deployment, and operation are necessary. For HAPs operating at stratospheric altitudes, aeronautic regulations are adhered to only during the take-off and landing phases [22]. The development of HAPs for wireless communications currently still faces some regulatory challenges such as the inability to allocate different spectrum especially in tropical areas, which is required mainly due to the significant attenuation experienced in the allocated 47/48-GHz and 38–39.5-GHz bands. Unfortunately, the 28/31-GHz and 21.4-27.5 bands with significantly reduced rain attenuation is not available in some regions. Another main challenge is the varying aeronautic regulations in different countries. Studies in [64] look at some regulatory challenges affecting the use of HAPs for wireless broadband service provisioning. The author discusses these challenges under global and regional spectrum challenges as well as privacy, safety and security issues.

Irrespective of the regulatory bottlenecks, the number of projects, which have either been completed or still on-going, demonstrate the viability of HAPs for wireless communications especially in low user density areas. Some of these projects are discussed in the following section.

D. HAP Projects

In recent times, a number of projects focusing on wireless communications applications from HAPs have been initiated. While most of the projects specified below are mainly focusing on the wireless communication applications from HAPs, numerous other current projects that focus on the development of platforms for varying applications are progressing notably.

Airbus's Zephyr S/T [43], BAE Systems' Phasa-35 [44], Boeing's Phantom Eye [66], Stratobus Airship [67], and Sceye [68] represent some of the interesting current HAP projects. Some of the projects highlighted below have been successfully completed, while some have been discontinued for various reasons. A few of the HAP projects highlighted are not the most recent projects but are still relatively popular and relevant.

1) Project Loon: Officially announced in June 2013, Project Loon aims to provide internet to remote areas using stratospheric balloons at an altitude of 20km. This project owned by Loon LLC (a subsidiary of Alphabet Inc.), partnering with MNOs, targets LTE coverage expansion using the Loon platforms with a pilot experiment conducted in New Zealand involving 30 balloons. The Loon project is premised on the idea of launching a constellation of balloons clustered in the stratosphere at a given latitude to provide coverage in that location. The Loon platform is composed of an envelope, solar panels, and electronics. Communication between the platform and a ground station is through lasers. The platform can support a payload weight of about 10kg for over 100 days, covering an area of 5000km^2 and powered solely by solar panels [7], [13], [14].

2) Aquila: Similar to the Loon project, Facebook's Aquila project launched in March 2014 intending to provide high-speed wireless communication to remote areas [7], [24]. The project planned to use the 42m wingspan solar-powered Aquila UAV with a total weight of 400kg. Facebook in a blog post [69] announced that it will be discontinuing the Aquila project. They plan to continue partnering with Airbus on HAP connectivity and relevant HAP technologies [69].

3) CAPANINA: This European Union Framework 6 project ran between 2003 and 2007, comprising a consortium of 14 partners. The main goal was to develop low-cost HAPs capable of providing coverage to users including users traveling at speeds up to 300km/hr using an optical backhaul. The project developed wireless and optical broadband technologies delivered from APs. It was coordinated by the University of York, which also developed the communications aspect of the project. Three practical trials of the technology took place with the project officially ending in 2007 [12], [70].

4) HeliNet: The HeliNet project preceded the CAPANINA project. The project's major focus was on delivering broadband services from a 70m wingspan solar-powered Heliplat HAP designed during the project [11].

5) HAPSMobile: HAPSMobile is a joint venture (JV) between American UAV maker AeroVironment and Japanese telecommunication company SoftBank announced in January 2018 [71]. This JV is yet another promising HAP project intent on providing wireless communications services from HAP for commercial purposes. The project recently announced the development of a platform called Hawk30 [40], which is specially designed for stratospheric communication systems. Hawk30 is solar powered, having a 78m wingspan, and flying at a speed of approximately 30m/s. With the pedigree of SoftBank as one of the largest global internet companies with access to finance and huge R&D investment [72], and AeroVironment, which designed the popular and successful Helios platform [73], HAPSMobile has the potential to be successful.

III. NETWORK TOPOLOGY AND HAP-TERRESTRIAL COEXISTENCE

HAPs can be deployed in wireless communication networks with different topologies. The ideal topology design aims to achieve high reliability, low power consumption and light payload. Whether this can be achieved depends on the HAPs application and coverage area, which determines the type and capacity of components required on the platform and those on the ground. The simplest HAP topology involves a transparent transponder in the HAP producing a single beam to the ground [74]. Irrespective of the topology, it is important that HAPs are designed to coexist with terrestrial systems, which are highly likely to exist within the footprint of a HAP. This section discusses the different HAP network topologies and approaches to ensuring coexistence with new or already existing terrestrial systems.

A. HAP Network Topology

Different HAP topologies and system configurations have been extensively studied in the literature [2], [22], [56], [75]. Commonly, the topologies are divided into hybrid and non-hybrid. In hybrid topologies, HAPs can be part of a HAP-Terrestrial or HAP-Terrestrial-Satellite system [22], [22], [75] as shown in Fig. 1. The HAP-Terrestrial topologies involves terrestrial base stations serving high user density areas while HAPs are used to provide services to places with lower user density and for hotspot. This configuration appears to be one of the most feasible for the near future communication systems [56]. The terrestrial system can potentially be backhauled to the HAP, which can be beneficial in places without core network infrastructure nearby. The HAP-Terrestrial-Satellite topology can be used to increase fault tolerance and prevent system failures [56] with the possibility of backhauling from HAP to satellite. A HAP-Satellite topology is discussed in [22] although the authors acknowledge that the significant distance between the HAP and satellite can be problematic for TCP services. The performance evaluation of a hybrid HAP-Satellite system is analyzed in [76] considering BER, noise and power consumption. The authors propose a hybrid communication system.

For the non-hybrid topologies shown in Fig. 2a, the HAP can either be configured as a single base transceiver station or as a part of a mesh network of HAPs [56], [75]. Single-HAPs require both RRH and BBU to be located in the HAP with a backhaul link to the core network. On the other hand, the multi-HAP topology shown in Fig. 2b can be used to extend wireless coverage and/or capacity [22]. Studies in [77]–[79] investigate the use of multi-HAP topology to improve

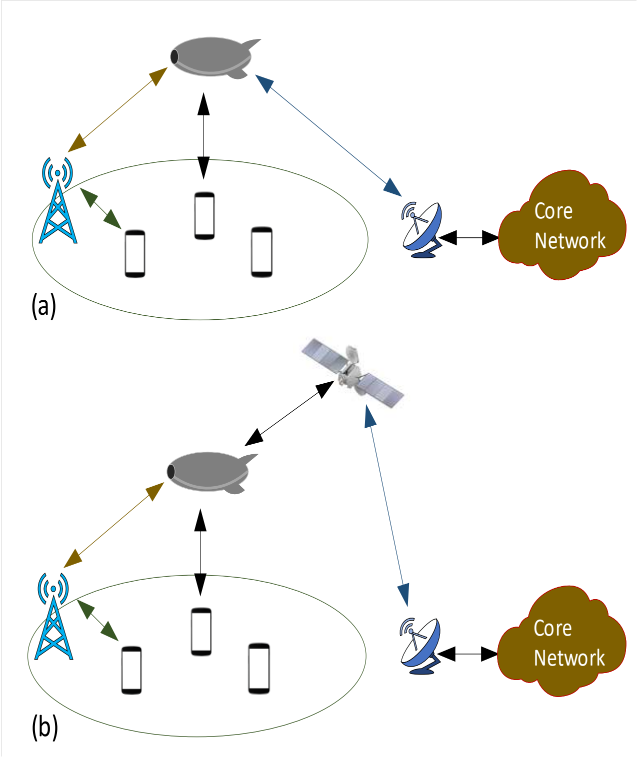

Fig. 1 – HAP-Terrestrial-Satellite (a) and HAP-Terrestrial topologies (modified from [22]). HAPs can be used both as access links with backhaul links to the core network, where fibre infrastructure is available. This may not be within the coverage area of the HAP. Alternatively, backhauling can be achieved using satellites via HAPs. There can be other form of communication between these entities.

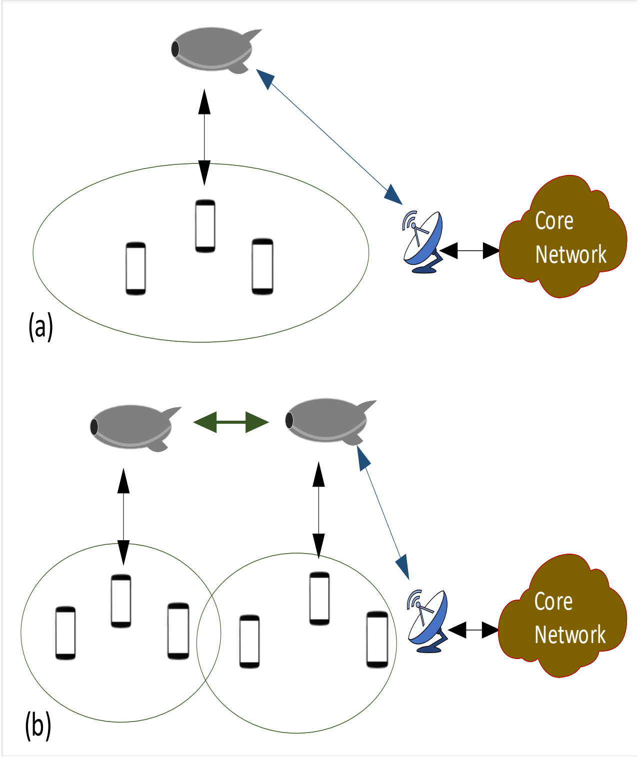

Fig. 2 – Single-HAP (a) and Multi-HAP (b) topologies (modified from [22]). HAPs can be deployed as a single network entity with connection to the core network or as a group of HAPs with extended coverage capabilities connected together by inter-platform links.

the system performance. Grace *et al.* show in [77], [79] that the system capacity of broadband services from HAPs can be improved through diversity by using multiple platforms sharing common spectrum, by leveraging on user antenna directivity. The diversity performance of multiple HAPs using virtual-MIMO transmission with different modulation schemes is studied in detail in [78]. The authors show that up to 10dB diversity gain can be achieved using 4x4 MIMO antennas in HAPs.

Considering the footprint of a typical standalone HAP topology, the majority of the studies on HAPs thus far focus on service provisioning in an area of 60km diameter. This is pessimistic considering the significantly better propagation performance is achievable from HAPs compared to terrestrial systems. In view of this, it is expected that a HAP system with much wider coverage is viable. ITU-R recommendation SF. 1843 [80] considers a HAPS service area of approximately 400km diameter. It partitions the coverage zones of HAPS stationed at an altitude of 21km into Urban Area Coverage (UAC) with radius between 0–36km from the sub-platform point (i.e. the point directly beneath the HAPS), Suburban Area Coverage (SAC) which is between 36–76.5km, and finally Rural Area Coverage (RAC) between 76.5–203km as illustrated in Fig. 3. On the one hand, this recommendation recognises the possibility of extended coverage from HAPS. On the other hand, the extension is too optimistic, as it will be difficult to achieve due to the significant pathloss and shadowing effects at extended distances among other factors. One other problem with extended coverage is beam (and hence cell) broadening when beams are pointed at distances well away from the sub-platform point. This causes cells deployed at the centre of the service area to differ in shape and size with those significantly away, and it results in the degraded performance at the edge of coverage (EoC). The degradation is because the further away from the centre of coverage, the tighter the link budget. To compensate for broadening, beam shaping is needed and this can be achieved through appropriate antenna system design. Power control and flexible dynamic resource management are some of the techniques that can possibly be exploited to improve EoC performance. The variation of data rate achievable between the centre and EoC can be reduced by the use of adaptive modulation and coding although that is beyond the scope of this work. Consequently, in order to achieve extended coverage from HAPs, flexible

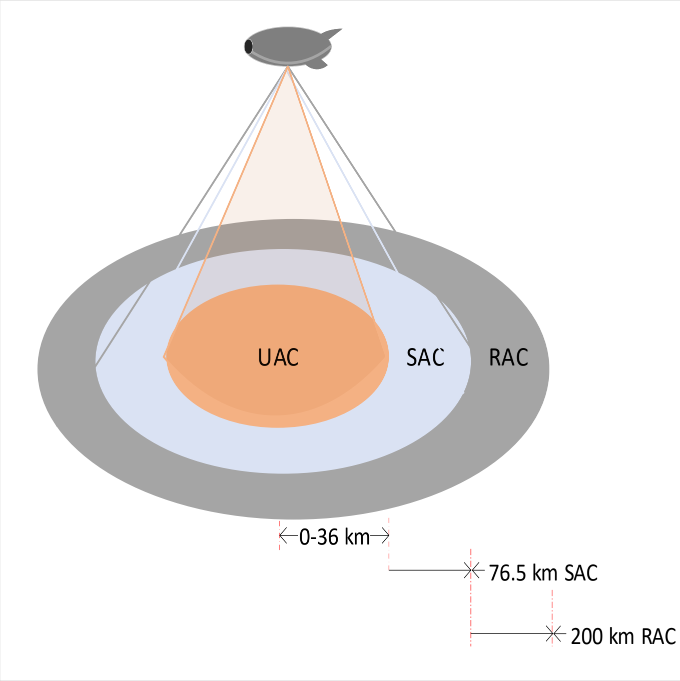

Fig. 3 – ITU-R defined HAPS coverage zones. This indicates the radius of the different coverage zones as defined by ITU-R.

beam deployment and management is required among other factors. This can be achieved using effective radio resource management and dynamic beamforming antennas, discussed in more details in sections V and IV respectively, as well as effective topology management.

Topology management is a desirable proposition for a HAP communication network due to its heterogeneity with respect to components, coverage, users, and traffic. As obtainable in all typical wireless communication systems, there is a spatio-temporal variation of users and traffic. Instead of having a fixed topology, HAPs can be designed to dynamically change its topology based on the subsisting user and/or traffic distribution within its footprint. However, consistently changing topology can be significantly energy consuming, which is undesirable considering the limited energy availability in HAPs. Therefore, energy constraints, user and traffic variation must be taken into consideration in the implementation of topology management in HAPs.

B. *Energy and Traffic Aware Dynamic Topology Management*

Since HAP payloads are likely to be power limited, maximization of energy usage is paramount. Dynamically managing the network topology can significantly improve energy efficiency (EE) and maximize energy usage. EE is defined as the total delivered information per unit energy [81] and it can minimize the mobile operator's operating cost. With the spatio-temporal variation of user density and traffic in cellular systems, in addition to the inherent low user densities in rural areas, it is sensible to adopt schemes that can dynamically power down HAP cells at times of low traffic. Neighbouring cells servicing higher traffic requests automatically increase their coverage area proportionally to handle the traffic in the powered-down cells [82]. Furthermore, non-coherent joint transmission and dynamic point selection/blanking can be exploited in varying the number and/or location of active HAP cells in response to a significant drop in traffic. This can be achieved by having a centralized entity, which will typically be located on the platform, that controls the transmission of the cluster of cells with some form of scheduling to reduce total system power consumption. This entity selects transmission nodes to be put in sleep mode while allowing coordination between the active nodes [83]. Cell zooming [84] also referred to as cell wilting [85] is one concept that can be used to vary system topology by varying cell sizes in response to variation in user density. Authors have also proposed other techniques of dynamically varying the topology of the AP system based on the state of the system.

Islam et al [86] propose a state-based, energy-efficient and delay-aware transceiver for ABSs They define three states for ABS transceiver - active, standby and sleep states. An MDP-based algorithm is used by the transceiver to switch between these states based on the offered traffic. Their simulations determined a 40% increase in energy efficiency compared to traditional base station transceivers. These strategies can be applied in HAP systems. For instance, changing the number and size of deployed beams based on user and traffic density can potentially improve EE. Fewer beams can be deployed with wider coverage in scenarios with small traffic density and considerable spatial spread. This can be achieved by dynamically varying the number of antenna elements actively used in beamforming. Since beamwidth is inversely related to the number of antenna elements, this becomes a plausible solution. In fact, Wang et al [87] suggest dynamically changing IEEE 802.11a access point coverage by methodically varying the weightings of individual antennas making up sectors of the overall cell. Furthermore, CoMP techniques can be used in regions of overlap of the HAP cells and/or the overlap regions of the HAP-Terrestrial cells.

It is important to note that these techniques, irrespective of their efficiency, depend on the condition of the communication system. Information such as the user and traffic densities across the network help the system decide the appropriate state. Therefore, the acquisition of this information is necessary. These techniques can also be influenced by HAP-terrestrial coexistence scenario. Expectedly, there will be cross interference between HAP and terrestrial systems. HAP can avoid causing interference on terrestrial systems by forming beams at a safe distance away and/or using cooperative techniques like CoMP and inter-cell interference techniques (ICIC) or even exploiting radio environment map (REM). These are discussed in more detail in the following section.

C. HAP-Terrestrial Systems Coexistence

With the extended service area of HAPs, there is a high probability of interference on terrestrial systems from HAPs. Considering the possible reuse of the terrestrial spectrum by HAPs, it is essential for both wireless networks to coexist harmoniously with minimal harmful interference between the networks. Perhaps, cross interference between HAP and terrestrial systems is one of the major impediments to HAP deployment for wireless communication systems. Antennas radiation pattern plays an important role in ensuring HAP coexistence with existing and new terrestrial systems, spectrum efficiency and good capacity performance. For instance, in order to facilitate HAP-CDMA system coexistence with terrestrial infrastructure in the IMT-2000 band, the ITU-R defined an antenna radiation pattern as a reference. The ITU-R mask is characterized by a maximum gain of -25dB relative to the peak gain and a far-in sidelobe of -73dB [88]. This mask with steep antenna roll-off, although minimizes adjacent cell interference, is not very realistic as the average sidelobe level of practical antennas may be higher [89].

When the same spectrum is shared between HAP and terrestrial system, the interference from a HAP cell to terrestrial cell is less than the interference on the terrestrial cell from other terrestrial cells for the same inter-cell distance. This is as a result of the fast roll-off of HAP transmit signal power with ground distance. In order to avoid excessive interference on the terrestrial system, HAP cells must be pointed at an appropriate distance away from the terrestrial cells. However, due to the fast transmit signal power roll-off with distance as shown in Fig. 4, HAP cells can be placed considerably close to terrestrial cells without causing excessive interference. Thus, adequate control of beam placement is necessary to mitigate HAP system interference on terrestrial system while keeping it below the internationally acceptable level. A pessimistically worst-case non-coordinated interference management approach can be adopted. However, it is expected that the cross interference from HAPs to terrestrial systems should be no worse than inter-cell interference within the terrestrial system. In fact, a significantly better cross-border interference performance is expected compared to the terrestrial system performance. The reason lies in the transmit power profile of both systems shown in Fig. 4. The power profile highlights the slow decay in power with distance in the terrestrial system scenario. However, power decays rapidly with distance in the HAP system. The decay pattern of the HAP system is also shaped by its antenna roll-off.

The majority of the research in HAP-Terrestrial system coexistence focus on capacity/interference management, resource allocations, and the individual system performance. Guaranteeing improved system capacity with limited interference on other systems needs advanced techniques like diversity, advanced radio resource management (RRM), smart antennas, multiplexing, MIMO etc [22]. The use of smart antennas and advanced RRM constitute the major techniques required to ensure coexistence. Adopting cognitive radio concepts in formulating the dynamic spectrum management (DSM) strategy can potentially ensure coexistence [22]. While DSM avoids interference by utilizing the unoccupied spectrum, smart antennas allow for spatial beamforming, which minimizes interference in a particular direction. Since radio resource management and interference mitigation is a significant part of wireless communications like HAPs, a separate section (V) is dedicated to addressing them comprehensively.

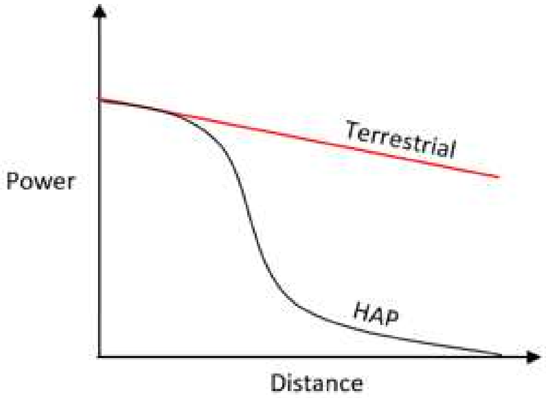

Fig. 4 – Transmit power profile of Terrestrial and HAP wireless communication systems.

Coexistence can be ensured based on ITU recommendation of interference-to-noise ratio (INR) of not more than -10dB at the primary receiver. Here, the terrestrial system could be regarded as the primary receiver. This regulation is somehow constraining as conventional receivers are expected to perform significantly well even in an interference limited environment. Most studies on HAP-terrestrial coexistence propose a minimum separation distance based approach where the minimum interference metrics are satisfied. In [90], [91] interference-to-noise ratio (INR) and carrier-to-interference-plus-noise ratio (CINR) based spectrum etiquettes are proposed for HAP systems. Both spectrum etiquettes use the INR level or CINR level of an incumbent user respectively as a reference level, to manage a newly activated system downlink transmit power. Considering a HAP as the newly activated user, the studies ensure that interference on the terrestrial incumbent user does not cause a drop in INR or a change of modulation scheme. The authors also suggest that appropriately exploiting power control of the terrestrial system can allow for the accommodation of more interference from the newly activated HAP system. Similar underlying ideas presented in [16], [92], [93], propose the implementation of an appropriate separation distance between the systems and antenna beam adjustment, as strategies that can be adopted to improve performance and ensure coexistence of the systems.

The current state-of-the-art in interference mitigation adopts techniques like CoMP [94] and/or ICIC [95], which potentially leads to improved coexistence performance. Increased coordination among the coexisting systems as well as the use of MIMO techniques help. CoMP introduced by 3GPP for LTE-A systems is one such state-of-the-art strategy for interference mitigation especially at the edge of cell. HAP and terrestrial systems within its footprint sharing the same spectrum can exchange information and cooperate using ICIC and/or CoMP to mitigate cross network interference. CoMP application in HAP is described [15], [96], which considers how a variant of CoMP referred to as joint transmission CoMP (JT-CoMP) can be implemented to improve HAP cell-edge user experience. The authors propose two-way and three-way CoMP region schemes involving coordination between two and three HAP cells with users included in a CoMP region based on power level difference.

IV. HAP COVERAGE EXTENSION

In some rural and suburban environments, wireless communication system coverage performance is more desirable than high capacity density. With HAPs as a potential alternative to terrestrial systems, maximizing the achievable coverage is more important in low user density areas. Most of the HAP studies [16], [31], [97], and projects (e.g. CAPANINA, Helinet, and Loon) consider a coverage area of around 30km radius by a single HAP. Considering that some terrestrial base stations can provide coverage in rural areas of up to 30km radius [6], HAPs should expectedly be delivering coverage well beyond 30km radius due to increased probability of line of sight coverage, which means better propagation performance. Irrespective of the lack of research work specifically on techniques and approaches for single-HAP coverage extension, a number of studies [98]–[103] have looked at extending wireless coverage from APs but focusing on LAPs with maximum platform altitude reaching 2km. Nevertheless, the proposed techniques and architectures in these studies can be implemented in HAPs provided the propagation channel difference between LAPs and HAPs and other factors are accounted for. A number of techniques for HAP coverage extension and some factors affecting it is presented in this section.

A. Coverage Extension Techniques

There are a number of possible methods of extending coverage from APs, however, we focus on coverage extension by platform placement and terminal cooperation.

1) Platform Placement: HAPs operating altitude can influence its footprint and hence coverage on the ground. Therefore, optimizing the altitude of a HAP directly optimizes its coverage on the ground. A few studies in the literature have investigated how the optimization of the flying altitudes of aerial platforms in general influences coverage and capacity. Studies in [98]–[100] the authors present models for coverage optimization based on platform placement, showing the relationship between the APs and the maximum achievable coverage. Analytical frameworks presented in [98], [100] show that the optimal altitude of a LAP, and by extension an HAP is a function of the maximum allowable pathloss. Increasing altitude results in a higher probability of LOS transmission, however, it also leads to increased path loss [100]. Therefore, it is important to determine the optimum altitude, which minimizes path loss while maximizing the achievable coverage. However, the achievable coverage is directly dependent on the characteristics of the propagation environment [99].

Furthermore, HAP coverage is extendible by a mesh network of HAPs. Sharma and Kim derive a model for the coverage probability of a UE in a multiple UAV network [102]. To derive the model, a ground-based UE is used with multiple UAVs placed in 3D locations. One UAV provides coverage to the UE while the others seen as interferers are located along the boundary of a circle a distance R away from the reference UE with dynamic altitude control. The results show the impact of various system and channel parameters on received signal quality and coverage probability. Interference from the other UAVs in the mesh network can be managed with good platform placement and intelligent reuse schemes. The study in [103] analyses the coverage problems for the multi-UAV system, presenting an algorithm for optimum UAV placement and resource allocation. To extend HAP coverage, array antennas can be used to exploit the spatial characteristics of waves. Antenna radiation pattern, signal propagation, transmission parameters, resource and topology management are some other important factors that can be exploited to achieve single-HAP coverage extension. A mesh network of HAPs using the multi-HAP architecture can achieve wider regional coverage.

2) Terminal Cooperation: Extending coverage from HAPs can be achieved through terminal cooperation (i.e. device-to-device (D2D) communication). D2D communication implemented for coverage extension can allow for a relay node under a HAP coverage area to cooperate with a source UE that is either located outside the coverage area or experiences poor signal coverage. This D2D approach is expected to play a significant role in next-generation cellular systems [104], [105]. D2D architectures, features, and possible usage scenarios are presented in [104]. Received signal strength in the extended coverage scenario can be boosted by forming multiple parallel paths, each made up of collaborative devices [104]. Studies in [106] investigated the use of terminal cooperation for coverage extension, capacity and energy-efficiency improvement in terrestrial cellular systems, showing that significant coverage improvements can be achieved using D2D communication.

Proper understanding of the capabilities of D2D for HAP coverage extension requires a clear understanding of D2D propagation characteristics, which is different for different environments. There are some propagation measurements for D2D communications for different enviroments such as rural areas [107] and forest terrains [108]. Despite the potential of D2D, many issues still need tackling, such as how a UE outside the coverage area can decide which UE within coverage to select as a relay, the communication protocol to use and how

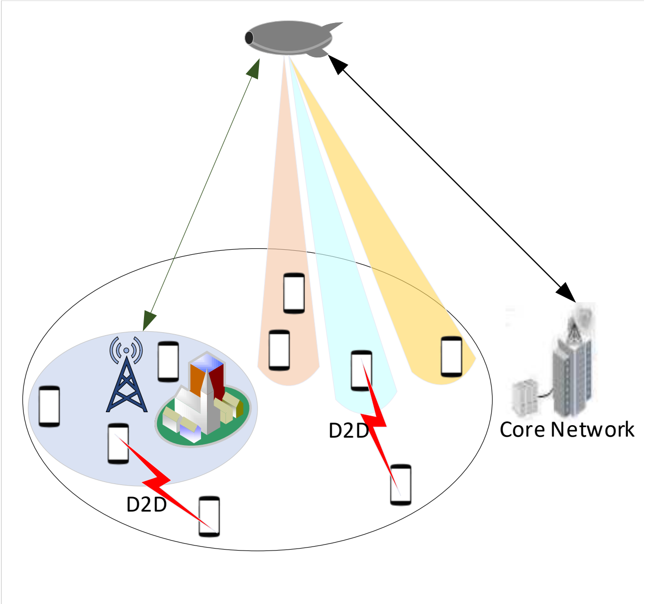

Fig. 5 – D2D communication for coverage extension in HAP-Terrestrial system architecture. Coverage can be extended by terminals at the edge of coverage cooperating with terminals with stronger signals.

to achieve satisfactory performance in terms of communication and energy efficiency for both devices. Fig. 5 shows the proposed system architecture for HAP coverage extension using D2D techniques. UEs at the EoC may initiate D2D communication with either terrestrial or HAP UEs within better coverage zones. It is important to highlight that D2D technology is already being implemented with a trial reported in [109].

B. *Factors Affecting Coverage Extension*

This section highlights two of the most important factors that affect HAP coverage extension implementation and modelling.

1) HAP Antennas: Long distance communication from HAP requires a very directive high-gain antenna system with multi-beam performance. Since interference to existing infrastructure is to be minimized, antennas with dynamic beam pointing ability are required to allow for interference cancellation. Highly directive multibeam horn and electronically steered array antennas have been used in earlier HAP projects like CAPANINA. The multibeam horn and electronically steered antennas consist of individual horns and microstrip patch antennas respectively as antenna elements. Prototypes for both types of antenna arrays were developed in [21] which shows that one of the disadvantages of the multibeam horn array is the weight.

The low profile, suitability for both planar and nonplanar surfaces, ease and lower cost of production with printed-circuit technology [110] are some of the factors which make electronically steered antenna systems ideal for HAPs. The combination of a number of antenna elements results in an increased collective directivity and gain but also increases the sidelobe level. A compromise between the number of antenna elements and weight, cost, directivity and gain, mainlobe beamwidth, sidelobe level, and power consumption is required. Hence dimensioning the system appropriately is necessary. This affects the radiation characteristics of the antenna. Contextually, increasing the dimensions of single elements expectedly results in increased directivity and gain for the individual element. In the case of phased arrays, the total antenna gain is the product of the antenna array factor and individual element gain. The total array factor, on the other hand, is the product of elements in the x- and y-axes for planar arrays. The analysis assumes that they are independent arrays. The detailed mathematical derivation of array factor is contained in [110]. Obviously, increasing the number of elements of the phased array consequently increases the antenna gain, but the antenna size increases as well. An important point to note is that the size of phased array antenna is limited by the payload carrying capability of the platforms.

Over the years, researchers have studied the effects of antenna characteristics on HAP communication systems. Thornton et al [111] compare the performance of circular and elliptical beam antennas in terms of carrier-to-interference ratio (CIR) in a HAP cell operating in the mm-wave bands. The authors approximate the elliptical beam main lobe directivity by a raised cosine function as follows.

$$D = D_{max}\,(\cos\theta)^{n} \tag{1}$$

where θ is the angle with respect to antenna boresight, and n is the roll-off of the main lobe.

It is highlighted that elliptical beams result in optimized power at the beam edge, providing better coverage than circular beam antennas. Also, having a steep roll-off factor results in quantifiable improvements in CIR, with the optimum value between 10-35dB [88]. In [112], two techniques of HAP antenna array steering are proposed. While one technique involves individual steering of the antennas to maintain the boresight at the cell centre, the second dynamically compensates for aperture pointing errors resulting from platform displacement. Practical deployments based on the first technique might be challenging because of its complexity especially, where there are significant number of antennas. This would require gimbals for each antenna, which will significantly increase the weight of the antenna subsystem. With respect to signal quality, the authors show that the error correction technique performs equally as well or better than the single adjustment technique. Albagory et al proposed a sinc-fed vertical linear array antenna for APs with half-wavelength spaced elements and conical power pattern in [113]. The authors propose an element feeding coefficient given as follows.

$$w(n) = \alpha(n)\,\mathrm{sinc}\left(\frac{\beta\theta_b}{\pi}\left(n - \frac{N+1}{2}\right)\right) \tag{2}$$

where $\alpha(n)$ is a windowing function used in controlling the radiation pattern, β is a design adjusting parameter that compensates for the limited number of antenna elements. θ_b is the required beamwidth while N is the number of antenna elements.

2) Propagation Channel Models: In comparison with terrestrial and satellite systems, radio communication links between a HAP and the Earth are characterized by lower propagation loss and multipath fading [114]. However, realistic and accurate propagation channel models are required for accurate predication of the HAP communication link. Significant studies exist on air-to-ground (A2G) channel models including measurement campaigns in diverse environments and at different frequency bands, as reported in the surveys [115], [116]. The models reported are based on measurement campaigns carried out using low-altitude platforms. Hence, there is the inherent concern about whether these models can be used directly for high-altitude communications considering the non-negligible differences in their propagation environments. Models derived from measurement campaigns are environment-specific. Nevertheless, actual measurement campaigns have not been conducted with a platform at stratospheric altitudes to the best of knowledge of the author. A significant majority of the channel models in the literature are analytical [117], [118] with some empirical models available [119]–[121].

a) Analytical Channel Models: A number of studies on statistical channel models exist in the literature. In [117], [122], [123], the HAP channel is modelled as a switched channel, which follows a Semi-Markovian process shown in Fig. 6. Three different states mirror the typical conditions of a propagation channel such as LOS, shadowed and obstructed states. The duration and distribution of these states as well as their transition probabilities are defined in the ITU-R Recommendation P.681-6.

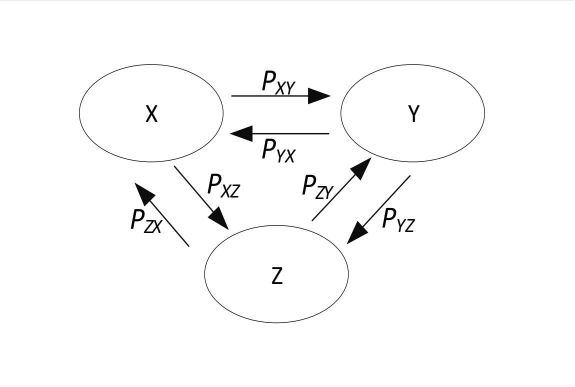

Fig. 6 – Semi-Markovian Process [123].

Mathematically, the Markov chain is defined by a state probability vector w with elements of the vector showing the duration in state i. This is expressed as follows [117]:

$$w = (w_X w_Y w_Z) \tag{3}$$

$$\sum_{i=1}^{n} w_i = 1, \forall i = 1, \cdots, n \tag{4}$$

Considering the state probability vector and transition matrix, the following expression is obtained.

$$w(I - P) = 0 \tag{5}$$

where I is an identity matrix.

While the Semi-Markovian process approach allows for accurate prediction of the channel, it increases the complexity of the communication system. This complexity follows the fact that the system maintains state time distribution and transition matrices in addition to the switching between the states. In [124], [125], a HAP-MIMO channel is represented by a channel matrix as a function of Rician factor, LOS and NLOS components. The HAP-MIMO channel is given as follows [124], [125].

$$H = \sqrt{\left(\frac{H}{1+K}\right)} H_{LOS} + \sqrt{\left(\frac{1}{1+K}\right)} H_{NLOS} \tag{6}$$

where K, H_{LOS} and H_{NLOS} are Rician distribution factor, LOS and NLOS components of the HAP-MIMO channel respectively. More discussion on H_{NLOS} and H_{LOS} is contained in [125]. This model is less complex compared to the Semi-Markovian process based model. However, accurate knowledge of the angle of arrival and departure of signals are required.

In [126], a circular straight cone model is proposed for the characterization of multipath propagation in HAP links using conic geometry as shown in Fig. 7. This model considers the single bounce multipath component to be the most significant contributor to the received signal power, and assumes that scatterers are generally located below a particular height from ground level [127].

As shown in [127], the probability and cumulative distribution functions of the circular straight cone model deviate from data obtained by measurements and predictions. The authors in [127] improved this model by relaxing the assumption that scatterers and single bounce echoes are uniformly distributed. In their study, the actual probability distribution function of the scatterers and single bounce echoes are taken into account to obtain a more realistic result. Furthermore, small-scale fading effects are modelled in [118] where the path amplitudes are considered as random variables with Weibull distribution. A Rician fading model is proposed for signals that have a LOS path between the transmitter and receiver.

b) Empirical Channel Models: In [115], [121], [128] an empirical propagation prediction model as a function of elevation angle is described for HAP communication in urban areas in the 2-6 GHz band. Considering LOS and NLOS propagation, the authors in [121] carried out a statistical model based simulation to characterize shadowing based on

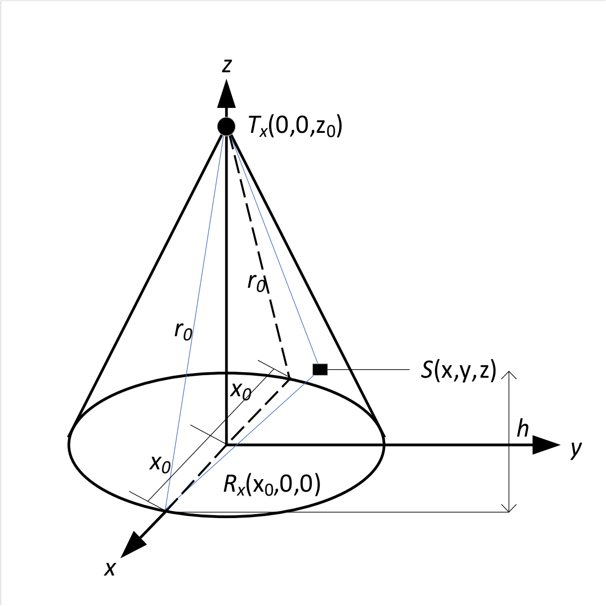

Fig. 7 – The circular straight cone model [127].

the geometry of basic LOS and NLOS scenarios. The scenarios were developed by randomly generating urban environments to simulate different built-up areas based on the ITU-R Rec. P1410 model. The authors, based on their simulations, proposed the following large-scale fading model.

$$L = \begin{cases} L_{FSL} + \zeta_{LOS} & LOS \\ L_{FSL} + L_s + \zeta_{NLOS} & NLOS \end{cases} \tag{7}$$

where L_{FSL} is free space path loss, ζ_{LOS} and ζ_{NLOS} are random variability components log-normally distributed with zero mean. L_S is random shadowing defined as a function of elevation angle. The evaluation of L_S for different elevation angles in given in [115], [121], [128]. Since this model is obtained for urban areas, there is a question of its applicability in other environments like rural or sub-urban areas.

Another elevation dependent shadowing fade margin model characterizing different built-up areas is proposed in [128] with a theoretical relationship with fade margin, outage and coverage probabilities established. Comparing results obtained from simulation to results obtained from measurements from a LAP, the model achieves reasonable performance. Studies in [129], [130] propose Okumura-Hata channel models for a LAP comparing its performance to other LAP models in the literature. The optimization of the Okumura model for a LAP using machine learning is proposed in [129]. It is important to note that these results cannot be directly related to HAPs because they were obtained by measurements from an altitude significantly lower than a HAP.

Other studies in the literature include a number of HAP-based statistical channel models [131], [132], which require real measurement data for validation. Such data may be specific to a particular environment or frequency or not available. While satellite models like the CCIR model [133], [134] and FSPL model can be seen as too pessimistic and optimistic respectively, the use of FSPL with some realistic shadowing can potentially give reasonable results. Further studies on HAP channels can be found in [119], [120], [135].

V. RADIO RESOURCE AND INTERFERENCE MANAGEMENT TECHNIQUES IN HAP

Efficient radio resource management (RRM) is relevant to ensuring high system performance. Inefficiency in RRM results in inefficient resource utilization and reduction in system performance. With increasing densification in next-generation wireless networks, the importance of adequate RRM for improved capacity and interference management cannot be overemphasized [136]. Reducing interference and achieving a given quality of service while methodically utilizing available spectrum resources, transmission power and antennas are vital [137]. In this section, we discuss radio resources and interference management strategies for HAPs, focusing on spectrum allocation, power control, and the exploitation of REMs. Most of the techniques discussed are not specific to HAPs, however, they can be exploited for use in HAP networks or a heterogenous network of HAP and terrestrial systems.

A. Channel Allocation

Channel allocation (CA) has evolved from the very simplistic fixed allocation schemes, which involves artificially partitioning the available spectrum into chunks for fixed assignment, to dynamic spectrum allocation schemes, which allocates spectrum based on the state of the network.

1) Fixed Spectrum Allocation: Fixed allocation schemes divide the available spectrum into a set and permanently assign this to each cell in a cellular network [138]. This scheme can be implemented in a HAP system by partitioning the available spectrum between the HAP cells. However, though less complex compared to other allocation schemes, the fixed allocation scheme is rigid in dynamic traffic and network scenarios thus resulting in poor QoS performance and spectrum utilization [139], [140]. An alternative to the fixed allocation is to dynamically allocate spectrum to the system based on the usage condition. Some of the early HAP studies [141], [142] investigated the performance of a HAP system using fixed and dynamic channel assignment strategies. Liu et al in [143] investigate radio resource management for multiple HAP use cases using interference-based techniques. Assigning fixed channels to spot beams uniformly while user terminals use the Personal Access Communications System-Unlicensed B (PACS-UB) channel assignment strategy, both terminals perform different tasks. Results show that using dynamic channel allocation (DCA) results in significantly better performance than fixed channel allocation (FCA). Furthermore, Katzis et al [144], [145] show that the performance of HAP users can be improved at the HAP cell edge by exploiting cell overlap using FCA. They propose a new method that manages the available channels between the overlapping and non-overlapping HAP coverage areas to ensure fairness. Considering the proposed heterogeneous network of HAPs coexisting with terrestrial networks, an FCA scheme will not guarantee the QoS performance and spectrum utilization required of such a system. Dynamic allocation schemes perform significantly better.

2) Dynamic Spectrum Allocation: In dynamic allocation schemes, channels are assigned dynamically to users from a pool, based on user requests and availability and the state of the network [138], [140]. It is by far the most common spectrum allocation strategy in present wireless communication systems. Significant studies [146]–[149] have developed different DCA algorithms. DCA schemes can be classified as either distributed or centralized [150], [151]. The schemes can further classified into intelligent-based schemes, which are sub-classified based on type of intelligence.

a) Distributed and Centralized CA: A distributed DCA (DDCA) implementation, spectrum users determine the channels to use depending on some QoS constraints. Alternatively, a network entity can be solely responsible for assigning or reassigning channels to users that satisfy the QoS conditions in Centralized DCA (CDCA). CDCA requires complex computations for optimal performance, however, this complexity minimized in DDCA but without guarantee of optimality [152]. Mochaourab *et al.* [153] propose a DDCA scheme where channels are associated with prices. Secondary users, which have allocated budgets and can be assigned more that one channel, requests for a set of channels based on their current prices and the users utility. The complexity of the proposed algorithm is shown to be low. In [151], a CDCA algorithm is presented. The algorithm uses harmony search to handle interference between nodes for optimum network performance. It requires channel coordination between the nodes.

b) Genetic Algorithm-based CA: Li et al [149] present a genetic algorithm based DCA for a wireless mesh network tested using real wireless mesh routers. The algorithm takes channel active time, busy time and transmission time into consideration. These parameters indicate the duration of time the channel is active, busy or employed for data transmission. During channel allocation, routers obtain a score for each channel based on the interference on the channel before running the the genetic algorithm for channel allocation based on the score. The proposed genetic algorithm uses a fitness function to evaluate the quality of each link using the assigned channel. Channels allocated to a link may be re-assigned due to mutation. The authors show that the proposed algorithm significantly improves system throughput.

c) Game Theory-based CA: A dynamic channel allocation model based on the concepts of game theory is presented in [148]. The model considers a heterogeneous network made up of primary and secondary users. Here, we can assume that the HAP system is the secondary user sharing spectrum with the primary terrestrial system. The primary user has channel allocation priority over the secondary user, which tries to maximise its CINR by choosing the best channel available. A secondary user can use licensed or unlicensed bands for transmission. However, when the user is occupying a channel in the licensed band and a primary user arrives without a good channel, the secondary user finds a channel in the unlicensed band. If unsuccessful, the secondary user terminates its call and hands over the licensed channel to the arriving primary user. The proposed model results blocking probability improvements.

d) Reinforcement Learning-based CA: The state-of-the-art in channel [154]–[157] allocation uses reinforcement learning to make decisions on the channels to allocate to requesting users based on the knowledge of past allocations and the state of the network. RL is a machine learning (ML) approach, which accumulates solutions to decision making problems by trial and error, updating an associated value computed using a value function for each successful or failed trail. The application of RL in resource management is becoming increasingly popular due to its suitability in resolving control issues, which are related to the typical issues that emanate from RRM [154], resulting in significantly improved system performance. RL algorithms for RRM can be classified as either centralized or distributed. However, distributed algorithms draw more attention due to the lack of need for significant overhead.

In centralized RL, a single agent makes the channel allocation decision for other agents in the system. On the contrary, each agent in a distributed RL implementation makes its own channel allocation decisions in a distributed manner. Agents can cooperate between each other by sharing information to speed up the learning process in what is referred to as transfer learning [155]. Whereas distributed RL is popular in cognitive radio networks (CRN), centralized RL is ideal for single-agent cellular networks [156]. These intelligence-based schemes can potentially be applied to HAP systems to dynamically learn favourable spectrum resource allocation for the different users/cells/regions of the HAP coverage areas. For instance, RL can be implemented globally for the HAP system or in a distributed manner for individual HAP beams. Whether the implementation of ML in HAP is centralized or distributed, the question of complexity and optimality in DCA systems arises. A distributed RL learning algorithm for cellular systems, which is based on Q-learning is proposed in [158]. The proposed algorithm uses ICIC messages shared by neighbouring agents to create heuristic functions, which influences the spectrum allocation decisions of the distributed Q-learning based algorithm. This drastically reduces the probability of retransmission when compared with a conventional Q-learning algorithm.

Comparison of different learning algorithms, their advantages and disadvantages, as well as specific application scenario, is discussed. In [154], the authors highlight the challenges and opportunities of RL for RRM. They propose an architecture to facilitate general ML-based solutions in a radio access network (RAN) in addition to their proposed RL-based framework, with the ability to independently generate targeted RRM algorithms directly from measured data. The architecture shown in Fig. 8 proposed for mobile broadband is extendable to other RAN technologies. The actor-learner architecture comprises a learner, which learns RRM policies from measured data and actors that implement RRM policies disseminated by the learner and continuously generate samples of experience. The learner can learn and make efficient RRM policies in the RAN environment based on radio measurements like SNR, interference, spectral efficiency, in addition to network characteristics such as terminal capabilities, traffic patterns, the type and number of cells, cell coverage, cell capacity, etc [154]. This proposed architecture can be implemented in HAP wireless communication systems. The learner can be deployed in the platform in a centralized way with a global view of the network, while the actors can be deployed in the BBUs, which may be distributed or co-located especially if Cloud-RAN is implemented. Alternatively, the learner can be distributed in cells, which independently learn the best resources to allocate. As suggested in [154], information can be exchanged between actors and learners through the backhaul network with minimal effect on the access network.

While RL presents an interesting proposal for RRM, it is important to note that despite the potentials of RL-based DCA, there is an issue of poor early learning stage performance, which is an inherent disadvantage of all classic trial-and-error-based RL algorithms. This limits their adaptability in dynamic environments [155] assuming a reasonable learning rate. With the limited studies addressing HAP specific intelligent DSA/DCA, the development of multi-learning RRM schemes, which can combine game theory and RL for instance, can potentially be beneficial. Game theory can deal with agents (HAP and/or terrestrial systems) maximizing their immediate reward (and hence performance) to obtain the best choice of resources (transmission power and spectrum) based on instantaneous measurements and information from the HAP user devices. RL can subsequently be used to learn from these choices and build a knowledge base, which is used to improve future performance. In other words, game theory and RL are good for short-term and long-term decisions respectively.

B. Antenna Beam Management

With the allocation of terrestrial spectrum for HAP use by the ITU-R, efficient interference management is key to ensuring that significant interference in both systems is mitigated. Furthermore, interference management is needed in the intra-HAP system to mitigate interference from the serving and adjacent beams on HAP users. Co-channel interference can occur between terrestrial and HAP users on the same channel. Similarly, overlapping mainlobes and sidelobes of the HAP antenna on the same channel introduces interference. Terrestrial systems are interference limited and there is difficulty in interference prediction at different locations due to the dissimilarity between terrains. HAPs on the other hand can better predict interference at various locations because propagation is mainly LOS [21]. The techniques and strategies discussed in this section are summarized in Table II.

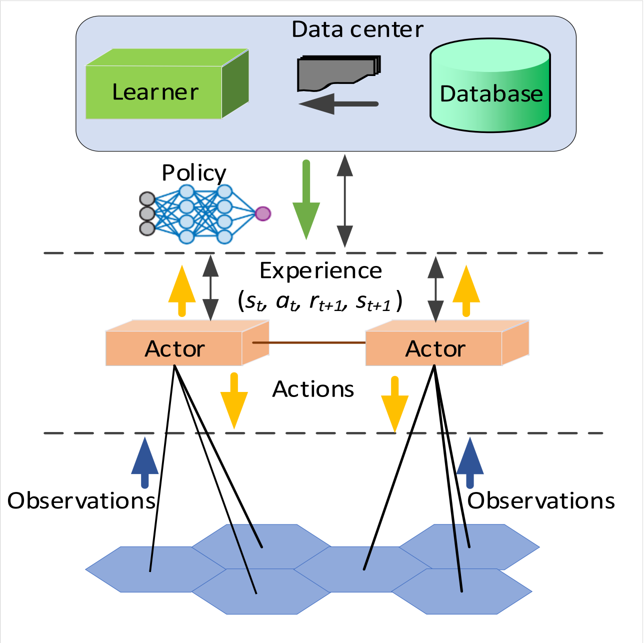

Fig. 8 – Machine learning based architecture for RAN [154]. Indicates the components of ML and the flow of information between them.

Thornton et al [11], [111] propose a method of predicting co-channel interference based on curve-fit approximations of elliptic antenna beam radiation patterns illuminating cell edges with optimum power. They propose a means of evaluating optimum antenna beamwidths for each cell of a regular hexagonal layout. In [11], it is shown that heavy frequency reuse worsens interference at cell edges and this can be improved with sidelobe suppression. Adaptive beamforming, high minimum elevation angle, antenna radiation pattern improvement, and dynamic channel assignment are some interference mitigation techniques [159].

C. Cell Coordination

In current and next-generation systems, coordination techniques are used to mitigate inter-cell interference and enhance capacity performance. For cross system interference mitigation between HAP and terrestrial systems, both systems can exploit coordination techniques to mitigate harmful interference between both systems. Current state-of-the-art includes the use of CoMP transmission and ICIC. CoMP enables base stations to cooperatively support data transmission to receivers and to constantly change channel state information (CSI), which improves cell performance. On the other hand, ICIC is used to exchange channel usage information between neighbouring cells frequently. This information is then used by these neighbours to avoid resources used by other cells, which might cause harmful interference to those cells if used for transmission. Major problems of coordination techniques include synchronization error and latency, which negatively affect the performance of the network [82], [160].

Pioneering the application of CoMP in HAPs is the study in [15], [96] where user-centric joint transmission JT-CoMP is used to improve overall system performance. The proposed JT-CoMP requires cooperation between two or more overlapping cells to send the same data simultaneously to a user, using an appropriate bandwidth allocation scheme in a CoMP region [15], [96]. The authors classify cell edge users into three (non-CoMP, 2-way and 3-way CoMP) based on the power level difference between the strongest received signals. All the cells participating in CoMP research a particular bandwidth, which cannot be reused in any other region of the cell, for use in the CoMP region. The allocated bandwidth is then allocated to the CoMP users depending on their location in the CoMP region. The results show an improved CINR performance especially for users at the edge and overlapping regions. In [161], a proposed Q-learning-based channel allocation scheme uses ICIC between neighbouring cells, which share their ICIC messages on a regular interval, to mitigate ICI, enhance system performance and speed up convergence.

D. Exploiting Radio Environment Map

Radio Environment Maps (REMs) can potentially be used for enhancing radio resource utilization, interference prediction and management in current cellular networks [162], [163] and even in virtualized 5G networks [164]. It is important in the creation of dynamic interference maps of a particular location at a given frequency based on information gathered from measurement capable devices (MCDs) [165]. Some of the information maintained by REM includes information about the radio elements, radio environment and radio scene, differing from a geolocation database by its ability to process information gathered from MCDs in conjunction with regulatory policies. While the radio elements maintain information of all radio devices like location, mobility and transceiver, the radio environment maintains interference data. The network operation information on a wide-ranging level is provided by the radio scene [165].

Coverage performance and RRM constitute very important aspects of radio networks. Periodically, MNOs carryout cost and time intensive drive tests to identify coverage holes. To minimize drive tests, 3GPP introduced a minimization of drive test (MDT) feature in LTE-A. This enables UEs to report specific radio measurements with respect to their location, which can be used for optimization. Logged Radio Link Failure (RLF) reporting is part of the MDT framework and allows UEs log measurements when they lose connection and report these measurements when they are reconnected [166]. A proposed technique in [167] uses regression Kriging to reconstruct radio maps with mean received power at points with no available measurements in 5G. Information like node location, base station height, transmission power provided by REM can potentially be exploited by a HAP using smart antennas for beam pointing, to avoid destructive interference on the terrestrial systems. It could also be used to ensure efficient radio resource assignment between HAP and terrestrial system users to ensure coexistence between the two systems.

Over the years, studies have been conducted on using REMs to improve wireless systems coverage, allocation of resources and interference management. The process of generating REMs combines actual measurements with applicable knowledge of the radio environment and predictions which is one of the main benefits of REM [168]. The REM topology may be made up of four main components: RRM/GUI, REM Manager, REM Storage, and Acquisition and MCDs, which can be UEs in LTE/LTE-A. Hierarchical REMs can be created by having different components or instances of all components in different layers of the network hierarchy [169]. These layers may be the Aerial eNB (AeNB), Terrestrial eNB (TeNB) and/or UEs depending on the application scenario. Implementation of REM in the AeNB deployed in HAPs may be referred to as global REM (G-REM) or local REM (L-REM) with respect to the TeNB and UE. This hierarchy determines the level of data needed. For instance, an AeNB on the HAP would require knowledge of all TeNB radio environments and the assigned UEs. With this information, the AeNB can form a service-area-wide G-REM. The TeNB, on the other hand, may likely only require information about the radio environment of its neighbor facilitated by LTE's Automatic Neighbour Relations (ANR) and assigned UEs. A direct technique involving spatio-temporal interpolation and indirect techniques involving transmitter localization and propagation modeling are the main techniques of constructing REMs. These techniques are explained in [168], [170]–[172].

Application of REM to the HAP-Terrestrial system presents potential advantages like facilitating coexistence of the two systems in addition to those discussed earlier. Since REMs can be used to discover coverage performance [160], [166], [173], properly exploiting the array antenna characteristics can allow for coverage improvement. Despite the obvious possible advantages of REMs in aerial networks, only a few studies [174]–[176] have so far investigated their applicability. UEs within the HAP footprint can report interference, throughput and bandwidth information to the HAP. REMs can then be generated by the HAP for coverage optimization.

VI. ISSUES AND CHALLENGES OF WIRELESS COMMUNICATIONS FROM HAPS

One of the most fundamental issues confronting the delivery of wireless communications services from HAPs is the design

Focus	Type	Approach	Network Type	Reference	Year
DCA	Stable matching DDCA	Cooperation and coordination between users	Cognitive Radio Network	[153]	2015
	Harmony search DDCA & CDCA	Network performance optimization	Cognitive Radio Network	[151]	2012
	Genetic algorithm	Multi-metric-based channel scoring	Wireless Mesh Network	[149]	2016
	Game theory DDCA	Strategy maximizes CINR using utility	Cellular Network	[148]	2018
	Reinforcement Learning DDCA	ICIC signalling as heuristic acceleration for Q-learning algorithm	Cellular HAP–LTE Network	[161]	2015
Cellular Coordination	CoMP	User-centric CoMP with joint transmission between neighbouring cells	Cellular HAP Network	[15]	2018
	ICIC	Q-learning algorithm with ICIC messaging between neighbouring cells	Cellular HAP–LTE Network	[161]	2015
Radio Environment Map	Interference prediction	Using spatial interpolation of information from MCDs	Cellular Network	[162]	2013
	Interference management	Categorizes REM-based RRM into different use cases	Cellular Network	[163]	2011
	Interference prediction	Regression Kriging method for radio map reconstruction in terms of average received power of MCDs	Cellular Network	[163]	2011

TABLE II – Radio resource and interference management techniques and algorithms

and development of aeronautic platforms with the appropriate form factor capable of maintaining its station at stratospheric altitudes over a long duration while carrying wireless communications payload with sufficient energy. Apart from this, some other challenges are faced in the development of appropriate wireless communication approaches and techniques such as cell formation, handover, backhaul and inter-platform communication, etc. This section presents some of these issues and challenges and some recent studies in the literature aimed at addressing them. Table III summarizes the issues discuss, highlighting the more recent references and their contributions. A higher level classification of some

A. Cell formation

Similar to terrestrial systems, delivering wireless communication services from HAPs require the formation of cells on the ground. There are some challenges in forming these cells, which can be contiguous over the service area or provide islands of coverage based on the spatio-temporal distribution of users and/or traffic, especially for extended coverage. Firstly, HAP cells pointed at significant distances from the sub-platform point broaden in shape and size due to the limitations of antenna beam forming [52]. The lack of consideration of broadening leads to a severe overlap between neighbouring cells, which in turn results in significant inter-cell interference (ICI). Secondly, the antenna radiation pattern producing the beams, which form cells, directly influences the ICI performance of the system. Therefore, in order to ensure an efficient HAP cellular communication system, cell formation must be careful considered, taking the effects of beam broadening and antenna radiation pattern into account. The majority of the studies on cell formation in the literature can be categorised into those that consider a limited coverage area with radius equal to 30km and others consider an extended coverage area with radius greater than 30km.

1) Limited Coverage Area: Logically, a HAP should provide coverage over an area of radius significantly more than 30km. In fact, ITU recommends that a HAP can have a footprint over an area of up to 400km radius [80]. However, most of the studies on cell formation for wireless communications are limited to within 30km radius coverage area. Considering that a number of strategies for HAP cell formation have been proposed over the years, we highlight some of the older schemes and the schemes proposed more recently.

Earlier studies [8], [177], [178] proposed a number of schemes, which include ring-shaped cell clustering and cell scanning as potential solutions for cell formation in their pioneering work on HAPs for wireless communication. Both solutions are rigid considering the spatio-temporal variation of users and traffic characteristics of current communication systems. Particularly, cell scanning, which involves beams scanning ‘visiting’ cells at intervals, become quite challenging

Challenge	Reference	Contribution	Approach & Assumpion	Parameter
Cell formation	[179]	Ring-shaped cell clustering	Uses vertical antenna array with windowing. Cell within 3-dB contours	20km altitude, 3 cell rings, 5° BW
	[51]	Irregular-shaped cells	Uses concentric ring array. Divides the coverage area into a grid of small pixel spots grouped into the desired shape	20km altitude, 5.6° BW
	[16]	K-means clustering - based cells	LOS between HAP and users. Cell centre is centroid of clusters	20km altitude, 32dBi gain, 40dBm power, 2.6GHz frequency
	[52]	Extended coverage cell tessellation	Uses square phased array LOS plus random shadowing between HAP and users.	20km altitude, 33dBm power, 2.1GHz frequency
Handover	[182]	Traffic-aware handover scheme	Only one new call arrival or handover in a small interval in same cell-reuse group	5 cells, 50–200km/h platform speed
	[183]	AMC-based handover	Divides cell into rate regions. Uses one-dimensional cellular model	5 cells, 100km/h platform speed, 10 channels/cell
	[184]	Cooperative handover	Uses one-dimensional cellular model. Velocity of the platform and neighbouring cell's channel state is known	5 cells, 10 channels/cell
	[185]	Inter-HAP handover	Platform flying within a position cylinder. Fixed users with different antenna types	15.5–17km altitude, 200km/h platform speed
	[202]	Multi-layer system handover	Users fixed on the ground or mobile and uniformly distributed with HAP moving	10–15 cells, 0–100km/h user speed, 10 channels/cell
Backhaul & IPL	[202]	Link & power budget for HAP RF	Receiver interference noise density and noise density equal. Accumulative atmospheric loss is 0.8	17km altitude, 32.6dBi antenna gain, 5° BW, 28GHz frequency
	[207]	Backhaul/Fronthaul FSO framework for NFP	NFPs flying autonomously in swarms. SBSs backhaul/fronthaul traffic aggregated athub located at the macro-BS	11–20km altitude, 200mW power, 10^{-9} BER
Networking	[216]	HAP routing algorithms	Link-state routing strategy	64Mbps HAP forward channel, 34.8Mbps HAP return channel, 1% packet loss ratio

TABLE III – Issues and challenges of high altitude platform wireless communications

when there is a large number of users and high traffic [52]. The authors presented no performance analysis to validate their proposed solutions. A different scehme based a sectorized concentric rings of cells with each sector illuminated by a separate orthogonal antenna beam is proposed in [177], [178]. Achieving orthogonality of the beams for each sector is a big challenge considering the number and size of cells within the coverage area. Falletti *et al.* [178] studied the performance of the sectorized cell architecture using three rings sectorized cells. Assumed that all sectors have equal area, they show that downlink capacity increases while traffic channel density reduces with increasing number of rings and sectors.

In more recent studies, the performance of the ring-shaped cell clustering solution proposed in [8] is investigated in [179] with the author proposing an improved vertical antenna array beam shape of the ring-cells, which results in a significantly improved carrier-to-interference ratio (CIR). However, the study did not addressed the concerns about the effect of beam broadening and user/traffic variation on the system performance. Some more flexible solutions considering irregular cell shapes, user clustering, and antenna beam broadening are proposed in [16], [51], [52]. In [51], the HAP coverage area is divided into pixel spots, grouping these pixels accordingly to obtain the desired cell shape. The results show that cells can be formed to follow the shape of a cluster of users with low sidelobe level. Furthermore, Studies in [16], proposes a cell formation scheme where users are clustered using k-means and cells pointed at the centroid of the clusters with the number of clusters determined a priori. The k-means-based scheme achieves a 95% coverage with around 42 antenna beams, outperforming the regular and random schemes. One of its benefits is that cells can be pointed to clusters to better serve the clusters. However, depending on the size of a cluster, more than once cell may be needed, unfortunately, this was not considered by authors who also limited their work within a coverage area of 30km radius.

2) Extended Coverage Area: There is a very limited study on extended coverage coverage earlier cell formation in the literature. Falletti *et al.* in their study described in the subsection VI-A2 considered a coverage area up to 60km radius. Arum *et al.* specifically studied the formation HAP cells for extended coverage considering beam broadening in [52], developing a cell tessellation algorithm that can adjust cell pointing locations. The authors compared the performance of the proposed algorithm with the scheme in [16] primed for coverage area radius 60km, showing that the proposed algorithm outperforms the schemes in [16] with a CINR improvement up to 15dB. However, the study did not consider user/traffic variation.

No study so far has investigated the combined effect of beam broadening, user/traffic variation and clustering on performance. A deeper understanding of the combined effect of these factors will facilitate HAPs use for wireless communication especially for coverage and capacity extension.

B. Handover

Handover in HAPs may occur either due to user mobility or motion/instability of the platform. With the increasing intolerance for delay in the LTE and 5G, strict constraints on the handover process must be satisfied by the HAP system. Appropriate handover schemes developed for different cell sizes and antenna array steerability [21]. This is particularly important in HAP extended coverage scenario where there are significant differences between cell sizes. This section presents a review of the work in literature, classifying the studies under intra/inter-HAP and multi-layer HAP handover.

1) Intra/Inter-HAP Handover: This refers to handover occurring within a HAP or between two or more HAPs, which could be as result of platform of user motion. It is by far the most common handover experienced in HAP communications systems. Apart from platform instability with effect on the communication system, which can be compensated with state-of-the-art payload stabilisation mechanism, existing solutions for handover in HAP can be exploited from conventional systems. However, a number of handover schemes have been proposed by various studies [180]–[186] in the literature. In [180], an adaptive soft handover algorithm is proposed and shown to outperform the conventional soft handover scheme with fixed parameters. Li *et al.* propose traffic-aware handover schemes in [182]–[184] that aim to minimize the traffic difference between current and target cells while considering the direction of travel of the HAP [182], adaptive modulation and coding [183], and cooperation between HAP cells [184]. The assumption of fixed users in these studies may be unrealistic in current communication systems with mobility expected from both the platform and users. Additionally, the assumption of equal distances to the centre of the neighbouring cells from the centre of the overlap area is untenable in extended coverage scenario where cells differ in size and shape due to beam broadening. He *et al.* propose adaptive handover schemes based on received signal strength (RSS) prediction [187] and cooperative transmission between multiple HAPs [188]. In [187], the HAP predicts the RSS of a mobile user at a given time instant, considering the user's speed and then decides whether the user should be handed over to another cell or not. The authors show in [188] that three platforms can cooperate during handover of a mobile user to minimize outage probability.

The effect of platform movement on handover is investigated in [181], [187]–[196]. The impact of platform swinging motion, at a frequency dependent on wind power and platform stabilization mechanism, on handover was studied in [189], [195], with the results showing that more network resources are required to support a burst of handover and that the probability of handover increases with increasing swing angle. Thornton *et al.* investigated the effect of lateral displacement of the platform, proposing models that let the HAP evaluate if it should handover a user to another channel to at least maintain its CIR. Studies in [191], [192], [194] highlight the effect of platform rotation on handover, showing that users at the edge of the HAP's coverage area suffer more from HAP rotation. Furthermore, vertical movement upwards or downwards can also affect handover performance as shown in [196], with results highlighting that downward movement has more negative effect on the probability of handover.

Excluding handover between cells in a HAP, users in a multi-HAP network can be handed over to different HAPs. An *et al.* proposed a mobile terminal (MT) controlled handover scheme where an MT decides when to handover to a target HAP based on its received signal strength indicator (RSSI) and available energy at the HAP in [185]. On the other hand, a platform in service may be required to be replaced by another platform, which will require handover from the in-service platform to the new platform. This change of vehicle is critical either due to maintenance requirements or because the system is designed to continually drift like in the Loon project [14]. Studies in [97], [181] present analysis on inter-HAP handover where one HAP is replacing another flying within a position cylinder. However, the incoming platform must be within the range of the user's antenna beamwidth and both platforms must satisfy the CINR threshold requirements [181]. Further studies is presented in [97], where the authors derive expressions for appropriate system parameters such as minimum user beamwidth, handover opportunity interval, handover success rate etc. The result show that having the incoming platform fly above the outgoing platform results in better handover performance since it detects wider user antenna beamwidth and that maintaining particular success rate requires that the platform instability must not move the platform beyond 0.1° away from the minimum user beamwidth.

2) Multi-layer System Handover: This refers to a handover occurring between a HAP and other communication systems such as terrestrial and satellite networks. This can be quite complicated to implement especially when a mobile user is moving between systems owned or operated by different platform operators. None of the studies in literature have specifically considers a multi-operator multi-layer system handover. Different algorithms for multi-layer handover between terrestrial base stations and an overlaying HAP based on the loading conditions of both systems are proposed in [197], [198]. In [197], the systems adaptively adjust their handover hysteresis margin based on their loading condition and that of the other system with results showing that load can be effectively balanced between the systems. Li *et al.* in [198] geographic information is used to make handover decision. If all resources in the target cell is occupied, the arriving call is handed over to another cell pending when resources become available. An intelligent scheme based on an adaptive neuro-fuzzy inference system with RSS, user distance and velocity as well as the available channels in the cells of both layers as inputs is proposed in [199]. Handover between HAPs and low earth orbit (LEO) satellites has also been studied in [200]. The authors propose a scheme where MTs estimate their location and time, report same to either LEO or HAP. The LEO alone then decides whether a handover should be initiated and to which system, reducing the complexity at the HAP.

C. Backhaul and Inter-platform Communication

Backhaul and inter-platform communication are extremely important in HAP wireless communication for integration of HAPs into the wider communication network as they are not expected to operate in isolation in most cases. A general HAP communication scenario consisting of user access links, backhaul and inter-platform links and alternative backhauling via satellite is presented in [17] as shown in Fig. 9. Backhaul communication network is needed to integrate a HAP into the wider core network on the ground or a satellite while inter-platform links are used to connect multiple HAPs together in a mesh network of HAPs. Backhaul and inter-platform communication can be implemented through radio or free-space optical (FSO) communication respectively, each of which has its advantages and disadvantages. The most suitable approach depends on many factors such as geographic location, available spectrum, bandwidth, radio regulations, weather, etc. Using radio communication for backhaul requires prohibitively high bandwidth at mm-Wave frequency bands and transmit power, which is usually not available or allowed. Alternatively, free-space optical provides high bandwidth at a fraction of the power required for radio communication, however, it can be severely affected by weather conditions and pointing error [58]. The high bandwidth capability and low power consumption of FSO makes it the preferred platform for backhaul and inter-platform link (IPL). A number of studies, some of which are highlighted in this section, have investigated the implementation of backhaul and IPL links using radio and FSO communications.

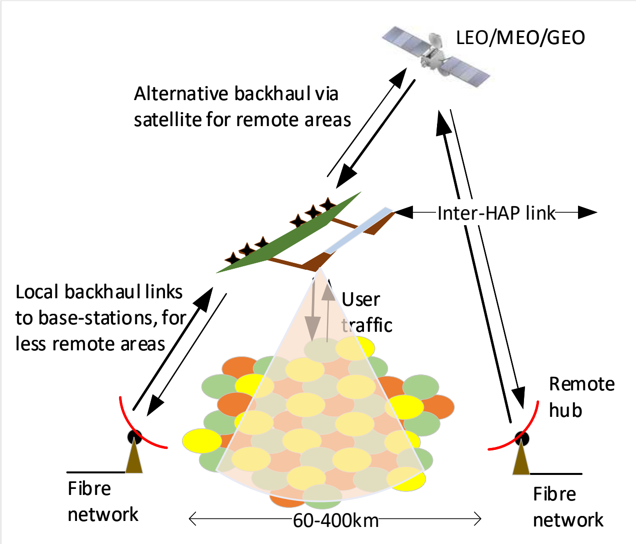

Fig. 9 – HAP communication scenario [17]. This highlights the possible communication links involved in delivering wireless communications from HAPs. These include HAP-Ground, HAP-User, HAP-HAP and HAP-Satellite links, etc.

1) Radio Communication: The possibility of implementing HAP backhaul and IPL using radio frequency (RF) is discussed in some studies such as [2], [201]–[204]. However, implementation of these links from HAP based on radio spectrum is not a popular proposition due to some reasons. The links required high bandwidth, typically at mm-Wave frequencies, and high transmit power in order to deliver high data rate at significant distances. Unfortunately, this can either be costly to acquire or not just available due to spectrum scarcity. Additionally, due to severe rain attenuation in tropical regions, backhauling at mm-Wave bands can be difficult for high availability HAP systems. Irrespective of these, work has been done on evaluating RF based backhaul or IPL systems for HAPs.

A report of an experiment of a WiMAX payload developed for HAP, using a RF based WiMAX customer premises equipment for backhaul link to the HAP, was presented in [201]. In the experiment, there was no dedicated radio link for backhaul of a WiFi access point whose backhaul was provided by the HAP, although the authors did point out out that a dedicated backhaul spectrum is preferable. Assuming line-of-sight propagation, link and power budgets for backhauling a terrestrial base station through a HAP is presented in [202]. Their result show that backhauling using digital video broadcasting protocol (DVB-S2) results in better bit error rate (BER) at low signal-to-noise ratio (SNR) compared to and worldwide interoperability for microwave access (WiMAX) 802.16e. The effect of weather conditions, like rain and strong wing, on HAPs backhaul link performance is highlighted in [203]. The authors propose that the polarization of the backhaul antenna can be adaptively changed depending on the prevalent weather conditions, with vertical polarization presenting the best performance.

2) Optical Communication: FSO is by far the most preferred technology for HAP backhaul and IPL based on the number of studies and projects in this area. The reason for this is not far fetched. Firstly, FSO provides high bandwidth with a low energy consumption, which is desirable at the HAP due to the limited availability of energy. Secondly, communication can be established at very long distances up to 5000k. Thirdly, beam divergence in FSO is smaller compared to radio systems, thus allowing designers to develop systems with smaller antennas for the same gain when compared to RF system [58]. These qualities contribute to the increasing interest in the use of FSO for backhaul and IPL in HAPs. Several studies have investigated FSO applications specifically in HAPs.

In the CAPANINA project, during the early days of HAPs for wireless communication, FSO airborne and ground terminals, which can be used for backhauling, were developed and trialled in the stratospheric optical payload experiment(STROPEX) [59], [70], [205]. The result of the experiment showed that using a 17.5kg airborne free-space experimental laser terminal (FELT) transmuting to a transportable optical ground station over a distance of 64km, a data rate of 1.25Gbps can be achieved at a BER $= 10^{-9}$ and less than 75W power consumption [205], which is significant. This BER and high power consumption can be significantly reduced as FSO IPL studies in [206] show. The authors show that when transmitting at an average transmit power of 1W and using an avalanche photodiode receiver with a gain of 150, a bit rate of 1.25Gbps can be achieved at a BER $= 10^{-16}$ between HAPs up to 400km apart. In [207], an FSO-based backhaul/fronthaul framework for 5G and beyond in a HetNet of terrestrial system and network flying platforms (NFP). In the proposed framework, a mother NFP,which connects the NFPs to the core network on the ground, controls the operation of the NFPs, which have a LOS fronthaul and backhaul point-to-point links to a CPE and nearest base stations respectively as well as IPL connection to the other IPLs. It is shown that in clear sky, a data rate of 100Gbps can be obtained. Furthermore, FSO can also be used for interconnecting HAPs and satellites [208], [209], with the system requirements discussed in [208].

The availability of FSO links in space faces a number of challenges. These challenges and some mitigation techniques are very explicitly discussed in [58]. The authors, highlight that optical links suffer from significant losses are incurred due to atmospheric effects such as absorption, scattering, atmospheric-turbulence, beam divergence, background noise, and sky radiance. They suggested different mitigation techniques such as multiple beam transmission, increasing receiver field-of-view, adaptive optics, hybrid RF/FSO, aperture averaging, diversity, modulation, coding, packet re-transmission, network re-routing, QoS control, and data re-play to improve reliability and availability. The availability of HAP backhaul links and IPLs can be enhanced by hybrid FSO/RF implementation [75], [207] and/or the use of diversity techniques [2]. The links can can be switched between FSO and RF depending on weather conditions, while access, orbital and site diversity can also ensure high availability.

D. Networking

In the next generation communication systems like 5G, traffic is completely based on data. Delivering 5G communication from HAPs requires the capability of routing data packets from the source to destination. It is likely that most routing algorithms developed for terrestrial systems can not be directly used in HAPs because they are based on the concept of shortest path between source and destination. In HAPs, this path can change due to the motion of the user and/or platform as well as satellites in the case of integrated HAP-satellite system, resulting topology information rapidly becoming obsolete [21]. A more detailed analysis of the challenges in routing in dynamic topologies like the HAP is presented in [210]. Networking in HAPs can be view from different perspectives such as topology, architecture, protocols, etc. Existing studies in literature can seamlessly fit into one or more of these perspectives. The main focus of this section is on routing in HAPs with different topology and architecture. Protocols for flow and transmission control in HAP networks are discussed in [211]–[213].

Irrespective of the routing algorithm or protocol, minimizing the end-to-end delay is important. A routing algorithm that identifies the minimum hop path that satisfies the maximum delay constraint in a mesh network of HAPs is proposed in [214]. The algorithm, which is based on ant colony behaviour and takes path length, delay, and traffic load into consideration, reduces propagation delay compared to the conventional Dijkstra shortest path algorithm. It requires series of messages exchanged between the source and destination HAPs through other HAPs in the mesh network in order to determine the optimum path. This exchange might introduce avoidable delays especially in very wide coverage scenarios. Alternative algorithms that forward packets without these exchanges is more desirable. A similar algorithm where a UAV forwards packets to the node closest to the destination in a distributed way is proposed in [215]. The packet is passed only if progress is made towards the destination otherwise it is dropped and retransmission requested. Results show that the average distance travelled by the packets does not change drastically with increasing number of UAVs. While these algorithms are designed for a mesh network of HAPs, it is not clear if they would work in a HetNet of satellite, HAP and terrestrial systems.

Studies in [216], [217] propose multi-layer inter-HAP-satellite routing algorithms for HetNets. The algorithm in [216] is based on available link capacity, number of hops to destination, and end-to-end delay. The algorithm forwards packets from source to destination HAP through the least congested IPL. If all IPL are congested or the delay of the available link is higher than the satellite link, the algorithm relaxes the maximum end-to-end delay constraint on the link and forwards the packet through the satellite link. Although the algorithm avoids congested IPLs, its scalability is yet to be demonstrated [218]. Irrespective of scalability, the implementation of IPLs influences the performance of routing schemes in the network. Therefore, it is necessary to use appropriate transmission technology to enhance routing performance [219]. A potentially more scalable topology-aware algorithm, which takes the position and speed of the platform provided by automatic dependent surveillance—broadcast (ADS-B) system into consideration is proposed in [220]. The algorithm builds up its neighbour table using the less frequent ADS-B messages from neighbouring platforms instead of the more frequent conventional hello messages, which causes more overhead. Instead of forwarding packets using shortest path, which can change quickly, to forward packets, the velocities and directions of the platforms provided in the ADS-B messages are considered to minimize propagation time. When a data cannot be forwarded because the next hop is out of proximity, the data is buffered up to a set time before being dropped if still not forwarded. These are desirable features considering the dynamic nature of HAP networks.

E. Multi-mode User Terminals

Another important aspect of wireless communications from HAP, which does not receive as much attention but is still necessary, is the development of multi-mode user terminals. Irrespective of how compliant to conventional system HAP networks are designed to be, there will be some bespoke differences in maybe standards, topology, protocols etc, which will make it a bit different from the conventional network. Business cases for HAPs are likely to be complementary with terrestrial and satellite systems and users will likely prefer to use the same terminals for these networks. The challenge is on the development of user terminals that can adapt to different wireless networks by reconfiguring themselves. Users can be able to select a network based on service requirements such as cost etc. Some problems such as need to support a wide range of frequency bands, the real-time execution of frequency conversion, digital filtering, spreading and dispreading, and power consumption need to be tackled [56], [221]. Unfortunately, there are very limited studies such as [222], [223] on multi-mode user terminal design in the literature.

VII. FUTURE RESEARCH DIRECTIONS

There has been an upsurge in interest in HAP-based wireless communications in recent times. This is not unconnected from recent success in aeronautic engineering of high altitude platforms, which are capable of maintaining their station at stratospheric altitudes. There are currently HAP platforms like Zephyr-S [43], which have achieved successful stratospheric flights and Phasa-35 [44], which shows promise. In wireless communications, advancements are being witnessed in antenna design, novel and approaches that are driving the developments in HAPs. Regardless of the significant developments in HAPs for wireless communications, there are some factors militating against its large scale use. For instance, current state-of-the-art platforms do not have sufficient payload capability to support wireless communications payload. Furthermore, wider coverage beyond what has been extensively studied in literature is desired by operators in order to maximise return on investments. These factors, some of which are presented in this section, are subject to further research. Also discussed are insights to future work in HAPs.

A. Extending HAP Coverage

Most of the studies on HAP wireless communication systems focus on a HAP coverage area of around 30km radius. However, some terrestrial base stations can provide macrocell coverage within an area of up to 30km radius [6]. Considering the superior propagation performance of HAPs [8], it should expectedly be delivering coverage well beyond 30km radius due to increased probability of line of sight coverage. Since HAPs are mostly desined for operation in rural and remote areas, potential HAP operators would be interested in maximizing the achievable coverage as much as possible to maximize their return on investment. Future studies should provide how HAP coverage can significantly be extended beyond the current state-of-the-art. Different approaches that can be used for HAP coverage extension includes novel array antenna designs, multiple HAP constellation, terminal coordination, etc. An array antennas can be designed such that its radiation maximises gain at wide distances. This could involve novel array shapes and aperture design. Furthermore, protocols and algorithms can be developed for coverage extension using D2D. The issue of how a UE outside the coverage area of HAP decides the UE within HAP coverage to select as relay in a D2D communication and the protocol to use needs to be addressed.

B. Interference Mitigation

Interference mitigation is one key area of HAP wireless communication. Different novel approaches to managing interference between HAP and terrestrial systems sharing the same spectrum are required to enhance coexistence of the two systems. Both systems may be able to coexist with coordination required to ensure that they do not interfere with each other. The state-of-the-art coordination techniques such as CoMP and ICIC can be used. However, during coordination, what message format will the systems use? How frequent will these messages be sent? If these systems are operated by two different MNOs, can they still be able to coordinate? If yes, how will the resulting security concerns be addressed. Answers to this questions are subject to further studies. The answers will also facilitate the exploitation of REMs for interference mitigation and radio resource management in a heterogeneous network of HAP and terrestrial systems. A novel way both HAP and terrestrial systems can access the REM database can be developed.

C. Radio Resource Management

As highlighted in section VII-C, very few studies propose a HAP-specific RRM approaches. While it is desirable to reuse as many conventional terrestrial system techniques as possible, bespoke HAP specific schemes are necessary. Advanced radio resource and interference management schemes taking into account HAP-Terrestrial system coexistence is key area of study. The state-of-the-art in spectrum allocation uses reinforcement learning. However, in conventional RL-based RRM schemes, early stages of learning are characterized by poor decision making [155]. Better intelligent based schemes, which optimizes decision during the early stages of learning, can be developed. This can be achieved using multi-learning RRM schemes combining game theory and reinforcement learning for instance. While game theory can be considered in the context of maximizing the immediate rewards of agents for improved early learning stage decision making, reinforcement learning can be used to improve the future performance of the system as it approaches convergence. Learning can be implemented on a global basis or beam-by-beam basis.

VIII. CONCLUSION

This paper discussed the concept of aerial platforms and their use in wireless communication. The developments in HAPs are presented with reference to achievements between 2000–2010 and 2010–2020. This includes developments in platform design and wireless communication approaches. The different classifications of aerial platforms including some existing HAP regulations were introduced. Some of the most common HAP network topologies were discussed, highlighting approaches for dynamic topology management. Since ensuring the coexistence of HAPs and terrestrial systems is paramount, different strategies for ensuring this coexistence was discussed. This focused on managing interference between the two systems. Furthermore, the state-of-the-art strategies for radio resource and interference management, including channel allocation, platform placement, HAP antenna beam management and the possible exploitation of radio environment map for interference management were presented. In addition, a number of issues and challenges confronting the use of HAPs for wireless communication were presented.

APPENDIX

Table III presents a list of acronyms used in this paper.

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Acronym	**Meaning**	**Acronym**	**Meaning**
AP	Aerial Platform	HAP	High-Altitude Platform
ABS	Aerial Base Station	RAN	Random Access Network
ITU	International Telecommunication Union	REM	Radio Environment Map
D2D	Device-to-Device	EO	Earth Observation
ISR	Intelligence, Surveillance & Reconnaissance	ROI	Return on Investment
SPF	Stratospheric platform	RRH	Remote Radio Head
RTT	Roundtrip Time	AP	Aerial Platform
UAS	Unmanned Aircraft System	IFR	Instrument Flight Rules
RPAS	Remotely Piloted Aircraft System	RLOS	Radio Line-of-Sight
BRLOS	Beyond Radio Line-of-Sight	LAP	Low-Altitude Platform
LALE	Low-Altitude Long-Endurance	MALE	Medium-Altitude Long-Endurance
LASE	Low-Altitude Short-Endurance	HALE	High-Altitude Long-Endurance
UAV	Unmanned Aerial Vehicle	TUAV	Tactical Unmanned Aerial Vehicle
CAA	Civil Aviation Authority	ITU-R	International Telecommunication Union - Radio
HAPS	High-Altitude Platform Station	IMT	International Mobile Telecommunications
WRC	World Radio Conference	MNO	Mobile Network Operator
LTE	Long Term Evolution	BBU	Baseband Unit
CDMA	Code Division Multiple Access	CIR	Carrier-to-Interference Ratio
RF	Radio Frequency	FSO	Free-Space Optical
MIMO	Multiple Input Multiple Output	UAC	Urban Area Coverage
SAC	Suburban Area Coverage	RAC	Rural Area Coverage
EoC	Edge of Coverage	A2G	Air-to-Ground
NLOS	Non Line-Of-Sight	LOS	Line-Of-Sight
FSPL	Free-Space Path Loss	CCIR	International Radio Consultative Committee
INR	Interference-to-Noise Ratio	SINR	Signal-to-Interference-plus-Noise Ratio
DSA	Dynamic Spectrum Management	mm-Wave	Millimeter wave
CoMP	Coordinate MultiPoint	ICIC	Inter-Cell Interference Coordination
3GPP	3rd Generation Partnership Project	JT-CoMP	Joint Transmission Coordinated MultiPoint
RRM	Radio Resource Management	QoS	Quality of Service
DCA	Dynamic Channel Allocation	FCA	Fixed Channel Allocation
RL	Reinforcement Learning	AIM	Advanced Interference Management
UE	User Equipment	REM	Radio Environment Map
AeNB	Aerial Evolved Node B	TeNB	Terrestrial Evolved Node B
LTE-A	Long Term Evolution – Advanced	UAS	Unmanned Aircraft System
CDCA	Centralised Dynamic Channel Allocation	DDCA	Distributed Dynamic Channel Allocation
EE	Energy Efficiency	CSI	Channel State Information
MCD	Measurement Capable Device	MDT	Minimization of Drive Test
CNR	Carrier-to-Noise Ratio	CINR	Carrier-to-Noise-plus-Interference Ratio
HetNet	Heterogeneous Network	SNR	Signal-to-Noise Ratio
CA	Channel Allocation	SNR	Signal-to-Noise Ratio
IPL	Inter-platform Link	NFP	Network Flying Platform
MT	Mobile Terminal	CIR	Carrier-to-Interference Ratio
AMC	Adaptive Modulation & coding	BW	Beamwidth

TABLE IV – List of acronyms.

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