Mobile communication via high-altitude platforms operating in the stratosphere is an idea that has been on the table for decades. In the past few years, however, with recent advances in technology and parallel progress in standardization and regulatory bodies like the 3rd Generation Partnership Project (3GPP) and International Telecommunications Union (ITU), these ideas have gained considerable momentum. In this article, we present a comprehensive overview of high-altitude platform stations (HAPS) as international...
mobile telecommunications (IMT) base stations (BS) (HIBS). We lay out possible use cases and summarize the current status of the development from a technological point of view as well as standardization in 3GPP and regarding spectrum aspects. We then present some system-level simulation results to shed light on the performance of HIBS. We conclude by pointing out several directions for future research.

**Introduction**

Over the past decades, mobile operators have greatly expanded the coverage of broadband wireless service, with the total number of mobile subscriptions exceeding 8 billion in 2021 [1]. Despite the wide deployment of terrestrial mobile networks, there is still a need for greater broadband connectivity services in remote communities. If nonterrestrial technologies could be deployed at a competitive cost, and if interworking with terrestrial networks (TN) could be achieved, they might have the potential to provide connectivity in remote areas, thereby complementing TNs.

The term *nonterrestrial networks* (NTN) refers to networks utilizing spaceborne or airborne payloads for communication. The recent interest in spaceborne satellite communication has been centered on low-Earth orbit (LEO) NTN that feature large constellations with thousands of satellites to provide global broadband access [2]. The focus of this article is on airborne NTN utilizing the same frequency bands as ground-based IMT BS. This concept is known under the designation high altitude platform stations (HAPS) as IMT base stations, or HIBS. By using the same spectrum as that already identified for IMT and where deployments already exist today, HIBSs can extend the operators’ coverage area and benefit from the already existing device ecosystem.

While HAPS and HIBS both refer to a high-altitude platform, they differ in the type of spectrum that they will be using. Often, the term HAPS is used also for the aircraft carrying the communications payload. Throughout this article, however, we reserve it (and the term HIBS) for the complete communications platform. For the aircraft alone, we use the term *high-altitude platform*.

HIBSs operate in the stratosphere, usually at an altitude of about 20 km. When compared to a TN, a HIBS system may provide wider coverage; when compared to a satellite network, a HIBS system may provide lower latency. Thus, in addition to satellite systems, HIBSs can play a role for expanding mobile coverage to remote communities.

The studies of high-altitude platforms for telecommunications and remote sensing can be traced back to the 1990s [3]. A milestone for HAPS initiatives was the identification of the first frequency bands for HAPSs in fixed service in the ITU Radio Regulations (RRs) in 1997, followed by the identification of additional frequency bands for HAPSs to provide IMT service (HIBSs) in 2000. Despite the early interest, the development of high-altitude platforms for commercial connectivity in the 1990s and 2000s was limited due to the immaturity of technical solutions. A resurgence of interest in providing connectivity using high-altitude platforms started around 2014, mainly driven by the Internet companies Google and Facebook, which invested in new technology to beam connectivity through the atmosphere to reach remote areas. Admittedly, technology advancements in connectivity as well as in areas such as solar panel efficiency, power storage, lightweight composite materials, avionics, microelectronics, and antennas, have now made HAPS/HIBS systems more viable, leading to the creation of HAPS Alliance [16].

A high-level overview of HAPS communications was provided in [4] back in 2007. A more recent survey on high-altitude platforms was presented in [3], which focused on technologies directly related to airborne platforms but did not address the connectivity aspect. A comprehensive survey of the communication aspects can be found in [5]. The work in [6] presented an investigation into the constellation design methodology of HAPS systems. A method for maximizing the sum rate in a HAPS system, based on the interference alignment, was proposed in [7].

Another study [8] used matching-game-based algorithms to find the optimal matching among users, HAPSs, and LEO satellites. The integration of HAPSs and satellites into a multilayered network was also investigated in [9]. Finally, [10] suggested using HAPSs as communications platforms with integrated computing resources, while [11] highlighted HAPSs as a potential enabler for next-generation parcel delivery networks.

In parallel with the academic studies about HAPSs/HIBSs, there have been notable new developments in standardization and on the regulatory front. In particular, the World Radiocommunication Conference 2019 (WRC-19) defined an agenda item (AI) for WRC-23 on HAPSs as IMT BSs, i.e., HIBSs [12]. In addition, 3GPP has been working on evolving 5G radio access technology—known as New Radio (NR)—to support TNs, which include HIBS systems [13].

Our article provides a concise but comprehensive survey of technical, regulatory, and standardization-related aspects of HIBSs. Unlike earlier works, we focus on HIBSs because their relatively straightforward integration with
Since HIBSs provide connectivity from the stratosphere, they represent a highly resilient network infrastructure against natural disasters such as earthquakes, floods, and bushfires.

TNs makes them a prime target for early commercial adaptation. We also provide some novel insights from state-of-the-art simulations of a combined HIBS and TN to shed some light on the system-level performance of such a combined network.

The remainder of this article is organized as follows. We start off by introducing the use cases of HIBSs and the key characteristics of the different types of HIBS aircraft. We continue by discussing the spectrum aspects of HIBSs and provide an overview of the HIBS standardization effort in 3GPP. Finally, we present system-level performance evaluation results on HIBSs and conclude by highlighting some interesting directions for future research.

The basic HIBS architecture is described in 3GPP technical report (TR) 38.811. The HIBS payload serves devices on the ground via a service link while being connected to the core network through a gateway via the so-called feeder link. While the feeder link is an integral part of a HIBS system, the focus in this article is on the service link. In particular, the HIBS frequency bands described herein refer to the service link only.

Use Cases of HIBSs
This section outlines some of the potential use cases for HIBSs.

- **Network coverage expansion**: HIBSs can cover sparsely populated or hard-to-reach geographical areas where terrestrial infrastructure is impossible or too costly to build (e.g., mountains, deserts, oceans, etc.). With the expected wide coverage from HIBS solutions, it might be possible to expand the network coverage area in a timely and cost-effective manner to narrow the infrastructure gap between urban and remote areas.

- **Disaster resiliency**: Since HIBSs provide connectivity from the stratosphere, they represent a highly resilient network infrastructure against natural disasters such as earthquakes, floods, and bushfires. A HIBS-based network can be used as a backup network in the situation where terrestrial infrastructure is not operative as a consequence of a natural disaster. This can ensure a high level of availability for critical operations.

- **Fostering Internet of Things (IoT) deployment**: The deployment of mobile networks traditionally follows the population density. A HIBS-based network could provide coverage for IoT devices and goods, considering their more diverse uses and locations (crops, forests, wildlife, oil and gas, and logistics). HIBS-based networks could complement TNs to expand the IoT deployment.

- **Drones**: As HIBSs are operating from the stratosphere, they can provide 3D coverage of a large geographical area to facilitate drone operations. TNs may not be optimal for serving drones due to their antennas being down-tilted to optimize coverage on the ground. A HIBS-based network can provide connectivity from the ground up to the sky.

**Characteristics of High-Altitude Platforms**
Overall, high-altitude platforms can be classified into three groups with different characteristics and challenges: airplanes, balloons, and airships. Airplanes need to move through the surrounding mass of air to generate lift and, thus, need part of their energy to power their engines. Balloons and airships, on the other hand, are lighter than air and, thus, do not need to spend energy to stay airborne. Airships are equipped with engines and can be flown to their desired operation areas. Balloons, on the other hand, move only with the winds, resulting in limited steerability at best. Common to these three classes is that the vehicles are generally unmanned and fully automated, which is a prerequisite to allow economical operation and flight durations of weeks or even months.

The operational altitude of about 20 km is chosen mainly because of the favorable atmospheric conditions in this part of the atmosphere. Almost all weather phenomena happen below, and, in particular, wind speeds are very low and comparable to those at the surface. An additional benefit is that the airspace above a height of approximately 20 km is not regulated by air traffic control in most countries [3].

A further requirement for long-duration missions is that the vehicles must not depend on any carried fuel and, thus, are solar powered. At the same time, this highlights one of the technological challenges of HIBSs: operation at high latitudes during the winter months, with little sunlight, is difficult. The current generation of HIBSs is restricted to a latitude band of approximately 35° north and south of the equator if year-round operation is desired.

Engineering challenges are plenty in high-altitude platforms, and each vehicle type has its own. Since the lift force generated by an airplane’s wing is proportional to the density of the surrounding air, which is reduced to about 5% at a 20-km height, these airplanes need to employ extreme lightweight construction methods and an extremely large wingspan. The largest models have a wingspan of more than 70 m but weigh only a few hundred kilograms. The payload capacity is typically in the range of tens of kilograms. A benefit of the large wing is a large area that can be covered with solar panels.

So far, the airplane category of high-altitude platforms has been explored the most by the industry, and several different prototypes have been built and flown during...
the past 25 years. In 2018, the Airbus Zephyr was the first high-altitude platform to enter serial production, albeit still in single-digit numbers. An Airbus Zephyr plane also holds the record for the longest flight by any airplane, with almost 26 days in 2018. The AeroVironment Sunglider (a descendant of the NASA Pathfinder/Helios program) also completed its first test flight in 2019. It is of particular interest because it was developed in a joint venture with the Japanese mobile network operator SoftBank and is intended to be used as a HIBS.

The world’s first HIBS operator, however, was Loon, providing commercial 4G LTE service in Kenya from 2019 until their shutdown in 2021. Loon did not use airplanes but high-altitude superpressure balloons, which are a proven technology and allow extremely long flight durations. In 2019, one of Loon’s balloons set the record, with a flight duration of 223 days. At the end of the flight, the balloons are landed and can be recovered. The biggest disadvantage of balloons is their relative inflexibility since they are not steerable and cannot easily be flown to a new region when demand changes. However, Loon developed methods to keep the balloons within their desired area of operation by utilizing different wind directions at different heights [14].

Finally, airships seem, at a first glance, to combine the strengths of airplanes (their steerability) with those of balloons (their ability to stay airborne without consuming electrical power and their robustness). However, to allow for a reasonable payload mass, they need to be of very substantial size (typical lengths are >100 m) and, thus, require large and expensive ground infrastructure. The thermal modeling of such large airships is rather complicated and not yet fully understood. So far, only very few prototypes have been built, and these have been plagued by technical problems. The only project in active development seems to be the Stratobus by Thales Alenia Space.

The main characteristics of the three types of high-altitude platforms are summarized in Table 1.

| Characteristic          | Airplane                      | Balloon                      | Airship                      |
|-------------------------|-------------------------------|------------------------------|------------------------------|
| Heavier or lighter than air | Heavier than air              | Lighter than air             | Lighter than air             |
| Steerability            | Fully steerable               | No or limited steerability   | Fully steerable              |
| Power source            | Solar powered                 |                              |                              |
| Operation altitude      | About 20 km                   |                              |                              |
| Technical challenges    | Large wingspan needed         | Limited steerability         | Large ground infrastructure  |
|                        | Fragile construction          | Cannot easily be flown to    | Thermal management           |
|                        |                               | the area of operation        |                              |

As HIBSs are operating from the stratosphere, they can provide 3D coverage of a large geographical area to facilitate drone operations.

Among other technical challenges described in the previous section, HIBSs need to follow spectrum regulations that are different from those of TNs. High-altitude platforms may provide user traffic in specific bands according to the ITU RRs [15]. Some of these bands are allocated to fixed service (referred to as HAPs in the RRs), while others are allocated to mobile service (i.e., HIBSs). It should be noted that this distinction is a regulatory one. As such, there is not necessarily a technological difference in HAPs versus HIBSs. However, fixed service is targeting ground stations at fixed locations, which enables the use of antennas with higher directivity than what is possible in mobile devices, such as smartphones. This is still true with the introduction of Earth stations in motion in the fixed service,
referring to ground stations on vehicles, such as ships or airplanes.

With regard to HIBSs, in particular, bands 1,885–1,980; 2,010–2,025; and 2,110–2,170 MHz in region 1 (Europe, the former Soviet Union, Africa, and the Middle East) and region 3 (most of Asia and Oceania) and bands 1,885–1,980 and 2,110–2,160 MHz in region 2 (North and South America) are identified in the RRs as bands that may be used by HIBS. Downlink (DL) transmission from HIBSs is allowed only in bands 2,110–2,170 MHz in region 1 and region 3 and 2,110–2,160 MHz in region 2.

Resolution 221 of the RRs stipulates the necessary technical conditions for HIBSs for the purpose of protecting cochannel services and applications in adjacent countries, including terrestrial IMT. In addition, conditions to protect adjacent services are required. A notification of the frequency assignment of these stations to the Radiocommunication Bureau is also compulsory.

The WRC-19 defined AI 1.4 for the upcoming conference, WRC-23, on the use of HIBSs in certain frequency bands below 2.7 GHz already identified for IMT and, in particular, the bands 694–960; 1,710–1,885; and 2,500–2,690 MHz. In preparation for WRC-23, the first meeting of the conference, Conference Preparatory Meeting (CPM) 23-1, tasked the ITU Working Party 5D to study the spectrum needs for HIBSs as well as to perform sharing and compatibility studies to ensure the protection of other services in these bands. The results of these studies will be the basis for any decision to be taken at WRC-23 in relation to AI 1.4. Table 2 gives an overview of the existing and planned HIBS frequency bands.

The ITU has identified a number of bands at higher frequencies for use by HAPs, e.g., at 6 and 28/31 GHz. These are allocated to the fixed service, however, and, thus, are not applicable for HIBSs.

### Table 2 The HIBS spectrum overview.

| ITU Region 1 | ITU Region 2 | ITU Region 3 |
|--------------|--------------|--------------|
| HIBS frequency bands as per RRs (Resolution 221) | 1,885–1,980 MHz | 2,010–2,025 MHz | 2,010–2,025 MHz |
| 2,010–2,025 MHz | 2,110–2,170 MHz | 2,110–2,170 MHz |
| 2,110–2,170 MHz | 1,710–1,885 MHz | 2,500–2,690 MHz |
| Frequency bands for consideration under AI 1.4 at WRC-23 (Resolution 247) | 694–960 MHz | 2,500–2,655 MHz |

### HIBS Initiative in 3GPP

3GPP Release 15 contains the first complete specifications of 5G NR, paving the way for large-scale commercial 5G deployments. The Release 15 NR specifications are also the basis for the continuous evolution of 5G technology. Enabling 5G NR to support NTNs is one direction under exploration in 3GPP.

In Release 15, 3GPP studied scenarios, requirements, and channel models for 5G NR-based NTNs, documented in 3GPP TR 38.811. In Release 16, 3GPP continued the effort by examining the solutions for adapting 5G NR to support NTNs, summarized in 3GPP TR 38.821. Though the NTN work in 3GPP has been primarily focused on satellite-based radio access networks, HIBS systems have also been considered when applicable. Specifically, to evolve 5G NR to support NTNs, there are four main challenges that must be addressed: long propagation delays, large footprint sizes, moving cells, and pronounced Doppler effects. These challenges are all more significant in satellite-based radio access networks than in HIBS systems. Although there were no specific analyses conducted for HIBS systems during Release 16, it is expected that the same enhancements considered for satellite-based radio access networks may be applicable for HIBS systems when needed.

The 5G NR has been designed with terrestrial communications in mind. However, 5G NR is a flexible air interface, and it was found that existing functionalities form a good basis for supporting NTN deployments.

To address the unique challenges in NTNs, 3GPP has conducted a work item to develop standardization enhancements to evolve 5G NR to support NTNs in 3GPP Release 17 [13]. The work item aims to introduce enhancements for LEO and geostationary satellite-based radio access networks while being compatible for supporting HIBS systems and air-to-ground communication.

### System-Level Performance of HIBSs

In this section, we present initial system simulation results to shed light on the performance of HIBSs. Our simulations are based on the assumptions described in 3GPP TR 38.811, including the overall geometry of the
setup, the antenna modeling, and the modeling of the radio propagation through the atmosphere. We simulate 19 cells, served by a single HIBS at an altitude of 20 km and an elevation angle of 90° as seen from the central cell. The beam footprint diameter of the innermost cell is approximately 10 km, resulting in a total service area of roughly 4,000 km². Table 3 lists the most important simulation assumptions.

Figure 1 shows the coupling loss distribution across the beam footprint, including the 16.5-dBi antenna gain of the HIBS antenna. It can be observed that the coupling loss values in outer cells are much higher than those in central cells. This is a purely geometric effect and a result of the comparatively low altitude of a HIBS (versus a satellite), which leads to a large variation in the HIBS-to-ground distance between the center and the outer regions of the coverage area. In the example simulated here, the distance to the central cell is 20 km (the flight altitude of the HIBS), while the distance to the outer edge of the simulated area is larger than 40 km. As a result, the outermost layer of cells shows a coupling loss that is at least 4 dB larger than that of the central cell. To counteract this effect, applying a different antenna beam pattern with a higher gain or a higher output power for the outer cells may be considered.

Figure 2 shows the signal-to-interference-and-noise ratio (SINR) distribution for different user densities. We simulate full-buffer data traffic; i.e., all users are receiving (DL) or transmitting [uplink (UL)] data all of the time. In DL, it can be observed that the SINR degrades with increasing user density. When the user density is below one, there is, on average, less than one user per cell. In this regime, as the user density increases, interbeam interference increases rapidly, leading to rapid degradation of the SINR. When the user density increases further, the system, on average, approaches a fully loaded state and enters an

**Table 3 The simulation assumptions.**

|                | TN                      | HIBS Network                      |
|----------------|-------------------------|-----------------------------------|
| Channel model  | TR 38.901 (rural macro) | TR 38.811 (rural)                 |
| Intersite distance | 9 km                   | N/A                               |
| Beam footprint size | N/A                   | ~10 km                            |
| Height         | 30 m                    | 20 km                             |
| Carrier frequency | 2 GHz                  | 2 GHz                             |
| Carrier bandwidth | 20 MHz                 | 20 MHz                            |
| BS antenna model | TR 36.873 (three-sector sites) | TR 38.811 (Bessel function) with 16.5-dBi antenna gain |
| BS transmit power | 49 dBm                 | 49 dBm                            |
| BS receiver noise figure | 5 dB                   | 5 dB                              |
| UE antenna gain | 0 dBi                   |                                   |
| UE transmit power | 23 dBm                 |                                   |
| UE receiver noise figure | 9 dB                   |                                   |
| Data traffic model | Full buffer            |                                   |

N/A: not applicable; UE: user equipment.
interference-limited scenario, making the SINR insensitive to the user density.

The UL SINR does not depend on user density. Compared with the DL SINR, it is always low, even with very low user densities. The reason is that we assume a regular handheld and, thus, power-limited terminal. As a result, the UL SINR is noise limited and not much affected by the increased interference resulting from increased user density. To reach a better SINR, a terminal with a higher transmit power or equipped with a high gain antenna could be considered.

We also study throughput performance for a HIBS network. To assess the service quality with respect to a TN, we extend the simulation setup with a TN of 12 three-sector sites arranged in a ring around a central coverage hole. The central area is served by a HIBS. For the sake of simplicity, we restrict the HIBS network to a single cell, roughly equivalent to the center cell of the previous simulation. The intersite distance of the TN is 9 km, corresponding to a rural environment. This setup reflects the main use case of HIBSs mentioned previously: expanding network coverage to remote areas. Figure 3 shows the simulation setup and the user association to the terrestrial and HIBS cells.

The resulting user and cell throughput is shown in Figure 4 as a function of the user density. The HIBS cell throughput is relatively constant at about 4.2 Mb/s, indicating that the cell is already saturated at very low user densities. The average terrestrial cell throughput fluctuates around 6 Mb/s for very low user densities before also saturating at close to 9 Mb/s. The HIBS user throughput is very low. At the lowest user densities, it reaches above 1.5 Mb/s, but it falls quickly to around 100 kb/s with increasing user density. The terrestrial user throughput also decreases when the available capacity has to be shared by more and more users, but it stays on a significantly higher level than in the much larger HIBS cell, which has to serve more than 10 times as many users, who are also located at much larger distances. The maximum spectral efficiency of the HIBS and TN is 0.23 b/s/Hz and 0.45 b/s/Hz, respectively.

Finally, we investigate user mobility. With the same network setup as before, we create users deep in the coverage of the terrestrial cells and let them move toward the center of the simulation area, where only the HIBS cell provides coverage. We also simulate the opposite case, where users are created within the HIBS cell and move toward the terrestrial coverage area. Figure 5 shows the locations where users have been handed over from the terrestrial to the HIBS cell (red) and vice versa (green). The shaded areas show the approximate coverage areas of the HIBS (blue) and TN (yellow). In the TN-to-HIBS direction, the handover happens approximately at the

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**Results from our Mobility Simulations Show that Users Moving from a HIBS Cell to a TN Might Be Handed Over Later than Necessary Due to the Slowly Decaying HIBS Signal Strength.**

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![Figure 3: The user association with a combined network of 12 terrestrial three-sector sites and a single HIBS cell.](image3)

![Figure 4: The DL user and cell throughput.](image4)
intended border area. In the reverse case, however, users regularly move far into the area covered by the TN before the actual handover is performed. This reflects the differences in signal propagation, where the HIBS signal strength decays only very slowly with increasing distance from the cell center and indicates that it might be beneficial to adapt the mobility procedures accordingly.

Conclusions and Research Directions
 Connectivity everywhere and at any time is critical, and mobile networks are key to achieving this goal. Indeed, 5G is not just an evolution of mobile networks but a revolutionary technology that will further advance society. As part of 5G, NR includes nonterrestrial connectivity. In particular, HIBSs can expand current mobile network operators’ coverage areas to remote areas where terrestrial deployments are challenging or impossible while reusing mobile spectrum assets and taking advantage of the available ecosystem.

In this article, we have presented a state-of-the-art primer on HIBSs, covering use cases, key characteristics of HIBS systems, spectrum aspects, 3GPP standardization, and system-level performance evaluations. Our results illustrate how the coupling loss between a HIBS and a terminal on the ground varies across the beam footprint. The results also show that, in DL, the SINR decreases with increasing user density. In UL, in contrast, the SINR is always low because of the power-limited terminals. Results from our mobility simulations show that users moving from a HIBS cell to a TN might be handed over later than necessary due to the slowly decaying HIBS signal strength.

We conclude by pointing out some fruitful avenues for future research:

- **Power consumption optimization**: Aerial platforms in HIBS systems usually rely on solar power systems to supply the necessary power for operations, including telecommunications transceivers and antennas. As a result, the power availability might vary across daytime and nighttime and over months/seasons. Adapting and optimizing the communications design to the power constraints of HIBS systems is a largely underexplored research area.

- **Connectivity for high-latitude regions**: Aerial platforms in HIBS systems relying on solar power may face challenges when flying at high-latitude regions during the winter months, when daylight hours are few. How to provide connectivity to high-latitude regions is an important challenge to overcome.

- **Coordination and coexistence between HIBS systems and terrestrial mobile networks**: As HIBS systems aim to use the same frequency bands as ground-based IMT BSs, how to coordinate HIBS systems with TNs is an important and rich area to look into. Example issues include interference coordination, seamless mobility, and load balancing. Adjacent channel coexistence with neighboring mobile operators is also a key area for further investigation.

- **Design aspects for feeder links**: Gateway transceivers are stationary, powerful, and typically dimensioned to make feeder links nonlimiting. Consequently, the focus of this article is on service links. Nevertheless, there are design aspects for the feeder links that deserve investigation. For example, the spectrum used by the feeder link may overlap with the spectrum used by other services, such as fixed satellite service. In such spectrum-sharing scenarios, interference coordination between HIBS systems and other types of systems is an interesting topic. In some scenarios, the feeder of a HIBS system can come from a satellite link rather than the ground gateway, leading to a “space–sky–ground” integrated network. How to jointly design the feeder link and other links in such an integrated network is an open question.

- **Trials and test deployments**: Due to the unique characteristics and challenges of deploying HIBSs in the
stratosphere, it is imperative to conduct extensive early trials and test deployments to collect feedback. Such trials and test deployments will help identify potential enhancement areas. The knowledge obtained can provide guidance to the evolution of 5G NR technology for better supporting HIBS systems.

Besides the technical and regulatory aspects described in this article, the realization of a commercial HIBS system faces many other challenges, e.g., to build the system in a cost-effective way or to demonstrate the high reliability that is required. These aspects deserve further theoretical and practical analysis as well.

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