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Overview of development and regulatory aspects of high altitude platform system

Dong Zhou, Sheng Gao, Ruiqi Liu*, Feifei Gao, and Mohsen Guizani

Abstract: High Altitude Platform (HAP) systems comprise airborne base stations deployed above 20 km and below 50 km to provide wireless access to devices in large areas. In this paper, two types of applications using HAP systems: one with HAP Station (HAPS) and the other with HAPS as International Mobile Telecommunication (IMT) Base Station (HIBS) are introduced. The HAP system with HAPS has already received wide recognition from the academia and the industry and is considered as an effective solution to provide internet access between fixed points in suburban and rural areas as well as emergencies. HAP systems with HIBS to serve IMT user terminal have just started to draw attention from researchers. The HIBS application is expected to be an anticipate mobile service application complementing the IMT requirement for cell phone or other mobile user terminals in which the service field of HAPS application cannot reach. After describing and characterizing the two types of systems, coexistence studies and simulation results using both the Power Fluxed Density (PFD) mask and separation distance based methods are presented in this paper. This paper also predicts future trends of the evolution paths for the HAP systems along with challenges and possible solutions from the standpoint of system architectures and spectrum regulation.

Key words: High Altitude Platform (HAP) system; HAP Station (HAPS); International Mobile Telecommunication (IMT); HAPS as IMT Base Station (HIBS); Power Fluxed Density (PFD) mask; separation distance

1 Introduction

Nowadays, with the ever-increasing demands for ubiquitous internet access, the High Altitude Platform (HAP) system emerges as one of the promising future network architectures. It permits the extension of broadband wireless telecommunication services in highly densely populated urban areas as well as rural and under-served areas. The World Radiocommunication Conference of 2019 (WRC-19) finalized the identification and associated resolutions for the promotion of worldwide harmonization with HAP Station (HAPS) applications in Fixed Service (FS), and developed a new Agenda Item 1.4 (AI 1.4) for WRC-23 to consider the use of HAPS as International Mobile Telecommunication (IMT) Base Station (BS) (HIBS) application below 2.7 GHz on a global or regional basis.

HAP system is a communication system using HAPS providing supplemental radiocommunication to unserved or underserved areas. The formal definition of HAPS was born in 1998 in the International Telecommunication Union Radiocommunication sector (ITU-R) Radio Regulation (RR) where HAPS is a station located on an object at an altitude of 20–50 km and at a specified, nominal, and fixed point relative to the Earth,

• Dong Zhou, Sheng Gao, and Ruiqi Liu are with ZTE Corporation, Shenzhen 518057, China. E-mail: zhou.dong1@zte.com.cn; gao.sheng@zte.com.cn; richie.leo@zte.com.cn.
• Feifei Gao is with the Department of Automation, Tsinghua University, Beijing 100084, China. E-mail: feifeigao@tsinghua.edu.cn.
• Mohsen Guizani is with the CSE Department, Qatar University, Doha 2713, Qatar. E-mail: mguizani@qu.edu.qa.
* To whom correspondence should be addressed.
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acting as the carrier of HAP services[1, 2].

Exploiting HAP system to practical applications, HAPS and HIBS are separated as two types of applications under fixed and Mobile Service (MS) in accordance with RR, in which FS is defined as a radiocommunication service between specified fixed points, and MS is defined as a radiocommunication service between mobile and land station or between mobile stations[2]. As emerging economies around the world focus on digital transformation as a path towards socioeconomic empowerment, bringing connectivity to all is increasingly critical.

Despite fast-growing Information and Communication Technology (ICT) segments, insufficient broadband internet access for 3.9 billion people is still a huge digital gap[3]. Exploiting novel network frameworks as non-terrestrial networks and Space-Terrestrial Internet Networks (STIN) benefits agencies and entities with tremendous opportunities for business and sacred missions[4, 5]. The HAP system is initiating a novel network providing architecture merging the digital gap through different radiocommunication services as an STIN design under various environments and scenarios.

HAPS systems as FS can be used to provide broadband connectivity to a fixed Customer Premises Equipment (CPE) and a fixed Gate Way (GW) for end user transmitting to core networks. HIBS systems as MS can be used as a part of terrestrial IMT networks to provide mobile connectivity to underserved communities and rural and remote areas with the ability to utilize a large footprint at low latency. Each type of HAP applications would enable wireless broadband deployment for FS or MS in remote areas, including in mountainous, coastal, and desert areas[6].

HAPSs are stratospheric stations, each is composed of an aerial vehicle and a payload that operates at around 20 km above ground. HAP systems have the potential to become an important tool for bringing broadband to bandwidth-hungry and unserved areas, supplementing existing networks to meet ever-increasing demand, and serving as instant infrastructure in emergency communications and disaster relief[7].

Diversified types of stratospheric unmanned aircraft systems, including airship, aerostat, balloon, drone, and so on, are under the consideration as a carrier to HAP system[8–11]. Based on the innovation of aircraft materials, HAPS has become more viable due to the evolution of technology through advances in solar panel efficiency, battery energy density, lightweight composite materials, autonomous avionics, and antennas[12–14]. Communication systems designed with efficient mobility and power management, serviceable antennas technology, short propagation delays, and good scalability of system capacity have been under continuous developments and innovations for decades[15–17].

Therefore, ITU-R has made tremendous efforts using HAP system for bridging the digital gap around the world. Global and regional harmonized identifications for HAPS in fixed service at WRC-19 will facilitate the development of these applications and allow trials to move towards commercial deployments.

As far back as the 1980s, the conception of Stationary High Altitude Relay Platform (SHARP) with a 600 km coverage was envisaged as a telecommunication device expending the traffic capacity for telephone service and broadcasting TV service to rural regions[18, 19].

In WRC-97, European common proposals for the work of the conference initially put forward a conception, which was high-altitude relay platform as an unprecedented technology. It was proposed to add a definition of HAPS in Section 4 of RR as a station in the fixed services situated on a platform at a high altitude (20 – 35 km) above the ground and a fixed position[20].

As global system for mobile communications developed by the European Telecommunications Standards Institute (ETSI), High Altitude Long Endurance (HALE) platform arised as a feasibility BS providing high quality of a cellular system[21]. A longevity service, which carries a larger payload platform, named High Altitude Long Range Observational Platform (HALROP) operating as a solar-powered electric propulsion system, was under the study for the solar cell material and energy balance[22].

The first worldwide designation for HAPS application to the fixed service in bands 47.2–47.5 and 47.9–48.2 GHz, which is subject to the provisions of resolution 122, was achieved in WRC-97 and officially published in RR in 1998[23]. In the same year, No. S5.388 was developed in RR intending for use, on a global basis, by administrations wishing to implement IMT-2000, which offered the possibility for HIBS applications to be utilized in 1885–2025 and 2110–2200 MHz[23].

Afterwards, in WRC from 2000 to 2019, multiple bands were identified for the use of HAP applications in fixed and mobile services. In WRC-2000, in Regions 1 and 3, the bands 1885–1980, 2010–2025, and 2110–2170 MHz, and in Region 2, the bands 1885–1980 and 2110–2160 MHz explained in No. 5.388A got authorization to be used by HAPS as BS to provide IMT-2000, which was the earliest permission in RR for the predecessor of the HIBS application[24]. In WRC-12, No. 5.388A changed the illustration of the footnote as providing IMT instead of IMT-2000, which expanded the telecommunication types of HIBS application. Through these years of development and standardization of HAPS and HIBS applications, many WRC agenda items were established to discuss the possible use cases and frequency bands for HAPS and many of them were agreed[24–28]. With more bands identified and more application scenarios recommended, HAP systems have emerged from some primitive concepts to commercialization in multiple countries and regions.

Resolution 160 in WRC-15 figured out that the existing HAPS application identifications were established without reference to today's broadband capabilities, and since WRC-12, the evolution of technology through advances in solar panel efficiency, battery energy density, lightweight composite materials, and autonomous avionics and antenna technology may improve HAPS viability.

Furthermore, the resolution invited ITU-R to study additional spectrum needs for gateway and fixed terminal links for HAPS application to provide broadband connectivity in the fixed service as well as the suitability of using the existing identifications on a global or regional level.

As for HIBS, the necessary studies of HIBS applications need to be further conducted in study period 2019–2023, including spectrum needs of HIBS applications, sharing and compatibility studies, appropriate modifications to the existing footnote, definition of HIBS, and developing related recommendations and reports[29]. All above topics are still being studied and discussed by both the academy and the industry.

In recent decades, burgeoning materialogy accelerated the process of HAPS industrially, breaking the silence to invest and launch the HAP system projects for providing omnipresent internet access infrastructure[30]. Both in civilian and military, HAP system embodies a noticeable preponderance than terrestrial networks, comparatively larger coverage area, less interference caused by obstacles, and shorter time to deployment. In comparison with satellites, lower latency and the possibility of returning for maintenance or payload reconfiguration attract investments realistically[31].

During the past 20 years, the industry has witnessed a save of active entrepreneurship and investment into HAP systems. In the early 2000s, UK based enterprise "Advanced Technology Group (ATG)" commenced StratSat programme, a solar powered airship combined with regenerative fuel cells/batteries for much of the time[32]. Google's project Loon graduated in 2018, partnered with Telefonica over couple of months to provide internet connectivity across Peru suffered under extreme rains and flood, and in collaboration with AT&T and T-Mobile, Loon team rehabilitated bringing internet to more than 20 000 people in Puerto Rico after Hurricane Maria made landfall[33]. Since 2014, Facebook arranged Aquila, a flying wing with a wingspan of 42 m and a total weight of about 400 kg, which is designed to be hauled up into the stratosphere by a helium balloon at altitudes between 18 and 27 km[34]. Analogous with homogeneous HAP system, Aqulia is designed to bring internet connectivity to unserved and underserved area. On August 2018, Airbus' Zephyr S logged a maiden flight of over 25 days, a world record[35]. Zephyr was regarded as filling capability gap with complement satellites, Unmanned Aerial Vehicles (UAVs), and manned aircraft in distributing persistent local satellite-like services[36]. In 2019, HAPSmobile was originated on the purpose of delivering communication network connectivity to mountainous terrain, remote islands, and developing countries[37]. HAPSmobile developed "HAWK30", a high velocity aircraft flying at altitude of

20 km. A solar-plane-based HAPS using beamforming techniques to create a coverage of 200 km is underway for providing smooth handovers between terrestrial and "HAWK30", for instance, between HAP systems and the Long Term Evolution system (LTE)[38, 39].

The communication convergence reflected the trends of diverse system and services of telecommunications, and the conceptual architecture of HAP dominant system has been studied for a long term. HAPS and HIBS applications identified in ITU-R RR are subordinated to fixed service and mobile service.

Dissimilar architecture and framework of high altitude platform system purpose on delivering continuous coverage and capacity enhancement, considering significant elements from variable segment, including local environment, economic implications, development level, and population density[40].

Figure 1 illustrates the typical model HAP dominant system architecture, containing HAPS and HIBS applications with different categories of deployment scenarios depending on cover area and utilization of HAPS.

Three types of diversity could be of use, including access diversity, backhaul orbital diversity, and backhaul site diversity, exploiting the architectures of HAP system via the characteristics from other communication systems[41]. Three types of diversity ensure the continuous connectivity via different HAPSs while unexpected weather and emergency situation occur and assist other types of communication service, such as satellite service and aeronautical service, seeking a stable non-blocking line in Fig. 1.

HAPS and HIBS applications share some similarities in certain features, including the carrier type, flight height, and coverage. Thus, the feeder link to core network could transfer via HAPS, the same as the typical HIBS to satellite link, separating the architecture in Fig. 1 into 3 sub-architecture types[42].

Figure 2 shows three types of HAP dominant system architectures, containing an integrated terrestrial HAP satellite architecture, an integrated terrestrial HAP system, and a standalone HAP system. Architecture A illustrates a powerful integrated network infrastructure

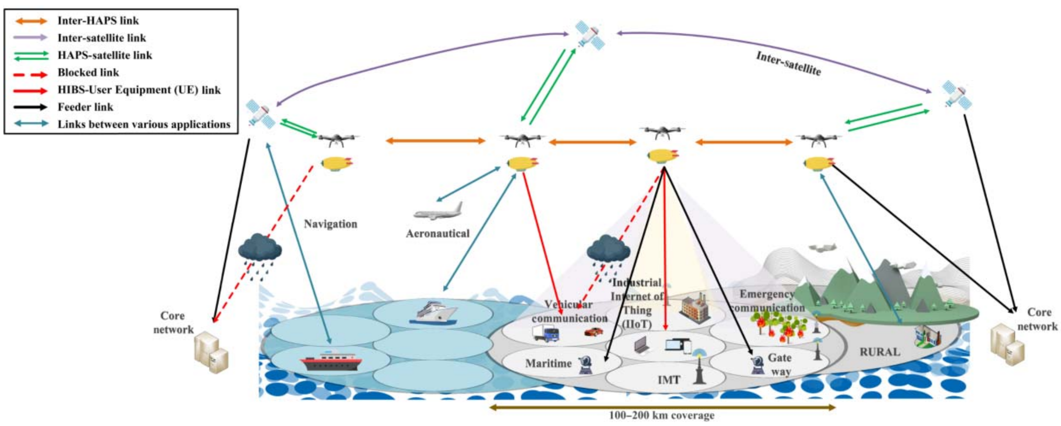


Fig. 1 High altitude platform dominant system architecture and deployment scenarios.

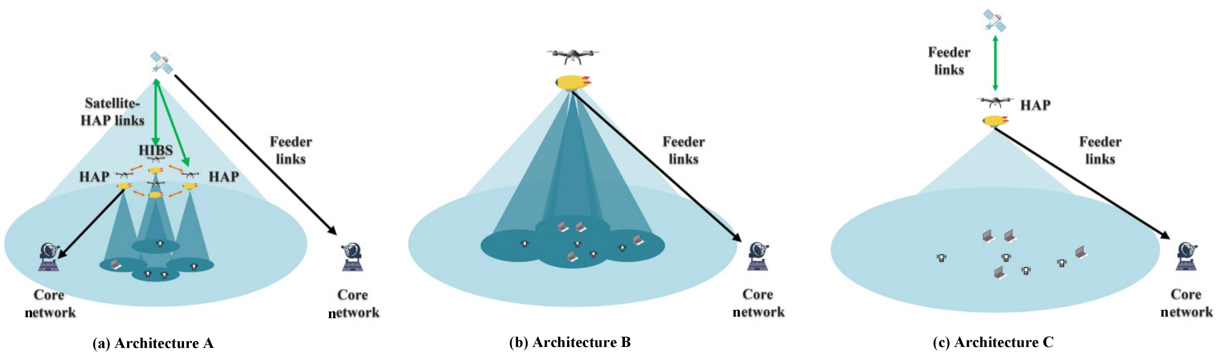


Fig. 2 Sub-architectures for using HAP dominant system.

with a hierarchical architectural solution, providing fault tolerance, system compatibility, and flexible access. Architecture B represents an architecture for IMT application, projecting for several macro cells and serving IMT users with low bit rates, and the feeder links are set by HAPS applications delivering by gateway or customer premise equipment. Architecture C depicts an HAP standalone architecture with the advantages of low-cost implementation for large area, building the sufficient large coverage, and solving the backhaul links issues when user traffic occurs via auxiliary HAP-satellite link[43].

The rest of the paper is organized as follows. Section 2 gives a review of the current systems and regulations. In Section 3, simulations and analysis are provided to testify the coexistence of HIBS and IMT systems. Finally, Section 4 concludes this paper with outlook on future development of HAP systems and possible challenges.

2 Review of current HAPS application and regulation

At the meeting of radiocommunication Study Group (SG) 9 held in October 1998, a draft revision of question ITU-R 212/9, fixed service system utilizing HAPS, was adopted, deciding essential question should be studied by ITU-R SG4 Working Party 4A (WP4A) and WP4A 4-9S[44].

Questions were remarked at some preliminary sections, including preferred characteristics of fixed service systems utilizing HAPS, preferred frequency bands for HAPS application in the fixed service, interference from the fixed service or other co-primary services, preferred methods, and frequency bands among HAPS[45].

Six HAP system models with various parameters and operation characteristics submitted by China, France, Germany, and USA are listed in Table 1. There are ongoing investigations and researches for two decades,

Table 1 System characteristics of HAPS used for spectrum needs and sharing studies.

System	Country	Frequency band (GHz)	Platform type	Service radius (km)	Minimum height (km)	Maximum height (km)	Flying radius (km)	Implementing scenario
1	France/ Germany	6.44–6.52 27.9–28.2 31.0–31.3	HTA	30 (for CPE) and 20 (for GW)	[18, 20]	26	5	All
2	France/ Germany	21.4–22.0 24.25–27.50 27.9–28.2 31.0–31.3 38.0–39.5 47.2–47.5 47.9–48.2	HTA	50 (for CPE) and 30 (for GW)	[18, 20]	26	5	All
4a	France	27.9–28.2 31.0–31.3 38.0–39.5	LTA airship	50	[18, 20]	25	5	All
4b	France	27.9–28.2 31.0–31.3 38.0–39.5	LTA airship	50	[18, 20]	25	5	All
5	China	27.9–28.2 31.0–31.3	LTA airship	50	18	25	1	Rural/ underseerved area
6	USA	21.4–22.0 24.25–27.50 27.9–28.2 31.0–31.3 38.0–39.5 47.2–47.5 47.9–48.2	HTA	50	20	26	5	Rural/ suburban

Note: HTA: heavier than air unnamed aircraft system; LTA: lighter than air unnamed aircraft system; CPE: customer premises equipment (serves fixed terminal links between HAPS and customer networks); and GW: gateway (provides feeder link services between ground and HAPS).

with outcomes including 6 published recommendations from ITU-R WP5C and contributions from various entities and states. The promotion of HAP system and the regulatory previsions on frequency bands using for HAPS application were accomplished on WRC-19 AI 1.14[29].

2.1 Spectrum need

Due partly to immature technology and regulatory issues, existing HAPS application identification and designation in fixed service bands were not under adequate utilization in the past, shown in Table 2. With reference to resolution 160 in WRC-15, the demand for greater broadband connectivity and telecommunication services in unserved or underserved communities and rural and remote areas was desirable to accelerate the development of radio frequency spectrum of HAPS application.

In the retrospect of resolution 160 of WRC-19, the spectrum needs for HAPS operating in the fixed service and the additional candidate bands were studied by WP5C in study period 2015–2019[46].

Based on the system characteristics and assumptions with various HAPS operation systems, spectrum needs were summarized in Table 3.

Under the estimation of various HAP systems, the spectrum needs emerge as an ultimate result for two links on the basis of hypothesis throughputs of HAPS as follows:

- In the range of 396 (for lower capacity) –2969 MHz (for higher capacity) for the ground to HAPS platform links.
- In the range of 324 (for lower capacity) –1505 MHz (for higher capacity) for the HAPS platform to ground links.

The existing designation for worldwide use by HAPS in fixed service prior to WRC-19 was a unique global band (47.2–47.5 and 47.9–48.2 GHz in both uplink and downlink) with an unexpected encounter to rain fade particularly in certain countries. On the secondary basis, 23 countries seek acceptance from neighboring administrations for using HAPS within 1000 km in frequency bands 27.9–28.2 and 31.0–31.3 GHz.

Given the regulatory provisions in the existing identifications and the current demand for multigigabit broadband, the existing identifications associated with current HAPS application regulatory provisions are not sufficient to accommodate the largest case requirements of all HAP systems in their more demanding spectrum

Table 2 Existing HAPS application identifications in FS bands.

Frequency band	Use	Direction	Bandwidth (MHz)	Identification
6440–6520 MHz	GW	HAPS-to-ground	80	5 admins (R1, R3)
6560–6640 MHz	GW	Ground-to-HAPS	80	5 admins (R1, R3)
27.9–28.2 GHz	GW and CPE	HAPS-to-ground	300	23 admins (R1, R3)
31.0–31.3 GHz	GW and CPE	Ground-to-HAPS	300	23 admins (R1, R3)
47.2–47.5 GHz	GW and CPE	HAPS-to-ground and ground-to-HAPS	300	Worldwide
47.9–48.2 GHz	GW and CPE	HAPS-to-ground and ground-to-HAPS	300	Worldwide

Note: R1, R2, and R3 stand for regions 1–3, respectively, see definition in RR[2].

Table 3 Spectrum needs for a variety of system characteristics.

Direction	Spectrum need (MHz)					Minimum spectrum need (MHz)	Maximum spectrum need (MHz)	Spectrum need in specific case (MHz)	Minimum spectrum need (including specific applications) (MHz)	Maximum spectrum need (including specific applications) (MHz)
	System 2	System 6	System 4a	System 4b	System 5					
GW to HAPS	1800	2727	1114	1424	247			110		
HAPS to CPE	900	938	576	200	164			15		
CPE to HAPS	240	117	213	59	24			15		
HAPS to GW	480	341	371	310	35			110		
Ground-to-HAPS	2040	2844	1327	1483	271	271	2844	125	396	2969
HAPS-to-ground	1380	1279	947	510	199	199	1380	125	324	1505

scenarios. Consequently, sharing and compatibility studies on possible new HAPS application identifications were conducted per resolution 160 in WRC-15.

2.2 Review of current spectrum band of 31.0–31.3 GHz

In WRC-2000, the use of 28.0 and 31.0 GHz bands was permitted for the fixed service by using HAPS in some countries[47]. Since the identification to HAPS application in 31.0–31.3 GHz, it is conspicuously owing to the favourable availability and feasibility performing in the rain environment and solutions for broadband wireless systems at tropical countries replacing satellite systems were proposed[48]. Project CAPANINA funded by the European Commission's 6th Framework Programme was commenced in November 2003, undertaking spectrum sharing studies, with emphasis on the use of 28.0 or 31.0 GHz bands within Europe[49].

In study period 1998–2000, the preliminary study sharing with systems in Fixed Satellite Service (FSS) using the band 29.0 GHz has been launched as well as the possible paring frequency band of 29.0 GHz, indicating the positive potential for sharing the bands with Geostationary Satellite Orbit (GSO) FSS earth stations which were not deployed ubiquitously[50]. In 2002, the ITU-R had performed a basic technical examination of a proposed system using HAPS in the fixed service within the bands 27.50–28.35 and 31.0–31.3 GHz, whose technical and operational characteristics of the HAP system presented in Annex of Recommendation ITU-R F.1569 were typical examples for future sharing studies, and it gave a guideline for development of HAPS using the band 28.0 or 31.0 GHz[51].

In WRC-07, ITU-R had developed studies on the feasibility of identifying a suitable and preferably a common 300 MHz segment of the band 28.9–29.2 GHz instead of 27.50–28.35 GHz paired with the 300 MHz band at 31–31.3 GHz[52], and various issues were studied in 31.0–31.3 GHz, indicated by WRC-03, including sharing studies among HAP systems, FS, FSS, Fixed Wireless Service (FWA), and FSS geostationary satellite orbit.

WRC-15 finalized resolution 160, facilitating access to broadband applications delivered by HAPS, and in 2016 – 2019 study period, ITU-R SG5 WP5C developed the research on sharing and compatibility studies of HAP system in the fixed service in 27.9–28.2 and 31.0–31.3 GHz frequency ranges, leading Report ITU-R F.2473[53].

In WRC-19, referring to Report ITU-R F.2473 properly, resolves in resolution 167 in the provisional final acts reached broad consensus effortlessly for the purpose of protecting fixed service, Earth-Exploration Satellite Service (EESS), and Radio Astronomy Service (RAS)[29].

2.2.1 Sharing and compatibility of FS and HAP systems operating in 31.0–31.3 GHz frequency range

Study results are accredited in WRC-19, for the purpose of protecting fixed-service systems in the territory of other administrations in the frequency band 31.0–31.3 GHz, and the Power Fluxed Density (PFD) level per HAPS produced at the surface of the Earth in the territory of other administrations shall not exceed the following limits, developed for clear sky conditions, unless the explicit agreement of the affected administration is provided at the time of notification of HAPS.

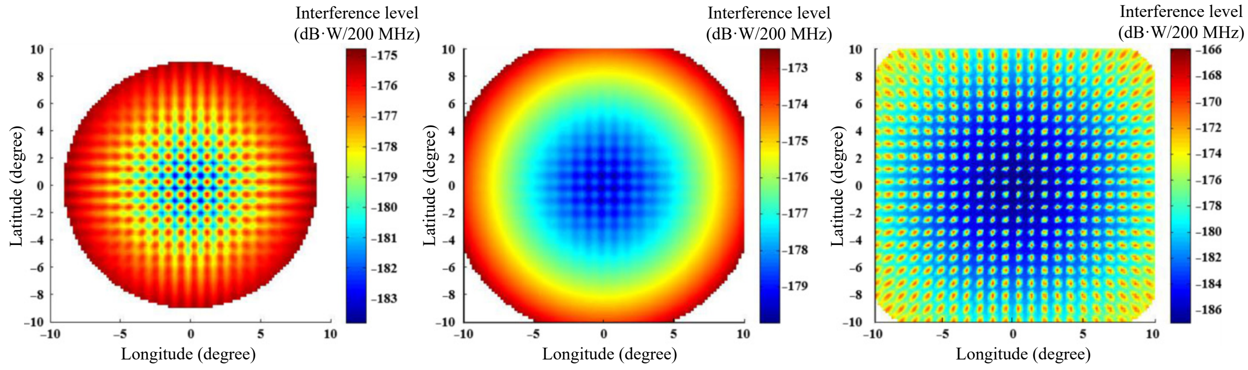
$$\text{PFD} = \begin{cases} 0.875\theta - 143, & 0^\circ \leqslant \theta < 8^\circ; \\ 2.58\theta - 156.6, & 8^\circ \leqslant \theta < 20^\circ; \\ 0.375\theta - 112.5, & 20^\circ \leqslant \theta < 60^\circ; \\ -90, & 60^\circ \leqslant \theta < 90^\circ \end{cases} \quad (1)$$

where θ is the angle of arrival of the incident wave above the horizontal plane, in degree[53]. Assume an isotropic radiator is situated at the center of the sphere having radius r, PFD is the ratio of power flow from a transmitter and unit receiver area, in $\text{dB}\cdot\text{W}\cdot\text{m}^{-2}\cdot\text{MHz}^{-1}$.

2.2.2 Sharing and compatibility of EESS and HAP systems operating in 31.0–31.3 GHz frequency range

With the worst case adopted in simulations over the ocean and the world, results are presented in Fig. 3. It represents the aggregate interference received by the EESS satellite receiver from all HAPSs with different satellite beam pointing directions.

The maximum impact corresponds to an EESS receiver antenna gain of 45 dBi (sensor G3) and



(a) Sensor G1 (b) Sensor G2 (c) Sensor G3

Fig. 3 Aggregate interference received by the EESS satellite receiver from all HAPSs (worst case).

is equal to –165.9 dB·W/200 MHz as indicated in Table 4. The worst case aggregate impact is 5.1 dB·W/200 MHz lower than the EESS protection criteria, which is –171 dB·W/200 MHz taking into account 5 dB·W/200 MHz apportionment.

In order to ensure the protection of the EESS (passive), the level of unwanted emission Equivalent Isotropically Radiated Power (EIRP) density per HAPS transmitter operating in the frequency band 31.0–31.3 GHz into the frequency band 31.3–31.8 GHz shall be limited to

$$\text{EIRP} = \begin{cases} -\theta - 13.1, & -4.53^\circ \leqslant \theta < 22^\circ; \\ -35.1, & 22^\circ \leqslant \theta < 90^\circ \end{cases} \tag{2}$$

2.3 Review of current spectrum band of 38.0–39.5 GHz

The frequency band 38.0–39.5 GHz and 1500 MHz spectrum bandwidth to fixed service appeared debut for operating HAPS since resolution 160 indicated that it was necessary to study 38.0–39.5 GHz on a global primary basis to meet any spectrum needs which could not be satisfied[54].

In the 1990s, some studies reclaimed to utilize higher frequencies including 38 GHz, offering wideband internet access, entertainment video, and audio services[55]. In December 1999, the third European workshop on techno-economics for multimedia networks and services was held in Aveiro, during which the telecommunication project Halo designed for 38.0 GHz bringing broadband fixed multimedia services was firstly introduced[56].

Table 4 Maximum interference level.

Sensor	Maximum interference level (dB·W/200 MHz)
G1	–174.8
G2	–172.4
G3	–165.9

Note: G1, G2, and G3 are different sensors of EESS, see details in Report ITU-R F.2473[53].

Decades ago, HAPS application obtained the permission in 6, 28, 31, and 47 GHz. The frequency band of 38.0–39.5 GHz was proposed to be used for fixed services after WRC-15 indicated that it was necessary to study the use of band 38.0–39.5 GHz on a global basis to meet spectrum needs which could not be satisfied with available bands[54].

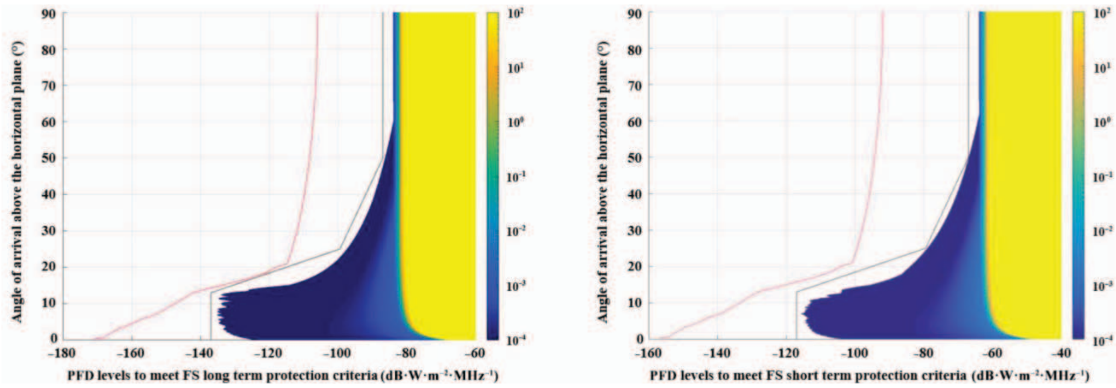
Re-emerged in 2016–2019 study period, WP5C initiated the study report on the sharing and compatibility studies of HAP systems in 38.0–39.5 GHz frequency range with the fixed service, the MS and FSS to which the bands are allocated on a primary basis, and also with the space research service in the adjacent band[57].

Most of the study results revealed for 39 GHz were adopted by WRC-19, and relevant provisions with regard to fixed service and FSS GSO earth station were incorporated in resolution 168.

2.3.1 Sharing and compatibility of FS and HAP systems operating in 37.9–38.2 GHz frequency range

According to ITU-R F.2475, the proposed HAPS PFD mask to protect FS receivers is compared with maximum PFD level of system 4a. As shown in Fig. 4, PFD of system 4a meets the proposed PFD mask requirements. It is therefore possible to design an HAP system which can protect FS receivers well enough[57].

Figure 4 presents the relationship between the PFD at FS station receivers and angle of arrival. The relationship



(a) (b)

Fig. 4 HAP system 4a compliance with the proposed PFD mask.

is formulated as

$$\text{PFD}=\begin{cases}-137, & 0°\leqslant\theta<13°;\\ -137+3.125(\theta-13), & 13°\leqslant\theta<25°;\\ -99.5+0.5(\theta-25), & 25°\leqslant\theta<50°;\\ -87, & 50°\leqslant\theta<90°\end{cases}\quad(3)$$

Note that the PFD level shown above is derived from a maximum interference level of –147 dB·W·m^{-2}·MHz^{-1} (i.e., Interference Noise Ratio (INR) = –10 dB not to be exceeded more than 20% of the time) for the long-term protection criteria. The FS parameters, deployment density, and FS antenna patterns are based on ITU recommendations[58–61]. Gaseous atmospheric attenuation is considered.

2.3.2 Sharing and compatibility of FSS GSO earth station and HAP systems operating in 37.9–38.2 GHz frequency range

As explained and illustrated in the above paragraph, as any other stations of the fixed service, HAPS can be coordinated on a case-by-case basis with individual GSO FSS earth stations in 38.0–39.5 GHz.

For that, it is proposed to trigger coordination on the basis of the minimum angle at the GSO FSS earth station between the line to the HAPS and the line to the GSO arc. The GSO FSS earth station antenna pattern conforms to ITU-R S.465–5[62], and by using a 68 dBi antenna gain, the GSO FSS antenna patterns of a 6.8 m antenna at 39 GHz are

$$G=\begin{cases}68-1954\varphi^2, & 0°\leqslant\varphi<0.136°;\\ 32, & 0.136°\leqslant\varphi<1°;\\ 32-25\log\varphi, & 1°\leqslant\varphi<47.9°;\\ -10, & 47.9°\leqslant\varphi<180°\end{cases}\quad(4)$$

where φ denotes the minimum angle at the GSO FSS earth station between the line to the HAPS and the line to the GSO arc (in degree) and G is the antenna gain in dB.

Hence, the maximum PFD produced by an HAPS can be expressed as

$$\text{PFD}_{\text{max}}=\begin{cases}-169.9+1954\varphi^2, & 0°\leqslant\varphi<0.136°;\\ -133.9, & 0.136°\leqslant\varphi<1°;\\ -133.9+25\log\varphi, & 1°\leqslant\varphi<47.9°;\\ -91.9, & 47.9°\leqslant\varphi<180°\end{cases}\quad(5)$$

The PFD produced by the HAPS can be calculated as

$$\text{PFD}_{\text{req}}=\text{EIRP}_{\text{max}}-10\log_{10}(4\pi d^2)-\text{Att}_{\text{gaz}}\quad(6)$$

where d is the distance between the HAPS and the GSO FSS earth station (in m), Att_{gaz} is attenuation to atmospheric gazes on the HAPS to GSO FSS earth station path (in dB), PFD_{req} is the required PFD at the GSO FSS earth station location to meet the FSS protection criteria (in dB·W·m^{-2}·MHz^{-1}), and EIRP_{max} is the maximum EIRP spectral density in the direction of the GSO FSS earth station (in dB · W · MHz^{-1}).

2.4 Review of current spectrum bands of 47.2–47.5 and 47.9–48.2 GHz

The spectrum band 47.0–47.5 GHz had been identified to HAPS application on worldwide basis in the RR in WRC-97, while technique of site diversity for satellite to earth radio links exploited the fact that high rain rates were associated with relatively small rain cells, at the order of a few kilometers in diameter[63].

In 1997, resolution 122 of WRC-97 requested urgent studies on the appropriate technical sharing criteria between systems using HAPS in the FS and systems in the fixed-satellite and mobile services in the bands

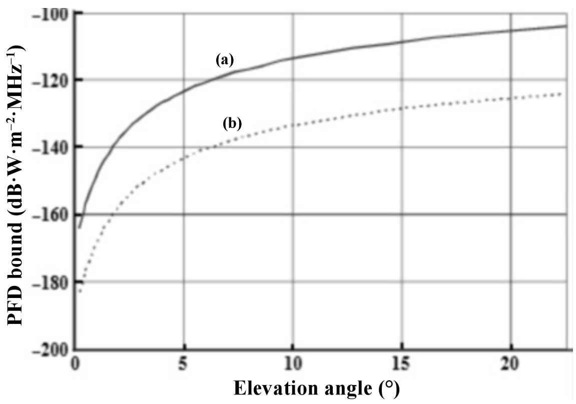
47.2–47.5 and 47.9–48.2 GHz[64].

In 2000, ITU-R F.1500 was published, presenting a set of technical parameters for high-density applications in the FS using high altitude platform[65]. In the meantime, ITU-R F.1501 provided calculation methods to determine coordination distances between the fixed service using HAPS and other systems in the fixed service in the bands 47.2–47.5 and 47.9–48.2 GHz[66].

2.4.1 Sharing and compatibility of FS and HAP systems operating in 47.0–47.5 GHz frequency range

The solid curve in Fig. 5 depicts the computed PFD bound as a function of the elevation angle of the HAPS as viewed from the fixed service station. The dashed curve shows the same bound after the 20 dB rain attenuation margin has been subtracted. Note that the computed PFD bound (20 dB·W·m^{-2}·MHz^{-1}) is fairly flat for elevation angles above 13°, and drops abruptly for elevation angles below 3°[67].

Figure 6 depicts the variation of the atmospheric attenuation due to atmospheric gases in 47.2–48.2 GHz band as a function of the elevation angle of the HAPS platform viewed from the fixed service station, in accordance with ITUR F.1501[66]. It indicates that the atmospheric attenuation remains small (0.57 dB at 90° and 1.9 dB at 22.5° or ∼ 50 km from nadir), until the elevation angle drops below 13° (atmospheric attenuation = 3.4 dB, distance ∼ 90 km from nadir), at which point the atmospheric attenuation increases almost exponentially, reaching a value of 42.2 dB at 0.154° (approximately 500 km from nadir). At 3° (∼ 280 km from nadir), the atmospheric attenuation is 13.9 dB. Note that the atmospheric attenuation decreases rapidly with altitude of the ground station. Above 10 km in altitude, the atmospheric attenuation varies from 0.47 to 1.22 dB between 76 and 200 km (from nadir).



Curve (a): PFD bound for EESS; Curve (b): PFD bound with attenuation margin for EESS.

Fig. 5 PFD bound vs. elevation angle.

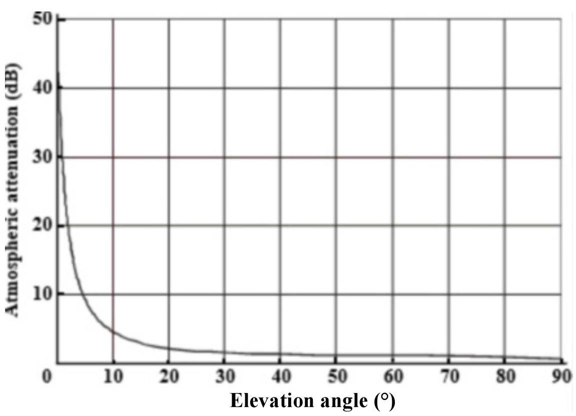


Fig. 6 Atmospheric attenuation vs. elevation angle.

2.4.2 Sharing and compatibility of RAS and HAP systems operating in 47.0–47.5 GHz frequency range

Figure 7 shows the estimated upper bound for the interference PFD that an RAS station at a distance between 50 and 500 km from the nadir of the HAPS platform is expected to experience. A transmitting bandwidth of 11 MHz and a combined cable/feeder loss of 5 dB are assumed, and the total stop-band attenuation of 95 dB is used to obtain the final results. The computed Spectral Power Flux-Density (SPFD) is in the range of –176.3 and –236.6 dB·W·m^{-2}· MHz^{-1} for distances of 50 and 500 km, respectively, as represented by the solid curve[68].

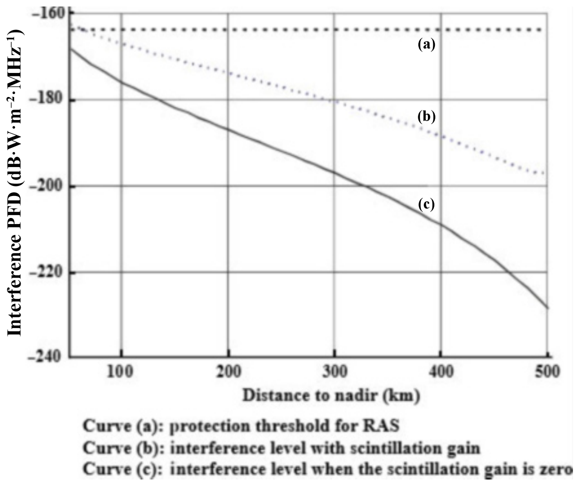


Fig. 7 Interference PFD vs. distance to nadir.

It is proposed in resolution 122 (Rev. WRC-19) that for the purpose of protecting radio astronomy observations in 48.94–49.04 GHz band from an HAPS platform operating in the frequency bands 47.2–47.5 and 47.9–48.2 GHz, the separation distance between an RAS antenna and the nadir of an HAPS platform should exceed 50 km.

In summary, reflected by WRC-19, the promotion of identification for using HAPS gained significant progress for global harmonization both in status and areas. Seven different spectrum bands approved to use HAPS by new identification, appropriate modification, and exquisite amendment, and Table 5 shows the majority spectrum bands finalized in WRC-19.

In WRC-19, both identification for using HAPS at 6 GHz lower band (6440–6520 MHz) and higher band (6560–6640 MHz) are None Of Change (NOC), maintaining a 5-country footnote on a secondary basis in the bands 6440–6520 MHz (HAPS-to-ground direction) and 6560–6640 MHz (ground-to-HAPS direction), to the RR. Generally, NOC in terms of HAPS application identification in 27.9–28.2 GHz, with China being added to footnote 5.537A and revision of resolution 145.

In particular, 31.0–31.3, 38.0–39.5, 47.2–47.5, and 47.9–48.2 GHz are especially enormous ameliorate on the evolution of HAPS, converting into a more practicable and available spectrum bands.

The spectrum band 31.0–31.3 GHz, prescribed via a 23-country footnote on a secondary basis in the ground-to-HAPS direction is paired with 28.9 – 31.2 GHz before WRC-19, identified for worldwide use by HAPS on a primary basis without limitation of direction in WRC-19, expanding the flexibility for implementing HAPS with less concerns on automatic power control issues.

The spectrum band 38.0–39.5 GHz, a spectrum band unidentified to HAPS application with a 1.5 GHz broadband before WRC-19, was identified for worldwide use by administration wishing to implement HAPS on a semi-primary, the HAPS ground station shall not claim protection from stations in the fixed, mobile, and fixed-satellite services, based on both direction. Bands 47.2–47.5 and 47.9–48.2 GHz have been adopted with appropriate modification for better use of this band in case of the raining attenuation.

3 Sharing study between HIBS and IMT-advanced system

On March 2018, at the 3rd meeting of Asia-Pacific Intercommunity (APT) Conference Preparatory Group, a proposal contributed from Japan was considered as an initial idea for inclusion in the agenda of future WRC meetings[69]. The proposal was to consider identification to use HIBS to provide IMT in the frequency bands around and below 2 GHz that have been already identified to IMT, and whether changes are needed to the set of existing bands identified for use by HIBS.

The HIBS was unveiled rapidly, directing liaison statement to the 23rd meeting of the APT Wireless Group in April 2018 and requesting the study results in a timely manner[70]. The proposal of HIBS has gone through the long evolution in APT Wireless Group (AWG), ITU-R SG5 WP5D, and WRC-19, and

Table 5 Summary of spectrum bands finalized in WRC-19.

Spectrum band (GHz)	Range	Status	Direction	Footnote	Prevision
6			NOC		
28	China added		NOC		Resolution 145 (WRC-19)
31	Worldwide	Primary	HAPS-to-ground and ground-to-HAPS	5.543B	Resolution 167 (WRC-19)
38	Worldwide	Semi-primary	HAPS-to-ground	5.550D	Resolution 168 (WRC-19)
38	Worldwide	Primary	Ground-to-HAPS	5.550D	Resolution 168 (WRC-19)
47	Worldwide	Primary	HAPS-to-ground and ground-to-HAPS	5.552A	Resolution 122 (Rev.WRC-19)

Note: Table 5 is the brief achievement in WRC-19 approved by 3 regions. Region 1 contains CEPT, ASMG, ATU, and RCC; region 2 is represented by CITEL, and region 3 is represented by APT. CEPT: European Conference of Postal and Telecommunications administrations. ASMG: Arab Spectrum Management Group. ATU: African Telecommunication Union. RCC: Regional Commonwealth in the field of Communications. CITEL: Inter-American Telecommunication Commission. APT: Asia-Pacific Telecommunity. Semi-primary reflects to "HAPS ground station shall not claim protection from stations in the fixed, mobile, and fixed satellite services; and No. 5.43A does not apply", which means HAPS application is a primary service but still has constraints.

matured as a new AI 1.4 in WRC-23 with a new resolution 247[29]. However, the HIBS application is a novel conception expecting to earn permission or authorization on future WRC-23. Consequently, there is no commercial HIBS systems, which is the reason that scenarios and characteristics in this section are based on assumptions offered by contributions in WRC WP5D[71].

In this section, a preliminary sharing study between HIBS and IMT-Adavanced (IMT-A) systems on spectrum bands 1710–1885 MHz mentioned in resolution 247 is presented aiming at providing the general simulation processes and offering the preliminary results as future possible references.

3.1 Simulation scenario

In this section, two coexistence scenarios are tested, single HIBS to IMT-A system and single HIBS station with multi-beam antenna pattern to IMT-A system under variable distances. In this section, the interference from HIBS to IMT-A UEs and BSs is mainly considered. One important parameter involved in evaluating the interference is the protection criteria. This criterion is set to protect the IMT-A system from the interference of HIBS since these two systems are likely to be deployed on same frequency bands. Note that the value of this protection criterion is irrespective of the number of cells and independent of the number of interference sources. The protection criterion is evaluated by the Interference Noise Ratio (INR), and is −6 dB in this paper. The INR is defined as

$$\mathrm{INR} = I/N \tag{7}$$

where I is the interference level and N is the noise power of the HIBS system. The INR is the ratio of the inter-system interference level received in the IMT-A receiver relative to the receiver's noise level.

3.1.1 A single HIBS to single IMT-A system

Deployment scenario for the single HIBS interfering IMT-A system is illustrated in Fig. 8. Intuitively, the larger the distance between the two systems, the lower the INR. The INR at a certain UE under different separation distances d' and antenna orientation angles θ_o can be calculated by

$$\mathrm{INR}(d', \theta_o) = \mathrm{EIRP_{HIBS}} + G_{\text{IMT-BS}}(d', \theta_o) - \mathrm{PL} - L_{\text{body}} - 10\log(kTB) - \mathrm{NF} \tag{8}$$

where d' denotes the separation distance, defined as the distance from center of HIBS service to IMT-A system, θ_o is the antenna orientation angle of the UE, which is defined by the projection of angle between the unit vector which is orthogonal to the plane of the antenna panel and the x axis on the x-y plane chosen in simulations ($\theta_o \in (0, 2\pi]$). $\mathrm{EIRP_{HIBS}}$ is the EIRP of HIBS in each beam specified in Table 6, $G_{\text{IMT-BS}}$ is the transmission antenna gain of IMT-A UE/BS specified in Table 7, PL denotes the total path loss, summed by free pace loss and gaseous attenuation, $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant, $T = 300$ K is the noise temperature, $B = 175$ MHz is the spectrum bandwidth, NF is the IMT-A receiver noise figure defined in Table 7, and L_{body} is the body loss. The body loss is 0 dB for BS and 3 dB for UE, respectively. Gaseous attenuation that is used to calculate PL is the interfering signal between the HIBS and the IMT-A receiver for iteration n, following ITU recommendations[72].

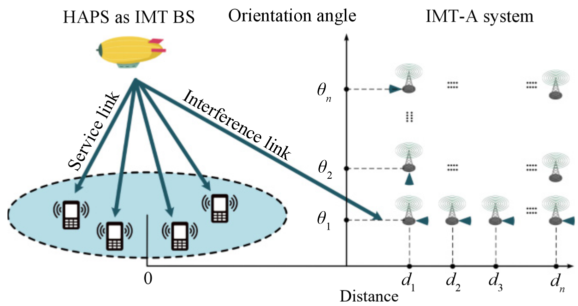


Fig. 8 Deployment scenario for the single HIBS interfering IMT-A system.

Table 6 System characteristics of HIBS (HIBS-to-ground direction).

System	Frequency (MHz)	Occupied bandwidth (MHz)	Height (km)	Number of beams	Number of co-frequency beams	Polarization	Tx gain (dBi)	EIRP per beam (dB·W)	EIRP spectral density per beam (dB·W·MHz^{-1})	Antenna pattern
Single HIBS	1710–1885	18	20	1	1	V/H	17	30	17.4	N/A
HIBS with multi-beam	1710–1885	18	20	7	7	V/H	17	30	17.4	ITU-R M.1891[68]

Table 7 Deployment-related characteristics for bands between 1 and 3 GHz.

Terminal	Characteristic	Value
BS	Antenna height (m)	30
	Downtilt (degree)	3
	Antenna pattern	ITU-R F.1336 (recommends 3.1) ka = 0.7 kp = 0.7 kh = 0.7 kv = 0.3 Horizontal 3 dB beamwidth: 65 degree Vertical 3 dB beamwidth: determined from the horizontal beamwidth by equations in ITU-R F.1336. Vertical beamwidths of actual antennas may also be used when available.
	Antenna polarization (degree)	Linear/±45
	Maximum BS output power (5 MHz/10 MHz/20 MHz) (dBm)	43/46/46
	Maximum BS antenna gain (dBi)	18
	Maximum BS output power/sector (5 MHz/10 MHz/20 MHz/) (dBm)	58/61/61
	Noise figure (dB)	5 (macro) 10 (micro) 13 (pico/femto)
UE	Maximum user terminal output power (dBm)	23
	Average user terminal output power (dBm)	2
	Typical antenna gain for user terminals (dBm)	−3
	Body loss (dB)	4

Different INR values under different distances and antenna orientation angles can be calculated by Eq. (8). Within all the INR values, which can satisfy the protection criteria, the minimum protect distance $d_{\min}$ is the minimum distance between IMT-A system and HIBS, which can give an INR satisfying the criteria. As specified earlier in this paper, the protection criterion is −6 dB, which gives

$$d_{\min} = \min\{d'\},\quad \text{s.t.}\quad \exists\theta_{\rm o}, \mathrm{INR}(d', \theta_{\rm o}) \leqslant -6\,\mathrm{dB} \tag{9}$$

3.1.2 A single HIBS platform with multi-beam to single IMT-A system

The beam number of HIBS is 7 as listed in Table 6, assuming the antenna pattern projection of beams form like a regular hexagon as it is shown in Fig. 9.

Now, we need to calculate the antenna gain in each beam additionally. At this scenario, the levels of interference, namely, $I_{\rm UE}$ and $I_{\rm BS}$ in each beam are calculated by

$$P_{\rm T} = \mathrm{EIRP} - G_{\rm T} \tag{10}$$

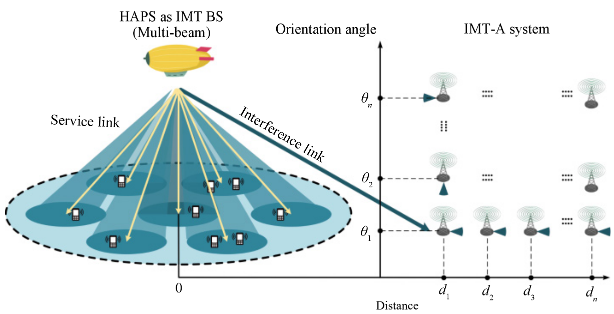


Fig. 9 Deploy scenario for a single HIBS interfere IMT-A system.

$$I_{\rm UE}(b) = P_{\rm T} + G_{\rm HAPS}(\theta_{\text{off-axis}}(b)) + G_{\text{IMT-UE}} - \mathrm{PL} - \mathrm{NF} - L_{\rm body} \tag{11}$$

$$I_{\rm BS}(b) = P_{\rm T} + G_{\rm HAPS}(\theta_{\text{off-axis}}(b)) + G_{\text{IMT-BS}}(\delta(b), \theta_{\rm o}(b)) - \mathrm{NF} - L_{\rm body} \tag{12}$$

where $G_{\rm T}$ denotes the HIBS platform transmission antenna gain, $G_{\text{IMT-UE}}/G_{\text{IMT-BS}}$ is the IMT-A UE/BS transmission antenna gain, $G_{\rm HAPS}(\theta_{\text{off-axis}})$ is the antenna gain at the angle $\theta_{\text{off-axis}}$ from the main beam direction calculated by ITU-R F.1891 (dBi)[68], and $\delta(b)$ is the azimuth angle of each IMT-A BS. The aforementioned parameters are specified in Tables 6 and 7.

The aggregate interference level at the IMT-A BS/UE is calculated from the addition of interference from all beams of the HIBS by

$$I_{\mathrm{BS/UE}} = 10\log\left(\sum_{b=1}^{b_n} 10^{I_{\mathrm{BS/UE}}(b)/10}\right) \quad (13)$$

where b_n is the number of co-frequency beams ($b_n = 7$ in this section).

The interference PFD in each beam is calculated by

$$\mathrm{PFD}_{\mathrm{UE}}(b) = I_{\mathrm{UE}} + 10\log_{10}\left(\frac{4\pi}{\lambda^2}\right) - G_{\text{IMT-UE}} + L_{\mathrm{body}} + \mathrm{Att}_{\mathrm{gaz}}(\delta, \theta_{\mathrm{o}}) + L_{\mathrm{f,IMT}} \quad (14)$$

$$\mathrm{PFD}_{\mathrm{BS}}(b) = I_{\mathrm{BS}} + 10\log_{10}\left(\frac{4\pi}{\lambda^2}\right) - G_{\text{IMT-BS}}(\delta(b), \theta_{\mathrm{o}}(b)) + L_{\mathrm{body}} + \mathrm{Att}_{\mathrm{gaz}}(\delta, \theta_{\mathrm{o}}) + L_{\mathrm{f,IMT}} \quad (15)$$

where $L_{\mathrm{f,\,IMT}}$ is the factor loss of the IMT terminal and λ is the wavelength (in m).

The aggregate interference PFD at the IMT-A receiver is calculated from the addition of interference from all beams of the HIBS by

$$\mathrm{PFD}_{\mathrm{BS/UE}}(\theta) = 10\log\left(\sum_{b=1}^{b_n} 10^{\mathrm{PFD}_{\mathrm{BS/UE}}(b)/10}\right) \quad (16)$$

where $\mathrm{PFD}_{\mathrm{BS/UE}}(\theta)$ is in the unit of $\mathrm{dB{\cdot}W{\cdot}m^{-2}{\cdot}MHz^{-1}}$.

3.2 Simulation setup

This sharing study adopts PFD mask and minimum coupling loss method to analyze the potential coexistence conditions between HIBS and IMT-A systems. HIBS provides service to ground UE, and the interference from HIBS-to-ground direction is considered. It is necessary to consider the interference from HIBS to IMT-A system.

3.2.1 HIBS system characteristic

It is considered that HIBS may deploy in the rural area, and Table 6 displays the characteristics and parameters of a single HIBS system. The parameters are chosen based on the 31st meeting of WP5D document 5D/TEMP/620 and AWG-24 document AWG-24/INP 83[70].

3.2.2 IMT-A system characteristic

The IMT-A parameters used in this simulation are based on ITU-R M.2292 and ITU-R M.2101. Table 7 shows characteristics of IMT-A BS and UE[73,74].

3.2.3 Other simulation setup

When calculating INR values according to Eq. (8), the values of θ_{o} are chosen from a total of n possible values, $\theta_{\mathrm{o}(1)}, \theta_{\mathrm{o}(2)}, \ldots, \theta_{\mathrm{o}(n)}$. For $1 \leqslant i \leqslant n$, $\theta_{\mathrm{o}(i)} = \frac{(i-1)2\pi}{n-1}$. The values of d' are also chosen from n possible values, creating a grid with different values of d' and θ_{o}. In the simulation, a total of n^2 combinations of d' and θ_{o} are used to calculate INR under different cases. The n used in this section is 1800. Multiple simulations were conducted with n larger than 1800 and similar results were obtained.

3.3 Simulation result

3.3.1 Single HIBS platform with multi-beam to single IMT-A system

The results of INR are identical for all antenna orientation angles of the UE, since the antenna gains are the same from all directions of the omnidirectional antenna of the UE. Figure 10 shows the calculated INR for HIBS to UE. The results are based on the EIRP. INR decreases with the increase of the protect distance smoothly on a large scale. When the IMT-A UE is right at the direction of the side lobe of the HIBS antenna, the INR could increase as shown in Fig. 10 where the protect distance is approximately 65 km. The starting point of the protect distance in this simulation is 50 km, because the IMT-A system must distribute out of the service range of HIBS with the coverage radius of 50 km, and the separation distance between the edge of HIBS service and IMT-A system is defined as protect distance minus 50 km. As shown in Fig. 10, the calculated INR is below the IMT-A protection criteria, which is –6 dB, for any protect distance.

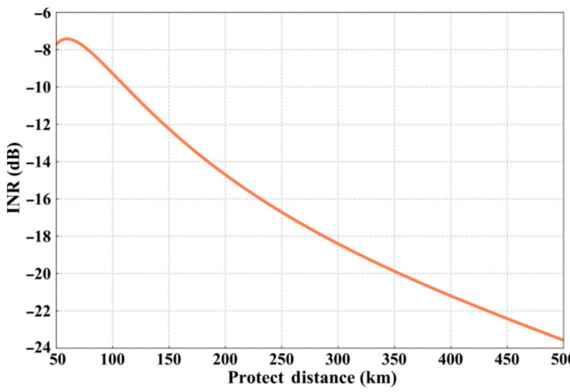


Fig. 10 INR of UE vs. protect distance.

The BS case for each kind of simulation may differentiate the orientation angle (from 0° to 360°) of the BS antenna, because the antenna gain may be different for all directions in the antenna pattern according to ITU-R recommendation F.1336[75]. The situation is divided into two cases for the best and worst case scenario when $\theta_o = 0°$ and 180°, respectively.

When $\theta_o = 0°$, as shown in Fig. 11, the INR is below –6 dB for a protect distance of 210 km, which is equivalent to a separation distance of 160 km. INR decreases with the increase of the protect distance smoothly on a large scale. When the IMT-A UE is right at the direction of the side lobe of the HIBS antenna, the INR could increase a bit as can be observed from Fig. 11. When the protect distance is 75–250 km, INR decreases significantly with protect distance because the antenna gain of both HIBS and IMT-A BS decreases significantly. When the protect distance is larger than 250 km, the antenna gain decreases slowly and INR mainly depends on the protect distance.

Figure 12 shows the calculated INR for HIBS to BS.

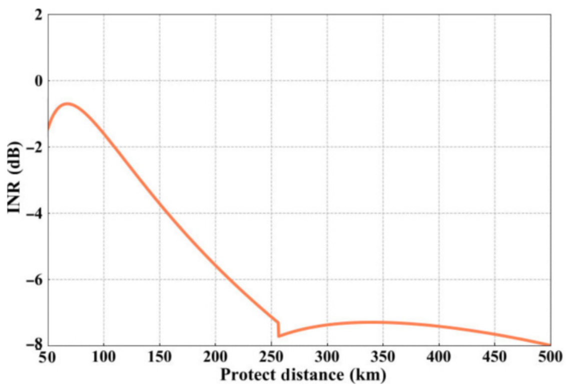


Fig. 11 INR of BS when θ_o = 0°.

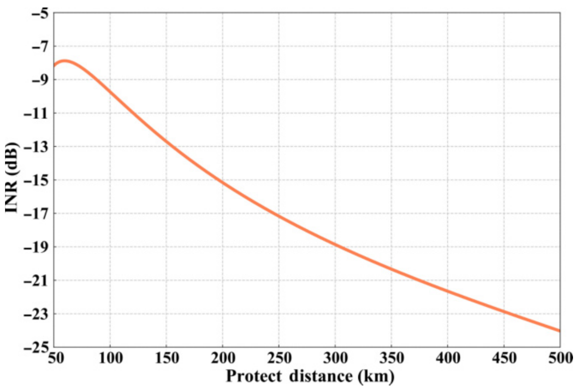


Fig. 12 INR of BS when θ_o = 180°.

The results are based on the EIRP. The protect distance starts at 50 km because the IMT-A system must distribute out of the service range of HIBS, whose coverage radius is 50 km. Similar to Fig. 10, INR decreases with protect distance and is subject to changes caused by the side lobe of antenna of HIBS.

As shown in Fig. 12, the calculated INR is below the IMT-A protection criteria (–6 dB) for any distance, there shall be no significant interference between HIBS and IMT-A BS when θ_o = 180°.

3.3.2 Single HIBS platform with multi-beam to single IMT-A system

Results illustrated in Fig. 13 indicate that the coexistence between a single HIBS platform with multi-beam and a single IMT-A system in same geographic region shall be feasible by following Eq. (17). The blue line and orange line show the PFD level in variable elevation angles of IMT-A UE and BS. This case is the worst case, because $\theta_o = 0°$ and the antenna gain of any IMT-A BS receiver was larger than any other θ:

$$\mathrm{PFD_{mask}}(\theta)=\begin{cases}-90+1.333\times\theta, & 0°\leqslant\theta<3°;\\ -110+8\times\theta, & 3°\leqslant\theta<75°;\\ -77, & 75°\leqslant\theta<90°\end{cases} \tag{17}$$

3.4 Summary and analysis of simulation result

In this section, the interference on IMT-A systems by a single HIBS with and without beamforming is evaluated. The simulation results of the protect distance for HIBS towards IMT-A UEs present a feasible way to implement HIBS with the given characteristics. The separation distance of 160 km between HIBS and IMT-A BSs is necessary according to the simulation of the worst case

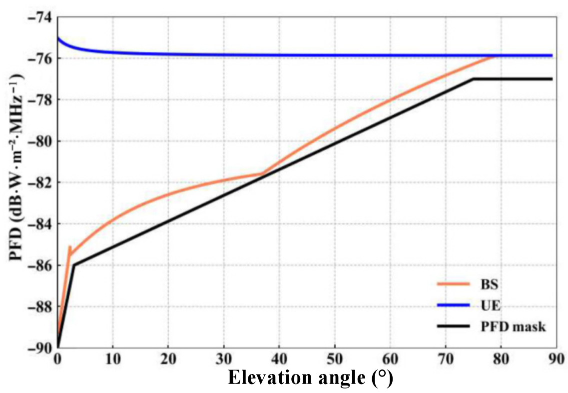


Fig. 13 PFD mask when θ_o = 0°.

scenario showing above. In addition, the PFD mask for the worst case scenario is also provided, indicating a more flexible way to protect IMT-A systems.

As also discussed in WRC-19, the PFD mask is a more flexible way to evaluate the interference to IMT-A systems. Evaluating the interference by the PFD mask has certain advantage over using the separation distance since by using the separation distance for protecting other services, while the actual geographical conditions and weather situations are overlooked. It's more than intuitive that two HIBSs with equal distance to a same IMT-A system can pose different interferences on the victim system due to the different geographical conditions and factors other than the distance, which might have impact on the received power of interfering signals at the victim system. As a matter of fact, the PFD mask based evaluation method has already been applied to the coexistence study of HAPS application. It is anticipated that the PFD mask based evaluation method will be used in future coexistence studies on HIBS and other systems thanks to its advantage in greater flexibility and accuracy.

Simulation results also provide a basic and universal model for compatibility studies between HIBS and other wireless systems. Whether the victim system is IMT-A or not, the simulation model can be generalized based on Eq. (8) with appropriate modifications. The following studies with more complex architectures and more accurate system characteristics will be developed and discussed in ITU-R WP5D in WRC 2020–2023 study period.

4 Outlook and challenge

The United Nation Sustainable Development Goals (SDGs) recognize that the spread of ICT has great potential to accelerate human progress, to bridge the digital divide, leverage sound economy, and build a better society. In particular, SDG Target 9.c aims to build resilient infrastructures, promoting inclusive and sustainable industrialization and fostering innovation. To achieve this objective, development of advanced telecommunication network is necessary. In recent years, with development of stratospheric telecommunication and satellite technology, the implement of STIN is recruiting various multidimensional technologies through fields in satellite, space, high altitude platform, and terrestrial systems progressively. This trend will continue and potentially create new applications and frost new markets.

As HAP systems receive more and more attention, the ITU has agreed to allocate more frequency bands to be used by such systems. In WRC-19, the conference agreed that frequency bands 31.0–31.3 and 38–39.5 GHz are identified for worldwide use by HAPS. They also confirmed that existing worldwide identifications for HAPS application in the bands 47.2–47.5 and 47.9–48.2 GHz are available for worldwide use by administrations wishing to implement HAPSs. In addition, there is a new agenda item to study HIBS in existing IMT bands below 2.7 GHz aiming to provide more flexibility on the use of these bands in ITU, in order to address the need to expand coverage and capacity in mobile broadband networks. With more frequency bands already allowed to be used by HAPS and the foreseeable allocation of more frequency bands for HIBS, we believe that HAP systems will gradually be developed and deployed in more countries and regions in the world to help create seamless connection complementing the terrestrial based wireless networks like the 5G/B5G.

HAP systems enjoy noticeable advantages than terrestrial networks in both civilian and military applications with much larger coverage area and less interference. HAP systems are also more resilient to disasters and cost shorter time and even less investment for deployment. In comparison with satellite based communication systems, lower latency and the possibility of return for maintenance or payload reconfiguration are some of the main advantages of HAP systems. In the future, we believe that HAP systems will evolve and emerge into new forms with possible connections to terrestrial based systems, satellite based systems, and marine based systems. There are already discussions going on to integrate HIBS into IMT systems by allowing HIBS to use same bands as terrestrial based IMT systems, which we think is one of the important future topics to be studied.

There are still challenges to overcome and doubts to relieve before the deployment of HAP systems in massive scale. Some major open issues of technical concerns towards HAP systems include the rain attenuation and the power supply. Since HAP systems are deployed above the clouds, the BSs are likely to suffer from heavy cloud causing significant attenuation even temporary blockage to the radio link, especially when HAP systems operate on mostly high-frequency bands, in the other hand, HIBS applications operating on low frequency bands could cause terrible interference as well. This issue, how to solve the feeder links block cloud, can possibly be alleviated by utilizing links to satellites and other HAPS, HIBS or satellites. When one HIBS cannot serve some particular UEs because of blockage due to cloud, for instance, that HIBS can instruct the UEs to handover to other HIBSs, which serve as relay nodes. Consistent energy source is another issue to be further studied, to ensure such airborne BSs, which might consume significant power, will operate steadily for a sufficient period of time. How to optimize the design for HAPS and HIBS to keep them as light-weighted and meanwhile as reliable as possible is also an issue that needs investigating. There are also some challenges posed on the regulatory side. For one thing, HAP systems might drift to the sovereignty of a different country than initially deployed, which might trigger geopolitical tensions if not handled delicately. The operators of HAP systems also need to take civil flight safety into account when choosing positions to deploy airborne stations. The above-mentioned advantages, drawbacks, and regulatory challenges are matter of discussion within the ITU-R community and Study Groups. That is certainly an encouragement to the proponents of HAPS applications, and in particular those of HIBS, to join the discussion and contribute with technical feasibility studies in support of their positions.

We see the future of wireless communications as an emerged network with BSs and devices located on the land, in the sea and the sky. HAP system, with its rapid growth and huge potential to realize, will be an important part of it. Combining with innovative use cases, such as remote industrial management, tele-health, digitized farmland with automatic and remote control and virtualized farming and shopping, industrial internet of things, and smart city management, HAP systems will play an ever important role in wireless communications and our lives.

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Dong Zhou received the master degree in computer software and theory from Xi'an Jiaotong University in 2009 before joining ZTE Corporation. He is now the director of spectrum policy and regulatory affairs at ZTE Corporation. His research interests include radio regulations, radio communicaiton technical policy, sharing and compatibility studies, cognitive radio and reconfigurable radio systems, high altitude platform systems, and satellite communication. He holds more than 20 authorized patents in wireless communication. He serves as the vice chairman of spectrum group of Global mobile Suppliers Association (GSA), spectrum working group of wireless communication committee of CCSA, and spectrum working group of future mobile communication forum. In WRC-15 study cycle, he was the APT coordinator of agenda item 1.14.

Feifei Gao received the BEng degree from Xi'an Jiaotong University in 2002, the MSc degree from McMaster University, Hamilton, Canada in 2004, and the PhD degree from National University of Singapore, Singapore in 2007. Since 2011, he joined the Department of Automation, Tsinghua University, where he is currently an associate professor. His research interests include signal processing for communications, array signal processing, convex optimizations, and artificial intelligence assisted communications. He has authored/coauthored more than 150 refereed IEEE journal papers and more than 150 IEEE conference proceeding papers that are cited more than 8000 times in Google Scholar. He has served as an editor of *IEEE Transactions on Wireless Communications*, *IEEE Journal of Selected Topics in Signal Processing* (Lead Guest Editor), *IEEE Transactions on Cognitive Communications and Networking*, *IEEE Signal Processing Letters*, *IEEE Communications Letters*, *IEEE Wireless Communications Letters*, and *China Communications*. He has also serves as the symposium co-chair for 2019 IEEE Conference on Communications (ICC), 2018 IEEE Vehicular Technology Conference spring (VTC), 2015 IEEE Conference on Communications (ICC), 2014 IEEE Global Communications Conference (GLOBECOM), and 2014 IEEE Vehicular Technology Conference fall (VTC) as well as the technical committee member for more than 50 IEEE conferences.

Sheng Gao recieved the BS and MS degrees from Xi'an University of Posts and Telecommunications in 2015 and 2018, respectively. Since 2020, he has been a standardization preresearch engineer at ZTE Corporation, acting as the delegate of ZTE at ITU-radiocommunication sector. His research interests include radio spectrum sharing and compatibility study, radio wave propogation modeling, spectrum strategy analysis, and future netwrok research.

Ruiqi Liu received the BS and MS degrees (with honors) in electronic engineering from Tsinghua University in 2016 and 2019, respectively. He is now responsible for research and standardization of latest wireless technologies at the wireless research institute of ZTE Corporation. His research interests include wireless communication systems, reconfigurable intelligent surfaces, wireless positioning, and visible light communication.

Mohsen Guizani received the BS (with distinction) and MS degrees in electrical engineering, the MS and PhD degrees in computer engineering from Syracuse University, Syracuse, NY, USA, in 1984, 1986, 1987, and 1990, respectively. He is currently a professor at the Computer Science and Engineering Department, Qatar University. Previously, he served as different academic and administrative positions at University of Idaho, Western Michigan University, University of West Florida, University of Missouri-Kansas City, University of Colorado-Boulder, and Syracuse University. His research interests include wireless communications and mobile computing, computer networks, mobile cloud computing, security, and smart grid. He is currently the editor-in-chief of the *IEEE Network Magazine*, serves on the editorial boards of several international technical journals, and the founder and editor-in-chief of *Wireless Communications and Mobile Computing Journal* (Wiley). He is the author of nine books and more than 600 publications in referred journals and conferences. He edited a number of special issues in IEEE journals and magazines as guest editor. He also served as the member, chair, and general chair of a number of international conferences. Throughout his career, he received three teaching awards and four research awards. He also received the 2017 IEEE Communications Society WTC Recognition Award as well as the 2018 AdHoc Technical Committee Recognition Award for his contribution to outstanding research in wireless communications and Ad-Hoc sensor networks. He was the chair of the IEEE Communications Society Wireless Technical Committee and the TAOS Technical Committee. He served as the IEEE Computer Society Distinguished Speaker and is currently the IEEE ComSoc Distinguished Lecturer. He is a fellow of IEEE and a senior member of ACM.